Analyzing the Economic Impact of Climate Change on Global Timber Markets

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Abstract

In this paper, we show how ecological and economic models can be linked to determine the economic impact of climate change on global timber markets. We begin by discussing some of the important issues relevant to global impact analyses such as this. We then outline our general modeling framework and discuss the particular models that will be used. Finally, we discuss some of the important issues involved with linking the two types of models.

Keywords: climate change; economic model; timber; timber market; dynamic; optimal control

JEL Classification Nos.: Q10, Q23, Q24

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1. INTRODUCTION

To date, most climate change research attempts to estimate the likely changes in atmospheric conditions that will result from an increase in the level of carbon dioxide in the atmosphere. This research has focused on both the scientific evidence for climate change and the models that can be used to predict the environmental impacts (IPCC, 1990). While many have suggested that climate change will irreparably damage the globe, only recently have researchers begun to consider the economic consequences of climate change (Nordhaus, 1991, and Cline, 1992).

Estimating the economic impacts of climate change brings up several important issues. First, although climate change will affect everybody in some way, the effects are not likely to be distributed evenly across the globe. Economists thus must develop tools to capture the important spatial components of climate change. Second, there is a strong dynamic component to climate change. The Inter-governmental Panel on Climate Change (IPCC, 1990) most likely case suggests that climate change will occur slowly over time as carbon dioxide levels slowly

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increase in the atmosphere. It is entirely possible that discrete changes in climate could occur, but these too exhibit temporal components. Third, climate change will impact the entire globe. To understand what effect it will have on global- and country-level markets, the geographic scope of inquiry must include the entire earth.

In this study, we address these three elements: the spatial detail, the dynamic components, and the global scope. By addressing these issues specifically, we advance the understanding of climate change impacts, and show how ecosystems and humans adjust and adapt to climate change. At this point, the discussion revolves around the methodology we will use, while future papers will present empirical results.

Earlier economic studies predicted that climate change would damage timber markets (Cline, 1992; Callaway et al., 1994). More recent evidence, however, suggests that these predictions may have been premature. While ecological analysis generally predicts that ecosystems may adjust slowly to changes in climate (Neilson, 1993), the integrated analysis of Sohngen and Mendelsohn (1995) suggests that markets will quicken the ecological adjustment as markets adapt to changing conditions. Adaptation and adjustment may ameliorate much of the harmful impact of climate change.

Because timber production is inherently tied to the underlying natural distribution of ecosystems, we must first understand changes in ecosystems before we can assess changes in timber markets. Atmospheric science, natural science, and social science models must be integrated (examples of which include Perez-Garcia et al., 1995; Joyce, 1995; and Sohngen and Mendelsohn, 1995). The Sohngen and Mendelsohn study improves upon the others in two ways. First, it utilizes a forward looking economic model; and second, it provides a broad sensitivity analysis over many potential ecological effects. That study, however, was limited to the United States. Here, we attempt to expand the work of Sohngen and Mendelsohn by incorporating important elements of the global Timber Supply Model (TSM) of Sedjo and Lyon (1990).

We begin by describing the theoretical basis for possible ecological changes due to climate change. We then discuss the two types of ecological models that will be important for global analysis. Although additional models will at some point be included in the analysis, we present results from only two particular models at this point. Using these two models will provide a framework for discussing some of the possible issues involved with joint economic and ecological analysis.

We then discuss the global timber market model that will be used for this research. It is based largely on the earlier work of Sedjo and Lyon (1990) and Sohngen and Mendelsohn (1995). The regions and timber types incorporated into this analysis are described, and we begin to link the ecological and economic models. Although the modeling framework is presented, empirical work is yet to be finished. We thus conclude with some discussion of the issues and considerations we have developed so far.

2. ECOLOGICAL MODELING

2.1. Review of the Literature

Ecologists long have worried that increases in CO2 and the resulting change in climate may drastically impact ecosystems (Shugart et al., 1986; Emanuel et al., 1985). Through increased CO2, and changes in temperature, nutrient cycles and precipitation levels, terrestrial plants may face drastically different growing regimes. Because plants have evolved complex processes for survival within their particular environments, they may be susceptible even to small changes in these conditions.

Warrick, et al. (1986) point out that there basically are two ways in which ecosystems can be affected by increased levels of CO2 in the atmosphere. The first is a direct fertilization effect of added carbon in the atmosphere. Because terrestrial plants by-and-large use CO2 for growth and reproduction, greater levels or concentrations of carbon tend to increase growth rates in plants (Solomon and West, 1985).

Early research into a carbon fertilization indicated that plant growth would increase due to doubled CO2, but the full extent of the effects varied (Solomon and West, 1985, and Strain and Cure, 1985). Korner (1993) surveys the articles in this area, and provides an up-to-date synthesis of major findings. A majority of results of plant level responses suggest that production increases with higher CO2. The level of change, however, may be limited over time due to limitations in other ecological factors, such as water and nitrogen. Unfortunately, the majority of results currently are limited to plant level responses that have been measured in glasshouse experiments. Problems exist with aggregating these to community-level and ecosystem-level responses.

The second impact discussed by Warrick et al. (1986) occurs because temperature and precipitation change under certain climate change scenarios. The link between the distribution of climate variables across the globe and the spatial patterns of vegetation has been recognized for many years (Koppen, 1884; Holdridge, 1947; and Thornthwaite, 1948). Holdridge's system (1947) was one of the first to point out systematically the importance of temperature and humidity in mapping global vegetation patterns. Since that time, others have explored this link in order to extend the basic model (Box, 1981; Neilson et al., 1992; and Prentice et al., 1992). The more recent works by Neilson et al. (1992) and Prentice et al. (1992) have shown that the rather large changes in temperature and precipitation, among other climatic variables, implied by increased atmospheric CO2, will cause large shifts in vegetation patterns.

In the literature, several ecological modeling approaches have been used to assess one or another aspect of the impact of increased atmospheric carbon. Prentice et al. (1993) classifies them as either steady state or dynamic. The steady state models produce results that are consistent with long run average climatic conditions resulting from a fixed shift in CO2. In other words, since many GCM models are calibrated to produce results of a doubled carbon scenario, steady state ecological models will produce results consistent with this steady state, where the steady state may take hundreds of years to evolve.

There are two types of steady state models. One type are the biogeographical distribution models. Like the seminal work by Emanuel et al. (1985), these studies use mechanistic rules to classify spatial vegetation patterns according to climatic variables (Monserud and Leemans, 1992; Neilson et al., 1992; Prentice et al., 1992; Cramer and Leemans, 1993; Tchebakova et al., 1993; and Woodward et al., 1995). Although they each depend on different algorithms and they each contain different levels of detail, these models all are based on the idea first presented by Holdridge (1947) that climate regulates the types of ecosystems that are able to exist in an area.

The other type of steady state models are biogeochemical cycle models (Parton et al., 1988; Running and Coughlan, 1988; Running and Gower, 1991; and Melillo et al., 1993).

These models capture how large scale changes in ecosystem cycles, such as for carbon, nitrogen, sulfur, or phosphorous, will impact the productivity of individual ecosystems. The dominant ecosystem of an area is an input the model, and productivity is calculated depending on the availability of nutrients within the system, and other soil and climatic variables.

Dynamic models attempt to portray forest stands in transition. The so-called forest succession, or GAP models (Botkin et al. 1972), simulate gap-phase transitions in forests. They are dynamic in the sense that they show the natural transition of species after natural or human disturbance. The transition is based on the sequence of tree species that will occur on a fixed plot after the death of a tree creates a forest gap. Several authors have used GAP models to analyze the impacts of climate change (Solomon, 1986; Urban and Shugart, 1989; Solomon and Bartlein, 1992; Bowes and Sedjo, 1993; and Urban et al., 1993). Results from GAP models are site specific, so that these papers model only particular regions of North America.

At the moment, the site specific nature of GAP models limits how well they can be adapted to broader conditions across world. They do not capture ecosystem level responses to large scale ecological impacts, such as climate change. In the future, some researchers have proposed developing large scale dynamic models of ecosystem response to climate change based on GAP models (Prentice et al. 1993), but this task has yet to be completed. Until they are developed for larger scales, GAP models cannot be adapted to global studies such as this.

The steady state models, on the other hand, are readily adapted for use in impact analysis because they are spatially oriented and because timber types correspond to ecosystem types across the world. The biogeographical distribution models provide insight into the spatial distribution of timber types both now and under doubled CO2 conditions, while the biogeochemical cycle models imply how forest net primary productivity will change as a result of climate change.

2.2. Steady State Models

Three types of steady state models are utilized in this analysis: Global Circulation Models (GCM), biogeographic distribution ecosystem models, and biogeochemical cycle ecosystem models. Although many different models have been used to assess climate change impacts on ecosystems, we will focus on those that predict changes in the distribution of ecosystems (biogeographical distribution models) and those that predict changes in the productivity of those ecosystems (biogeochemical cycle models). GAP models have not been implemented broadly enough to consider them for analysis of global scope. For this paper, we consider the MAPSS (Neilson and Marks, 1994) and the TEM (Melillo et al., 1993) models.

2.2.1. Global Circulation Models (GCM)

GCM models provide spatially explicit information on the steady state change in climatic variables across the globe. In this paper, the changes are recorded for .5° x .5° grid cells. For example, the GCM models first predict baseline temperature and precipitation for each grid cell with existing levels of atmospheric carbon dioxide. They then predict the new steady state temperature and precipitation that would occur when carbon dioxide is doubled. Both the baseline and the climate scenarios are used by ecological models to predict steady state changes in ecosystem structure and function, as described below. Unfortunately, steady state equilibrium experiments such as this reveal no information about how long it may take for such changes to occur.

2.2.2. Biogeographical Distribution Models: *MAPSS*

One ecosystem change discussed above is the redistribution of ecosystem types due to changes in climate. In this paper, we discuss these types of changes by presenting an example from the biogeographic distribution model known as MAPSS (described in Neilson and Marks, 1994). Climate change is assumed to occur according to a doubled CO2 scenario and the GFDL-r30 climate change scenario (Manabe and Wetherald, 1987).

Steady State Changes in Ecosystem Distribution

The steady state changes in ecosystems are described by comparing maps of the distribution of ecosystem types under the baseline climate with maps of the distribution of ecosystem types under doubled CO2 (the ecological models do not currently suggest any time limit or time frame for the redistribution to occur). The baseline case maps are shown in Figure 1 for four quadrants of the globe. The maps distinguish between only the different forested ecosystem types. All grasslands and tundra are categorized together as "Non-Forest." Because we are concerned only with timber markets, this limits the confusion of seeing to many different types on the map.

This same baseline model was described fully by Neilson and Marks (1994), but it is instructive to consider several important points. In this paper, forests are divided into two broad classifications, closed forest and savanna. The main distinguishing factor between these two types is the leaf area index (lai). In general lai above 3.75 indicates that a closed forest will exist. Savannas or open forests are presumed to exist when lai ranges from 2- 3.75. Below 2, the cover is assumed to be classified as "Non-Forest."

The MAPSS model uses a hierarchical ecosystem classification system based on lai, leaf phenology, leaf morphology, and thermal zone (Neilson and Marks, 1994). Once the model has determined the maximum lai that can be supported based on atmospheric and hydrologic conditions provided by the GCM models, it will determine the tree or savanna classification based on the parameters above. The exact determination of the ecosystem type at any particular location is thus directly tied to the site water balance, as well as the atmospheric conditions.

Baseline Case

Using current climate, the MAPSS model predicts a distribution of ecosystem types that fits well with the distribution described by Olson et al. (1983). Neilson and Marks (1994) have partially validated that the lai predicted by MAPSS closely resembles the lai that actually occurs. Unlike the distribution of ecosystem types predicted by Olson, the MAPSS model (and other biogeographical distribution models) predicts only potential vegetation types. Many areas that are classified as forestland may already have been converted to other land uses, such as agriculture, cities, or highways.

In North America (Figure 1a), the ecosystems are situated where we would expect them to be. In the southeastern part of the country, Forest Mixed Warm Deciduous-Broadleaf (FMWDB) dominates. This ecosystem type is classified as a mixture of deciduous and evergreen types that would exist in warmer, non-tropical regions. Looking farther north, land converts to Forest Deciduous Broadleaf (FDB), Forest Hardwood Cool (FHC), Forest Mixed Cool (FMC), and ultimately to Forest Evergreen Needle Taiga (Boreal). In the west, land is dominated by Forest Evergreen Needle Continental (FENC), Forest Evergreen Needle Maritime (FENM), and Forest Mixed Warm Evergreen (FMWE).

Mexico and parts of Central America (Figure 1a) contain mainly Non-Forest, Forest Seasonal Tropical (FST), Forest Broadleaf Evergreen Tropical (FBET), Forest Savanna Dry Tropical (FSDT) and some Forest Mixed Warm Evergreen (FMWE). The same is true of many islands in the Caribbean. In South America (Figure 1b), one can see similar types of forests as in Central America. The tropical rainforests of the Amazon are clearly delineated, as are the dryer, more arid areas. Further the coastal forest ecosystems of Chile are shown as Forest Mixed Warm Evergreen (FMWE).

Figure 1c shows the distribution of ecosystem types in Europe and Africa. Europe clearly is dominated by Forest Mixed Cool (FMC), which contains the northern hardwoods, such as oaks, maples, and cherries, as well as the spruce, pines, and aspens. Many of the eastern coastal areas are dominated by Forest Mixed Warm (FMW). For the most part, Africa is dry, except for a belt of forested land along the equator, and forested land in the southern part of the continent, in the Republic of South Africa, as well as Madagascar. The central forests are dominated by rain forests, which are Forest Evergreen Broadleaf Tropical (FEBT), Forest Seasonal Tropical (FST) and some Forest Savanna Tropical (FSaDT). The southern forests contain some Forest Mixed Warm Evergreen (FMWE) and some Forest Mixed Cool (FMC).

Finally, Figure (1d) shows the distribution of ecosystem types in Asia and the South Pacific. New Zealand contains mostly Forest Mixed Warm Evergreen (FMWE), Forest Mixed Warm Deciduous-Broadleaf (FMWDB), and Forest Evergreen Needle Continental (FENC). Australian forests contain the first two types that were in New Zealand, as well as the Forest

Mixed Cool type. On the northern edge of the Australian Continent, there is an area of Forest Savanna Dry Tropical. Farther to the north, the Asian-Pacific islands are composed of Forest Evergreen Broadleaf Tropical. These are the immense dipterocarp forests of countries such as Indonesia. Mainland southeast Asian forests are somewhat dryer, as they are composed of Forest Seasonal Tropical types (the monsoon forests, or those that have a distinct dry season).

India does have some Forest Seasonal Tropical types, but is mostly savanna land, or land with low tree density. In extreme northern areas of the Himalayas, there are some other types. China has by far has the most diverse forest ecosystem types of this region. From rainforests (the Forest Evergreen Broadleaf Tropical) in the far south, to the Forest Mixed Warm Evergreen farther north, to the Forest Mixed Cool and the Forest Evergreen Needle Conifer farther to the north, and finally, some Boreal forest in the extreme north. Russian Siberia, as one can see, is dominated by Boreal forests and Non-Forest (which is mainly tundra).

Climate Change Case

The steady state prediction of ecosystem distribution under the GFDL-r30 climate change case is presented in Figure 2. For North America (Figure 2a), the changes are fairly substantial, as most types move farther to the north. This is particularly noticeable with the increase in the area of boreal forests. While forests are moving farther north, forests do not decline in the south, they merely convert to different types. For example, in Florida, the tropical types currently there convert over to full broadleaf tropical forests (as FEBT). Some areas of savanna type are seen to move into the northeastern part of the United States. In the western part of the continent, we see a large increase in forested area overall for this climate change case.

In South America (Figure 2b), the area of tropical rainforests increases significantly, as do the Forest Mixed Warm Evergreen types. Many areas of dryer, seasonal tropical forests are converted to tropical rainforest. The situation is similar in Africa (Figure 2c), but not as pronounced. The area of tropical dry, seasonal forest area increases by converting dryer grasslands or savannas over to seasonal forests. Europe (Figure 2c) sees a similar northward migration of ecosystem types as was seen in North America. Tundra in the north is converted to forestland. In the southern part of Europe, however, some areas of drying and dieback occur, especially in the Iberian peninsula. The Forest Mixed Warm Evergreen (FMWE), Forest Evergreen Needle Continental (FENC), and the Forest Evergreen Needle Maritime (FENM) all increase their area significantly.

Finally, in Figure 2d we see that forests expand in Asia as well. In the northern areas, the forests expand into areas currently holding tundra. In the tropical areas, the tropical rain forests types expand in favor of the seasonal tropical types. Australia gains some additional forest, but at the same time their existing forest is converted to new types. New Zealand's forest area does not expand, but the types of ecosystems present there do change. India sees a large expansion of savanna type forests.

2.2.3. Biogeochemical Cycle Models: *TEM*

The TEM model, as described by Melillo et al. (1993), will provide the basis for describing changes in the growth of forests. The TEM model predicts a change in net primary productivity (NPP), which is the net amount of carbon available for plant growth from photosynthesis in any given period. Of all the carbon fixed by photosynthesis, net primary productivity represents that part which is not used by respiration, but which can be used by plants for growth.

Two important points must be made about the calculation of NPP. First, it is a steady state concept. Under a given climate scenario (whether the baseline or a doubled carbon climate), the model will determine NPP based on a presumed climax vegetation coverage. This assumes that all atmospheric and ecological variables have stabilized at their long run equilibrium points. Second, NPP depends on the underlying ecosystem type. Different ecosystem types will have different rates of photosynthesis, respiration, and other ecosystem functions, so that NPP must be determined specifically for each type.

NPP can be linked to timber models through the yield function. Although there is not an exact correlation, NPP is similar to the yearly growth of timber stock. We assume that growth of timber is proportional to NPP. Unfortunately, the TEM model is calibrated to determine the change in NPP when forest structure and function has obtained a long run equilibrium. Most forests, particularly those that are used for timber purposes, are significantly younger than this however, so we assume that the adjustment due to climate change affects all age classes similarly. In steady state, the yearly growth of timber, adjusted for climate change influences is

$$\dot{V}_i(a,\bar{t}) = \overline{\alpha}_i \dot{V}_i(a) \tag{1}$$

where α is the steady state change in NPP predicted by the TEM model for type i.

Table 1 presents the changes in steady state NPP described by the TEM model for certain ecosystem types around the globe. Unfortunately, that paper did not discriminate between the different types in different regions, so that these are global averages. This will provide an idea as to the direction of change in NPP predicted by this model, however. Interestingly, the TEM model predicts increases in productivity on a global scale.

Table 1: Percentage change in steady state NPP for forested and savanna ecosystem types predicted by the TEM model (derived from Melillo et al., 1993).

Vegetation Type	% change in NPP
Boreal Woodland	14.3
Boreal Forest	15.8
Temperate Conifer Forest	18.2
Temperate Savanna	26.0
Temperate Deciduous Forest	20.0
Temperate Mixed Forest	17.6
Temperate Broadleaf Evergreen Forest	21.7
Tropical Savanna	10.5
Xeromorphic (dry) Forest	37.0
Tropical Deciduous Forest (Monsoon)	32.4
Tropical Evergreen Forest	33.5

The results in Table 1 also are presented for more aggregated ecosystem types than are suggested by the MAPSS model. Although they are more aggregated, there still is a close correspondence between the types. Thus, a boreal forest in Table 1 is correlated to the taiga evergreen types in the MAPSS model results presented in Figures 1 and 2. These numbers are presented only to give the reader a general idea of the changes in NPP suggested by the TEM model.

2.3. Dynamic Climate Change

Thus far, we have considered only a steady state ecosystem response to climate change. The steady state, however, is likely to occur many years in the future because of the slow changes in climatic variables (IPCC, 1990) and lags in the response of ecosystems to these slowly evolving climatic conditions. Rather than assuming that ecosystems change instantly, we implement both a dynamic climate adjustment and a dynamic ecosystem adjustment.

2.3.1. Dynamic Climate Model

The first step is to define the "dynamic" climatic response to a gradual doubling of CO2 in the atmosphere. This means proposing a time path for temperature and precipitation change. The IPCC (1990) projects that uncontrolled carbon emissions will result in a linear increase in temperature from now through 2060, the time by which green house gases will have doubled. This type of change is shown in Figure 3 for a 70 year adjustment to additional atmospheric carbon. For the moment, only linear paths such as this are examined, although in principle, many different paths could be examined. We assume that temperature and precipitation will stabilize in 2060.

2.3.2. Dynamic Model of Ecosystem Change

The dynamic model of ecosystem change begins by tying ecological change directly to temperature and precipitation by assuming that ecosystems change proportionally to changes in temperature, precipitation, or both. As climate variables are assumed to increase linearly over a given number of years, the ecological adjustment occurs linearly over that time period as well. Dynamic ecosystem change is described by area and growth change, where dynamic area change is derived directly from the biogeographical distribution models, and dynamic growth changes are described by the biogeochemistry models.

Dynamic Area Change

Introducing a dynamic shift into the redistribution of timber types is difficult for two reasons. First, there is considerable debate over what will happen to the old type that is displaced. For example, ecologists question whether the old type will die off, or whether it will be replaced competitively by other species. Second, ecosystems and trees, unlike some animals, do not migrate quickly. They rely on mechanisms, such as wind or fire, to disperse pollen and seed, so that migration rates at the frontier of ecosystem boundaries may be very slow (Overpeck et al., 1991).

We thus consider two methods of stock removal, one of which is dieback. Some modelers have suggested that timber species will die-back as the conditions under which they grow change (Neilson et al., 1992; Shugart et al., 1986; and Solomon, 1986). These modelers imply that conditions will become too different from those to which plants currently are accustomed. This in turn will stress the plants, and cause the standing stock to die.

The second method of stock removal occurs at the regeneration stage, generally through the competitive displacement of ecosystem types. Here the only way an ecosystem type is removed from the land is through difficulties in regenerating the old type. New types may either be planted or grow naturally (although it may take a while for natural migration to occur). There is no additional mortality assumed to occur due strictly to climate change. This scenario flows from the spatial distribution of tree species. Looking across a broad array of climatic conditions, we find that the tree species exist in many different areas. Oaks, for example, range from Connecticut all the way to Louisiana. Since tree species are found to live in such a broad spectrum of climates in the present, there is little reason to believe that they will dieback as a result of climate change.

Dealing with tree migration involves both seed dispersal rates and land management activities. While natural rates of migration are relatively slow, humans are assumed to react quickly by replanting the most healthy, and profitable, timber types within a region. We account for this by utilizing several different management types in the economic model. Plantations are managed for timber purposes and are regenerated immediately after either dieback or harvest. We assume that managers replant species that are appropriate to the new climate. Low intensity managed lands are held for multiple management reasons. Although the land may be restocked either naturally or by humans, there may be long lags between harvest or senescence and regeneration. The final type of land is the inaccessible land, where currently there are no timber harvests. As prices rise, these lands may be utilized.

Biogeographical distribution and biogeochemistry models do not consider human influences. By allowing for plantations and low intensity management, we account for the impacts of both natural and human adaptation to climate change. On plantation land, managers will replant the right species and will suppress the growth of competing trees or shrubs. On low intensity managed land, natural adaptation will take longer, and there will be lags before regeneration occurs. This will limit the ability and speed of species to compete effectively when they are invading a new area.

Dynamic Yield Change

Like the redistribution of timber types, changes in yield will occur proportionally to temperature changes. This results directly from assuming that NPP changes proportionally to changes in temperature as well. A yield function describes the total amount of biomass in terms of timber yield, but it also contains much more information about the growth of trees. The first derivative of the yield function, with respect to the age of the trees, describes the rate of growth of trees at any time during their life cycle.

Let us first consider the steady state situation. We assume that the change in NPP affects each tree the same at any age. Thus, if NPP increases by 20% due to climate change, then at every age, yearly growth must be 20% greater than in the previous steady state. This situation was described by equation (1) above, where α is 1.2.

Dynamically, however, we need to adjust this shift so that it is proportional to the temperature or precipitation change, that is, so it occurs linearly over time. This means that α varies linearly as

$$\alpha(t) = 1 + \gamma t, \tag{2}$$

where γ is the yearly increment in total biomass. The total amount of change is limited by the number of years over which this shift can occur. After the adjustment period, α is held constant.

The steady state equation (2) cannot be implemented directly into the dynamic model, however. Improved growing conditions can only enhance future growth, not past growth. It is important to follow trees during the period of transition and attribute ecological effects to each year's growth. For example, suppose there is an instantaneous increase in NPP of 20%. The existing stock of trees is not affected, only growth which occurs after the instantaneous moment. When there is a continuous and slow shift, as with climate change, the same principle is applied.

Mathematically, this can be expressed as

$$V_i(a_i, t) = \hat{V}_i(a_{t^*-1}) + \int_{t^*}^{T} \left\{ \alpha_{i,(t)} \hat{\dot{V}}_i(a_{(t)}) \right\} dt \quad , \tag{3}$$

where $\hat{V}_i(a_t)$ is the base yield function for a particular region, $V_i(a_t, t)$ is the climate adjusted yield function and t* is the age of the timber at the time of the shock. This adjustment accounts for the age of the trees when the climate shock begins, as well as the amount of time the trees have had to grow at the new, changed rates before they are harvested. We implement the linear change this way because the total biomass at any particular point in time is a function of both the past growth rates, and the current period's growth rate.

3. ECONOMIC MODELING

The large-scale ecosystem adjustments predicted by the ecological models suggests that timber markets will experience changes that are beyond the scope of the historical experience. As such, it is important that the economic model captures basic aspects of human activity, particularly how humans adapt and adjust to the changing conditions. To do this, we rely on dynamic optimization processes that attempt to maximize the net present value of net consumer surplus in timber markets. Elements from the work of Sedjo and Lyon's global Timber Supply Model (TSM; 1990) and the more recent work of Sohngen and Mendelsohn (1995) will form the basis for our economic model. Assuming that humans are rational creatures, the collective actions of millions of people across the globe will maximize the net present value of welfare in timber markets over time.

Dynamic models such as this rely on the rational expectation's approach to determine harvesting and replanting activities over time. In this study, rational expectations suggest that the consumers and producers in timber markets are forward looking. By forward looking, we mean that consumers and producers formulate price expectations about future market activity, which are correct on average. Decisions made today must be consistent with those expectations.

3.1. The Dynamic, Economic Model

The dynamic economic model is formulated as a non-linear, dynamic programming problem, where the objective is to maximize the net present value of net consumer surplus in timber markets over time. This is:

$$\underset{H_{i,a,t},b_{i,t}}{Max} \sum_{0}^{T} \rho^{t} \left\{ W\left(\sum_{i} \sum_{a} Q_{i,a,t} \right) - \sum_{i} c_{i} \sum_{a} H_{i,a,t} - \sum_{i} b_{i,t} \sum_{a} H_{i,a,t} - \sum_{i \in l} R_{i,t} \sum_{a} X_{i,a,t} \right\} \tag{4}$$

$W(\cdot)$ is total consumer surplus; $Q_{i,a,t}$ is the total quantity harvested out of land class i, age class a in period t; $H_{i,a,t}$ is the number of acres harvested; c_i is the harvesting cost; $b_{i,t}$ is the replanting cost; $R_{i,t}$ is a rental value for certain plantation classes of timberland; and $X_{i,a,t}$ is the number of acres in each land and age class at time t.

In this model, we allow for several types of timber stocks, reflecting both alternative uses of the land as well as accessibility constraints. For example, a sub-set of land in the world is managed intensively in timber plantations. These lands will generally have higher yield functions than other lands of similar species, and they will incur higher regenerating costs.

Regeneration costs are chosen endogenously in this model; they increase or decrease over time as a function of future timber prices. Timber yield at the time of harvest will be related directly to regeneration expenditures made when the land was planted (as in Sedjo and Lyon, 1990).

Another set of land, call low intensity land, is assumed to be managed less intensively than these plantations. This land is nonetheless accessible to people who would harvest it, but they may choose not to harvest the land exactly according to the Faustmann Formula. For example, in Europe, a high level of management occurs on land, but they harvest timber at ages that are generally higher than elsewhere in the world. This reflects a lower rate of social discounting (among other possibilities), which is difficult to incorporate for a specific region within this model. We capture current harvesting strategies by altering the yield function on timber in some European regions to reflect longer rotation periods.

A final set of land is the completely inaccessible land. We assume that due to the cost of extraction, land in certain regions of the globe has not been harvested because there is no infrastructure, or it is too far from the markets. Of course, accessibility is related to the price of timber. This models allows for the possibility that as prices rise, inaccessible land becomes accessible. By allowing for these three broad classes of land, we hope to capture the major types of production behavior observed in timber markets.

The maximization above is subject to several constraints:

$$X_{i,a+1,t+1} = X_{i,a,t} - H_{i,a,t} \qquad \forall\ i,a,t \tag{5}$$

$$X_{i,1,t+1} = \sum_{a} H_{i,a,t} \qquad \forall\ i,a,t \tag{6}$$

$$z_{i,1,t+1} = f(b_{i,t}) \qquad \forall\ i,t \tag{7}$$

In addition to these constraints, we must be given initial and terminal values for the stock of timberland, as well as non-negativity constraints for the stock and control variables. Equation (5) is the equation of motion for stock of any timber type, any age class, and any time period. It shows what will happen to the remaining stock after harvests occur. Equation (6) accomplishes the regeneration of timber, while equation (7) shows how the amount of money spent on regeneration will affect timber yield. $z_{i,1,t}$ is directly related to the yield of timber a time ($t+a^*$), where a^* is the rotation age of the timber.

Written in such a way, this is a non-linear programming problem which can be solved using the maximum principle (Pontryagin et al., 1962), as shown by Sedjo and Lyon (1990). In the forward looking framework we have chosen to use in solving this problem, all time periods are solved simultaneously. When all periods are solved this way, it should achieve the same transitional price path as discussed by Lyon (1981), Brazee and Mendelsohn (1990), and Sohngen (1995). Similarly, it should respond to shocks which may occur as a result of such phenomena as climate change.

3.2. Description of Timber Supply Regions and Timber Types

The model described above allows us to consider different geographic supply regions around the globe, as well as different management, accessibility, and species types within each region. In this section, we describe the regions we will consider and we discuss the different timber types within them. The information from this section is derived from a number of different sources.

Table 2 shows the regions upon which we will be concentrating for this model. Unlike the previous effort of Sedjo and Lyon (1990), this modeling effort must include additional forested areas in order to account for climate change. The types of ecological impacts discussed above are likely to influence a broader set of regions than they considered originally. We thus attempt to incorporate information and data on these additional regions.

Table 2: Comparison of forested area, net annual increment and industrial roundwood production for the nine regions of the world that you will consider in the global timber market model.[a]

Region	Total forest	Closed forest	Closed forest	Volume	NAI on forest land	Industrial Rndwd.
	million ha		percent	billion m^3	million m^3	million m^3 [c]
I. North America	749	457	13.3 %	53.4	968.0	581.7
II. South America	1260	967	28.1	104.2	NA	116.7
III. Non-Soviet Europe	195	149	4.3	19.3	577.0	278.5
IV. Former Soviet Union	942	755	21.9	84.2	700.0	256.0
V. China	175	142	4.1	9.8	NA	93.4
VI. India	83	65	0.2	2.4	NA	24.6
VII. Oceania[b]	154	48	0.1	3.7	82.4	31.5
VIII. Asia-Pacific	353	260	7.6	40.6	NA	133.3
IX. Africa	1137	545	15.8	55.7	NA	59.0
Other	72	54	0.2	20.4	NA	28.66
Total	5120	3442		383.7	NA	1603.7

[a] The data for this table comes from three separate FAO documents (1992, 1993b, 1995)

[b] This includes all of Australia and the plantation lands in New Zealand.

[c] Roundwood production is the total industrial production in 1992, as reported by FAO (1992)

Table 3: Specific timber types associated with each region of the world that is modeled. SWD refers to softwood types and HWD refers to hardwood types in this table.

		Timber Types	
Region	Plantations	Low Intensity	Inaccessible
I. North America	PNW (Douglas Fir) Southern SWD (pine) Southern HWD Northern SWD Northern HWD	Southern HWD Northern HWD	Northern SWD
II. South America	SWD (Pine) HWD (Eucalypt)	Tropical Moist Tropical Dry	Tropical Moist Tropical Dry
III. Non-Soviet Europe	Nordic SWD Central SWD,HWD Southern SWD, HWD Iberian Plantation		Nordic SWD
IV. Former Soviet Union		Taiga SWD Temperate SWD HWD	Taiga SWD
V. China	NE Montane-Boreal SW SWD SO SWD	NE SW	NE SW
VI. India	Long Rotation Short Rotation		
VII. Oceania	HWD (eucalypt) SWD (southern pine)	HWD	HWD
VIII. Asia-Pacific		HWD (dipterocarp)	
IX. Africa	SWD (southern pine) HWD	Tropical Moist Tropical Dry	Tropical Moist Tropical Dry

Nine different regions are considered explicitly, and there are multiple timber types and accessibility types for each region. In the baseline case, the specific timber types utilized depend on both the distribution of ecosystems described above by the MAPSS model, as well as the distribution of plantation types across the globe. Over time, and in response to climate change, the types of species in a particular region are likely to adjust. Thus, while the overall number of regions will remain the same, the number of timber types in fact changes. Modeling global timber markets this way will give us insight into changes in production levels for particular regions and for particular nations. The specific timber types considered in the baseline case are shown in Table 3. In the sections that follow, we discuss each region individually.

3.2.1. North America

The North American continent contains approximately 457 million hectares of closed forestland, which is 13% of the total amount of closed forest area around the globe (FAO, 1995). Of this land, only 308 million hectares are currently considered to be exploitable. The remainder of hectares are in areas that are too far removed from human activity, or in areas that are set-aside from production, or in areas that are not productive enough to warrant timber harvesting (and particularly, replanting). With only 13 % of the worlds forests, however, Table 1 shows that North America produces 36% of the worlds industrial roundwood (FAO, 1992).

Four timber types dominate production in North America: southern softwoods, northern interior softwoods (Boreal), pacific northwestern softwoods, southern hardwoods, and northern hardwoods. Among these types of timber, there is an array of site classes and management types possible. Both softwoods and hardwoods are assumed to be managed as plantations in all regions of North America. In the northern areas, the distinction is made between the western coastal forests (mainly Douglas Fir) and the interior softwood forests.

In addition, some softwoods and hardwoods are managed under lower intensity regimes. These are assumed to occur mainly in the interior and eastern parts of the country. A large part of northern Canada is assumed to be inaccessible at the moment, and is not incorporated into current harvest considerations. If prices rise significantly, however, one may expect harvests to begin in this inaccessible region.

3.2.2. South America

South America (Central America included) holds 28.1% of the total area of forested land in the world. Approximately 65% of this is classified as wet or moist tropical rainforest, while the remainder is dry or seasonal forest (FAO, 1993b). In addition to the natural forest cover, this region is well known for its productive plantation forests, particularly those in Argentina and Brazil, but also in other countries such as Chile, Venezuela and Mexico. Currently, there are approximately 6,450,000 hectares of plantation forests in South America (Bazett, 1993). About 3.5 million of these are planted to coniferous types, while the rest are planted to hardwood types.

South America is generally classified as one of the "emerging" regions for forestry (Sedjo and Lyon, 1990) because the plantations in this region have been growing in importance as global suppliers of timber fiber. Plantations throughout South America are utilizing fast growing pines, such as monterey, southern, or caribbean, or they are utilizing eucalyptus (eucalyptus spp.) from Australia (Sedjo, 1995). Pandey (1992) estimates that Brazilian and Argentinean plantations account for 60% of the total industrial wood production in those countries, despite the fact that they represent only about 2% of the total forest area.

An interesting question arises when one attempts to link the broad biogeographic distribution models with timber markets: How are we to deal with the issue of the exotic types that have been transplanted in many regions of the world? For example, eucalyptus is indigenous to Australia, but has been moved to places like Brazil and Chile, where it apparently thrives. In this analysis, we assume that even when timber types are moved to other regions, they exist in climatic conditions that are similar to their original habitat. A cursory comparison of the map included in Sedjo (1995) and Figure 1 suggests that this is true in reality.

For example, eucalyptus is a hardy, dry ecosystem type native to Australia. The same conditions that allow this species to exist in Australia are found in many areas but particularly the dry tropical zones of South America. Gary Hartshorn (in Sedjo, 1983) reports that eucalyptus have even been transplanted to tropical regions of the Andes. These are areas that historically have been devoid of forests. Eucalyptus is most likely to be found in a dry ecological life zone (Holdridge, 1947), or a tropical dry forest/savanna, or warm grass/shrubland region (Olson et al., 1983).

The pine types that have been transplanted into both tropical and non-tropical south America are typically the southern and caribbean pines that thrive in wetter, hotter climates, for example pinus taeda and pinus caribbea. Sedjo (1983) examines two pine plantations in South America. The caribbean pine plantation is located in central Brazil, in the heart of the rainforest. The other, southern pine, is located along the coast in southern Brazil in areas that are considered to mixed warm forests, or tropical rainforest (according to MAPSS). In Chile, plantations of monterey pine have been transplanted to the lush mixed warm evergreen forests along the western coast of that country. In fact, according to Pandey (1992), Chile has the largest plantation area in the world under monterey pine.

3.2.3. Non-Soviet Europe

The forests of non-Soviet Europe are dominated by mixed warm forests (FMWE) along the western coasts, mixed cool forests (FMC), and some continental evergreen types, particularly in mountainous, northern, and interior areas (Figure 1c). While the MAPSS model suggests that most of Europe is forested, much of this area has been converted to something else, mainly agriculture or buildings (Olson et al., 1983). This is by and large born out by the statistics about forests in Europe (Table 2), which suggest that there are only 149 million hectares of closed forest remaining (representing 4.3% of the total forestland area in the world). Despite this low area of forestland relative to other countries, Table 2 also indicates that European forests are among the worlds most productive. With less than half of the total area and volume of North American forests, the net annual increment on European forests is greater than half of North America's, indicating either a younger growing stock, or a higher level of management overall (or some of both). Kauppi et al. (1992) has noted that the volume of timber in forests in Europe has increased substantially since the 1950s.

Europe will be divided into six plantation timber types. The Nordic region will be treated separately as a softwood region, consisting of slow growing spruces and firs and some pines. Because 89% of the area of forests in Nordic Europe is coniferous (Kuusela, 1994), we ignore the influence of hardwoods there in the baseline case. In the rest of Europe, the forests are more evenly split between coniferous and non-coniferous, although approximately 63% of the land area is in coniferous types. We attempt to capture potential differences in growth rates by considering softwoods and hardwoods in the central and the southern European regions as separate types. We also allow for plantation types in the Iberian peninsula.

European forests are mostly accessible, except for extreme areas of the Nordic countries, where we incorporate an inaccessible region. We do not allow for a low intensity management in Europe, because European forests are usually managed, even though they are harvested at a later time than places like the United States. To allow for this, we incorporate altered yield functions which will increase the rotation age in those land classes.

3.2.4. Former Soviet Union

The Former Soviet Union (FSU) might be thought of as two separate regions, the European part and the Asian part. The European part is dominated by hardwood types, such as mixed cool forests (FMC) and continental evergreen forests (FENC), whereas the Asian part is dominated by taiga type evergreens. In total, the forests of the Former Soviet Union account for almost 22% of the total area of global closed forest (Table 2).

Despite the size of the standing forest resource in the FSU, production in that region is fairly low. Backman and Waggener (1991) suggest that one of the biggest issues associated with utilizing the forest resources of the FSU is that they are not easily accessible. Sedjo and Lyon (1990) further point out that the bulk of the forest resources of the Soviet Union are located remotely from the bulk of the population, an issue which limits the economic incentives to continue accessing newer, more remote areas.

The FSU will be divided into three different low intensity management types of timber, taiga softwood, temperate softwood, and hardwoods. Because the timber resource in this country is relatively old (Backman and Waggener, 1991), access and mining of old growth is an important issue to consider. Mining of the old growth is tempered by the supply of available timberland, which in turn is regulated by accessibility considerations. Backman and Waggener (1991) suggest that almost one-quarter of the forests of the FSU are currently beyond the limits of the transportation system, and its projected growth in the next 20 years.

When considered with the other areas that are set aside from forest production, only 60% of the land considered closed forest in the FSU is theoretically exploitable. We thus incorporate an inaccessible region, whose harvest depends on price.

In addition to the amount of land available for harvest, one must consider how much land is being replanted to forestry in the FSU. Between 1985 and 1989, 1.4 - 1.7 million hectares were reported as replanted each year, which was about two-thirds of the area of forest clear-cut annually. Despite this, the area of forest land in the FSU has increased continuously between 1953 and 1988. This may indicate that the forest stocking density is declining, because regeneration occurs naturally rather than artificially.

Recall that in this model, one of the choice variables is the effort which is put into regenerating forests. In the FSU, the effort will be suppressed initially relative to other regions. Over time, it will be related to price, so that if prices increase, the incentives to replant timber, rather than wait for natural regeneration, will increase.

3.2.5. China

Forests of China represent only a small proportion of the world's total area and volume. Although Figure 1d suggests that China should be mostly forested, particularly in the eastern part of the country, much of the land has been converted to agriculture and other uses. Of the forests that is does have, stocking densities run lower than the world average, as China has about 4.1% of the worlds closed forest area, but only 2.6% of the total volume. Given projected economic growth in that region, the resource base certainly is an issue in question.

China has one of the most varied set of ecosystem types of any country in the world, as its forest resources fall into both tropical and temperate categories (Figure 1d). In the extreme northern parts of Mongolia and China, taiga evergreens dominate the forested types. In other areas of the north, continental evergreen forests (FENC) exist, as do mixed cool forests (FMC). Moving farther south, mixed warm evergreen forests begin to dominate. In the southern-most parts of the country, tropical rain forests exist.

Unlike the situation in the FSU, both the forest resource and the bulk of the people in China are located in the eastern part of the country (Espenshade and Morrison, 1987). Large tracts of natural, unexploited forests exist mainly in the extreme northeastern corner and the southern and southwestern part of China (FAO, 1982). Access has not been considered a dominate issue in forest management in China.

China's political system is perhaps more involved with the timber market than in most other countries. In 1949, only about 8.6 % of the land area in China was forested. Between then and 1980, the government was able to increase this to approximately 12.7 % by planting over 30 million hectares of forestland (FAO, 1993a). The state goal is to have 20% of the land area forested by the year 2000. The 1990 FAO assessment suggests that they are closing in on this target as 17.3 % of the land is classified as forest or other wooded land, while 14.3% of the land is closed forest. Of the closed forest, 24% has been planted in plantations.

We will recognize three distinct plantation timber types in China, which generally follow the ecosystem types outlined in Figure 1d. These include northeastern boreal softwoods, southwestern softwoods, and southern softwoods, including the tropical types along the southern coast. In addition, we will allow for two low intensity management types, which include northeastern and southwestern forests. These may include both softwoods and hardwoods. Finally, there are two inaccessible regions, in the northeast and the southwest.

3.2.6. India

India, like China, has few timber resources compared to other regions, and a fairly low level of industrial wood production. Much of their production comes from plantations, which recently have been planted (Pandey, 1992). In addition, Figure 1d shows that the natural forest cover of India is limited mainly to dry savanna types and dry or seasonal tropical forests. These are fairly low density forests, and are often considered wastelands in the country.

Pandey (1992) suggests that the plantation area in India is approximately 18.9 million hectares, with much of the land being planted in non-native eucalyptus types. Over half of the area in plantations have been planted since 1985. Since the 1940s, much of the original forestland area has been converted to agriculture. More recently, the government has reduced this conversion, as concern over future fuelwood and industrial wood supply has emerged (Collins et al., 1991). Many of the plantations have been established in dryland areas in order to provide for these fuelwood concerns. Given the large population in that country, and the prospects for economic growth, it is likely that the area of plantations will continue to expand in that country.

In this study, we will consider only two plantation types, short rotation and long rotation types. The long rotation plantations will consist of teak and pine, predominately in the tropical coastal areas. The short rotation plantations will be eucalyptus species, which are housed in the drier forest and savanna areas. Combining these two types provides for most of the industrial wood utilized by that country. During climate change, however, additional types may be introduced.

3.2.7. Oceania

Oceania includes both Australia and New Zealand. These two countries are most noted for their expanding area of forest plantations. Of the estimated 2.2 million hectares of land in forest plantations, over 95 % have been planted to coniferous types (Sedjo, 1995). For the most part, these plantations have been planted to radiata pine.

Almost the entire country of New Zealand is potentially timberland according to Figure 1d. This includes either mixed warm evergreen types, maritime evergreen types, or even mixed warm deciduous types. Australia is naturally a blend of mixed warm evergreen and deciduous, as well as warmer savanna types. The warm savanna types are the home region to eucalyptus types that have been transplanted throughout the world.

Given the emphasis on conifers in the plantations, we will concentrate on the softwood types when modeling Oceania. We will, however, account for eucalyptus harvests in Australia as part of low intensity type lands, because currently over half of Australia's total production is derived from natural forests of this type. We also will concentrate on modeling the rate of establishment of plantations in theses two countries, as it is perceived that the future supply of timber will be dominated by plantation grown wood.

3.2.8. Asia-Pacific

The timber types of the Asia Pacific region are dominated by both wet and dry tropical forests. As shown in Figure 1d, these are the Forest Evergreen Broadleaf Tropical and the

Forest Seasonal Tropical. These countries supply much of the world's tropical hardwoods, particularly the countries of Malaysia and Indonesia. Although much of the resource in this region is supplied by natural forests, Pandey (1992) presents data indicating increased plantation areas in Indonesia. Some of the plantations have been started in pines, others in eucalyptus, and still others in teak and other industrial woods.

In this study, we will consider only one type of low intensity management. In reality, these forests contain a range of management classes, from the new plantation types discussed above to natural low intensity management. For this study, however, we will condense the various classes into one low intensity management class. The yield of industrial wood that results will represent an average of the natural and plantation management in that region, as will the costs of harvesting and regenerating.

3.2.9. Africa

The final distinct region in our analysis is Africa. The African continent is second (among our regions) only to South America in terms of total forest area, but it ranks third in terms the closed forest area, behind South America and the FSU. This results from the generally dry conditions that prevail throughout much of Africa. The dryer conditions, as pointed out by the MAPSS model, lead to lower lai. There is a direct relationship between lai and closed forest (as lai increases, forests become more dense, or closed).

While many of the forests in Africa are dominated by dryer types, the region has attracted international attention of late because of the growth of area in plantation types. Countries like South Africa, Angola, Congo, Kenya, and Zimbabwe have been planting exotic timber types recently. To date, approximately 2.5 million hectares are in these plantations (Bazett, 1993). They are composed either of pine, eucalyptus, or other species.

For this model, we will concentrate on both plantation type exotics and low intensity managed forests. The plantation types will be categorized into either softwood or hardwood types. The low intensity managed forests will be classified as they were in South America, moist tropical or dry tropical. This classification of low intensity forests relate to the Forest Evergreen Broadleaf Tropical and Forest Seasonal Tropical in MAPSS, respectively. In addition, there will be two inaccessible regions corresponding to the two low intensity types.

4. INTEGRATING ECOLOGICAL MODELS AND ECONOMIC MODELS

Integrating economic and ecological models will require making specific links between the different types of models. For this section, the analysis will follow the work of Sohngen and Mendelsohn (1995). That study concentrated on the effects of changes in three ecological variables: (1) the proportion of land shifting out of each ecosystem type; (2) the ratio of final forest area to initial forest area in each ecosystem type; and (3) the change in forest growth. Although the ecological models provide steady state results, dynamic changes are more important for our analysis. For this, we assume that all changes occur proportionally to the temperature and precipitation path described in Figure 3 (above).

For the rest of this section, we focus on some of the major issues involved with linking the ecosystem changes to the global economic model. These result from previous work (Sohngen and Mendelsohn, 1995), as well as the current research. We will refer to specific regions as necessary.

The first issue revolves around the link between the ecosystem types and the forest types. In general, there is a one-to-one correspondence between the ecosystem types predicted by the biogeographic models and those used by the economic model. For example, areas predicted to be taiga softwood forests in the ecological model correspond to boreal softwood forests in the economic model. We have discussed these links in section three and refer the reader back to that section for further details.

The second issue has to do with determining where dieback occurs and where it does not occur. Dieback in timber types is mainly a function of lai: any time lai decrease, dieback must occur. When ecosystem types change, however, lai may increase, decrease, or remain the same. Thus, if lai decreases along with a conversion from one ecosystem type to another, dieback occurs; if lai increases, dieback does not occur. When ecosystem types change without dieback, a competitive displacement of one ecosystem type for another occurs. We allow for the possibility of both dieback and competitive (regeneration) displacement, as discussed in section 2.3.2 above.

The third issue revolves around plantations. In many areas of the world, plantations are composed of species that are transplanted from elsewhere. It appears that they grow in conditions that are very similar to their original range, however, a fact which we utilize in determining the effect of climate change on the particular areas of plantations. For example, in South America, there are large changes in the size and distribution of potential forests (compare Figure 1b to 2b). The tropical rainforests expand significantly, taking over areas currently dominated by seasonal and dry tropical forests. Also, the warm evergreen forest area along the coast of Chile expands, as does the area of tree savanna in that country. The warm evergreen type expands in Peru and Bolivia as well.

In a country like the United States, this situation would suggest that forestland area increases, timber stocks increase, and production increases. In South America, however, the economic situation is somewhat different. The rainforest has not become an important commercial producer of timber because of the high costs associated with converting rain forest timber into end-products (Sedjo, 1983). Assuming that these trends continue, and that the costs of "mining" the tropical rainforest remain prohibitive, harvests from tropical rainforests may not to increase despite increased timberland area.

This increase in tropical forestland area also suggests that the area available for plantations increases. Plantation area throughout the tropics, however, will continue to depend on other land-use considerations, the changing resource base in other regions, and ultimately, the price of timber. In this sense, the amount additional land planted to exotic types is determined endogenously with other markets across the globe over time. One possibility that must be entertained with climate change is that if the changes suggest that the area of potential forestland increases across the globe, then it is entirely possible that other low cost producers of timber could dominate South America. It is also possible that the area of plantations in South America would decrease as world-wide production schedules change to reflect changing production in different regions during climate change. Thus, the amount of plantation timber needed globally must be determined endogenously across the globe.

The fourth issue has to do with what happens at the northern extremes of the globe. We see that large areas of "Non-Forest" are converted to timber types, particularly taiga.

While this change is important to consider, particularly ecologically, much of this timber may remain inaccessible to most markets. The economic model, by placing this area of timberland into inaccessible regions, will allow us to control harvests there by broader economic concerns, such as price.

The fifth issue is how other land uses are considered in this model. In many regions of the world, sectors like agriculture and forestry are linked closely together, either through agro-forestry practices in some tropical countries, or through the competition for land, as in the United States. Although we will not build a competitive land supply model in this effort, we recognize that this is one potential extension for future research at the global level. We will, however, utilize the Olson database to determine the current extent of land use throughout the world.

This database is clearly out of date, yet no new sources have been more recently compiled. Despite this, the Olson database will provide a baseline forestry/non-forestry distribution upon which we can calibrate our baseline economic scenario. During climate change, land can shift from one use to another. For the U.S., Sohngen and Mendelsohn (1995) broke the high valued agricultural lands out from the ecological analysis, and assumed that these lands would remain in agriculture even during climate change. This assumption relied on agricultural studies (Mendelsohn et al., 1994) which had shown that those areas would not be harmed significantly.

In this study, we will adopt this same approach with lands that already have been converted from forests to other land uses by using the Olson database. In places like China, however, where government policies specifically attempt to increase forest area in degraded agricultural land, we will allow for some displacement of the agricultural lands. We also will borrow from other studies, which have assessed the impact of climate change on agricultural areas, such as Darwin et al. (1995) and Leemans and Solomon (1993). In particular, our rules will remain flexible if the change in lai suggested by the biogeographic model is significantly large.

Sohngen and Mendelsohn (1995) also considered land where forests and other uses co-exist over the landscape. For example, throughout much of the temperate forest zone, agriculture, highways, cities and forests are inter-mixed, and throughout the tropic, agro-forestry and swidden agriculture occur near forest stands. As climate changes and the potential distribution of ecosystems adjust, we have to allow for adjustment of land use as well.

We allow for this adjustment by first recognizing that the area of forests shown in Figure 1 is the land that potentially could contain forests. The area of land that actually contains forests, such as the number obtained from inventory statistics, is somewhat less than that. During climate change, we assume that the ratio of actual forestland to potential forestland remains constant on these areas of inter-mixed forestry/non-forestry lands. Thus, if the potential area of forested ecosystems types across the world doubles due to climate then the actual area of forested ecosystems must double as well.

This may mean that agricultural land area increases or that it decreases, depending on the land-use structure of the land shifting into forested ecosystems. If all of the land that shifts into forests currently is used by agriculture, then agricultural area decreases.[2] If some of the

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[2] It is worth noting that although agricultural land area decreases, the land remaining is likely to be more productive. This occurs because any land that converts from non-forest to forest must display an increase in lai, which implies greater productivity.

land that shifts into forests currently is not used by agriculture, then it is entirely possible that additional land may convert to agricultural uses because it will become more productive.

The extensive forest area increase at the polar regions of the globe (see Figure 2 for example) provides another example. Forests expand into tundra land, which is mainly un-used and un-inhabited. This increase in forest area in these regions is likely to occur slowly and naturally, as species migrate. Our economic model considers these regions inaccessible, and we assume that they will remain that way. We will not allow for increased areas of agricultural land in those regions. Sensitivity analysis may involve additional model runs where different land uses are allowed to enter these higher latitude areas.

The final issue involves the change in growth rates of timber types. The steady state changes in net primary productivity shown in Table 1 are generally positive, suggesting an increase in growth rates. Unfortunately, these changes are not tied to the changes in ecosystem type. In future model runs, changes in growth rates must be determined simultaneously with changes in ecosystem distribution.

5. CONCLUSION

In this paper, we describe how ecosystem and economic models can be integrated at the global level to determine the economic impact of climate change on timber markets. Without providing empirical results, we pay special attention to describing the particular models that are available for understanding these impacts. We also begin discussing how the ecological and economic models can be integrated to determine the economic impacts. Several important points result from this discussion.

First, two types of ecological results must be considered, biogeographical and biogeochemical effects. Although these effects are determined by different models for this paper, the next generation of ecological models must incorporate the combined influences. Changes in productivity predicted by the biogeochemical models must be integrated with the changes in distribution described by the biogeographical models.

To some extent, the MAPSS model provides some information on the productivity in ecosystems by reporting changes in leaf area index (lai). Lai, however, does not translate easily into changes in yield functions, as does NPP. Thus, for the moment, it is best to use the NPP results from a model such as TEM.

Second, in addition to linking the two major ecological models themselves, the ecological models also must begin to address complex dynamic processes. This is perhaps one of the most interesting areas of future analysis because it will require a close working relationship between economists and ecologists. The dynamic processes of ecosystems are sure to be influenced by humans and the dynamic processes of markets are likewise going to be influenced by changes in ecosystems. It is important to recognize that these two systems are inherently integrated, and to begin to build models that incorporate aspects of models both from natural and social sciences.

Third, both ecological and economic models can benefit from a better representation of land uses throughout the globe. One of the most widely used maps is the Olson data set, which was developed in 1983. Given the large scale changes in land cover use throughout much of the world since then, updated maps must be produced and utilized. This is particularly important in understanding the relationship between forest uses of land and all other uses. Currently, information on the distribution of land uses in many developed countries is fairly well known, but the distribution elsewhere is less certain.

Fourth, the timber model at this stage does not incorporate a trade component. Unfortunately, this makes it difficult to assess welfare impacts in different regions of the world. Although we can assess changes in the quantity of timber harvested in different regions, it is more difficult to understand changes in welfare that result from these changes. Others have gotten around this issue by developing a trade model. Trade models, however, often do not capture the essential "dynamic" issues of timber supply that are deemed to be important for assessing climate change impacts.

Despite these limitations, this study present a good opportunity to begin to link these models on a global scale. The changes predicted by climate change across the globe are indeed massive. We hope to be able to address several important issues in this study. At the same time, this study will open the door to many new and exciting issues, particularly those relevant to assessing changes in goods that are not marketed.

FIGURES

1) MAPSS baseline case distribution of ecosystem types based on current climate variables.
    a) North America
    b) South America
    c) Europe and Africa
    d) Asia and the South Pacific

2) MAPSS model predicted vegetation distribution under $2xCO_2$ conditions and the GFDL-r30 GCM model.
    a) North America
    b) South America
    c) Europe and Africa
    d) Asia and the South Pacific

3) Dynamic response of temperature and precipitation to increasing levels of CO_2 in the atmosphere. Doubling occurs in 2060, and carbon emissions are assumed to stabilize after that.

Figure 1a.

Figure is available from:

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Figure 1b.

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Figure 1c.

Figure is available from:

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Figure 1d.

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Figure 2a.

Figure is available from:

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Figure 2b.

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Figure 2c.

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Figure 2d.

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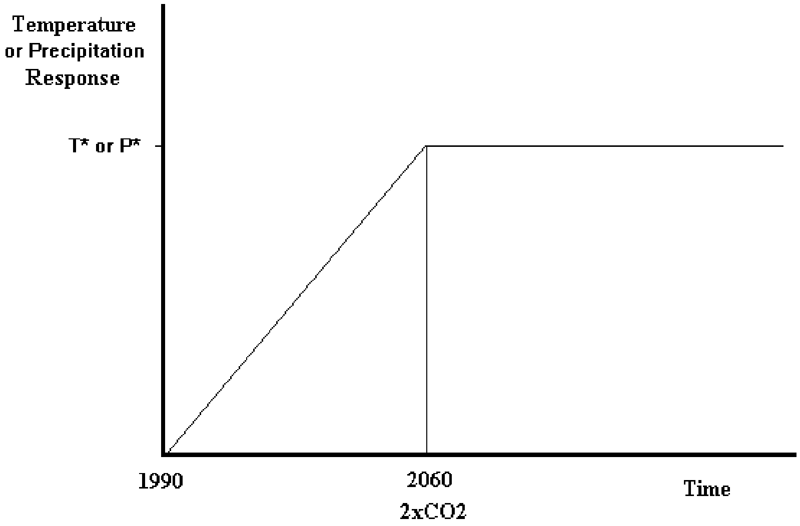
Figure 3: Dynamic response of temperature and precipitation to increasing levels of CO_2 in the atmosphere. Doubling occurs in 2060, and carbon emissions are assumed to stabilize after that.



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