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# A Dynamic Analysis of the Global Timber Market and Carbon Flux of Forest under Global Warming: An Integrated Modeling Approach

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# A DYNAMIC ANALYSIS OF THE GLOBAL TIMBER MARKET AND CARBON FLUX OF FOREST UNDER GLOBAL WARMING: AN INTEGRATED MODELING APPROACH

by

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ABSTRACT

A Dynamic Analysis of the Global Timber Market and Carbon Flux of Forest under Global Warming: An Integrated Modeling Approach

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As global warming migrates ecosystems toward the poles, the result has been a change in the distribution of ecosystem types and the productivity of ecosystem as well. Similar to other natural resources, forests are also potentially affected as ecosystems move toward the poles. Consequently, human beings are forced to adapt, and global warming will generate an impact on the global timber market through changes in timber harvests, regeneration inputs, stumpage prices, etc. In addition, the dynamic process of forest change in response to economic activities of human beings will accelerate or dampen the amount of carbon in the atmosphere. In this context, we propose an integrated modeling approach to identify the effect of global warming on the global timber market, and examine the feedback effect of the global timber market on global warming.

To perform the primary research objective, we estimated dynamic ecological change based on (1) the simulation results of BIOME 3 using Hamburg and (2) the linearity assumptions about change in climate and ecosystem. With the estimates of dynamic ecological change, we modified the Timber Supply Model 2000 (TSM 2000) to reflect the dynamic ecological change caused by climate change. After simulating the base scenario and the climate change scenario of TSM 2000, we identified that global warming has a positive effect on the global timber market.

For the secondary research objective, we extended the modeling framework by incorporating the Terrestrial Carbon Model (TCM) designed to investigate net carbon release into the atmosphere. Simulating both the base TCM and the modified TCM which reflects climate change, we identified that the global timber market has a dampening (negative feedback) effect on global warming through net carbon sequestering. For sensitivity analyses, we performed these simulation procedures under three different timber demand growth scenarios.

(172 pages)

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# CHAPTER I

# INTRODUCTION

Beginning in the latter part of 20th century, natural scientists and policymakers alike have paid much attention on global warming associated with accumulation of greenhouse gases in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 1990) predicted that average global temperature would increase about 3 to 6 degrees centigrade between 1900 and 2100.[1] Since then, many scientific groups have warned policymakers of the potential adverse impact of global warming on ecosystem health and have called for severe curbs on anthropogenic emission of greenhouse gases into the atmosphere. At the same time, a growing number of scientists have questioned the scientific basis of global warming predictions. These skeptics suggested the need for a more comprehensive assessment of climate model predictions before implementing policies that may adversely affect opportunities for worldwide economic growth. In spite of the controversy, governments around the world have recently approved a framework of treaties on climate change and continue to engage in dialog aimed at addressing potential impacts from various global warming scenarios.

The Earth Summit in Rio de Janeiro, Brazil (1992) and the United Nations conference in Kyoto, Japan (1997) were convened to discuss global environmental issues, such as monitoring greenhouse gas concentration into the atmosphere, its natural

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[1] Nordhaus (1993) also predicted that the global temperature would increase about 1 to 5 degrees centigrade between 1900 to 2100. In addition, the preliminary research of U.S. National Assessment Synthesis Team (NAST 2000) indicates that the temperature in the U.S. territory will rise 3 to 6 degrees centigrade in the next 100 years.

effect, and protection of the world's environmental resources. As a partial response to discussion in these fora, NAST of the U.S. Global Change Research Program recently released a document that attempts to assess the potential consequences of climate variability and change on the United States (NAST 2000). Similar comprehensive research efforts are being spearheaded by countries around the globe. In these studies, scientists generally attempt a comprehensive assessment of greenhouse gas concentration in the atmosphere for long periods, but they are somewhat deficient in developing integrated assessment models that capture economic effects associated with global warming. Recent exceptions include the work of Nordhaus (1991) and Cline (1992), who have begun to consider integrated economic models that tackle impacts of climate change, economic costs of deterring climate change, and alternative approaches for implementing policies designed to protect natural environments on a global scale. Our research, summarized below, contributes to a growing body of literature that attempts to a develop a dynamic integrated model of ecosystem and economic system interactions that arise from predictions of global warming. The particular focus of inquiry is on the global timber market.

**Problem Statement**

One prediction of global warming is that if global warming forces ecosystems to migrate toward the poles, the distribution of ecosystem types and the productivity of ecosystems will be altered. The transformation and adjustment of ecosystems resulting from climate change also change the environmental conditions under which natural resources are extracted through the economic activities of human beings. Similar to other natural resources, forests are also potentially affected as ecosystems move toward the poles. It has been discussed and predicted that changes of forest types will occur along two dynamic processes--the first is dieback and the second is regeneration (King and Neilson 1992, Shugart et al. 1986, Solomon 1986).

According to the explanation provided by ecologists, dieback occurs when environmental conditions of the forest significantly deviate from those to which current growing trees are accustomed. Changing climate conditions continuously harass growing trees and cause standing trees to stop growing. Eventually, standing trees die out. According to the regeneration process, as climate changes, current forest types are able to continue growing in the area where they are currently standing. Regeneration occurs through either competitive displacement of forest types or plantation management. As existing trees are harvested or die out naturally, however, old species are not regenerated again in the area in which they were growing. Instead, new species naturally migrate into the area with a time lag (i.e., through competitive displacement) or are planted by human beings to establish new plantations for economic profit.

As forest types change along these dynamic processes, human beings are forced to adapt as well. As a result of economic spillovers, climate change will generate an impact on the global timber market through changes in volume harvested, the level of regeneration input, and stumpage price. This process underlies the effect of global warming on the global timber market.

In addition, dieback will reduce the capability of the forest to sequester carbon from the atmosphere. Moreover, dead trees that are not salvaged by forest management will release more carbon into the atmosphere through the process of decaying. On the other hand, regeneration will reinforce the ability of the forest to absorb carbon from the atmosphere as the young trees keep growing vigorously after currently standing trees are harvested. These dynamic processes of forest change will affect the amount of carbon in the atmosphere.

These dynamic processes, in turn, will affect global warming with the consequence of moderating or accelerating the rate of temperature change. As a consequence, ecosystems around the globe experience feedback chains that will result in dynamic impacts on humans' ability to adapt and plan for changing ecosystems. This process is referred to as the feedback effect of the global timber market on global warming. In this context, we propose an integrated modeling approach that identifies the effect of global warming on the global timber market, and examines the feedback effect of the global timber market on global warming.

Most literature that has attempted to identify the effect of global warming on timber markets has only investigated the effect of global warming on timber markets in limited regions. Binkley (1988) studied the impact of global warming on boreal forests and Joyce et al. (1995), Burton et al. (1998), and Sohngen and Mendelsohn (1998) focused only on the conterminous United States.

Perez-Garcia et al. (1997) and Sohngen et al. (1999) extended the effect of global warming on the global timber market. Although Perez-Garcia et al. (1997) studied the impact of global warming on the global timber market, they did not consider change in the distribution in forest types, but only examined the change of forest productivity after climate change. Also, most literature, with the exception of Sohngen (1996) and Sohngen et al. (1998), used comparative static analysis based on comparison of current steady-state ecological equilibrium and changed steady-state ecological equilibrium. They considered neither dynamic ecological change nor dynamic change of timber markets after climate change.

Studies of the feedback effect between timber markets and global warming include works by Bonan et al. (1992) and Kirschbaum et al. (1996) who studied the role of forests in global warming in order to correct potential bias in the IPCC forecasts of future temperature. They identified a net release of carbon from forests producing a positive feedback effect on global warming. It is of value that these studies have identified the feedback effect of carbon flux of forests on global warming. Nevertheless, their studies did not cover the worldwide forests and failed to link ecological change to human adaptation.

To address integrated modeling approaches, the following economic and ecological models were required: timber supply model (TSM), general circulation model (GCM), terrestrial carbon model (TCM), and a steady-state ecological model. The TSM was used to model the dynamic economic behavior of human beings involved in the global timber market in the context of global warming. Dynamic interactions among the other three models were utilized to identify the ecological feedback loop of global warming and forest carbon flux.

Of several competing economic models developed to analyze timber market behavior (Adams et al. 1996, Berck 1979, Brazee and Mendelsohn 1990, Sedjo and Lyon 1990, 1996, Sohngen and Mendelsohn 1998, Sohngen et al. 1999), the TSM proposed by Sedjo and Lyon (1990, 1996) was chosen for the present study. The TSM is a nonlinear optimization model that is designed to examine theoretical and practical issues in the world timber supply. The dynamic characteristics of timber supply such as aging of trees, harvesting of timber, and regenerating forest have been modeled using discrete time, optimal control theory. This model generates the optimal time profile in the sense that the model maximizes the sum of discounted present value of net surplus (consumers' surplus and producers' surplus), subject to the initial conditions and the laws of motion governing the evolution of the system. Two laws of motion are formulated for both hectares of trees by age and level of regeneration input. In addition, the TSM traces out the system-wide time profile of harvesting volume in aggregate and by each land class, and generates a system-wide dynamic market price while determining the economically efficient regeneration by time period and by each land class.

The GCM identifies change of climate variables in a given grid cell across the globe. We proposed to employ a GCM to estimate the change of climate variables under two competing assumptions: currently existing carbon dioxide concentration in the atmosphere and a doubled carbon dioxide concentration in the atmosphere. Comparing the distribution of climate variables in the grid cell allowed us to capture variations in climate change across the globe. Among numerous GCMs that have been developed by atmospheric scientist groups, Hamburg (Claussen 1996) was used as the GCM for this research. Climate change slowly affects ecosystem types as well as the productivity of ecosystem type. Unfortunately, there does not currently exist a dynamic ecological model that spans the entire globe. Participants of VEMAP (1995) have only recently made efforts to develop a dynamic ecological model for the conterminous U.S, which is called VEMAP Phase II. However, the VEMAP Phase II is not currently available for general use.

In order to examine dynamic ecological change based on a steady-state ecological model approach, we used the BIOME 3 as a steady-state ecological model. Haxeltine and Prentice (1996) developed BIOME 3, which is a large scale, quantitative ecological model covering the entire globe. BIOME 3 combines both a biogeographical distribution model and a biogeochemical cycle model within a single framework. BIOME 3 allows us to mechanically simulate the direct effect of carbon dioxide change on vegetation patterns, net primary productivity (NPP), and leaf area index (LAI). In this context, simulation results of BIOME 3 using Hamburg were used to identify dynamic ecological change that results from doubling of carbon dioxide in the atmosphere.

We also followed the IPCC projections (Houghton et al. 1990) that climate variables will linearly increase from 1990 to 2060. On the basis of IPCC convention, we assumed that climate variables are linearly increasing from 1990 to 2060 and then stabilize. Furthermore, both the change of ecosystem types and the change in NPP were assumed to be proportional to the climate change (Sohngen 1996). Under these assumptions, we derived critical information about dynamic ecological change from the steady-state ecological model.

In order to examine the feedback effect of the global timber market on global warming, the TCM (Yan 1996) was utilized. TCM predicts the capability of carbon storage in forests when harvesting and regeneration occurs in forests. The difference of carbon storage in forests between before and after climate change through uptake and release of carbon will play a critical role in assessing the impact of global warming. As a consequence, carbon storage or release will accelerate or decelerate the responsiveness of ecosystem change to climate change. The proposed integrated modeling approach provided a much clearer prospective to systematically accomplish our research objectives.

**Research Procedures**

This research aims to identify both direct and feedback effects of global warming on the global timber market. To achieve the primary objective, the TSM developed by Sedjo and Lyon (1990, 1996) had to be modified to consider the impact of global warming. Modification of TSM resulted in two scenarios for the global timber market. We labeled these scenarios as the base scenario and climate change scenario. In addition, for the secondary objective, the TCM was also modified to investigate the net effect of carbon release into the atmosphere after climate change. Integrating both modified TSM and modified TCM within a dynamic framework played an important role in identifying the combined effect of global warming and global timber markets on carbon flux. The following process outlines the modeling approach.

1. Using simulation results of BIOME 3 using Hamburg we examined change in the distribution of ecosystem type as well as the change in NPP of ecosystem type between before and after climate change. For each responsive region supplying stumpage to the global timber market, we calculated the dieback ratio, the regenerated land area per year, and the change in NPP of ecosystem types in each responsive region. According to ecosystem type of each land class in a given region, we disaggregated the regional estimates into each land class.
2. Based on these results, we modified the TSM for climate change scenario. Modification of the TSM included change in the law of motion of hectares of trees by age, and the volume of timber harvests for each land class.
3. We examined the optimal time profile of timber volume harvested, regeneration input, stumpage prices, and welfare level for each scenario (the base scenario and the climate change scenario).
4. Based on simulated intertemporal estimates of endogenous variables in TSM, we used the TCM to identify the net release of carbon for each scenario.
5. Changes of carbon storage in the atmosphere will, in turn, affect the global warming. Again changed global warming would transform ecosystems around the globe, and so on. In this context, we were able to identify whether there is either a positive or negative feedback effect on global warming.

**Research Objectives**

Briefly, our main research objectives are summarized as follows.

***Objective 1***

Simulate the effect of global warming on the global timber market and examine the net release of carbon into the atmosphere by integrating both TSM and TCM. On the basis of empirical simulation results, if the feedback effect is not run back through the model, we only identify the carbon flux effects of climate change. If the feedback loop is considered, it requires more complicated and difficult modeling. To assess the feedback loop, we must not only predict the effects of atmospheric carbon change on climate through the GCM, but also simulate the change of ecosystems through the steady-state ecological model.

***Objective 2***

Analyze model results under several different timber demand growth scenarios. The timber demand growth would be affected by and is coming from mostly housing demand, population, and per capita income growth. High demand growth as well as very high demand growth scenarios were analyzed.

***Objective 3***

In addition to reporting simulation results of important endogenous variables in the TSM including the volume of timber harvests, timber prices, and the level of regeneration input, economic welfare level was evaluated for the base scenario and the climate change scenario. Differences in welfare level between the base scenario and the climate change scenario indicate how much global warming affects the global timber market in the economic welfare sense.

# CHAPTER II

# THE TIMBER SUPPLY MODEL

Forests have very distinctive characteristics that largely separate them from other natural resources. Specifically, their distinctive characteristics lie in the supply curve of the forest resource. In the short run, we can view the supply of timber as similar to that of nonrenewable resources. The short-run timber supply function relates to the existing inventory stock of forest, the marginal cost of extraction, and the transportation cost. Because forests have the characteristics of renewability, however, the short-run timber supply function has limitations to account for the long-run behavior of forests.

The long-run timber supply function relates to the rate of drawdown of current inventory stock and also to the rate of renewablity of the forest. The rate of renewability is in turn a function of the level of investment in forest regeneration as well as the natural endowments in the harvesting site. In this context, we can envisage that the short-run timber supply function deals with the extraction of timber while the long-run timber supply relates importantly to the costs of timber farming such as costs of planting, growing and harvesting trees (Sedjo and Lyon 1990).

This short- and long-run dichotomy in forest management and forest ecology suggests the following questions. First, what would be the determination of an economically optimal transition from an old growth forest to new stationary state forest? Second, at what rate does society proceed in the process of drawing down the old growth inventory and replace it with regenerated forest? Third, what is the optimal level of regeneration investment in the regenerated forest?

**Review of Literature**

To address potential responses to these questions, several economic timber models have been developed to date. These models include work by Adams et al. (1996), Brazee and Mendelsohn (1990), Berck (1979), Sedjo and Lyon (1990, 1996), Sohngen (1996), Sohngen and Mendelsohn (1998), and Sohngen et al. (1998). In this section, we briefly review the defining characteristics of each economic timber model.

In order to reconcile different behavior of the rate of timber production between private and public landowners, Berck (1979) constructed an economic timber model of the forest industry that focused only on the Douglas-fir sector in the Pacific Northwest. In his model, he considered seven quarter century time horizons (about 150 years), which is long enough that the initial time period's supply is insensitive to a change in the end-time conditions. For each time period, he tried to maximize the present value of the profits that entrepreneurs can extract from their forested lands subject to their initial endowments of land and timber, and biological constraints of growing timber.

Using the envelope theorem, he derived the timber supply function from a profit function, which is dependent on the nominal rate of time preference of the entrepreneur. He also estimated a demand function that included price and other variables. Equilibrating timber supply and timber demand, he derived the price of timber in each time period. He argued that the resulting equilibrium price is the rational expectation price of a private entrepreneur and emphasized the fact that this price depends upon the entrepreneur's own rate of time preference. Substituting this equilibrium price into the supply function, he derived the supply of timber as a function of the interest rate parameter for each time period.

Brazee and Mendelsohn (1990) developed a continuous time, optimal control model of a forest to demonstrate the adjustment path of the timber market from one stationary state to another stationary state. Their objective function for harvesting standing stumpage is the discounted revenue from harvests minus the rents paid on the used land, subject to change of the total number of acres of standing forest at time *t*. For the formulation of total costs, they considered three costs, including harvesting costs, planting costs, and land rent. Also they assumed that the marginal harvesting cost, planting cost, and land rent are all constant.

Through application of the pontryagin maximum principle (Pontryagin et al. 1962), Brazee and Mendelsohn (1990) provided the optimal harvesting schedule from necessary conditions. The optimal harvesting schedule is governed by a marginal rule, which is an arbitrage equation that is dependent on the marginal benefit and the marginal cost of postponing the harvest. The arbitrage equation is a differential equation of price; hence, the optimal time path of price can be determined as long as any standing stock remains.

In this context, they suggested that as long as prices are changing according to the arbitrage equation, the private entrepreneur could not be made better off by switching timber harvests to another date. Thus, they argued that a competitive market should choose an optimal intertemporal harvest path. They presented two examples of simulation results based on timber demand changes including a 20% timber demand increase as well as a 20% timber demand decrease to see how endogenous variables change as demands change. Brazee and Mendelsohn (1990) found that while entrepreneurs harvest old growth trees, the growth rate of price of old growth timber is rising more rapidly than the rate of market interest. As such, old growth timber is consumed more quickly than in the case of nonrenewable resources with no rent for land. It indicates that the pricing rule of old growth timber does not follow Hotelling's rule (1931).[2]

Sedjo and Lyon (1990) modeled dynamic economic behavior in the global timber market and labeled their model as TSM. Their model is a nonlinear dynamic optimization model designed to examine dynamic characteristics of timber supply such as aging of trees, timber harvesting and regenerating investment. Discrete time optimal control theory is used to formulate their model. To generate the optimal time path of economic variables, TSM defines the objective function as the sum of discounted present value of net surplus (consumers' surplus and producers' surplus) subject to initial inventory stock and two laws of motion of state variables. This objective function generates the property that the optimal time profile of timber harvesting is economically efficient from society's point of view.

Sedjo and Lyon (1990) included heterogeneous forest types in 22 land classes in seven responsive regions to observe the systemwide time profile of timber harvesting and price in aggregate and by each land class. In particular, they extended their TSM to analyze the supply of solidwood and pulpwood in the world market. In an extended

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[2] For more details, see Hotelling (1931).

model (TSM 96), they not only subdivided the timber demand into solidwood and pulpwood demand, but also did merchantable volume of industrial wood into solidwood and pulpwood using variable proportions, which vary by land classes.

Adams et al. (1996) analyzed how public timber harvest policies affect the private timber production in the conterminous U.S. timber markets by using a dynamic economic model. Prices, private harvest, and private forest management investments were modeled as endogenous variables. They differentiated log products by six product classes including sawtimber, pulpwood, and fuelwood from both hardwoods and softwoods. They employed nine log-producing regions in the U.S including two private-ownership classes, as well as a single national demand in their model. In addition, they also incorporated softwood and hardwood species groups, three site classes, and four timber management intensity classes for the forest inventory stock.

Species groups were used to reflect variations in timber yields, financial returns, and other attributes. They described the species of a particular inventory aggregate by one of four possible intertemporal species order classes such as SOFSOF, SOFHAR, HARHAR, and HARSOF. For instance, a HARSOF referred to land areas in which currently growing stock is in the softwood group, but the previous rotation was in the hardwood group. Inventory stock was also subdivided into three site classes (low, medium, and high) in the two southern regions and the Pacific Northwest Westside, and for elsewhere it was classified as only a single "average" site class. They also considered different timber yields by management intensity class. In this context, four timber management intensity classes for both private owner groups were included such as passive, low, medium, and high management intensity classes.

Based on their model specification, they defined their objective function as the maximization of the discounted sum of future log consumers' and producers' surplus. To calculate consumer and producers' surplus, they estimated consumers' willingness to pay for six timber products according to classifications of logs. From estimated consumers' willingness to pay, they subtracted the total cost of production, which includes timber management cost, log production cost, transportation cost, and costs of investment to expand domestic log processing capacity. In addition, they included export demand and import supply functions for each domestic timber producing region, and incorporated their respective surpluses in the objective function to emulate competitive trade.

Although their modeling approach was consistent with an optimal control modeling framework, they formulated the optimization problem as a nonlinear programming problem to escape the computational difficulties of optimal control solutions. They used currently available nonlinear programming algorithms (in particular, a variant of the MINOS optimizer) to estimate the intertemporal endogenous variables in their base model. They illustrated the simulation results of the sensitivity analysis to important exogenous variables. In addition, they also simulated alternative public harvest scenarios and examined the impacts on private harvests and management, and welfare shifts among groups and regions.

Sohngen (1996) and Sohngen and Mendelshon (1998) constructed a dynamic ecological-economic timber model using continuous time, optimal control theory in order to observe how much global warming would affect timber markets in the terrestrial U.S. They basically followed the model specification by Brazee and Mendelsohn (1990). However, in order to reinforce the theoretical weakness of Brazee and Mendelsohn's model, they defined their objective function to be the discounted present value of the net surplus (consumers' surplus and producers' surplus) as Sedjo and Lyon (1990, 1996) did. In their model, they considered two control variables including how much to harvest, and how many hectares to regenerate. As a consequence, the change of land area in forest, which played as a constraint in their model, was formulated as the difference between land area harvested and regenerated. Also, they included the regeneration cost of trees in their total cost formulation.

In modeling dynamic ecological change impacted by climate change, they considered two dynamic paths of ecological change discussed by ecologists: dieback scenario and regeneration scenario. To estimate dynamic ecological change, they utilized the simulation results of VEMAP (1995), who simulated steady-state ecological change associated with climate change by combining an independently developed biogeographical distribution model and biogoechemical cycle model. VEMAP used MAPSS, DOLY, and BIOME 2 as biogeographical distribution models; TEM, CENTURY, and BIOME-BGC as biogeochemical cycle models; and UKMO, OSU, and GFDL R30 as general circulation models.

Dynamic ecological change was derived from the results of steady-state ecological change and linearlity assumptions about adjustment in climate and ecosystems. With the estimates of dynamic ecological change, they modified a dynamic economic model of U.S timber market in order to reflect dynamic ecological change. Using a modified dynamic economic model, they simulated the timber price path over the simulation period for each dynamic ecological scenario, respectively, and examined the welfare change caused by climate change by comparing the welfare level for the base scenario and each of the climate change scenarios (dieback and regeneration scenario).

Sohngen et al. (1996, 1998) modified the TSM (Sedjo and Lyon 1990) to study how global warming would affect the global timber market. They classified forests across the globe into both timber types and management classes. Management classes were decomposed into five broad categories including regular, plantation, tropical inaccessible, circumpolar inaccessible, and semi-accessible. Based on classification of management classes, they also incorporated 44 different timber types in their model. Consideration of different management classes allowed them to specify differential harvesting patterns in their model. For example, in the circumpolar inaccessible class, timber harvesting does not follow the traditional harvesting rule where the oldest timber is harvested first.

In particular, they did not assume constant marginal cost for timber production for tropical inaccessible and circumpolar inaccessible class. Instead, they defined increasing marginal cost for these classes. Also, they specified marginal cost as an increasing function of cumulative timber harvesting for the semi-accessible class. They specified the laws of motion governing both the hectares of trees by age and the regeneraton input according to the classification of management classes. They also endogenized the choice of plantation establishment by incorporating a cost for purchasing new land in the emerging region plantation.

In order to model dynamic ecological change impacted by climate change, Sohngen et al. (1998) used the simulation results of BIOME 3 using two general circulation models (the Hamburg [Claussen, 1996] and the UIUC [Schlesinger et al. 1997]). They considered two paths of dynamic ecosystem type changes: dieback and regeneration. Using the dynamic ecological change framework in Sohngen (1996) and Sohngen and Mendelsohn (1998), they simulated the optimal time path of endogenous variables in their model for the base scenario and each of the two climate change scenarios (dieback and regeneration scenario). When they compared simulation results between the base scenario and each of climate change scenarios, they identified that global warming would affect positively the global timber market through an increment of timber harvests and a decrease of timber price.

Sohngen et al. (1998, 1999) extended the model developed by Sohngen (1996) and Sohngen and Mendelsohn (1998) to observe dynamic behavior of the global timber market. In addition, by modifying their extended model to account for the dynamic ecological change, they investigated how much global warming would impact on the global timber market. After simulating both the base scenario and each of the climate change scenarios, they again identified that global warming would have a positive impact on the global timber market through the increase of economic welfare.

Among economic timber models reviewed above, the TSM developed by Sedjo and Lyon (1990, 1996) provided significant comparative advantages in the analysis of diversified forest ecosystem management strategies. In general, harvesting levels in TSM were affected by seven types of adjustment: (1) rotation length of age, (2) the rate of drawn-down of old growth inventories, (3) the number of forested land classes that are utilized in the harvest, (4) the level of regeneration input applied to the various land classes, (5) the rate at which new industrial plantations are added to the world's timber producing regions, (6) the rate of technical change, and (7) changes in production from nonresponsive regions of the world (Lyon and Sedjo 1992). Because of these comprehensive natures of the TSM framework, we adopted it as the key economic model to achieve our research objectives.

**Description of the Timber Supply Model**

The TSM was constructed to examine theoretical and empirical issues in the world timber market. The dynamic characteristics of timber supply such as aging of trees, timber harvesting, and regenerating input are modeled using discrete time optimal control theory. This model generates the optimal time path of economic variables in the timber market in the sense that the model is to maximize the sum of discounted present value of net surplus (consumers' surplus and producers' surplus), subject to the initial inventory and laws of motion governing evolution of the system.

In this model, two laws of motion are formulated, one for the hectares of trees by age and the other for regeneration input level. These two laws of motion explicitly recognize that timber harvest levels depend on both existing capital stock and the growth of trees resulting from regeneration. In this sense, the TSM allows for estimations and projections of the economically efficient rate of harvesting from existing old growth forests, natural regeneration of second growth, and man-made plantations.

From a social perspective, the TSM maximizes total benefit to the society as a whole, not the net income stream of an individual landowner. Compared to other economic timber models (Berck 1979, Brazee and Mendelsohn 1990), whose objective function is to maximize the discounted present value of net income stream of the landowners, the TSM provides economically efficient solutions.

The TSM traces out the systemwide time profile of harvesting volume in aggregate and by each land class, and generates a systemwide dynamic market price while determining the economically efficient regeneration by time period and by each land class. In the TSM, timber supplying regions are decomposed into two categories; one is the responsive region and the other is nonresponsive region. The responsive regions are defined because they are assumed to respond to profit-maximization incentives and therefore generally behave in a way that we have termed as economically efficient. Actually, these regions have predominant market economies and are functioning largely in response to market forces. The responsive regions consist of seven regions including: U.S. South, U.S. Pacific Northwest, western Canada (British Columbia), eastern Canada, Nordic Europe, Asia-Pacific, and the emerging region.

These seven responsive regions are subdivided into 22 land classes in the model to capture both physical and economic conditions.

Among these responsive regions, the emerging region has played a critical role in increasing the supply of timber to the global market. Over the past 20 years, a large area of plantations has been established in both subtropical and tropical regions of the globe. Sedjo (1995) estimated that 9.8% of global industrial wood production is supplied from this emerging region. The emerging region in the TSM includes Brazil, Chile, and Venezuela in South America; Australia and New Zealand in Oceania; and South Africa, Spain, and Portugal in Europe.

The nonresponsive regions include the former Soviet Union, other European subregions, and all other regions in the globe. These regions are not included in the TSM because timber harvesting in these regions is viewed as autonomous and is determined independently of the usual economic incentives. However, according to Sedjo et al. (1993) almost 50% of worldwide industrial wood production in the mid 1980s was supplied from the non responsive regions.

**Specification of TSM 2000**

In addition to both theoretical and regional characteristics of the TSM described above, we extended the TSM by considering more important up-to-date components to achieve our research goals. First, the extended TSM (referred to as the TSM 2000) considers the former Soviet Union as a part of the responsive region due to more liberal economic incentives that exist in timber markets that are undergoing market-oriented reform. Since the former Soviet Union has been in the process of transformation from a centrally planned and regulated economy into market functioning economy since 1990, the former Soviet Union will participate in the global timber market in the future. It will, therefore, play a critical role in supplying stumpage to the global timber market since it is estimated that it contains approximately 25% of worldwide forest growing stock (Backman and Waggener 1991).

The Soviet forestry establishment has traditionally divided the country into two distinctive regions: European USSR and Asian USSR, including Central Asia. Moreover, the traditionally defined Asian USSR region can be divided into an East Siberia region encompassing most of the mountain forests and West Siberia region that lies immediately adjacent to the European part of the country. For this research, we subdivided the former Soviet Union into three subregions: European USSR, West Siberia, and East Siberia. Also, according to ecosystem types and the degree of accessibility for harvesting, these three subregions consist of 16 land classes: eight land classes for European USSR, four land classes for West Siberia and East Siberia, respectively.[3] Specific land classes for subregions in the former Soviet Union are shown in Table A-1 (see Appendix A).

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[3] According to the BIOME 3 simulation, European USSR is subdivided into four ecosystem types; including Boreal Coniferous, Temperate Conifer, Temperate-Boreal Mixed, and Temperate Deciduous. Also, West Siberia and East Siberia are subdivided into two ecosystem types; Boreal Coniferous and Temperate-Boreal Mixed, respectively. On the basis of ecosystem types for each subregion, we classified a land class as "North" if the forest type is *coniferous* and as "South" if the forest type is *deciduous* for each subregion. In addition, we considered a land class as accessible if the age of forest is young class I, II, and middle age; and as inaccessible if the age of forest is approaching mature, mature, and over mature. For age categories of the forest, the method used in Backman and Waggener (1991) was followed.

Second, we included more plantation forests in the emerging region in TSM 2000. Plantation forests in India, the Asia-Pacific region, and subregions in Africa except South Africa are not included as part of the emerging region in the original TSM. Both tropical and subtropical regions have experienced an increase in plantation forests (Sedjo 1995). Land areas in these regions, which are exploited for agricultural production or were being conserved for the future use, are now being turned into plantation forests. In order to obtain more detailed projections of the intertemporal time profile of the world stumpage price and harvesting level, we needed to include plantation forests of these regions as part of the emerging region in the TSM 2000. About six million hectares had been planted in the emerging region by 1980 (Sedjo and Lyon 1990); however, it is estimated that plantation forest acreage included in these area was about 38 million hectares in 1990 (United Nations Food and Agricultural Organization [UNFAO] 1993a, 1993b, 1995).

Third, there has been a trend to withdraw forest land from timber harvesting and conserve it for wilderness, ecological reserves, parks, scenic corridors, and other purposes in many major timber-producing countries. The International Union for Conservation of Nature and Natural Resources (IUCN) has published the *United Nations List of National Parks and Protected Areas* since 1962. Recent publications in 1990 and 1994 included all the areas designed to be protected by individual governments as well as the international organizations. These land areas are based on three criteria such as size, management objective, and authority of the management agency (IUCN 1994). According to management categories of these versions, category 1 through category 5 are the areas where all commercial timber harvesting is officially prohibited. Yan (1996) calculated the conserved hectares of forest for seven responsive regions being included in the TSM since 1981 (1980 for Asia Pacific region) based on publication of IUCN (1994). He designed nine scenarios of forest conservation by combining these calculations with more information on conservation actions for each responsive region.[4]

Obviously, forest conservation will have an impact on commercial forest inventories and the time profile of timber harvesting, stumpage price, and forest management practices. Current trends to promote conservation of forest for environmental protection suggest that conservation patterns modeled in TSM 2000 will be an important factor affecting worldwide timber supply. In this respect, we modeled conservation of forest for each region by adopting Yan's (1996) scenario five and the forest conservation ratio of sub-regions of the former Soviet Union in Backman and Waggener (1991).[5] Table A-2 in Appendix A shows the conservation ratio of forest for each land class in the TSM 2000. Based on the conservation ratio of forest for each land class, we calculated the commercial inventory of forest with conservation for each land class (see Table A-3 in Appendix A).

Fourth, the TSM considered only 22 land classes in seven responsive regions to project the optimal time profile of important endogenous variables in the model. To meet the first research objective (i.e., to identify the effect of global warming on the

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4 For more details, see Chapter 4 of Yan's dissertation (1996).

5 For the former Soviet Union, the conservation ratios of forest for European USSR, West Siberia, and East Siberia are 29%, 16%, and 14%, respectively. According to Backman and Waggener, Group I Forest is most commonly restricted for forest conservation.

global timber market), we considered changes in the distribution of ecosystem type (vegetation pattern) and changes in the productivity of ecosystem type from simulation results of a steady-state ecological model after climate change. When we examined change in the distribution of ecosystem types on the basis of BIOME 3 predictions using Hamburg as our GCM, we observed that in some regions a large potion of an ecosystem type would be transformed into other ecosystem types after climate change. This reflects the fact that some species die out from the area where they are currently standing, and new species are regenerated naturally or planted by human beings for economic benefit. In this respect, we subdivided land classes in more detail in the TSM 2000 in order not to lose the ecological information detail acquired from the BIOME 3 predictions on ecosystem type change. The TSM 2000, therefore, included 42 land classes in 10 responsive regions so that we might examine the impact of global warming on forest types in more detail. Detailed land class classifications are shown in Table A-1.

In the TSM 2000, we included demand curves for both solidwood and pulpwood. Net surplus in year *j* is defined as the area under year *j*'s demand curve for solidwood from zero to the volume of harvested, plus the area under year *j*'s demand curve for pulpwood from zero to the volume of harvested minus harvesting, transportation, and regeneration costs for year *j*, where the costs are the sum of costs over the 42 land classes.

The volume of merchantable timber was divided between solidwood and pulpwood using variable proportions that were determined endogenously as a function of the price of solidwood relative to the price of pulpwood. These ratios also vary by land class.

In addition, each land class has its own cost function, which is determined by specific features such as harvesting terrain, log size, accessing terrain, distance to mill, and distance to the international timber market. The costs for a land class in year $j$ depended on the cost function, the volume harvested in year $j$, and the hectares of land harvested and regenerated in the land class in year $j$.

The volume of timber harvested for each land class depends on the yield function for the land class and the hectares by age group of trees harvested. The yield function for each land class is determined by characteristics such as climate, terrain, and soil quality. In addition, the yield per hectare is a function of the age of trees (years since the trees were regenerated) and the intensity of management practices used on that hectare during this rotation.

The initial conditions are set by observing historical characteristics of forest areas, including hectares of forest by age group and land class, as well as the level of the composite regeneration input for each of the hectares. The composite input is the present value of all planting and silvicultural operations, including precommercial thinning. This is referred to as the level of regeneration input or as the intensity of forest management.

The laws of motion for the system are the rules governing the system, including rules for aging and regenerating the forest. Such rules redefine hectares of trees in age group $i$ in year $j$ to be hectares of trees in age group $i + 1$ in time period $j + 1$. They regenerate each harvested hectare in the time period during which it is harvested. Also, the laws of motion redefine the level of regeneration input associated with age group $i$ in time period $j$ as the level associated with age group $i + 1$ in time period $j + 1$ in order to keep together each hectare of trees and their associated level of regeneration input.

The choice (control) variables for each year include the hectares harvested by age group and land class, and the level of regeneration input for each land class. Selection of these determines the rotation age by land class, volumes harvested, and costs in each year. Therefore, with the laws of motion and the initial conditions, these variables determine the structure of the forest, hectares of forest, and regeneration input by age group and land class in each year.

The problem is structured so that it evolves to the stationary state, which is a state where the same flows occur and the same stocks exist each year. This is sometimes called the regulate forest. The computer optimization program first solved for the stationary state solution values of the control and state variables. The state variables are the stock variables discussed above, hectares of trees by age group and land class, and the associated levels of the regeneration input. It solved for the optimal length of the rotation period, the stumpage (net) price of timber, and the volume of timber harvested by land class in the transition period. This was done by solving the difference equation problem identified by the law of motion, the first-order conditions, the initial conditions, and the terminal conditions, where the terminal conditions were determined by the solution stationary state.

The role of discrete optimal control theory lies in identification of the laws of motion and the equations and equalities for the necessary conditions. These were used to identify the equations that were iteratively solved to numerically solve the problem.

**Formulation of TSM 2000**

Functional representation of the model and economic variables used in the TSM 2000 are presented in this section. The net surplus in the year j can be defined as

$$s_j = \int_0^{Q_j} D_j^s(n)dn + \int_0^{\tilde{Q}_j} D_j^p(n)dn - C_j \tag{1}$$

where $Q_j$ is the quantity or volume of timber for solidwood harvested in year *j*; $D_j^s(Q_j)$ is the inverse demand function of industrial wood for solidwood in year *j*; $\tilde{Q}_j$ is the volume of timber for pulpwood harvested in year *j*; $D_j^p(\tilde{Q}_j)$ is the demand function of industrial wood for pulpwood in inverse form; and $C_j$ is the total cost in year *j*. The total costs are the summation of harvest, access, transportation costs *($CH_j$)* and regeneration cost *($CR_j$)*. Harvesting and transportation costs in year j depend on the total volumes harvested by land class, and regeneration costs depend on hectares harvested (regenerated) and the level of input used.

We define $x_{hj}$ to be a vector of hectares of trees in each age group for land class *h* in year *j* with elements $x_{hij}$. The subscripts *h*, *i*, and *j* correspond to land class, age group, and the year, respectively. The equatin $x_{hij}$ denotes for land class *h*, the number of hectares of age group *i* in year *j*; let $z_{hj}$ be the vector of state variables for the regeneration input with elements $z_{hij}$, the level of regeneration input associated with age group $i$ in year $j$ for land class $h$. Next, $u_{hj}$ is defined to be control vector of hectares harvested. The elements of $u_{hj}$ denote for land class $h$ the portion of the hectares of trees in age group $i$ harvested in year $j$. Let $w_{hj}$ be the level of regeneration input per hectare for those hectares regenerated in year $j$, and let $p_{wh}$ be the price of regeneration input for land class $h$.

The merchantable volume of timber per hectare for land class $h$ in time period $j$ for a stand regenerated $i$ time periods ago depends on $i$ and on the magnitude of the regeneration input used on this stand ($z_{hij}$). We denote this merchantable volume as follows:

$$q_{hij} = f_h(i, z_{hij}) \tag{2}$$

This volume is divided between solidwood and pulpwood using variable proportions that vary by land class, with $\phi_h$ referring to the portion going to solidwood and (1 - $\phi_h$) the portion going to pulpwood. The proportion $\phi_h$ a constant elasticity function of the price of solidwood relative to the price of pulpwood $(p_j^s / p_j^p)$. When this relative price is greater than or equal to 1.05, it is given by

$$\phi_{hj} = A_h (p_j^s / p_j^p)^{\varepsilon} \tag{3}$$

where $p^s$ and $p^p$ are solidwood and pulpwood price, respectively; $\varepsilon$ is the elasticity of $\phi$ with respect to relative price, which is the same for all land classes, and $A_h$ is a scaling factor that varies by land class. When, however, the relative price is between 1 and 1.05, we use the function

$$\phi_{hj} = [(p_j^s / p_j^p) - 1]^{\varepsilon 2h} \tag{4}$$

where $\varepsilon 2h$ is selected so that these two functions for $\phi_{hj}$ give the same value at a relative price of 1.05. Note that the value of this function approaches 0 as the relative price approaches 1. For the base case and several scenarios to be considered, we use an elasticity, $\varepsilon$, of 0.6, and select the scaling factors so that the reference level of $\phi_h$, given in Table A-8 (Appendix A), would exist at a relative price of 1.5.

With these definitions, the volume of commercial timber harvested for solidwood and pulpwood from land class $h$ in year $j$, $Q_{hj}$ and $\tilde{Q}_{hj}$ is given by

$$Q_{hj} = \phi_{hj} u_{hj}^{'} X_{hj} q_{hj} \tag{5a}$$

$$\tilde{Q}_{hj} = (1 - \phi_{hj}) u_{hj}^{'} X_{hj} q_{hj} \tag{5b}$$

and

$$Q_j = \sum_h Q_{hj},\ \tilde{Q}_j = \sum_h \tilde{Q}_{hj} \tag{6}$$

where $X_{hj}$ is a diagonal matrix using the elements of $x_{hj}$, and the total volume harvested in the responsive regions is the summation of these over all land classes.

Costs including harvest, access, and transportation cost for land class $h$ are a function of the volume harvested in that land class;

$$CH_{hj} = c_h (Q_{hj} + \tilde{Q}_{hj}) \tag{7}$$

and regeneration cost for land class $h$ in time period $j$ is given by

$$CR_{hj} = (u_{hj}^{'} x_{hj} + v_{hj}) p_{wh} w_{hj} \tag{8}$$

where the inner product in parenthesis gives the hectares harvested in land class $h$, $v_{hj}$ is the exogenously determined number of hectares of new forest land in land class $h$, and the product of the last two terms gives expenditure per hectare. Total costs are formulated as

$$C_j = \sum_h (CH_{hj} + CR_{hj}) \tag{9}$$

With these definitions, the objective function of TSM 2000 is the discounted present value of the net surplus as follows:

$$S_0(x_0, z_0, u, w) = \sum_{k=0}^{J-1} \rho^k s_k + \rho^J S_J^*(x_J, z_J) \tag{10}$$

where ρ is the discount factor, $e^{-r}$, with $r$ as the market interest rate; $J$ is the last time period; $u$ is any admissible set of control vectors, $u_0, u_1, ..., u_{J-1}$ (including all land classes); $w$ is any set of admissible control scalars, $w_0, w_1, ... w_{j-1}$ (also covering all land classes); and $S_J$* (.,.) is the optimal terminal value function.

The equation (10) should be maximized subject to the laws of motions of state variables and constraints on the value of control variables.

The portions of hectares harvested are constrained to be nonnegative and less than or equal to 1, and the regeneration inputs are constrained to be nonnegative;

$$0 \le u_{hij} \le 1 \qquad \text{for all } h, i, j \tag{11a}$$

$$0 \le w_{hj} \qquad \text{for all } h, j \tag{11b}$$

The laws of motion for the given system are given by

$$x_{h,j+1} = (A + BU_{hj})x_{hj} + v_{hj}\, e \qquad \text{for all } h, j \qquad (12a)$$

$$z_{h,j+1} = Az_{hj} + w_{hj}\, e \qquad \text{for all } h, j \qquad (12b)$$

where

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 1 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 1 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 1 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 0 & 1 & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad e = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 & 1 & 1 & 1 & \cdot & \cdot & \cdot & 1 \\ -1 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & -1 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & -1 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 0 & -1 & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}$$

*A, B,* and *U* are *M*-square matrices; $U_{hj}$ is a diagonal matrix using the elements of $u_{hj}$; and ***e*** is an *M*-vector where *M* is equal to or greater than the index number of the oldest age group in the problem.

The product $Ax_{hk}$ moves $x_{hij}$ *to* $x_{h,i+1,j+1}$. Each year each age group becomes older by one year. The product $BU_{hj}x_{hj}$ subtracts from the redefined quantities the hectares harvested and places them in the one-year-old category (newly regenerated category). $v_{hj}$ is the exogenously determined hectares of new forest plantation in time period $j$, and $v_{hj}\,e$ adds these hectares to the one-year-old age group in time period $j + 1$. These can be expressed as;

$$x_{h,1,j} = u'_{hj} x_{hj} + v_{hj} \qquad \text{for all } h, j \qquad (13a)$$

$$x_{h,i+1,j+1} = x_{h,i,j} - u_{h,i,j} x_{h,i,j} \qquad (i = 1, 2, \ldots, \text{M-1}) \qquad (13b)$$

In the law of motion for $z$, the product $Az_j$ moves $z_{h,i,j}$ to $z_{h,i+1,j+1}$. This parallel redefining of $x$ and $z$ keeps the regenerated hectares and the level of their regeneration input in the same relative position in their respective state vectors. The scalar product $w_{hj}\,e$ places $w_{hj}$ in location $z_{h,1,j+1}$. Thus,

$$z_{h,1,j+1} = w_{hj} \qquad \text{for all } h, j \qquad (14a)$$

$$z_{h,i+1,j+1} = z_{h,i,j} \qquad (i = 1, 2, \ldots, M\text{-}1) \qquad (14b)$$

## The Solution Techniques

### *Necessary Conditions*

The problem of maximizing objective function (10), subject to the constraint equations (11a-12b), is a discrete time, optimal control problem that can be solved by the discrete time maximum principle. Applying the maximum principle for this timber supply problem, we can derive the necessary conditions. The maximum principle is a theorem that states that the constrained maximization of equation (10) can be decomposed into a series of subproblems. In each time period, the following Hamiltonian is maximized with respect to $u_{hj}$ and $w_{hj}$ subject to constraints.

The Hamiltonian for year $j$ is

$$H_j = \int_0^{Q_j} D_j^s(n)dn + \int_0^{\bar{Q}_j} D_j^p(n)dn - C_j + \sum_h \lambda'_{h,j+1}[(A+BU_{hj})x_{hj} + v_{hj}e] + \sum_h \psi'_{h,j+1}(Az_{hj} + p_{wh}w_{hj}e) \qquad (15)$$

where

$$\lambda_{hj} = \rho\,[\partial S_J^*(x_J, z_J)/\partial x_{hj}] \qquad (j = 1,.........J)$$

$$\lambda_{hj} = \rho\,[(\partial s_j^*/\partial x_{hj}) + (A+BU_{hj}^*)'\lambda_{h,j+1}] \qquad (j = 1,.........J-1) \qquad (16a)$$

and

$$\psi_{hj} = \rho\,[\partial S_J^*(x_J, z_J)/\partial z_{hj} \qquad (j = 1,..........J)$$

$$\psi_{hj} = \rho\,[(\partial s_j^*/\partial z_{hj}) + A'\psi_{h,j+1}] \qquad (j = 1,..........J-1) \qquad (16b)$$

The derivatives with respect to vectors are gradient vectors, and $S_{j+1}^*(\ )$ is the solution function in $j+1$. The solution function in year $j+1$ can be conceptualized as the result of an application of Bellman's optimality principle and backward recursion. The $\lambda_{hj}$ and

$\psi_{hj}$ are costate (adjoint) vectors and identify the shadow values of the hectares of forest and the regeneration input, respectively, in each age group in year $j$.

The necessary conditions for constrained maximization of the Hamiltonian in equation (15) are both necessary and sufficient for the constrained maximization of equation (10). The correspondence of necessary conditions is the essence of the maximization principle (Halkin 1966). The conditions are sufficient because an equivalent form of the constrained maximization of (10) can be shown to be the maximization of a quasi-concave function subject to a set of linear constraints.

The Lagrnagian function and the Kuhn-Tucker necessary conditions of this optimization problem are:

$$L_j^H = H_j + \sum_h \xi_{hj}'(1-u_{hj}) \tag{17}$$

$$\partial L_j^H / \partial u_{hj} = [D(Q_j) - C_h'(Q_{hj})]X_{hj}q_{hj} - x_{hj}p_{wh}w_{hj}$$
$$+ X_{hj}^{'}B^{'}\lambda_{h,j+1} - \xi_{hj}^{'} \leq 0 \qquad \text{(for all } h\text{)} \tag{18a}$$

$$(\partial L_j^H / \partial u_{hij})u_{hij} = 0 \qquad \text{(for all } h \text{ and } i\text{)} \tag{18b}$$

$$\partial L_j^H / \partial w_{hj} = -u_{hj}x_{hj}p_{wh} + \psi_{h,j+1}p_{wh} \leq 0 \qquad \text{(for all } h\text{)} \tag{18c}$$

$$(\partial L_j^H / \partial w_{hj})w_{hij} = 0 \qquad \text{(for all } h \text{ and } i\text{)} \tag{18d}$$

$$\partial L_j^H / \partial \xi_{hj} = (1-u_{hj}) \geq 0 \qquad \text{(for all } h\text{)} \tag{18e}$$

$$(\partial L_j^H / \partial \xi_{hj})\xi_{hij} = 0 \qquad \text{(for all } h \text{ and } i\text{)} \tag{18f}$$

These Kuhn-Tucker conditions, the laws of motion for the state variables (equations

12a-12b), and the laws of motion for costate variables (equations 16a-16b) identify a two-point boundary value problem that can be used to solve both theoretical and numerical problems.

***The Analytic Solution***

Equations (12a-12b) identify the method for calculating the values of state variables (hectares of forest by age group and stock of regeneration investment) in each year, given the values of the control variables in each year. These equations move the state variables forward through time. Equations (16a-16b) identify the method for calculating the costate variables (shadow values of the state variables) in each year, given the values of the control variables in each year. This procedure calculates the costate variables starting at year $J$ and moving backward through time to the present ($j = 0$). Finally, equations (18a-18f) identify the method of finding the values of control variables in each year. Now, we will manipulate equations (18a) and (18b) into a set of difference equations and use the difference equations in our solution algorithm and in our theoretical discussions of the solution time profiles. The elements of $\partial L_j^H / \partial u_{hj}$ in equation (18a) can be written as

$$p_{hj} x_{hij} q_{hij} - x_{hij} p_{wh} w_{hj} + x_{hij}(\lambda_{h,1,j+1} - \lambda_{h,i+1,j+1}) - \varsigma_{hij} \leq 0 \quad \text{(for all } h \text{ and } i\text{)} \qquad (19)$$

where $p_{hj}$ is the net price or stumpage price of timber for land class $h$. Stumpage price is equal to the market price of solidwood weighted by the portion of timber in land class $h$, that is solidwood, $\phi_h D_j^s(Q_j)$, plus the price of pulpwood weighted by the portion that is pulpwood $(1-\phi_h)D_j^p(\tilde{Q}_j)$ minus the marginal harvesting, access, and transportation cost of timber $c_h^{'}(Q_{hj}+\tilde{Q}_{hj})$. This equation gives the marginal net surplus (net shadow value) of harvesting hectares of trees by age group and land class.

In equation (19), $\lambda_{h,1,j+1}$ is the shadow value of trees that are one year old in year *j* + *1* (i.e., trees regenerated in year *j*). Examination of equation (16a) indicates that its solution value is the discounted value of the actual harvest of these trees in the future. The costate variable, $\lambda_{h,i+1,j+1}$, is the discounted value of age group *i* in the land class *h* from next year. For age group *k* in this land class it can be written as

$$\lambda_{h,k+1,j+1} = \rho(\lambda_{h,1,j+1} + p_{h,j+1}q_{h,k+1} - p_{wh}w_{hj+1}) \tag{20}$$

which states that the opportunity cost of harvesting *k* year old trees in year *j* is the discounted value of the trees that could be regenerated a year in the future plus the stumpage price of timber next year times the merchantable volume of timber on that hectare one year in the future minus the optimal regeneration expenditures on that hectare. Combining equation (20) with equation (19) yields

$$p_{hj}q_{hk} - p_{wh}(w_{hj} - \rho w_{hj+1}) + \lambda_{h,1,j+1} - \rho\lambda_{h,1,j+2} - \varsigma_{hkj}/x_{hkj} - \rho p_{hj+1}q_{hk+1} \leq 0 \tag{21}$$

The solution to this discrete time optimal control model is the time paths of state variables, control variables, and costate variables, such that the laws of motion for state variables, equations (12a-12b), the laws of motion of costate variables, equations (16a-16b), the difference equation for the net price of timber (stumpage price) given in equation (21), and the remaining first-order condition, equations (18b-18f) through

(2.14f), are simultaneously satisfied. These form a two-point boundary value difference equation problem.

### *Solution Algorithm*

Our solution algorithm solves the optimal values of the control (choice) variables in the transition period. These time paths generate an evolution of the state variables (e.g., hectares of trees by age group) from their initial values to those in the stationary state. The algorithm uses a shooting (binary search) method to solve a constrained difference equation problem. The difference equations are the law of motions of the state variables; the law of motions of costate variables; and an equation that is derived from the first two necessary conditions. These form a two-point boundary value difference equation problem, which is to be solved subject to the remaining first-order conditions. The boundary values are determined by the initial and terminal conditions.

These difference equations with their initial conditions have a set of solutions, one for each value of market price of timber in the first time period. The shooting method is a search for the member of this set that satisfies the terminal conditions. This search is carried out by starting with an arbitrary element from the set of solutions and systematically eliminating solutions that do not satisfy the terminal conditions until a satisfactory solution is found.

# CHAPTER III

## THE ECOLOGICAL CHANGE IMPACTED BY GLOBAL WARMING

The primary objective of this chapter is to explicitly model the dynamic ecological change generated by global warming. While a dynamic ecological model that covers all regions of the globe has not yet been developed, recent advances by VEMAP (1995) have focused efforts on development of a dynamic ecological model for the conterminous U.S. This model is referred as VEMAP Phase II, and is not currently available for general use among the scientific community working on global warming issues. As a result, we depended on steady-state ecological models in order to derive necessary information about dynamic ecological change. Steady-state ecological models have been constructed only to observe the change of steady-state equilibrium of ecosystems before and after climate change.

In order to observe the change of steady-state ecological equilibrium, a GCM was used to capture the climate change when carbon dioxide is doubled in the atmosphere. Using changed-climate variables as inputs, the steady-state ecological model simulated not only the change of distribution of ecosystem type, but also the change of productivity of ecosystem type across the globe.

Steady-state ecological models are, in general, classified into two types of models: the biogeographical distribution model and the biogeochemical cycle model. The biogeographical distribution model predicts the change of distribution of ecosystem types (vegetation patterns) and the biogeochemical cycle model evaluates the change of productivity of the ecosystem. Steady-state ecological models only provided information on the change of steady-state ecological equilibrium, but they did not supply information on the transient change of ecosystem type during the time period of climate change. We compensated for this limitation by assuming that both climate change and ecosystem change occurs as a linear function of carbon dioxide accumulation in the atmosphere. Under this assumption, we were able to simulate dynamic ecological changes between steady-state ecological equilibria before and after climate change. In the following sections, we examine characteristics of the two conventional steady-state ecological models and discuss our attempt to extract information about dynamic ecological change based on the results of a steady-state ecological model.

## The Steady-State Ecological Model

### *The General Circulation Model*

The GCM is designed to predict the distribution of climate variables in a geographic grid cell (e.g., .5° x .5°) latitude and longitude grid cell. To examine climate change, we supposed that the current distribution of climate variables across the globe serves as the base climate. Using the GCM, we simulated the distribution of climate variables, at the cell level, contingent upon a doubling of carbon dioxide in the atmosphere. Once the distribution of climate variables between the base scenario and the scenario in which atmospheric carbon dioxide is doubled is compared, the variation of climate across the globe can be examined. Simulation results from the GCM were used as inputs in the steady-state ecological model.

There are approximately 30 GCMs in use by scientists investigating climate change issues. These include GISS (Hansen et al. 1988), UKMO (Wilson and Mitchell 1987), GFDL-R30 (Manabe and Wetherald 1987), OSU (Schlesinger and Zhao 1989), Hamburg (Claussen 1996), and UIUC (Schlesinger et al. 1997), etc. We used Hamburg for our GCM since it is designed to simulate most aspects of the observed time-mean circulation and its intraseasonal variability with remarkable skill (Claussen 1996).

***The Biogeographical Distribution Model***

The biogeographical distribution model (geographic model) is designed to simulate the potential natural distribution of vegetation patterns as a function of climate and soils across the globe. MAPSS (Neilson and Marks 1994), BIOME 2 (Prentice et al. 1992), and DOLY (Woodward et al. 1995) were developed and used to simulate the change of distribution of ecosystem types under various climate scenarios. These models use mechanistic rules to classify spatial vegetation patterns which are dependent on climate variables. Although each model utilizes a different algorithm to generate the change of distribution of ecosystem type, all models are dependent on the fact that climate determines vegetation patterns in the site in which they are growing. In general, it is known that the distribution of forest types is highly correlated with the distribution of ecosystem types. On the basis of this relation, we can acknowledge that if the ecosystem types are adjusted or transformed by the global warming, forest types across the globe will follow the change in ecosystem types.

### *The Biogeochemical Cycle Model*

The biogeochemical cycle model (biogeochemistry model) has been developed to simulate biogeochemical fluxes through ecosystems given a prescribed distribution of ecosystem types. These models consider the processes involved with carbon, nitrogen, and water cycles to determine ecosystem production under given climate conditions. Given that a specific ecosystem type is present, biogeochemical cycle models predict net primary productivity (NPP). The NPP is defined as the net amount of carbon available for plant growth from photosynthesis in any given period. Net primary productivity represents the carbon stored in plants per unit time, which is not used for respiration, but is exploited only for plant growth (Sohngen 1996). In this sense, the difference in the NPP between the base climate and changed climate affects the size of a tree. Biogeochemical cycle models currently in use include TEM (Mellio et al. 1993), CENTURY (Parton et al. 1988), and BIOME-BGC (Running and Coughland 1988, Running and Gower 1991).

Both the biogeographic distribution models and the biogeochemical cycle models have, for the most part, been developed independently. Both have been used for large geographic regions using various GCMs. It is, however, widely acknowledged that any serious attempt to assess how global climate change will affect natural ecosystems must combine the insight provided by both models (VEMAP 1995). VEMAP began to employ several models of each type and to compare combined models in order to provide more realistic simulation of ecological response to climate change. Their efforts have resulted in models providing more robust insight into the process of steady-state ecological change which underlies climate variation. However, they failed to link formally specific models so that both models interact truly. In addition, the VEMAP project included only the conterminous U.S., but did not span the entire globe.

### *Description of BIOME 3*

The work of Haxeltine and Prentice (1996) reflects an attempt to provide explicit interaction between the biogeographical distribution model and the biogeochemical cycle model within a single global framework. They labeled their model BIOME 3. BIOME 3 has been developed to simulate ecosystem types around the globe using a minimal set of just five woody and two grass plant types as plant functional types (PFTs).[6] This classification scheme was used to map outputs to biomes. Biomes across the globe are classified into 18 legends. Of these, forests are mapped using only nine legends.[7]

An important application of BIOME 3 is to simulate the equilibrium response of vegetation patterns to climate change, which results from change in atmospheric carbon dioxide concentrations. The model captures the direct response of photosynthesis and

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[6] For more detail about the plant functional types, see the Haxeltine and Prentice (1996).

[7] Nine legends denoting the forests are as follows; 1: Boreal Deciduous Forest/Woodland, 2: Boreal Coniferous Forest/Woodland, 3: Temperate-Boreal Mixed Forest, 4: Temperate Conifer Forest, 5: Temperate Deciduous Forest, 6: Temperate Broadleaved Evergreen Forest, 7: Tropical Seasonal Forest, 8: Tropical Rain Forest, and 9: Tropical Deciduous Forest.

stomatal conductance to change in carbon dioxide. Its output consists of a quantitative vegetation state description in terms of the dominant PFTs, the total leaf area index (LAI), and the NPP. Thus, this model is used to simulate the direct effect of changing carbon dioxide on vegetation distribution, the net primary productivity, and leaf area.

We utilized the BIOME 3 for our research to observe steady-state ecological equilibrium change. Simulated results of BIOME 3 using Hamburg provided the necessary information about steady-state ecological changes when carbon dioxide is doubled in the atmosphere.

## The Dynamic Ecological Model

### *Linearity Assumptions*

When carbon dioxide is doubled in the atmosphere, the steady-state ecological model predicts a steady-state equilibrium response in the distribution of ecosystem type as well as in the productivity of ecosystem type. In reality, the steady-state equilibrium response for climate and ecosystems is likely to occur with a time lag. Climate variables will change slowly as the amount of carbon dioxide is accumulated into the atmosphere. Ecosystems also respond slowly as changes in climate variables occur slowly over a time period. In this sense, both climate and ecosystem change are considered in a dynamic process rather than in a steady-state process.

In order to examine the dynamic ecological change, we imposed three linearity assumptions about adjustment in climate and ecosystems as Sohngen (1996) and Sohngen and Mendelsohn (1998) did. First, climate variables are linearly increasing from 1990 to

2060. After 2060, climate variables are assumed to stabilize as environmental agencies around the world successfully regulate the anthropogenic emission of carbon dioxide into the atmosphere. This assumption is consistent with the IPCC (Houghton et al. 1990) projection of a linear increase of temperature from 1990 through 2060, the time in which carbon dioxide is posited to double. Second, dynamic ecosystem adjustment occurs proportionally to climate change. Third, the annual net primary productivity also changes in proportion to climate change. These linearity assumptions enable us to identify dynamic ecological change from outputs of a steady-state ecological model.

Dynamic ecological changes are decomposed into two categories: change in land area of each ecosystem type and change in productivity of each ecosystem type. Dynamic land area change can be derived from the biogeographical distribution model, while dynamic productivity change can be estimated from the biogeochemical cycle model. Changes in distribution of ecosystem type, as well as change in net primary productivity, are simultaneously provided by BIOME 3 through their functional interaction.

***Dynamic Land Area Change***

There has been considerable controversy among ecologists surrounding how the old type forest is transformed and displaced as climate changes over time (King and Neilson 1992, Shugart et al. 1986, Solomon 1986). In general, two processes for dynamic ecosystem type change were considered among ecological scientists. One is dieback and the other is regeneration. Dieback occurs when environmental conditions of the forest become significantly different from those to which the currently growing trees are accustomed. Changing climate conditions continuously harass the growing trees and, finally, cause them to die. Dieback results from large-scale fires in forests, bug infestations, or other harassment that kill trees. Naturally, new species migrate slowly into the sites where dieback occurs, and replace old type species. However, if human beings regenerate the forest by planting it rather than waiting for natural regeneration, the migration of new species will occur more rapidly.

According to the regeneration process, currently standing trees are able to continue growing in their current site prior to climate changes. However, as these growing trees are harvested, or die out naturally, old species are not naturally regenerated. Instead, new species migrate naturally into the area with a time lag, or are planted by human beings for economic benefit. These changes in ecosystem types force human beings to adapt to the change of forest types; therefore, climate change will have an impact on the economic structure of the global timber market.

In the context of these two processes of dynamic ecosystem type change, we identified the dynamic land area change in potential forest. In Sohngen (1996) and Sohngen et al. (1998), they only estimated the dynamic land area change of ecosystem types instead of considering the potential forest.

In order to identify the dynamic ecological change in potential forest, we first created potential forest area by eliminating nonforest land area from ecosystem types simulated by BIOME 3. In order to perform this objective successfully, we chose the world geographic map created by Olson (1989-91), which displays 74 ecosystem categories across the globe, including nonforest land area within .5° x .5° as well as 10 min x 10 min grid cells. In Olson's map, nonforest land area categories include farmland and settlements, city complexes, paddy, cropland and pasture, coastal, and water and islands. After synchronizing the grid cells in Olson's map within a BIOME 3 simulation map, we derived the potential forest area by subtracting nonforest area in Olson's map from the BIOME 3 simulation map.[8]

On the basis of potential forest, we calculated steady-state ecological changes of ecosystem types in each responsive region after climate change such as the dieback ratio and the regeneration ratio. Specifically, we considered two factors in selecting ecosystem types in each responsive region. These factors include dominant forest types for commercial use, as well as a degree of ecological transformation after climate change. For most responsive regions except European USSR and Nordic Europe, ecosystem types were selected according to the dominant forest types for commercial use. On the other hand, for European USSR and Nordic Europe, ecosystem types were chosen by considering the dominant forest types for commercial use, as well as the degree of ecological transformation after climate change.

For each ecosystem type in a responsive region, the dieback ratio was calculated by dividing a dieback land area by the total base land area (total land area in the absence of climate change). The regeneration ratio was also calculated by dividing a regenerated land area by the total base land area. To calculate the dieback ratio and the regeneration ratio, Geographic Information System (GIS) was used from previous published work. Instead of using GIS, however, we made a computer program to facilitate what we

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[8] Simulation results of BIOME 3 using Hamburg is displayed in .5° x .5° grid cells.

intended to calculate. Appendix B shows regional steady-state ecological changes including land area change and net primary productivity change of each ecosystem type.

TSM 2000 included four land classes in 10 responsive regions; each land class was identified according to biological and geographical characteristics such as ecosystem type as well as the degree of harvesting accessibility. Thus, the regional steady-state ecological changes were disaggregated into each land class according to its ecosystem type.

Under the linearlity assumptions that were imposed to estimate dynamic ecological change, we estimated dynamic land area change of all 42 land classes. The dieback ratio and the regenerated area per year for each land class are tabulated in Table A-4. The regenerated area per year was calculated through following two steps. First, we calculated the yearly regeneration ratio by dividing the calculated regeneration ratio into 70 years. Second, we calculated the regenerated area per year by multiplying the yearly regeneration ratio with the commercial inventory area with conservation (see Table A-3 in Appendix A for the commercial inventory stock with conservation).

### *Dynamic Productivity Change*

The NPP is not a dynamic concept, but a steady-state concept in the sense that the biogeochemical cycle model predicts the equilibrium NPP at given time. Thus, as part of the dynamic ecological specification, the dynamic path of NPP was assumed to be linear over the period of climate change. In the context that the NPP is the net amount of carbon garnered for plant growth, changes in net primary productivity (NPP) that result from climate change allow for inference about change in plant growth. We assumed that the growth per unit of time of the trees is proportional to NPP. Letting $t = 0$ for 1990 and $t = 70$ for 2060, we linearlized the effects of climate change using

$$\kappa_h(t) = 1 + \kappa \cdot t \tag{22}$$

where

$$\kappa = \left( \frac{NPP_{70}}{NPP_0} - 1 \right) / 70$$

The nonclimate change yield function per hectare was defined as $q_{hij} = f_h(i, z_{hij})$ for land class $h$ in time period $j$ and the standing trees were regenerated $i$ years ago.[9] To capture the effects of NPP change, we modified the yield function for trees for the time period during which climate change occurs. To simplify this discussion we wrote the nonclimate change yield function as

$$q_{hij} = \alpha \ e^{\frac{\beta}{i-\gamma}} \tag{23}$$

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[9] In this research, we used the yield function of trees formulated by Sedjo and Lyon (1990) as a non climate change yield function. The nonclimate change yield function of tree consists of functional components such as age of trees and management of practices (regeneration input). The nonclimate change yield function of tree is as

$$q = q^1(z) \cdot q^2(age)$$

$$q^1(z) = (z+1)^{c^1} \qquad \text{for } z \le \bar{z}$$

$$(z+1)^{c^1} + az + bz^2 + c \qquad \text{for } z \le \bar{z}$$

and

$$q^2(age) = c^2 \exp(c^3 + c^4 /(age - c^5)) \qquad \text{for } age > c^5$$

$$0 \qquad \text{for } age > c^5$$

and the growth per unit time due to aging of the tree is

$$\frac{dq}{di} = -\frac{\beta}{(i-\gamma)^2} \cdot \alpha \cdot e^{\frac{\beta}{(i-\gamma)}} \tag{24}$$

On the other hand, while climate change is occurring (*j* ∈*[1990, 2060]*)) the growth due to aging at year *j* is given as

$$\begin{aligned} \frac{d\tilde{q}}{di} &= -\frac{\beta}{(i-\gamma)^2} \cdot \alpha \cdot e^{\frac{\beta}{(i-\gamma)}} \cdot (1+\kappa(i-a)) \\ &= -\frac{\beta}{(i-\gamma)^2} \cdot \alpha \cdot e^{\frac{\beta}{(i-\gamma)}} - \frac{\beta}{(i-\gamma)^2} \cdot \alpha \cdot \kappa(i-a) \cdot e^{\frac{\beta}{(i-\gamma)}} \end{aligned} \tag{25}$$

where $a$ is the age of trees at year $j^*$ at which climate change begins to occur; thus, $i$ and $j$ are related by the equation $i = a + (j - j^*)$, and $1 + \kappa(i - a)$ denotes the level of NPP at year $j$. Thus, the yield function is the solution to the differential equation (25). In addition, the yield function for $j \in [2061, \infty]$ would be the solution to

$$\frac{d\hat{q}}{di} = -\frac{\beta}{(i-\gamma)^2} \cdot \alpha \cdot e^{\frac{\beta}{(i-\gamma)}} \cdot \bar{\kappa} \tag{26}$$

where $\bar{\kappa} = 1 + \kappa \cdot 70 = NPP_{70}/NPP_0$. We used these yield functions to reflect the growth of tree associated with the increment of net primary productivity. The ratios of net primary productivity change of each land class are also provided in Table A-5.

# CHAPTER IV

# TIMBER MARKET ANALYSIS

In this chapter, we focus our attention on the effect of global warming on the global timber market through the simulation of TSM 2000. To assess the effect of the global warming on the global timber market, we modified the TSM 2000 to reflect dynamic ecological change associated with climate change.

We start with a brief overview of the underlying assumptions of the nonclimate change base scenario of TSM 2000. Then, for the simulation of climate change we explain how the TSM 2000 was modified to reflect dynamic ecological change. Modification of the TSM 2000 includes both the law of motion of hectares of trees by age and the volume of commercial timber harvested per hectare. Under the assumption of a normal timber demand (ND) scenario, we estimated intertemporal values of endogenous variables for both the base scenario and the climate change scenario of TSM 2000 over a time horizon of 90 years, starting in 1995.[10] The estimations obtained for both the base scenario and the climate change scenario allow us to predict the effect of global warming on the global timber market. Moreover, estimates obtained from model simulation for each scenario provided not only the aggregate projections of intertemporal endogenous variables in the TSM 2000, but also estimates of the changing regional structure of endogenous variables in response to economic and ecological forces.

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[10] We refer to a timber demand scenario, which has the properties of timber demand growth assumed in the section entitled "*An Analysis of the Base Scenario,*" as a normal timber demand scenario.

To assess sensitivity of the results to different assumptions of timber demand growth, we also simulated the model under both high timber demand growth and very high timber demand growth. We referred to these two timber demand scenarios as the high timber demand (HD) scenario and the very high timber demand (VHD) scenario, respectively. Under these different timber demand scenarios, we also observed different projections of the endogenous variables in both the base scenario and the climate change scenario, respectively. Analysis of changes in projections of different timber demand scenarios provided significant insights into the behavior and the responsiveness of the global timber supply systems over the long run.

Finally, we also examined the changes in economic welfare (i.e., economic benefit and cost) between the base scenario and the climate change scenario under each of the timber demand scenarios. Comparison of the welfare level between the base scenario and the climate change scenario indicated how much impact global warming would have on human behavior in the global timber market. We begin by analyzing the base scenario and then the climate change scenario of TSM 2000 under a normal timber demand scenario.

**An Analysis of the Base Scenario**

In our modeling framework, we assumed that in the absence of climate change, the base scenario is likely not only to be the best reflection of the world in estimating intertemporal endogenous variables in the model, but also to provide the most accurate forecasts. As such, if there is no climate change, the base scenario outcomes are considered most presumable and will be used as the baseline to compare with and contrast against all other scenarios. The assumptions used for model simulation of the base scenario under normal demand scenario are as follows.

1. World demand schedule for industrial wood (combined pulpwood and solidwood products) will increase at an annual growth rate of 1.0% in the first year and decreases in a linear fashion each successive year until growth rate is zero in the 90th year.
2. World demand schedule for pulpwood initially increases at an annual growth rate of 2.72% in the first year and decreases in a linear fashion each successive year until the growth rate is zero in the 90th year.
3. New forest plantations are established in the emerging region at a annual rate level of 2,773,298 hectares for 10 years.
4. The dollar exchange rate is assumed to remain at an intermediate level throughout the period of analysis.[11]

In addition to the probable assumptions for the base scenario, we will discuss some other economic components used in the base scenario in the context of the real world. In previous TSM versions, Sedjo and Lyon (1990, 1996) specified the timber demand function for responsive regions as an excess or residual demand function. The quantity of demand for the responsive regions is estimated by subtracting the quantity supplied by the nonresponsive regions from the quantity of total world demand. In the

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[11] These four conditions were also used in the analysis of the climate change scenario, which will be discussed later.

formulation of TSM 2000 the former Soviet Union as well as plantation forests in India, African countries, and Asia Pacific were included as a part of responsive regions.

As a result, we needed to estimate the new demand function for responsive regions. Due to this regional realignment, we considered the world timber demand function as the demand function for the responsive regions in TSM 2000. Initial total world timber demand is estimated by the following function

$$P = 250 - 0.001215 \cdot Q \tag{27}$$

Following the method in estimating the initial solidwood and pulpwood demand functions connoted in TSM 96 (Sedjo and Lyon 1996), we assumed that the initial demand portion of solidwood is 60% of the total world demand. On the basis of this portion, the initial solidwood and pulpwood demand functions were specified as follows:

$$P^s = 162 - 0.001215 \cdot Q^s \tag{28a}$$

$$P^p = 118 - 0.001215 \cdot Q^p \tag{28b}$$

By extending land classes from 22 land classes contained in TSM to 42 land classes in TSM 2000, we needed to include not only the cost functions but also the yield functions for new land classes. Estimated components of cost function for new land classes such as harvest, access, domestic and international transportation cost are shown in Table A-6 (Appendix A). Yield functions for the new land classes were selected to have the same basic equations as those in Sedjo and Lyon (1990). The coefficients of these yield functions were selected to reflect characteristics of the region such as climate and topography, in which each land class is located.

The variable proportions of production in solidwood, $\phi_h$, for new land classes were constructed from those given in Sedjo and Lyon (1996) by considering land classes with similar geographical characteristics, ecosystem type, climate, NPP, etc. Both the parametric values of yield functions and the variable portions going to solidwood, $\phi_h$, for 42 land classes are given in Tables A-7 and A-8 (Appendix A). In general, the annual market discount rate would fluctuate over the simulation period; however, in this research we used a 4% fixed interest rate as the annual discount rate for the entire simulation time period.

Given the initial commercial timber stock inventory for each land class, we simulated the base TSM 2000 scenario and identified the optimal time profile of harvesting volumes and prices of solidwood and pulpwood, respectively.

**Simulation Results of the Base Scenario**

Simulation results of the base scenario are shown in Figures 1-4. Figure 1 shows that the total industrial wood production increases 31% from 1.59 billion cubic meters in 1995 to 2.08 billion cubic meters in 2085.

Figure 2 shows a 55% increase of the volume of pulpwood production from 821 million cubic meters in 1995 to 1.28 billion cubic meters in 2085. The estimate of pulpwood production suggests that 93% of the increase in total industrial wood (455

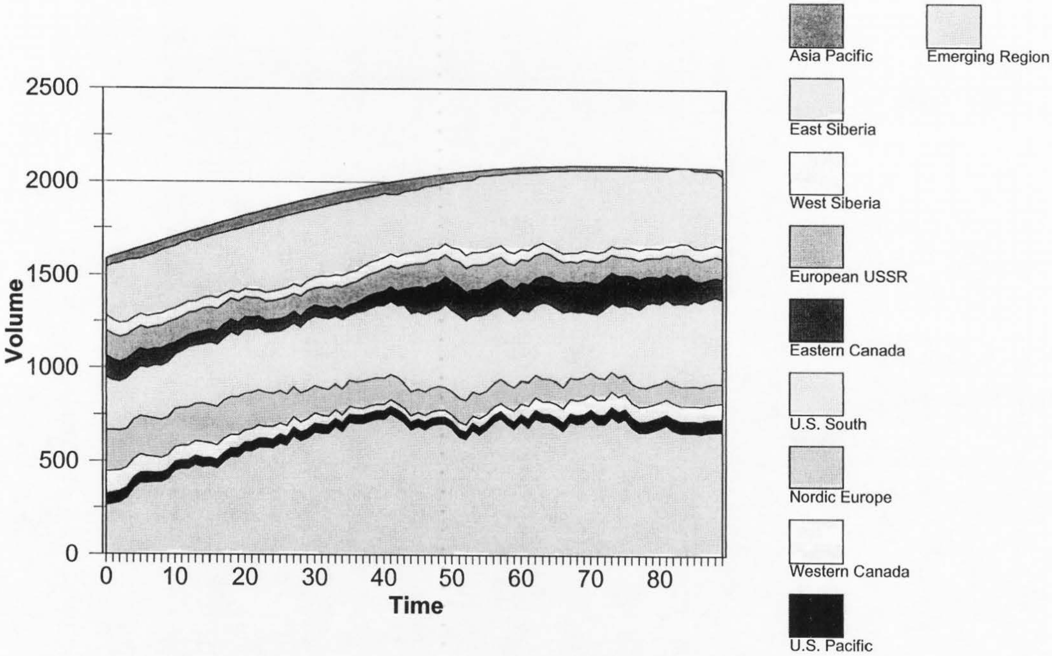


**Figure 1. Total volume [ND base scenario].**

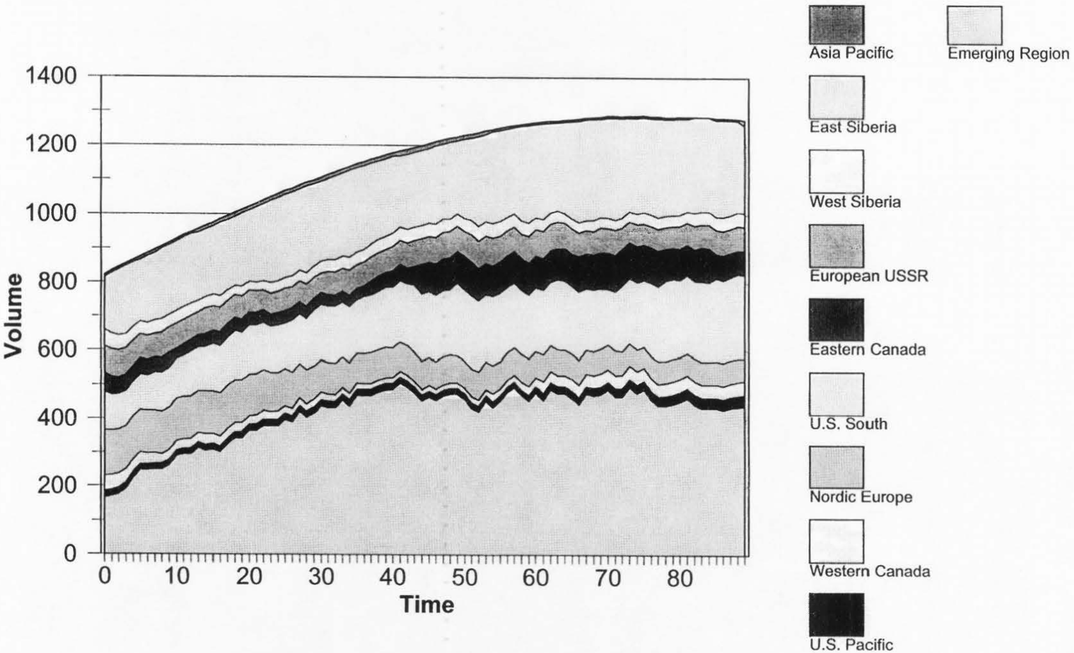


**Figure 2. Pulpwood volume [ND base scenario].**

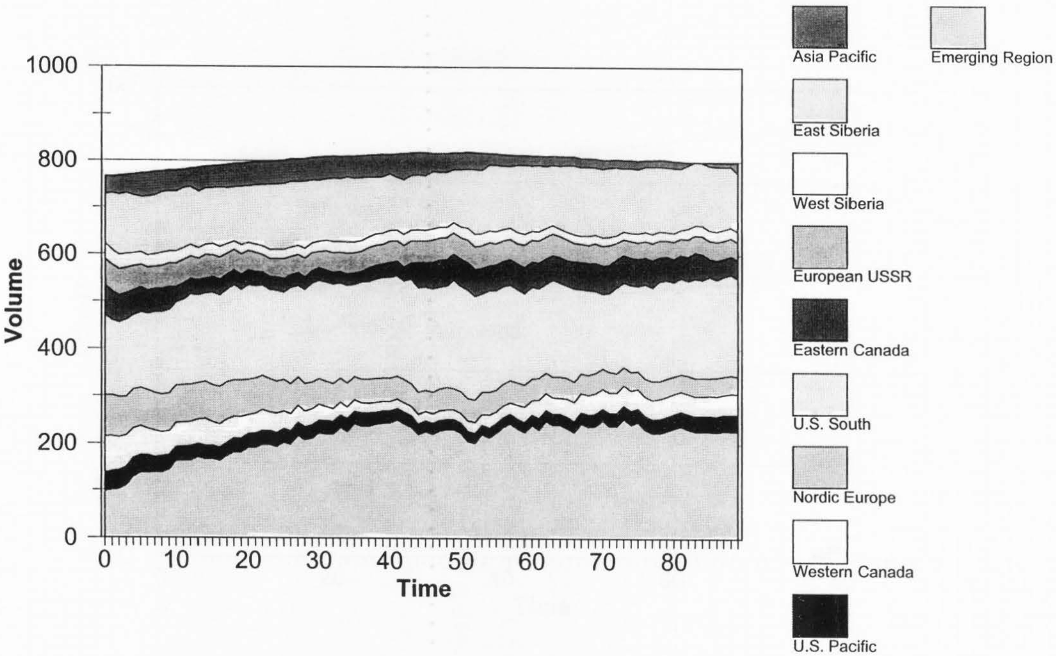


**Figure 3. Solidwood volume [ND base scenario].**

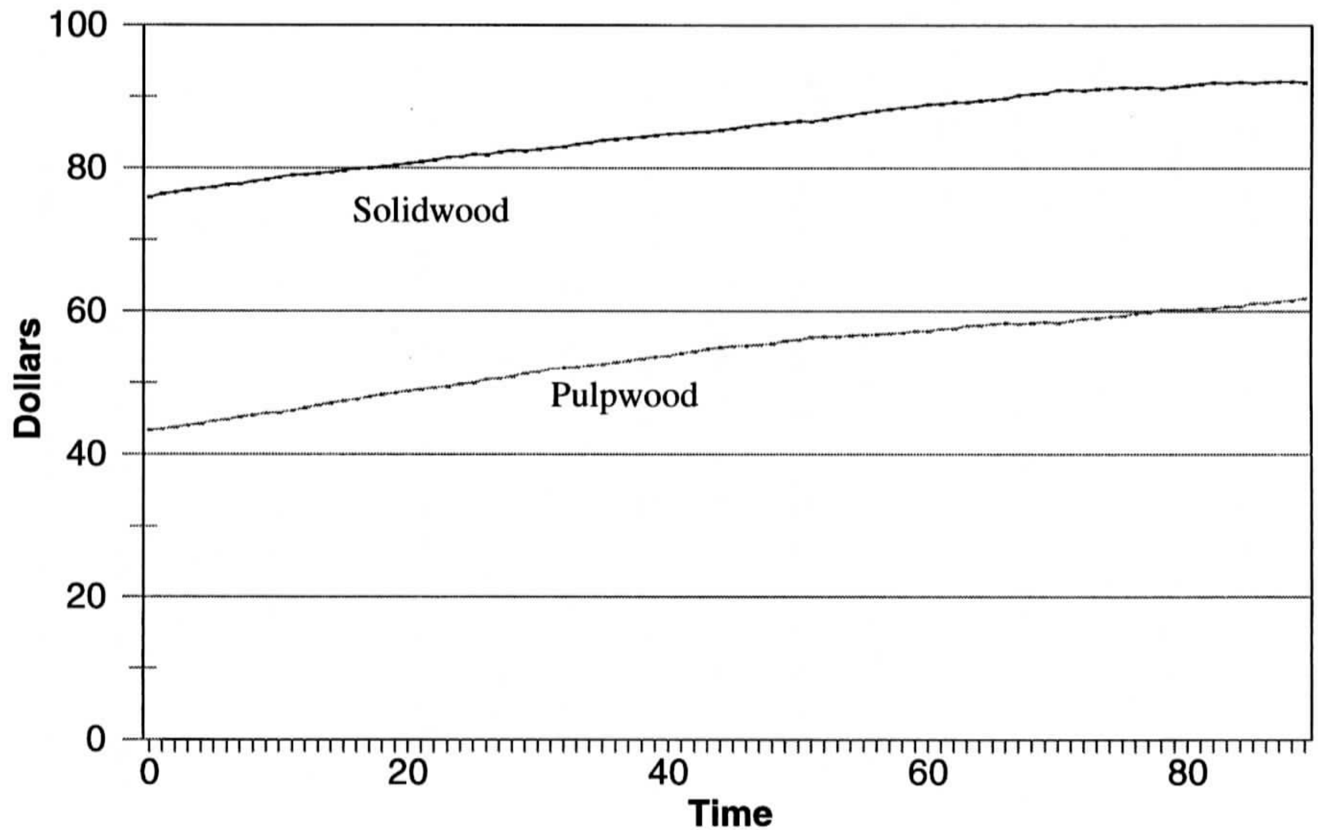


Figure 4. Timber prices [ND base scenario].

million cubic meters) would be pulpwood and only 7% of increase in total industrial wood would be solidwood production over the 90 years. This suggests that the large portion in the composition of industrial wood would be shifted away from solidwood to pulpwood in order to accommodate the more rapidly rising demand growth in pulpwood. As a result, the solidwood production increases very slowly to allow such a large portion of total industrial wood to shift into pulpwood. Figure 3, therefore, shows that the solidwood increases 4.6% from 765 million cubic meters in 1995 to 800 million cubic meters in 2085.

Figure 4 shows estimated price changes for solidwood and pulpwood over the simulation period. The prices for pulpwood and solidwood experience an increasing trend over the simulation period: the price of pulpwood increases 44% from $43 in 1995 to $62 in 2085, while the price of solidwood increases 21% from $76 in 1995 to $92 in 2085. The faster rise of pulpwood price is due to higher demand growth for pulpwood relative to solidwood. This relative price increase of pulpwood signals producers to switch away more industrial wood production from solidwood to pulpwood.

Simulation of timber production by regions suggests that the current dominant production regions, as well ast those in 2085, are in the emerging region, the U.S. South and East Siberia. Over 90 years, the emerging region increases production by a factor of three while the U.S. South and the East Siberia regions roughly double their timber production. Most timber production of these regions contributes to the increase of pulpwood production.

Eastern Canada and European USSR also increase timber production, mostly in supplying pulpwood. Nordic Europe maintains fairly substantial timber production over the first 70 years; after that, timber production declines slightly. The change of timber production patterns in Nordic Europe suggests that a fairly substantial amount of timber production over the early period is a result of matured postwar regenerated trees being harvested (Sedjo and Lyon 1990). However, declining timber production after year 70 is due to the fact that standing matured, second growth trees are not sufficient to maintain the harvest level even though the timber demand grows.

The U.S. Pacific Northwest, western Canada, West Siberia, and Asia Pacific are only modest producers of timber, and experience a minimal change over the 90-year period. Prior to the initial simulation year, both the U.S. Pacific Northwest and western Canada experienced increasing government oversight directed at withdrawal of forests on public lands. These conservation efforts will only allow these regions to show the modest timber production over the entire simulation period.

**An Analysis of the Climate Change Scenario**

Climate change caused by the accumulation of carbon dioxide in the atmosphere generates a change in the distribution of ecosystem types as well as a change in productivity of ecosystems. Simulated results of BIOME 3 using Hamburg for each land class were analyzed to examine dynamic ecological change. Dynamic ecological changes were denoted as the dieback ratio, the regenerated hectares per year, and change in NPP.

In order to identify how the global warming affects the global timber market, we modified the TSM 2000 on the basis of estimated magnitudes of dynamic ecological change. Modification of TSM 2000 included the law of motion of the hectares of trees by age and the harvesting volume of trees for each land class.

First, we will discuss the modification in the law of motion of hectares of trees by age. Modification in the law of motion of hectares of trees by age required explicit characterization of how global warming transforms the distributions of ecosystem type during the transient time period. The distributions of ecosystem type were changed in accordance with two dynamic ecological processes: (1) dieback and (2) regeneration. In this context, land area of ecosystem type was subdivided into two mutually exclusive areas: (1) the area where standing trees were expected to die out, and (2) the area where the standing trees were expected not to die out.

For the land areas where standing trees were expected to die out, the dieback hectares per year on the basis of estimated dieback ratio for each land class were calculated.[12] With this result, we were also able to calculate the ratio of dieback area to total commercial land area for each year during the transient time period. The ratio of dieback area to the total commercial land area for land class in year j was denoted as

$$\frac{\text{dieback per year}_h}{\sum x_{h,i,j}}, \quad \text{for } i = 2, 3, \ldots \ldots M. \tag{29}$$

[12] We calculated the dieback hectares per year by following two steps. First, we calculated the yearly dieback ratio by dividing the calculated dieback ratio into 70 years. Second, we calculated the dieback hectares per year by multiplying the yearly dieback ratio with the commercial inventory area with conservation.

Thus, equation (14a), which denoted the law of motion of the hectares of trees by age, was changed as follows:

$$x_{h,j+1} = (C + DU_{hj})x_{h,j} \qquad \text{for all } h, j \tag{30}$$

where

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 1 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & d_j & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & d_j & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 0 & d_j & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & d_j & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} d_j & d_j & d_j & d_j & \cdot & \cdot & \cdot & d_j \\ 0 & 0 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & -d_j & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & -d_j & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 0 & -d_j & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & -d_j & 0 \end{bmatrix}$$

and

$$d_j = 1 - \frac{\text{dieback per year}_h}{\sum x_{h,i,j}}, \qquad \text{for } i = 2, 3, \ldots\ldots\ldots M \tag{31}$$

This equation can also be expressed as

$$x_{h,1,j+1} = d_j u'_{h,j} x_{h,j}$$

$$x_{h,2,j+1} = x_{h,1,j} \qquad \text{for all } h, j$$

$$x_{h,i+1,j+1} = d_j (x_{h,i,j} - u_{h,i,j} x_{h,i,j}) \qquad (i = 2, 3, \ldots\ldots\ldots\ldots M-1) \qquad (32)$$

For the land areas where standing trees were expected not to die out, equation (14a) was also changed as follows:

$$x_{h,j+1} = (A + BU_{hj}) x_{hj} + (v_{hj} + RR_h) e \qquad \text{for all } h, j \qquad (33)$$

where $RR_h$ denotes the regeneration hectares per year for land class $h$, and $A, B, U_{hj}, v_{hj}$, and $e$ are the same as defined in Chapter II (see the equations (12a-12b)). This equation can be expressed as

$$x_{h,1,j+1} = u'_{hj} x_{hj} + v_{hj} + RR_h \qquad \text{for all } h, j$$

$$x_{h,i+1,j+1} = x_{h,i,j} - u_{h,i,j} x_{h,i,j} \qquad (i = 1, 2, \ldots\ldots\ldots\ldots, M-1) \qquad (34)$$

Next, the volume of commercial timber harvested for the total industrial wood after climate change was modified by identifying three harvesting categories. In the first category, commercial harvesting occurs in the land areas in which standing trees were expected to die out after climate change. The second category accounts for the possibility that some portion of dieback trees was salvaged from dieback areas. The third category considers commercial harvesting in the land areas in which standing trees were expected not to die out after climate change.

For the salvage of dieback trees, the salvage rate of dieback trees was assumed to be 60% of normal merchantable volume on average for both accessible and inaccessible land areas, and 70% of merchantability ratio for all salvage operations.[13] The merchantability ratio is defined as the minimum age of salvage trees divided by the optimal harvest age.

At year $j$, the three cases of commercial harvesting volume were specified as follows: Commercial harvesting volume in the land area in which standing trees were expected to die out after climate change is

$$u_{hj}' d_j X_{hj} q_{hj} \qquad \text{for all } h, j \tag{35}$$

where $X_{hj}$ is a diagonal matrix using the elements of $x_{hj}$, the vector of hectares of trees in this land area; $q_{hj}$ is the vector of non climate change yield function (see equations in footnote 10 in Chapter III). Salvage volume of dieback trees is

$$s(1-d_j)\cdot\sum_{i=k}^{M} x_{h,i,j}\, q_{h,i,j} \qquad \text{for all } h, j \tag{36}$$

where $s$ is the salvage rate, and age $k$ is the margin for the salvage of dead trees.[14] Commercial harvesting volume in the land area in which standing trees were expected not to die out after climate is

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[13] In reality, both salvage rate and the merchantability ratio are not fixed as we assumed here, but they change as timber prices change. To simplify the analysis of salvage of dead trees after climate change, we assumed that both ratios are fixed.

[14] Age $k$ (i.e., the marginal age for salvage of dead trees), is identified through the merchantability ratio if the optimal harvesting age is determined in the land area where standing trees are expected to die out.

$$u'_{hj} X_{hj} \tilde{q}_{hj} \qquad \text{for all } h, j \qquad (37)$$

where $\tilde{q}_{hj}$ is the vector of modified yield function of trees when climate change occurs (see equation (25) in Chapter III).

The total volume harvested of industrial wood after climate change is the sum of harvesting volume of these three cases. Harvesting volume for solidwood was calculated by multiplying the total harvested volume of industrial wood by $\phi_h$, while harvesting volume for pulpwood was calculated by multiplying the total harvest volume of industrial wood by $(1-\phi_h)$.

**Simulation Results of the Climate Change Scenario**

In order to project intertemporal endogenous variables over the entire simulation period, we modified the TSM 2000 computer program to include the change in the law of motion and the change in total commercial harvesting volume described above.

Output projections are shown in Figures 5-8. Figure 5 reveals that total industrial wood production increases from 1.64 billion cubic meters in 1995 to 2.70 billion cubic meters in 2085. The increment of total industrial wood is 1.06 billion cubic meters (65% increase) over the entire simulation period. Relative to the base scenario, production is larger by 625 million cubic meters in 2085, and it reflects 30% larger production than in the base scenario.

Estimated gains in timber production due to climate change are the result of two important factors: First, BIOME 3 predicts an increase in net primary productivity for all land classes, and second, BIOME 3 predicts that there will be an increase in hectares of

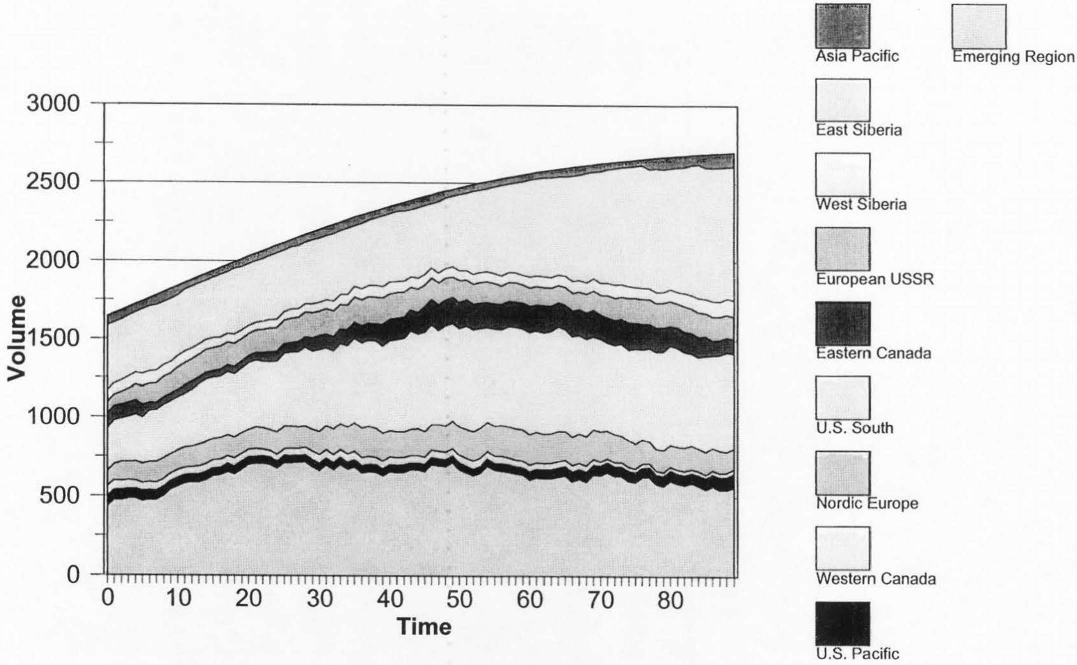


**Figure 5. Total volume [ND climate change scenario\.**

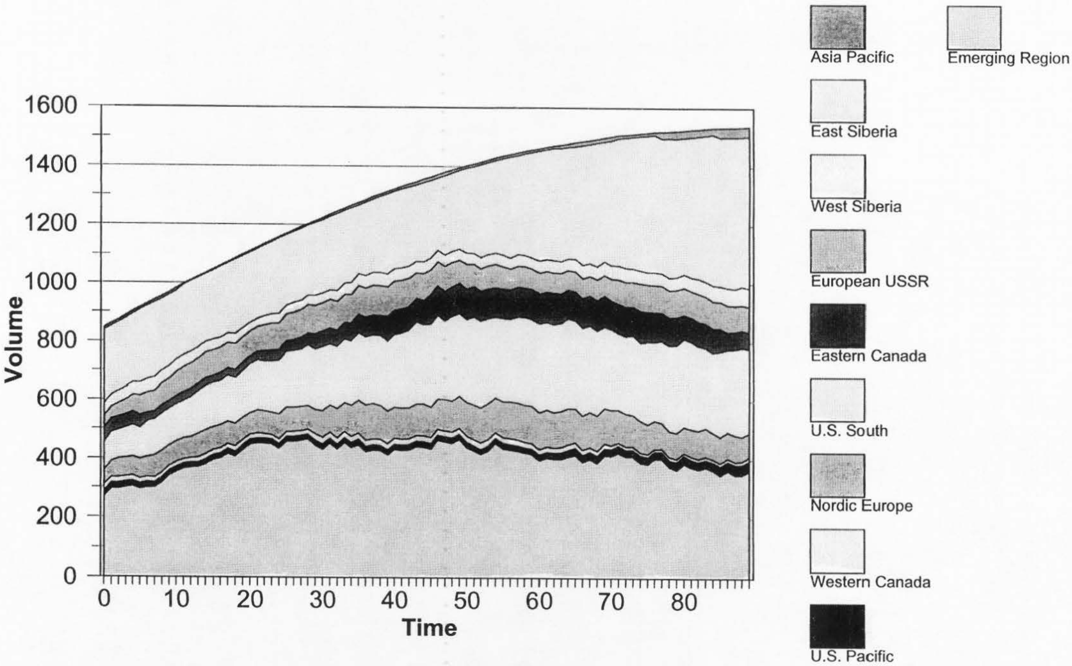


**Figure 6. Pulpwood volume [ND climate change scenario].**

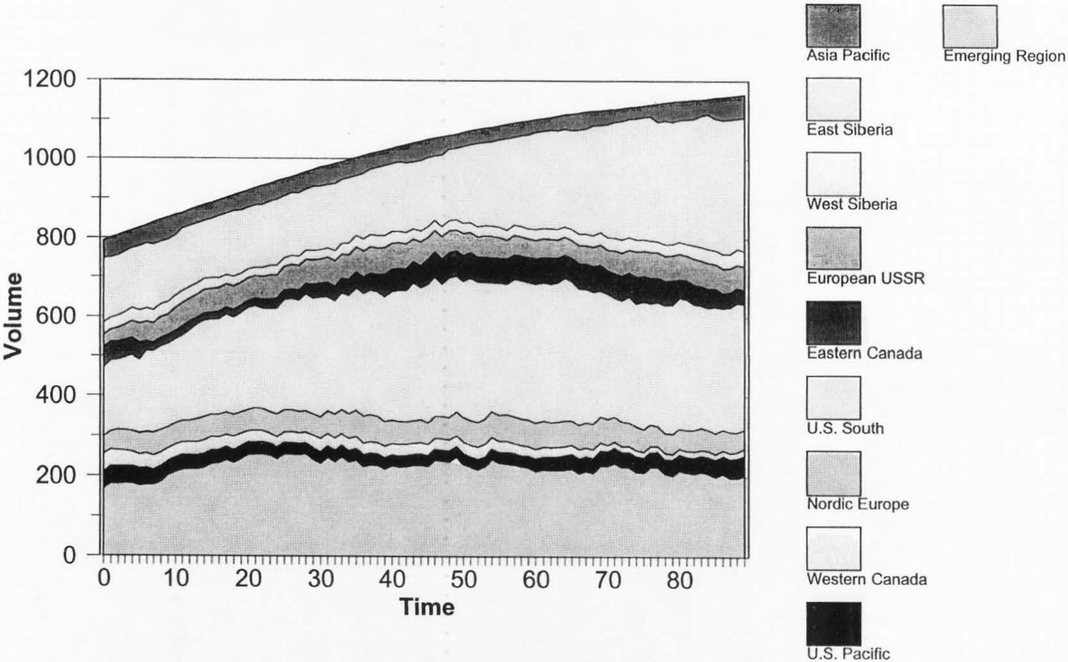


**Figure 7. Solidwood volume [ND climate change scenario].**

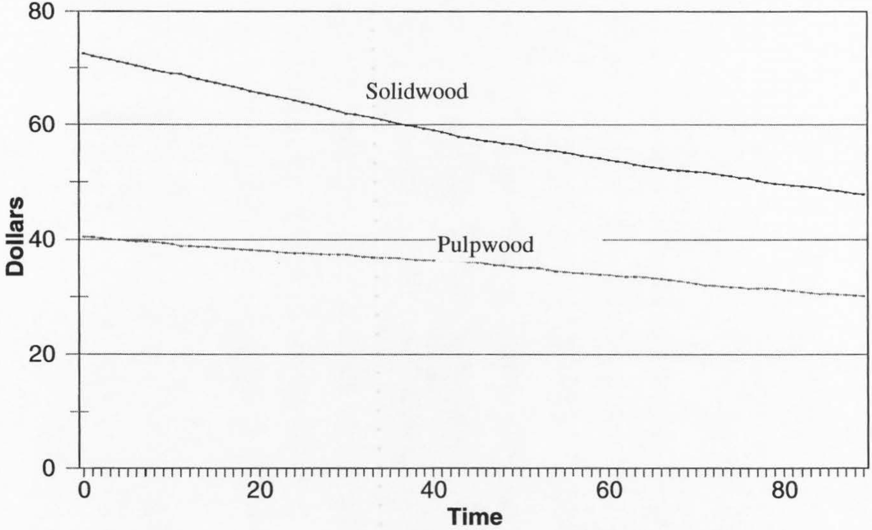


**Figure 8. Timber prices [ND climate change scenario].**

faster growing tree species. As a result, the climate change scenario shows global timber supply grows faster than global timber demand, resulting in declining timber prices.

Specifically, Figure 6 shows that the volume of pulpwood will increase from 846 million cubic meters in 1995 to 1.54 billion cubic meters in 2085. This increment of pulpwood production will be 694 million cubic meters over the entire simulation period. In the climate change scenario pulpwood production in 2085 is 261 million cubic meters larger than in the base scenario.

Figure 7 shows the volume of solidwood production increasing from 793 million cubic meters in 1995 to 1.16 billion cubic meters in 2085. Solidwood production in the base scenario shows only modest gains; however, in the climate change scenario, production gains are larger. Estimates for the climate change scenario indicate that solidwood production in 2085 is 364 million cubic meters larger than in the base scenario.

Figure 8 shows that the supply response induces a substantial price decrease for both solidwood and pulpwood. Solidwood price is estimated to decrease about 34% from $73 per cubic meter in 1995 to $48 in 2085. Pulpwood price will decrease about 25% from $40 in 1995 to $30 in 2085. This simulation suggests that the global warming will have a positive effect on the global timber market through increasing timber production and decreasing the prices of solidwood and pulpwood.

Regional variation in timber production suggests some differences relative to the base scenario. The dominant production region over 90 years is East Siberia, followed by the U.S. South and the emerging region. In East Siberia, the total volume of industrial wood increases 107% from 413 million cubic meters in 1995 to 854 million cubic meters in 2085. Unlike the base scenario, this region has an increase in the production for both pulpwood and solidwood. The volume of pulpwood and solidwood increases to 267 million cubic meters and 174 million cubic meters, respectively. In the U.S. South, the total volume of industrial wood increases 126% from 268 million cubic meters in 1995 to 605 million cubic meters in 2085. The volume of pulpwood and solidwood increases 196 million cubic meters and 142 million cubic meters, respectively.

In the emerging region, the total volume of industrial wood increases 29% from 435 million cubic meters in 1995 to 562 million cubic meters in 2085. The volume of pulpwood and solidwood increase 92 million cubic meters and 34 million cubic meters over the simulation period, respectively. The increment of timber production in the emerging region after climate change is relatively less than in the other dominant region. Also, most of the production increase in total industrial wood is in pulpwood. Unlike other dominant regions, the increase in production of solidwood in the emerging region is very modest.

Regional production estimates imply that East Siberia and the U.S. South are greatly impacted by the global warming, mostly through the increase in hectares of faster growing species, and the increase in NPP. In these regions, global warming increases timber production for both pulpwood and solidwood. Although the emerging region is also impacted by climate change, timber production in this region is predominantly used for pulpwood rather than solidwood because of the regional characteristics of fast growing trees and plants that have short rotations (Sedjo 1995).

Other regions also show that both pulpwood and solidwood production increase over the entire simulation period. Both eastern Canada and European USSR show substantial timber production over 90 years. Nordic Europe shows a fairly substantial timber production over the earlier simulation time period, but since then timber production decreases until 2085 as in the base scenario. The remaining regions show a modest increase of timber production as discussed in the base scenario.

**A Sensitivity Analysis of Timber Demand Scenarios**

For an example of sensitivity analysis, we analyzed model results under two different timber demand scenarios, high timber demand scenario and very high timber demand scenario. The primary determinants of timber demand growth are housing demand, population, and per capita income growth. The high timber demand scenario is mainly based on recent FAO forecasts. The FAO forecasted the demand of total industrial wood to increase by 1.8% annually and pulpwood to increase at a rate of 2.5% annually to the year 2010. For this research, we extended the growth period to 2085, with the timber demand growth declining linearly to zero in 2085. For the very high timber demand scenario, we took into account the growth rate of demand as twice that of the FAO forecasts. In this case, the total industrial wood demand initially grows at 3.6% annually, and pulpwood demand growth increases initially 5.0% annually to the year 2085, but both will decline linearly to zero at the end of 90 years in year 2085.

***Simulation Results of High Timber Demand Scenario***

Figures 9-12 show the simulation results of the base scenario. Figures 13-16 also present the simulation results of the climate change scenario. Figure 9 suggests that total industrial wood production increases 90%, from 1.15 billion cubic meters in 1995 to 2.18 billion cubic meters in 2085. Figure 10 indicates the volume of pulpwood production increases 114%, from 665 million cubic meters in 1995 to 1.42 billion cubic meters in 2085. Figure 11 shows that solidwood production increased 58%, from 484 million cubic meters in 1995 to 759 million cubic meters in 2085.

In the high-demand scenario, Figure 9 presents that the initial annual total industrial wood production is about 437 million cubic meters lower than that in the normal demand scenario. In particular, Figures 10 and 11 show that the initial annual production for both pulpwood and solidwood are also lower than those in the normal timber demand scenario, about 157 million cubic meters and 281 million cubic meters, respectively. These lower initial annual timber productions imply that rational forward-looking producers postpone the initial timber production with the anticipation of higher prices in the future. In addition, in 2085, their rational forward-looking behavior in timber production generates a larger timber production than in the normal timber demand scenario by about 100 million cubic meters in total production. This is primarily the result of the higher demand causing higher prices.

Figure 12 shows the price change of solidwood and pulpwood over the entire simulation period. Over the simulation period, the price of solidwood increases 32%, from \$126 to \$166, while the price of pulpwood increases 64%, from \$76 to \$125. The

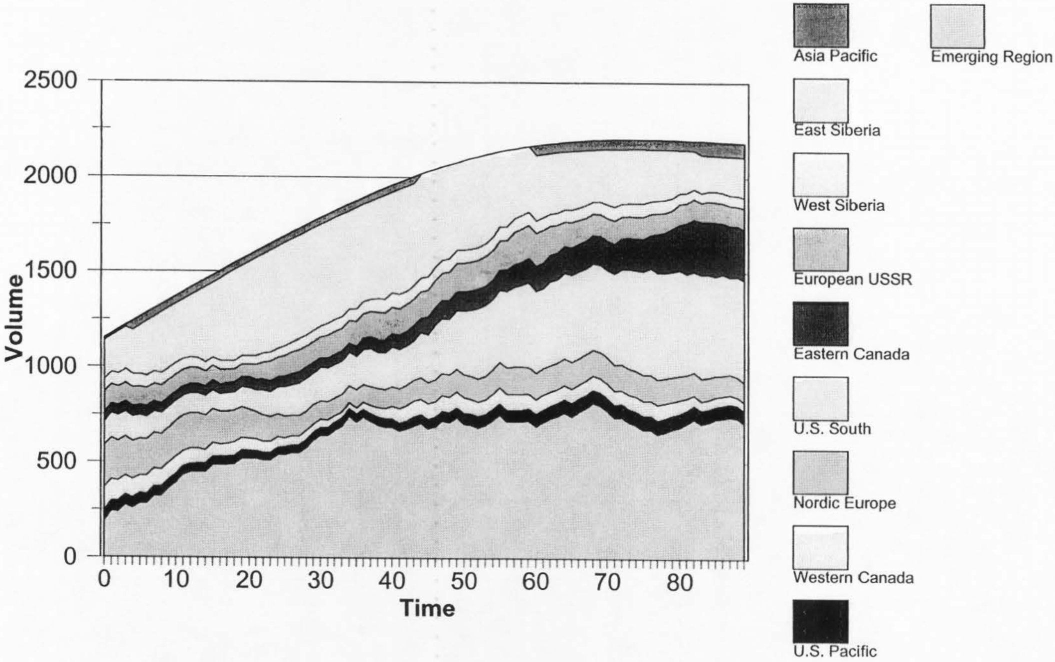


**Figure 9. Total volume [HD base scenario].**

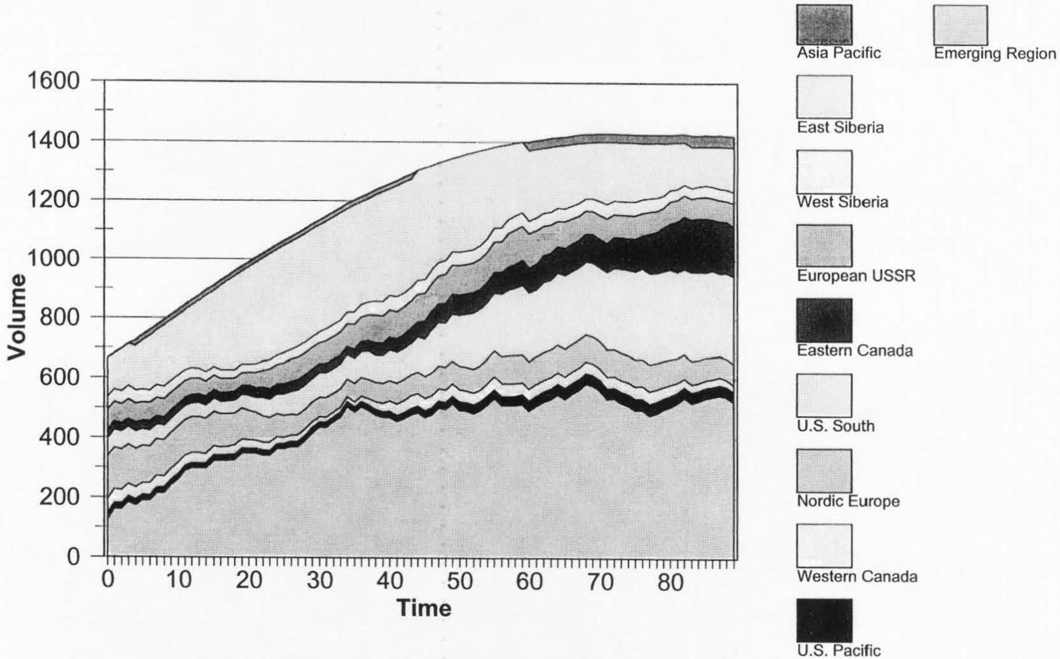


**Figure 10. Pulpwood volume [HD base scenaro].**

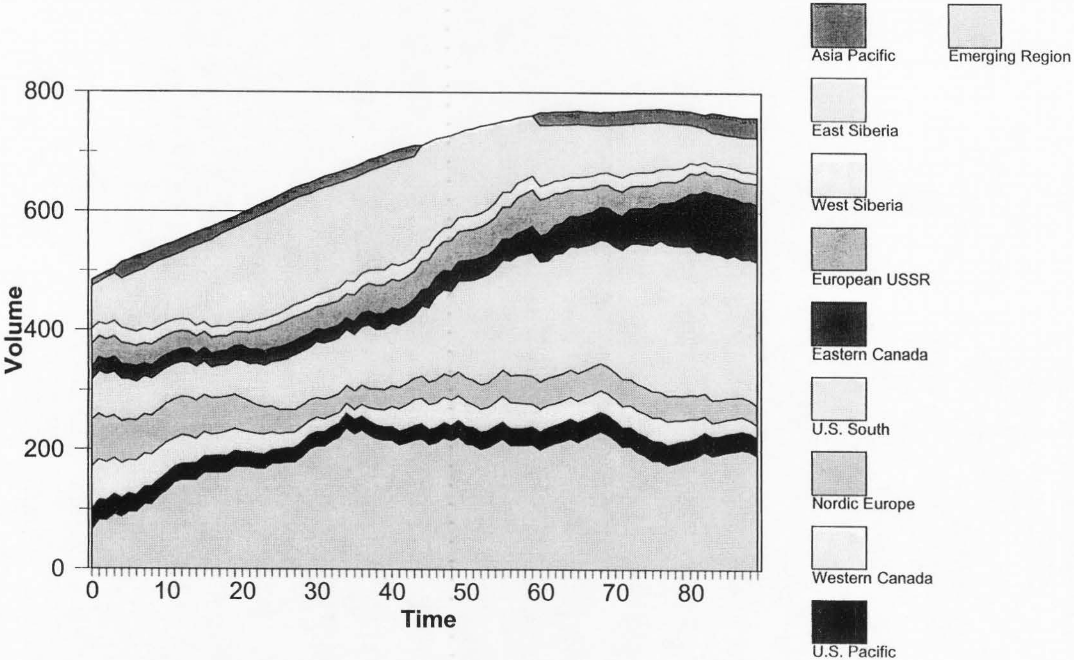


**Figure 11. Solidwood volume [HD base scenario].**

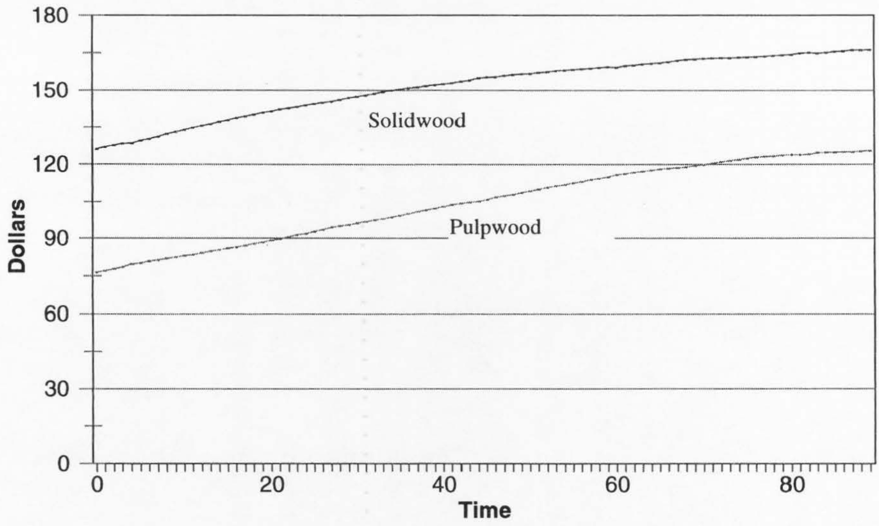


**Figure 12. Timber prices [HD base scenario].**

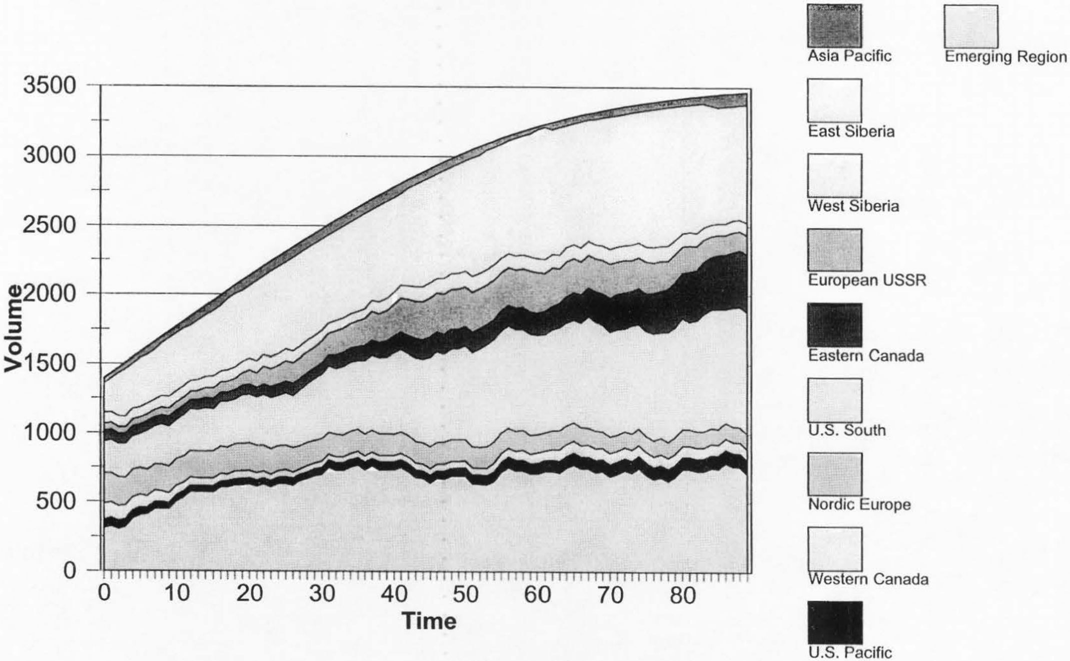


**Figure 13. Total volume [HD climate change scenario].**

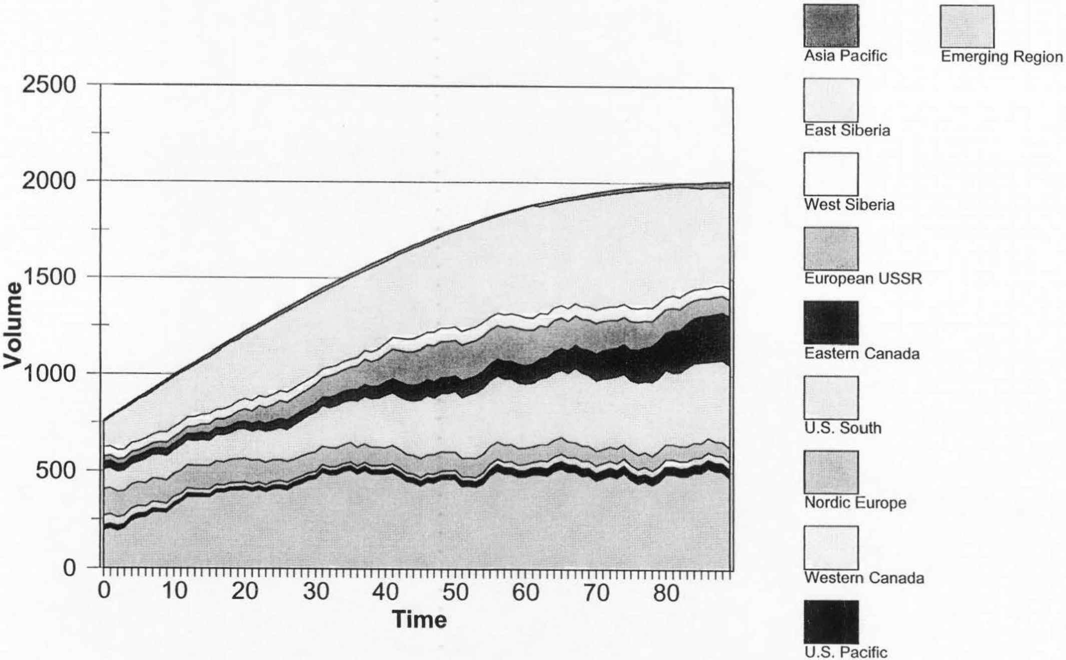


**Figure 14. Pulpwood volume [HD climate change scenario].**

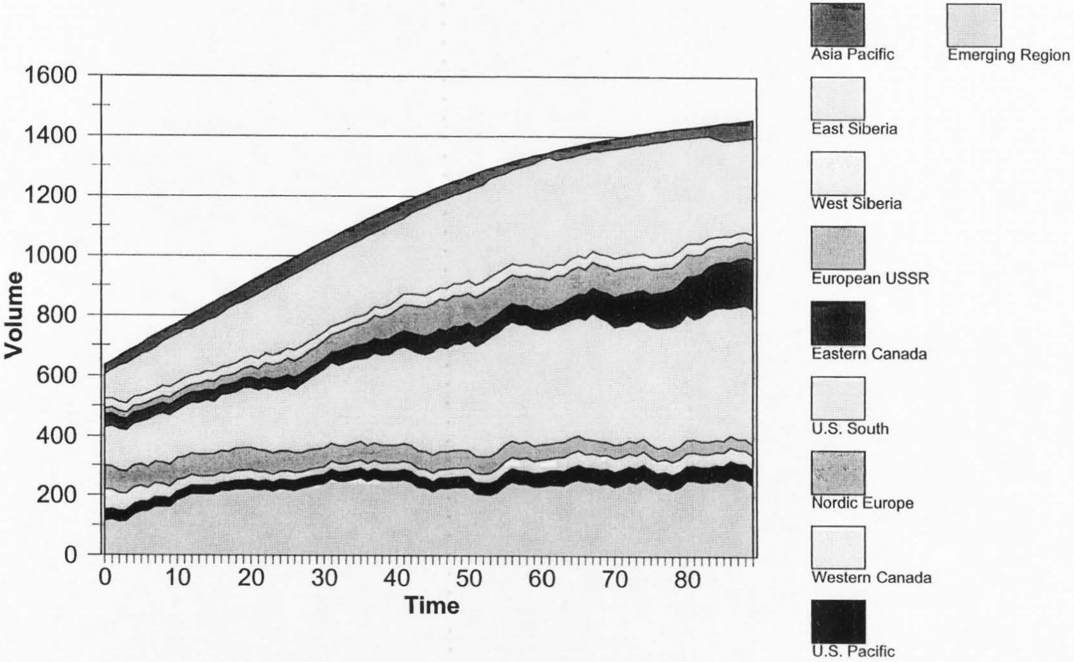


**Figure 15. Solidwood volume [HD climate change scenario].**

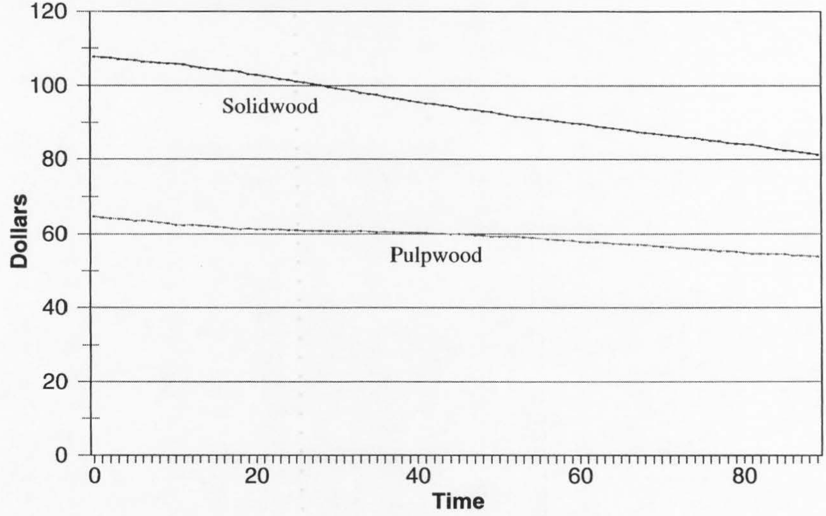


**Figure 16. Timber prices [HD climate change scenario].**

price trends suggest that high-demand growth induces higher prices in both the initial year and the terminal year than in the normal timber demand scenario.

Figures 13 and 14 present the simulation results of the climate-change scenario. Figure 13 shows that the total industrial wood production increases 150%, from 1.39 billion cubic meters in 1995 to 3.47 billion cubic meters in 2085. The total industrial wood production in 2085 is about 1.29 billion cubic meters larger than in the base scenario. Figures 14 and 15 also show that production for both pulpwood and solidwood in 2085 is 588 million cubic meters and 698 million cubic meters larger than in the base scenario, respectively. As with the base scenario, simulation results of the climate change scenario also show that the initial production of timber is lower than in the climate change scenario under the normal timber demand scenario.

Similar to the climate scenario under the normal timber demand scenario, the larger timber production due to climate change exceeds the growth rate of timber demand. As a result, the supply response due to climate change decreases the prices of timber in the market. Figure 16 presents the change of prices for solidwood and pulpwood. The price of solidwood decreases 24%, from $107 in 1995 to $81 in 2085, while the price of pulpwood decreases 17%, from $64 in 1995 to $53 in 2085. In this sense, under the high timber demand scenario, we also identified a positive effect of global warming on the global timber market through the increment of timber production and the decrease of timber prices.

Regionally, under the high timber demand scenario, most of the increase in timber production occurs in East Siberia and U.S. South. However, Nordic Europe, eastern

Canada, and European USSR also show a substantial increase of timber production. The remaining regions, including the emerging region, experience only modest gains in production. In particular, although the timber production in the emerging region maintains a large portion of timber production for the world timber market, the simulation indicates that the emerging region shows a modest rate of timber production increment over the entire simulation period.

***Simulation Results of the Very High Timber Demand Scenario***

Figures 17-20 show the simulation results of the base scenario. Figures 21-24 also present the simulation results of the climate scenario. In the base scenario, total industrial wood production increases about 1 billion cubic meters, from 1.74 cubic meters in 1995 to 2.71 cubic meters in 2085. The pulpwood production also increases about 1 billion cubic meters, from 943 million cubic meters in 1995 to 1.97 billion cubic meters in 2085. This production trend suggests that most of the increment of industrial wood production contributes to the pulpwood production.

The solidwood production increases modestly over the first 25 years; after year 25, it decreases over the remainder of the time horizon. As a consequence, the solidwood production decreases about 20 million cubic meters from 761 million cubic meters in 1995 to 743 million cubic meters in 2085. This trend suggests that too large a portion of industrial wood is shifted from solidwood to pulpwood over later simulation years due to a more rapidly rising price of pulpwood relative to that of solidwood.

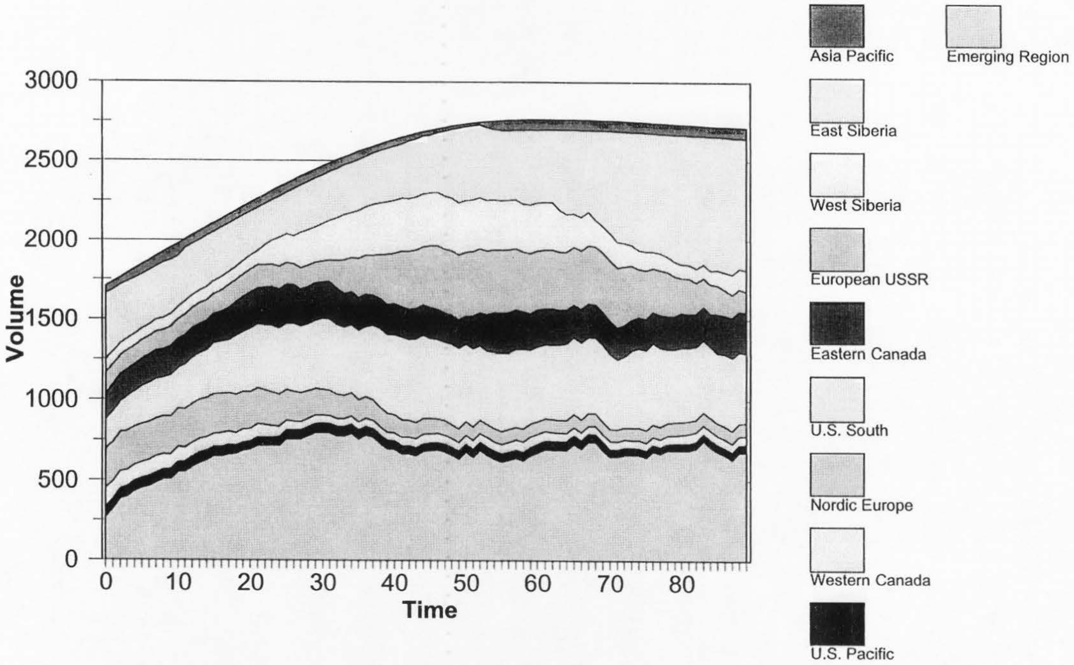


**Figure 17. Total volume [VHD base scenario].**

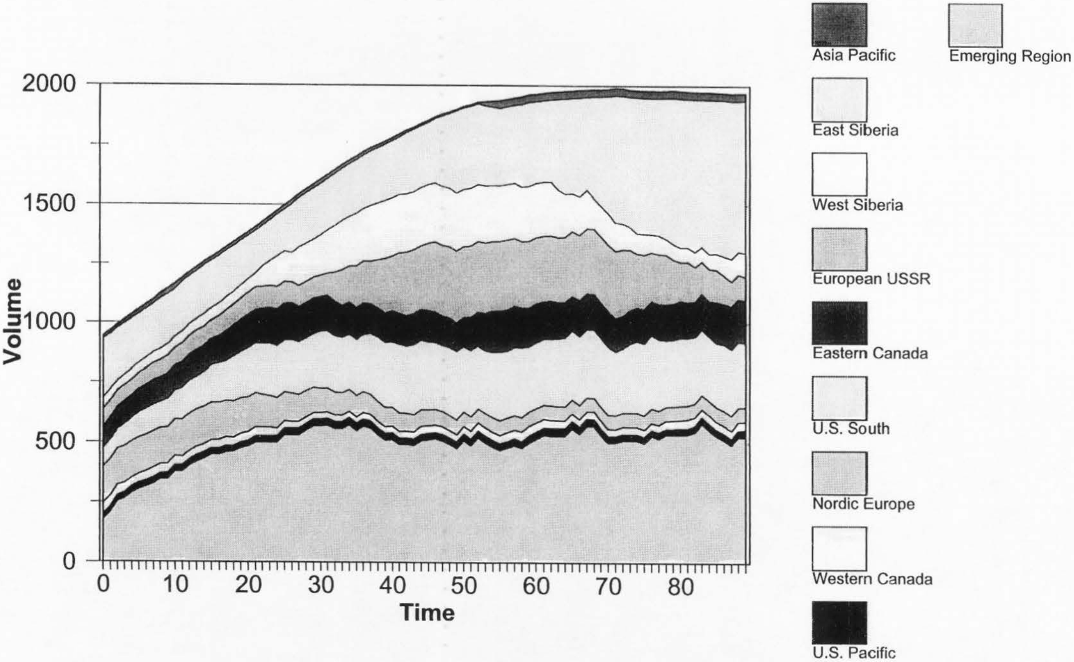


**Figure 18. Pulpwood volume [VHD base scenario].**

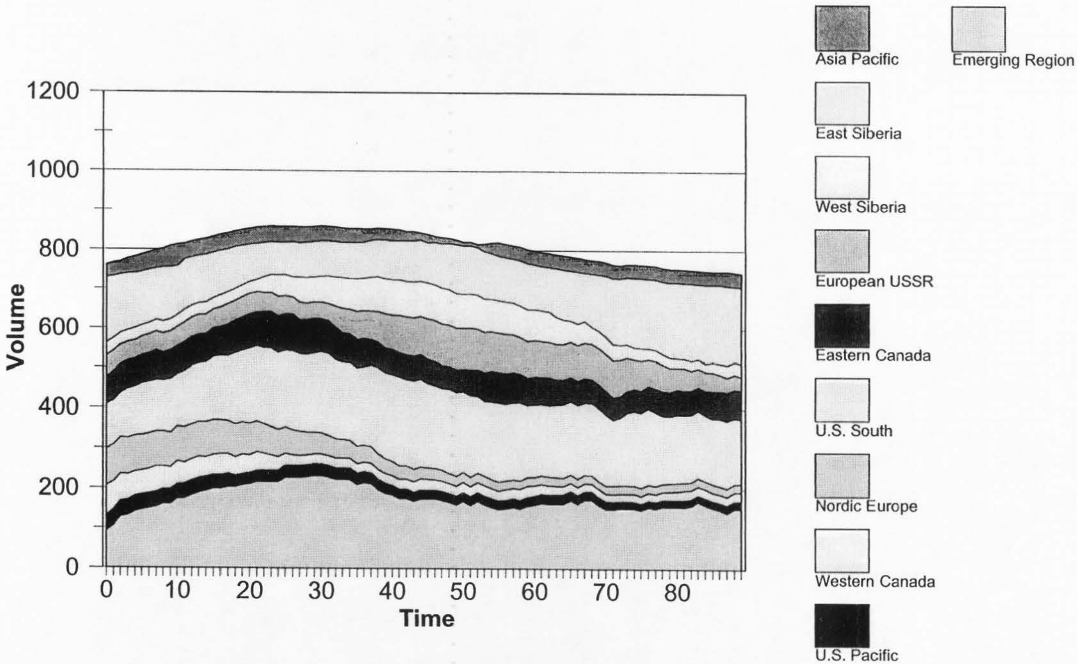


**Figure 19. Solidwood volume [VHD base scenario].**

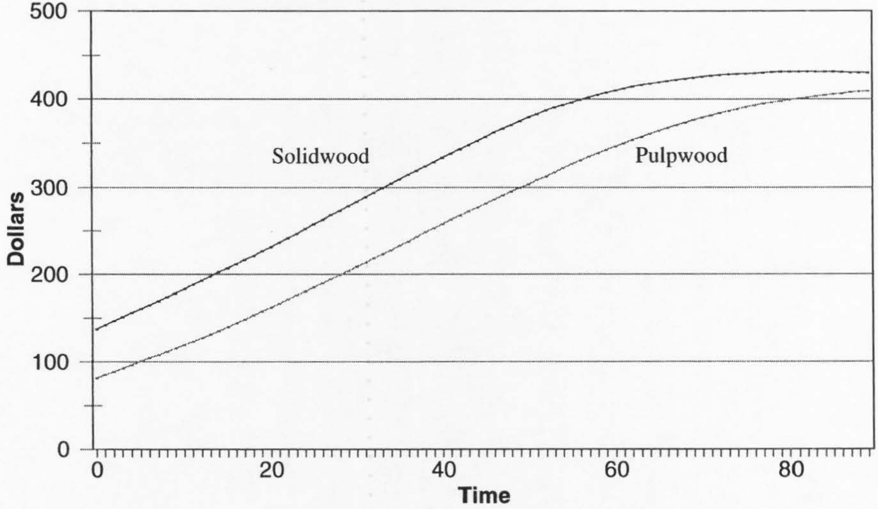


Figure 20. Timber prices [VHD base scenario].

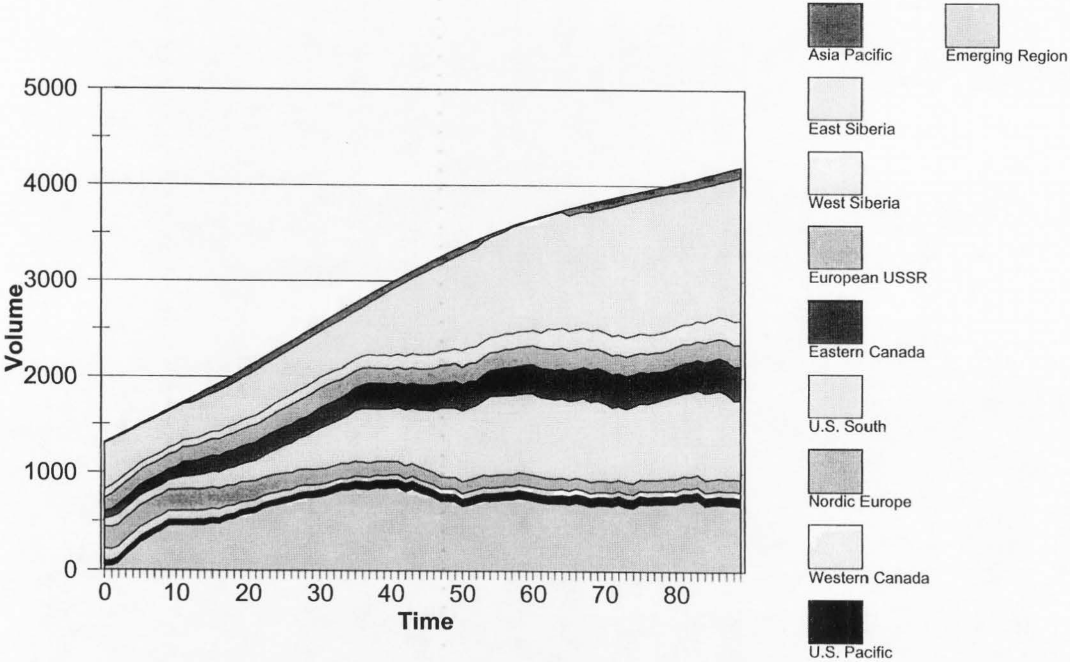


**Figure 21. Total volume [VHD climate change scenario].**

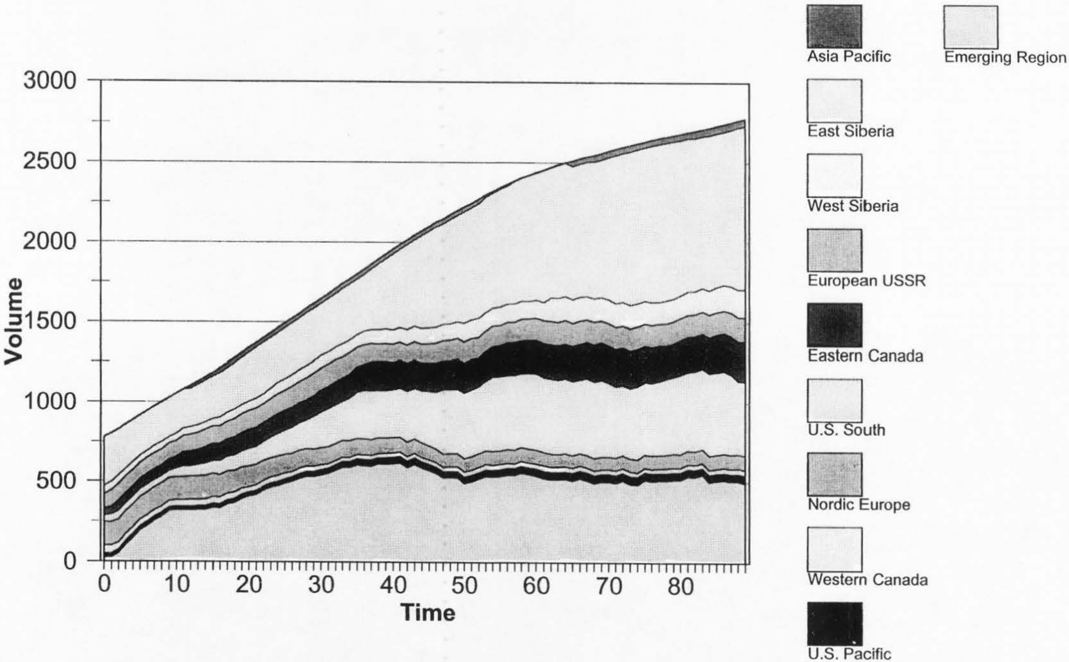


**Figure 22. Pulpwood volume [VHD climate change scenario].**

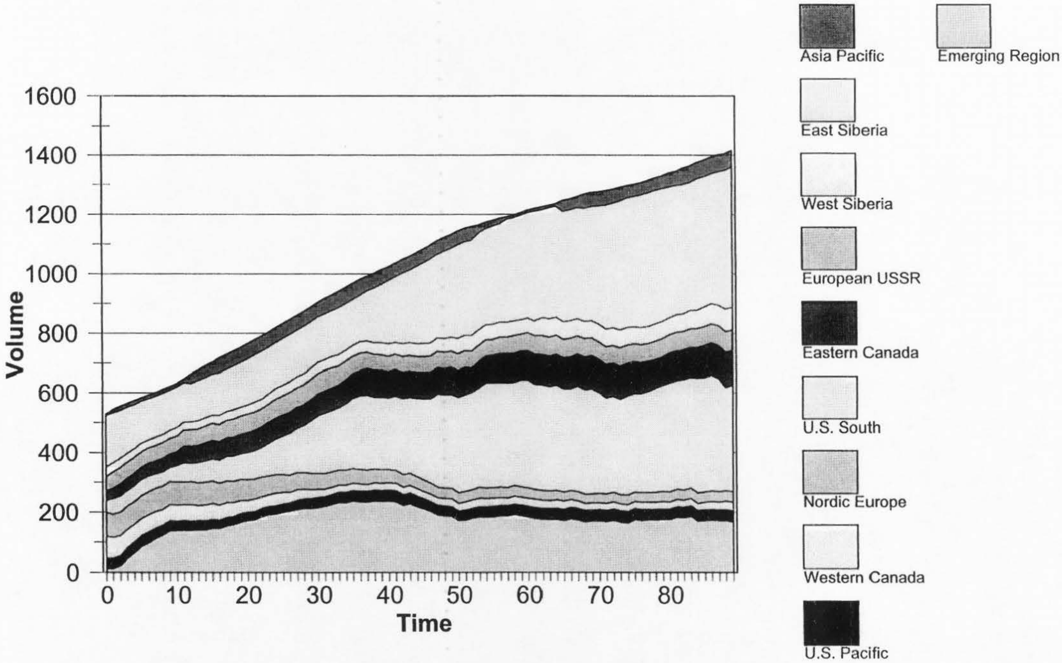


**Figure 23. Solidwood volume [VHD climate change scenario].**

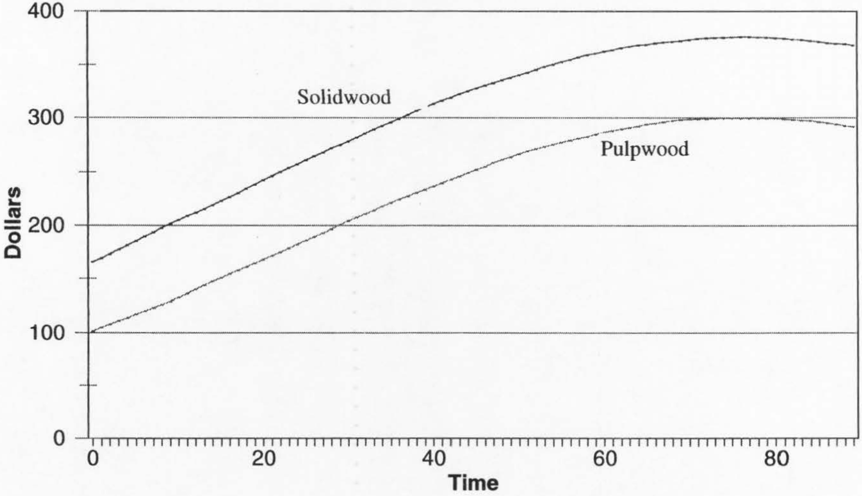


**Figure 24. Timber prices [VHD climate change scenario].**

Figure 20 shows the price of pulpwood rises faster because the rise in demand for pulpwood is a higher proportionate relative to solidwood. The price of solidwood increases 213%, from $137 in 1995 to $430 in 2085, while the price of pulpwood increases 405%, from $81 in 1995 to $409 in 2085. The faster rising price of pulpwood also signals producers to switch resources from solidwood production to pulpwood production.

In the climate change scenario, the total industrial wood production increases 2.88 billion cubic meters, from 1.31 billion cubic meters in 1995 to 4.19 cubic meters in 2085. The pulpwood production increases 2.0 billion cubic meters, from 780 million cubic meters in 1995 to 2.78 billion cubic meters in 2085. The solidwood production also increased 891 million cubic meters, from 529 million cubic meters in 1995 to 1.42 billion cubic meters in 2085. The increment of total industrial wood in 2085 is about 1.48 billion cubic meters larger than that in the base scenario. The increment of both pulpwood and solidwood in 2085 is about 807 and 673 million cubic meters larger than in the base scenario, respectively.

Figure 24 presents the price changes of pulpwood and solid wood over the simulation period. The price of solidwood increases 122%, from $166 in 1995 to $368 in 2085, while the price of pulpwood increases 189% from $101 in 1995 to $292 in 2085. The larger timber production, due to the climate change, results in a lower growth rate of timber prices. As a result, the prices of pulpwood and solidwood in 2085 are about $118 and $62 lower than in the base scenario, respectively. The trends of timber production and timber prices suggest that the climate change also have a positive impact on the global timber supply under the very high timber demand scenario.

We have investigated how much global warming affects the global timber market under three different timber demand scenarios. We found the estimates of intertemporal endogenous variables in the TSM 2000 responded significantly to changed environments generated by different timber demand growth scenarios. This sensitivity analysis provides significant information on the direction, magnitude, and natures of various adjustment mechanisms in the global timber market.

In summary, the economic system responded to increasing growth of timber demand through changes in timber production and prices. Differences in timber production and prices are highly related with differences in the growth rate of timber demand and in the potential capacity to produce and expand available supply.

Also, if growth of pulpwood demand increases at a significantly higher rate than solidwood demand, the production of solidwood increases at a very modest rate or decreases in the later part of simulation period. This trend results from the fact that higher growth of pulpwood demand relative to solidwood demand switches industrial wood from solidwood to pulpwood. Finally, if timber demand grows at a higher rate than that in the normal demand scenario, the initial timber production is lower, but timber production is ultimately larger than in the normal timber demand scenario. This structure suggests that rational forward-looking producers postpone the initial timber production with the anticipation of higher prices in the future.

**An Analysis of Welfare Change in Timber Market**

In order to examine how much global warming affects the global timber market in the economic welfare sense, we measured the welfare change between the base scenario and the climate change scenario under each of timber demand scenarios. As already stated, the welfare level in TSM 2000 is the sum of discounted present value of net surplus over the simulation period. Suppose that the optimal volume of timber production for solidwood and pulpwood in year *j* is $Q_j^*$ and $\tilde{Q}_j^*$. Then the net surplus at optimum in year *j* is

$$s_j = \int_0^{Q_j^*} D_j^s(n)dn + \int_0^{\tilde{Q}_j^*} D_j^p(n)dn - C_j^* \quad (38)$$

and the sum of the discounted present value of the net surplus at optimum over the simulation period is

$$S_0^*(x_0, z_0, u, w) = \sum_{k=0}^{J-1} \rho^k s_k^* + \rho^J S_J^{\ *}(x_J, z_J) \quad (39)$$

where $k = 0$ for year 1995 and $k = J$ for year 2085.

Under the normal timber demand scenario, we calculated the welfare levels for both the base scenario and the climate change scenario. The total discounted present value of the net surplus (the welfare level) for the base scenario is about 336 million dollars, while that for the climate scenario is about 352 million dollars. The welfare level in the climate change scenario is 16 million dollars (4.8%) larger than in the base scenario. This amount of welfare increase suggests that society will experience an economic benefit through the global timber market when climate change occurs.

Under the high timber demand scenario, the welfare level for the base scenario is about 385 million dollars, while that for the climate change scenario is about 450 million dollars. The welfare level in the climate scenario is about 65 million dollars, 16.9% larger than in the base scenario. Also, under the very high timber demand scenario, the welfare level for the base scenario is 750 million dollars, while that for the climate scenario is 878 million dollars. The welfare level in the climate scenario is about 128 million dollars, 17.1% larger than in the base scenario. These amounts of welfare increase in both timber demand scenarios also indicate that the global warming is economically beneficial to society through the global timber market.

# CHAPTER V

# THE NET RELEASE OF CARBON INTO THE ATMOSPHERE

Up to this point, we have modeled and simulated the effect of global warming on the global timber market. Using a modified TSM 2000, we identified a positive effect of global warming on the global timber market through an increase of timber production and a decrease of timber prices. In this chapter, we extend the modeling framework by incorporating the TCM to investigate the feedback effect of the global timber market on global warming. In order to achieve this objective, we estimated the net release of carbon into the atmosphere using both the base TCM and the modified TCM, which reflects climate change. The reference TCM used for the base TCM is the same as that developed by Yan (1996).

Model simulations of the base TCM and the modified TCM allowed us to identify the net release of carbon into the atmosphere for six different scenarios (i.e., the base scenario and the climate scenario for three timber demand scenarios). Under each timber demand scenario, the difference in net release of carbon between the base scenario and the climate change scenario of TCM provided information to assess the feedback effect of the global timber market on global warming.

## Description of the Terrestrial Carbon Model

The TCM was developed to examine net carbon release into the atmosphere after mature trees are harvested and when new trees are regenerated in the harvested site of the mature trees. Harvested mature trees release stored carbon into the atmosphere from all parts of the tree (bole, debris, and root), and from the soils on which mature trees have been standing. On the other hand, if young trees are replanted in the harvested sites, they will sequester carbon from the atmosphere as they grow vigorously. Simultaneously, the soil builds up carbon storage to a certain level as young trees grow.

In the TCM, *CV(h)* denotes the level of carbon storage in the tree, where *h* is the land class. The tree is divided into three parts, including the merchantable bole, nonmerchantable part (tops, branches, and barks, etc), and the roots. *CW(h)* is the level of carbon stored in the bole; *CD(h)* is the level of carbon stored in the debris left on the harvested site; and *CR(h)* is the level of carbon stored in the roots. Hence, the level of carbon storage in vegetation is the sum of the bole, the debris, and the roots. This holds the following relation:

$$CV(h) = CW(h) + CD(h) + CR(h) \tag{40}$$

It is assumed in the TCM that both the merchantable bole and debris follow the exponential functional form in the process of decomposition (or decaying) after harvesting. In addition, following Houghton et al. (1983), the TCM assumes that the decaying rate is primarily dependent upon the final product of harvested timber. Houghton et al. (1983) observed that it takes over 100 years for solidwood to decompose, while it takes about 10 years for paper. For decomposition of debris, it is also observed that almost 40% of the carbon stays in debris at the end of the first year after harvesting. Another 20% decomposes from the second year to year 10. Finally, the remaining 20% decays from year 11 to year 100. Carbon in the roots is assigned to the decay pool of the soil and will decay in a few years following the harvest.

To observe the change of carbon storage in the soil, $CS_a(h)$ is defined as the level of carbon storage in the soil on which the matured trees have been standing, and $CS_b(h)$ for the next generation of trees. After harvesting matured trees some of the carbon is added to the soil as dead roots; hence the carbon in the soil increases immediately after the harvest to $CS_h(h) = CS_a(h) + CR(h)$ for the matured trees. However, as more of the soil is exposed to oxidation after harvesting, decomposition of the organic matter in the soil is enhanced. As a result, carbon storage in the soil decreases due to loss of the organic carbon in the soil, and approaches its minimum level as it continuously declines until the harvested site is regenerated with young trees. From the minimum level, the addition of carbon to the soil, in the form of litter, increases as replanted young trees grow. Carbon storage in the soil increases to the level of carbon storage, $CS_b(h)$.

It is assumed that $T_a(h)$ is the time of harvesting, and $T_m(h)$ is the time for reaching the minimum carbon storage in the soil after harvesting the matured trees. $T_b(h)$ is the time of next harvest. Therefore, time period $T_b(h)$ - $T_a(h)$ is the rotation cycle and determines the level of carbon storage in the soil. Table A-9 (Appendix A) illustrates the data used in the TCM to define changes of the carbon in the soil during the time period between harvests.

If the harvested trees are regenerated with young trees, carbon in the young trees increases as the young trees grow vigorously. In this context, the TCM assumes that the increase of carbon storage in the three parts of young trees follows the yield function pattern of the standing volume of young trees. To estimate the carbon of trees, the dry weight of timber per hectare is calculated and then converted into carbon in the trees per hectare. The volume of merchantable bole of trees per hectare in year $\hat{j}$ is denoted by $q(h,i,\hat{j})$;[15] *cf1(h)* is the specific gravity of forest type; *cf2(h)* is the portion of the carbon in the dry weight of the merchantable bole. The dry weight of the merchantable bole is calculated by multiplying $q(h,i,\hat{j})$ by *cf1(h)*. Also, the dry weight of the merchantable bole multiplied by portion of carbon, *cf2(h)* generates the carbon content of merchantable bole per hectare. Conversion factors, which are used to calculate carbon storage in each part of tree, are tabulated in Table A-10 (Appendix A) for 42 land classes.

We further define $XH(h,\hat{j})$ as hectares of timber harvested in land class *h* and year $\hat{j}$ and *CSI(h)* is the initial level of carbon storage in the soil of land class *h* at the timber harvesting time. *CSI(h)* will be $CS_a(h)$ if mature trees are harvested, and $CS_b(h)$ if the next generation of trees is cut; $CW(h,\hat{j})$ is carbon in the harvested wood at the time of harvest. The decaying rate of harvested wood is *rw(h)*, which is a weighted average of solidwood and pulpwood decaying rates. $CD(h,\hat{j})$ is carbon in debris left on the harvested site, and *rd(h)* is the decaying rate of debris. $CR(h,\hat{j})$ is the carbon in the roots, which is transferred to the decaying pool of the soil. $CY(h,\hat{j},j)$ is carbon storage of young trees per hectare in year *j*, which is regenerated in year $\hat{j}$ ($j > \hat{j}$).

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[15] In the equation, $q(h,i,\hat{j})$ which defines the volume of merchantable bole of trees per hectare in land class *h*, *i*, and $\hat{j}$ denote the age of trees and the year of harvesting, respectively.

## Formulation of Terrestrial Carbon Model

### *Formulation of Net Carbon Release in the Base Scenario*

For the base scenario, the net carbon release from trees in year $j$, which are harvested from land class $h$ in year $\hat{j}$, is estimated using the following formula:

$$\begin{aligned} NC(h,\hat{j},j) = {} & CW(h,\hat{j})(e^{-rw(h)(j-\hat{j}-1)} - e^{-rw(h)(j-\hat{j})}) \\ & + CD(h,\hat{j})(e^{-rd(h)(j-\hat{j}-1)} - e^{-rd(h)(j-\hat{j})}) \\ & + [XH(h,\hat{j})(CSI(h) - CS_m(h)) + CR(h,\hat{j})]/(T_m - \hat{j}) \\ & + XH(h,\hat{j})(CY(h,\hat{j},j) - CY(h,\hat{j},j-1)) \end{aligned}$$

$$\text{when } \hat{j} < j \leq T_m(h) \qquad (41)$$

and

$$\begin{aligned} NC(h,\hat{j},j) = {} & CW(h,\hat{j})(e^{-rw(h)(j-\hat{j}-1)} - e^{-rw(h)(j-\hat{j})}) \\ & + CD(h,\hat{j})(e^{-rd(h)(j-\hat{j}-1)} - e^{-rd(h)(j-\hat{j})}) \\ & + [XH(h,\hat{j})(CS_b(h) - CS_m(h)) / (T_b(h) - T_m(h)) \\ & + XH(h,\hat{j})(CY(h,\hat{j},j) - CY(h,\hat{j},j-1)) \end{aligned}$$

$$\text{when } T_m(h) < \hat{j} \leq T_b(h) \qquad (42)$$

In year $j$ for land class $h$, the net carbon release due to timber harvests is the sum of the net carbon release from all harvesting activity occurring before year $j$. This holds as follows:

$$SNC(h,j)=\sum_{\hat{j}=0}^{j} NC(h,\hat{j},j) \tag{43}$$

According to previous statements, $CW(h,\hat{j})$, $CD(h,\hat{j})$, $CR(h,\hat{j})$ and come from

$$CW(h,\hat{j}) = cf1(h) \cdot cf2(h) \cdot qlc(h,\hat{j}) \tag{44a}$$

$$CD(h,\hat{j}) = cf3(h) \cdot CW(h,\hat{j}) - CW(h,\hat{j}) \tag{44b}$$

$$CR(h,\hat{j}) = cf3(h) \cdot CW(h,\hat{j}) \cdot (cf4(h) - 1) \tag{44c}$$

where $qlc(h,\hat{j})$ is the total volume harvested for land class $h$ and year $\hat{j}$; $cf3(h)$ is the ratio of carbon in the tree above the ground over that in the bole, and $cf4(h)$ is the ratio of carbon in the whole tree over that in the tree above the ground. Both $cf3(h)$ and $cf4(h)$ are reported in Table A-7 (Appendix A). $CY(h,\hat{j},j)$ is calculated as

$$CY(h,\hat{j},j) = cf1(h) \cdot cf2(h) \cdot cf3(h) \cdot cf4(h) \cdot q(h,i,j) \tag{45}$$

where $q(h,i,j)$ is the merchantable volume of tree per hectare in year $j$ of land class $h$, which is regenerated in year $\hat{j}$ $(age\ i = j - \hat{j})$.

***Formulation of Net Carbon Release in the Climate Change Scenario***

For the climate scenario, the net carbon release from trees in year $j$, harvested from land class $h$ in year $\hat{j}$, is estimated using the following formula:

$$NC(h,\hat{j},j) = CWcl(h,\hat{j})(e^{-rw(h)(j-\hat{j}-1)} - e^{-rw(h)(j-\hat{j})})$$
$$+ CDcl(h,\hat{j})(e^{-rd(h)(j-\hat{j}-1)} - e^{-rd(h)(j-\hat{j})})$$
$$+ [(XHcl(h,\hat{j}) + XHslvg(h,\hat{j}))(CSI(h) - CS_m(h)) + CR(h,i)]/(T_m - \hat{j})$$
$$-( XHcl(h,\hat{j}) + RR_h)(CYcl(h,\hat{j},j) - CYcl(h,\hat{j},j - 1))$$

$$\text{when } \hat{j} < j \leq T_m(h) \qquad (46)$$

and

$$NC(h,\hat{j},j) = CWcl(h,\hat{j})(e^{-rw(h)(j-\hat{j}-1)} - e^{-rw(h)(j-\hat{j})})$$
$$+ CDcl(h,\hat{j})(e^{-rd(h)(j-\hat{j}-1)} - e^{-rd(h)(j-\hat{j})})$$
$$- (XHcl(h,\hat{j}) + XHslvg((CS_b(h,\hat{j}))CS_b(h) - CS_m(h)) / (T_b(h) - T_m(h))$$
$$- (XHcl(h,\hat{j}) + RR_h)(CYcl(h,\hat{j},j) - CYcl(h,\hat{j},j - 1))$$

$$\text{when } T_m(h) < \hat{j} \leq T_b(h) \qquad (47)$$

where $XHcl(h,\hat{j})$ is the hectares of trees harvested in land class $h$ and year $\hat{j}$ after climate change; $XHslvg(h,\hat{j})$ is the hectares of trees salvaged in the land class $h$ and year $\hat{j}$; $RR_h$ is the regenerated hectares per year for land class $h$. $CWcl(h,\hat{j})$, $CDcl(h,\hat{j})$, and $CRcl(h,\hat{j})$ come from

$$CWcl(h,\hat{j}) = cf1(h) \cdot cf2(h) \cdot \tilde{q}lc(h,\hat{j}) \qquad (48a)$$

$$CDcl(h,\hat{j}) = cf3(h) \cdot CWcl(h,\hat{j}) - CWcl(h,\hat{j}) \qquad (48b)$$

$$CRcl(h,\hat{j}) = cf3(h) \cdot CW(h,\hat{j}) \cdot (cf4(h) - 1) \qquad (48c)$$

where $\tilde{q}lc(h,\hat{j})$ is the total volume harvested for land class $h$ and year $\hat{j}$ including trees salvaged after climate change. $CYcl(h,\hat{j},j)$ is calculated as

$$CYcl(h,\hat{j},j) = cf1(h) \cdot cf2(h) \cdot cf3(h) \cdot cf4(h) \cdot \tilde{q}(h,i,j) \tag{49}$$

where $\tilde{q}(h,i,j)$ is the modified merchantable volume of tree per hectare in year $j$ of land class $h$, regenerated in year $\hat{j}$ (age $i = j - \hat{j}$). In year $j$ for land class $h$, the net carbon release due to timber harvest activity is the sum of the net carbon release from all harvesting activity occurring before year $j$. This holds as follows:

$$SNC(h, j) = \sum_{\hat{j}=0}^{j} NC(h, \hat{j}, j) \tag{50}$$

***Decaying Rates***

The decaying rate of the bole of a tree is divided into two different rates that depend on the final products manufactured from harvested timber. If the final product of timber harvested is paper, then the decaying rate is

$$rw^{p}(h) = \frac{-\ln(0.01)}{10} \tag{51}$$

If the final product usage is solidwood, then the decaying rate is

$$rw^{s}(h) = \frac{-\ln(0.01)}{100} \tag{52}$$

The decaying rate of the bole of tree is a weighted average of that of solidwood and pulpwood decaying rates. This is expressed as follows:

$$rw(h) = rw^{s}(h) \cdot \phi_h + rw^{p}(h) \cdot (1 - \phi_h) \tag{53}$$

The decaying rates of debris left on the harvested site are calculated as follows:

$$rd_1 = -\ln(0.40) \qquad \text{when } t = 1 \qquad (54a)$$

$$rd_2 = \frac{-\ln(0.20/0.40)}{9} \qquad \text{when } 1 < t \leq 10 \qquad (54b)$$

$$rd_3 = \frac{-\ln(0.01/0.20)}{90} \qquad \text{when } 10 < t \leq 100 \qquad (54c)$$

**Simulation Results of Terrestrial Carbon Model**

***Net Carbon Release under Normal Demand Scenario***

On the basis of formulations of TCM, we simulated the projections of net carbon release for both the base scenario and the climate change scenario under three timber demand scenarios. Figure 25 shows net carbon release for both the base scenario and the climate change scenario under the normal demand scenario. In the base scenario, the net carbon release is positive during the first 48 years, with the peak in year 11 releasing 1014.39 x $10^{12}$ g amount of carbon into the atmosphere. After year 48, the net carbon release becomes negative, with decreasing rate until year 2085. In 2085 the net carbon release will be -641.7 x $10^{12}$ g (negative value implies net carbon sequestering).

The structure of net carbon release over the entire simulation period suggests that in the early years most carbon released into the atmosphere comes from the harvested volume of wood, debris, roots, and the soil. At the same time, the regenerated young

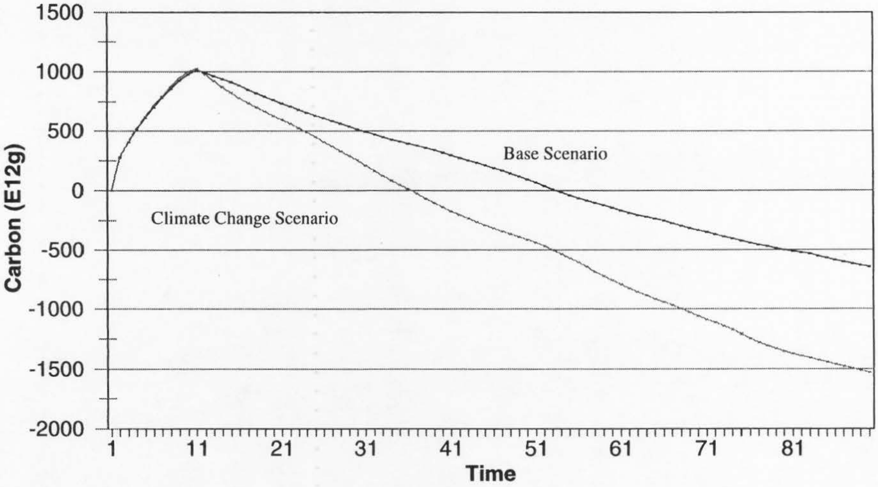


**Figure 25. Net carbon release [ND scenario].**

trees in the harvested land sites sequester carbon from the atmosphere as regenerated young trees grow. Carbon release is larger than carbon sequestering in the early years because absolute volume of regenerated young trees is smaller. However, as the regenerated young trees grow vigorously, resulting in the increase of volume of regenerated young trees, they sequester more carbon from the atmosphere. Consequently, carbon sequestering dominates carbon release. From year 48, carbon sequestering of regenerated young trees is larger than carbon release from timber harvests.

In the climate change scenario, the net carbon release is positive during the first 37 years. After year 37, it becomes negative with a decreasing rate until 2085. Thus, in the climate scenario, the year when net carbon release changes from positive to negative is achieved 11 years earlier than in the base scenario. Furthermore, the amount of net carbon release is $-1527.1 \times 10^{12}$ g in 2085. This shows that net carbon sequestering (negative value of net carbon release) in this scenario is about $885 \times 10^{12}$ g larger than in the base scenario in 2085.

The accumulated differences in net carbon release between the base scenario and the climate scenario measure how the global timber market has a long-run feedback impact on global warming when climate change occurs. Table 1 shows the accumulated differences in net carbon release by every 1.5 decades between the base scenario and the climate change scenario under normal timber demand scenario.

As shown in Table 1, the accumulated difference in net carbon sequestering between the base scenario and the climate change scenario increases over the

**Table 1. The accumulated difference in net carbon release ($10^{12}$g) between the base scenario and the climate change scenario under ND scenario.**

| | Time (year) | | | | | |
|---|---|---|---|---|---|---|
| Scenario | 15 | 30 | 45 | 60 | 75 | 90 |
| Base[a] (A) | 10,893 | 21,268 | 26,553 | 26825 | 22,433 | 14,313 |
| Climate change[a] (B) | 10,797 | 18,601 | 17,766 | 10,016 | -6,203 | -25,966 |
| Difference in net carbon release[a] (B-A) | -96 | -2,667 | -8,787 | -16,809 | -28,636 | -40,279 |

[a]Denotes accumulated amount of net carbon release.

simulation period. This structure suggests that the global timber market will have a long-run dampening (negative feedback) impact on global warming through net carbon sequestering. This structure is also dependent on two important factors presented in the simulation results of BIOME 3. BIOME 3 predicted an increase in net primary productivity for all land classes as well as an increase in hectares of faster growing tree species.

These two factors predicted by BIOME 3 not only increase total industrial wood production, but also spur the regenerated young trees to grow faster. Consequently, the increase of total industrial wood production releases more carbon into the atmosphere; at the same time, the regenerated young trees sequester more carbon from the atmosphere. Although both carbon release and carbon sequestering increase simultaneously due to the climate change, Table 1 shows that an increase of carbon sequestering exceeds that of carbon release as simulation time passes. This trend implies that the global timber market has a dampening (negative feedback) impact on global warming through the increment of net carbon sequestering.

***Net Carbon Release under Both High Timber Demand Scenario and Very High Timber Demand Scenario***

Net carbon release under both the high timber demand and very high timber demand scenarios shows a similar tendency to that under the normal demand scenario. For the high timber demand scenario, Figure 26 presents net carbon release for both the base scenario and the climate change scenario over the simulation period. In the base scenario, net carbon release is positive during the first 66 years, with the peak in year 11 releasing 751.57 x $10^{12}$ g amount of carbon into the atmosphere. After year 66, the net carbon release is negative with a decreasing rate until 2085. The net carbon release will be -625.5 x $10^{12}$ g in 2085. In the climate change scenario, positive net carbon release is during the first 54 years, with the peak in year 11 releasing 978.63 x $10^{12}$ g amount of carbon into the atmosphere. By 2085, net carbon release is -1145.1 x $10^{12}$ g. Thus, in the climate change scenario the year when net carbon release changes from positive to negative is achieved about 12 years earlier than in the base scenario. In 2085, net carbon sequestering is about 520 x $10^{12}$ g larger than in the base scenario. Figure 26 also shows that the net carbon release in the climate scenario is lower than in the base scenario from 27 years.

For the very high timber demand scenario, Figure 27 shows net carbon release for both the base scenario and the climate change scenarios. In the base scenario, net carbon release is positive during the first 45 years, with the peak in year 12 releasing 1147.43 x $10^{12}$ g amount of carbon into the atmosphere. In year 2085, net carbon release is -1350.7 x $10^{12}$ g. In the climate change scenario, net carbon release is positive during the first 45

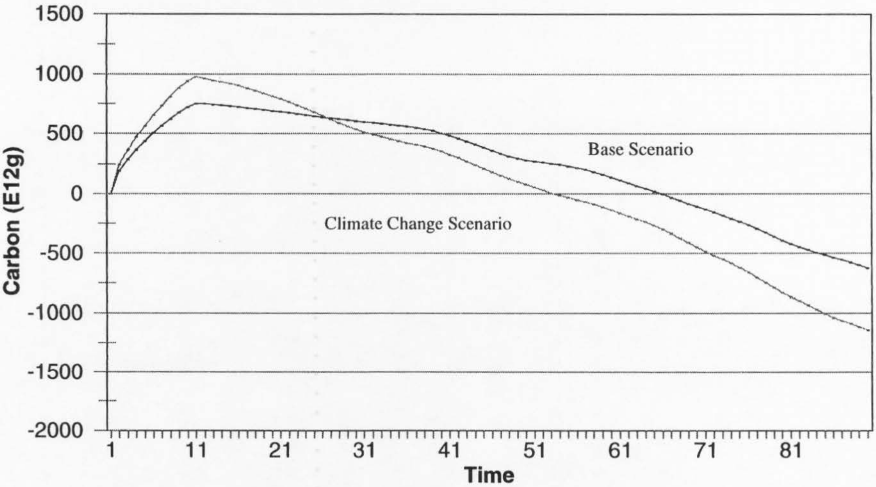


**Figure 26. Net carbon release [HD scenario].**

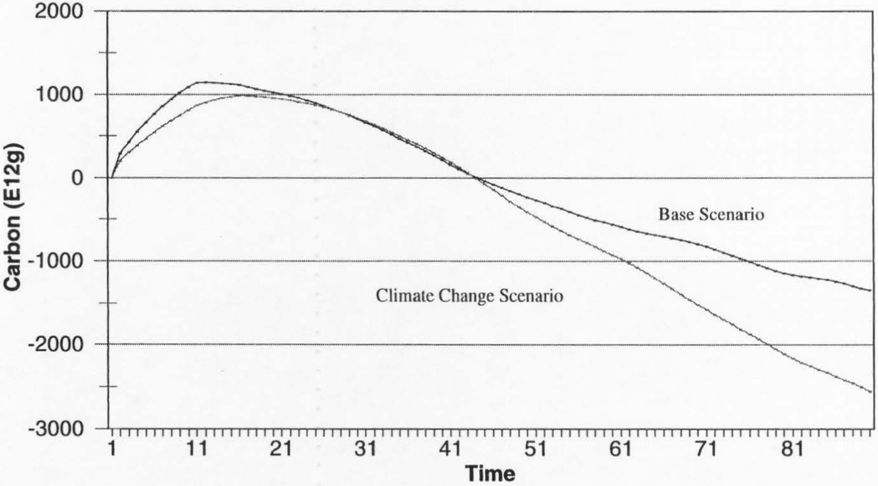


**Figure 27. Net carbon release [VHD scenario].**

years, with the peak in year 16 releasing 986.39 x $10^{12}$ g amount of carbon. Also, in year 2085 the net carbon release is -2556.2 x $10^{12}$ g. Tables 2 and 3 show the accumulated difference in net carbon release between the base scenario and the climate scenario for both high timber demand and very high timber demand scenario.

According to Tables 2 and 3, the accumulated difference in net carbon sequestering between the base scenario and the climate change scenario increases as simulation time

**Table 2. The accumulated difference in net carbon release ($10^{12}$g) between the base scenario and the climate change scenario under HD scenario.**

| | Time (year) | | | | | |
|---|---|---|---|---|---|---|
| Scenario | 15 | 30 | 45 | 60 | 75 | 90 |
| Base[a] (A) | 8,076 | 18,028 | 25,805 | 29,571 | 28,713 | 21,830 |
| Climate change[a] (B) | 10,412 | 21,359 | 27,057 | 27,300 | 21,598 | 7,760 |
| Difference in net carbbon release[a] (B-A) | 2,336 | 3,331 | 1,252 | -2,271 | –7,115 | -14,070 |

[a]Denotes accumulated amount of net carbon release.

**Table 3. The accumulated difference in net carbon release ($10^{12}$g) between the base scenario and climate change scenario under VHD scenario.**

| | Time (year) | | | | | |
|---|---|---|---|---|---|---|
| Scenario | 15 | 30 | 45 | 60 | 75 | 90 |
| Base[a] (A) | 12,297 | 26,353 | 31,081 | 26,062 | 14,630 | -3,216 |
| Climate change[a] (B) | 9,386 | 22,744 | 27,759 | 19,289 | -1,566 | -35,091 |
| Difference in net carbbon release[a] (B-A) | -2,911 | -3,609 | -8,787 | -6,773 | -16,196 | -31,875 |

[a]Denotes accumulated amount of net carbon release.

passes. As a result, these structures also suggest that the global timber market has a dampening (negative feedback) impact on global warming through the increment of net carbon sequestering.

To estimate dynamic ecological change in Chapter III, we used the simulation results of BIOME 3. In the process of simulation of BIOME 3, the Hamburg was used as a GCM to identify the change of climate variables between current carbon dioxide concentration and a doubling of carbon dioxide concentration in the atmosphere. According to Sohngen et al. (1998), the Hamburg used 340 ppmv for current carbon dioxide concentration and 500 ppmv for a doubling of carbon dioxide concentration in the atmosphere.[16] In Table 1, we found that the accumulated difference in net carbon release between the base scenario and the climate change scenario is -40,279 x $10^{12}$ g in 2085 for the normal timber demand scenario. In this context, we identified that climate change reduces about 3.8% of the amount of carbon dioxide concentration in the atmosphere in 2085.

For both the high timber demand and very high timber demand scenarios, the accumulated difference in net carbon release shows that the climate change reduces 1.3% and 3.0% of the amount of carbon concentration in the atmosphere over 90 years, respectively. The accumulated difference in net carbon release, which reduces the amount of carbon concentration in the atmosphere, is so negligible that it has little feedback impact on global warming. In this sense, we do not need to identify the repeated effect of climate change on the global timber through the feedback loop.

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[16] The relationship between ppmv and g is 1 ppmv = 2.123 x $10^{12}$g.

# CHAPTER VI

# SUMMARY AND RECOMMENDATIONS

## Summary of Research Results

Our main research objective was to identify the direct and feedback effects of global warming on the global timber market. To achieve this research objective, the TSM 2000, Hamburg, BIOME 3, and TCM were used as suitable economic and ecological models. The TSM 2000 was used to model dynamic economic behavior in the global timber market. The other three models were utilized to identify both the dynamic ecological change and forest carbon flux through their dynamic interactions when climate change occurs.

We developed the TSM 2000 by extending the existing TSM to consider more important up-to-date components in the global timber market. These components included the former Soviet Union as a part of the responsive regions, increased plantation forests in the emerging region, forest withdrawals for environmental protection, and the transformed ecosystem types after climate change.

In order to estimate dynamic ecological changes, a steady-state ecological model (BIOME 3) was used to simulate a steady-state ecological change before and after climate change. Based on the simulation results of BIOME 3 and linearity assumptions about adjustment in climate and ecosystems, we derived dynamic ecological change as measured by the dieback ratio, the regenerated land areas per year, and the change in

NPP. With these estimates of dynamic ecological changes, we modified both the TSM 2000 and the TCM to reflect the dynamic ecological change after climate change.

Using an integrated model, we simulated both the base scenario and the climate change scenario of TSM 2000 over 90 years under three timber demand scenarios. After simulation of each scenario, we identified the intertemporal projections of important endogenous variables in the model. Simulation results suggest that global warming will have a positive impact on the global timber market through an increase of timber production and a resulting decrease of timber prices.

Also, in order to examine the effect of global warming on the global timber market in the economic welfare sense, we calculated the sum of discounted present value of net surplus at optimum for both the base scenario and the climate change scenario under each timber demand scenario. When comparing the welfare level of the base scenario with that of the climate change scenario, we also observed that global warming is economically beneficial to society through the global timber market.

Finally, we simulated both the base scenario and the climate change scenario of TCM under each demand scenario to identify net carbon release into the atmosphere. As a result, the accumulated difference in net carbon release over the simulation period under each demand scenario suggested that the global timber market has a dampening (negative feedback) impact on global warming. However, the accumulated difference in net carbon release is so negligible that it would have little impact on global warming.

**Recommendations for Further Research**

We achieved our research objectives as stated in the beginning of this study; however, there are several remaining studies to be conducted in the future. We would briefly recommend the following as remaining studies.

1. In this research, we used the simulated results of BIOME 3 using Hamburg as the GCM to identify dynamic ecological change. However, there are approximately 30 GCMs in use to forecast climate change by atmospheric and biospheric scientists. Also, it is known that some research is still underway to develop a better GCM to assess the climate change more accurately. In this sense, sensitivity of our results to currently existing GCMs or a better GCM to be developed in the future should be investigated.
2. Because a dynamic ecological model that covers the globe has not been developed yet, we depended only on a steady-state ecological model (BIOME 3) to estimate dynamic ecological change. Consequently, we derived the dynamic ecological change from the simulation results of BIOME 3. If a dynamic ecological model covering the globe is developed in the future, it will serve as a better way to estimate more robust results of how global warming affects the global timber market, and vice versa. In addition, if more accurate yield functions for new land classes are estimated, our research results will also be improved by further validation of these functions.
3. For sensitivity analyses, we simulated both TSM 2000 and TCM under high timber demand and very high demand scenarios to examine the combined effect

of global warming and the global timber market on carbon flux. We suggest broadening the number of different scenarios to further explore the implications of our research objectives, including other timber demand scenarios, different plantation forest establishments, biotechnological changes, parametric values in the model, etc. These sensitivity analyses will provide significant insights into how the TSM 2000 and TCM respond to the changed environments generated by different scenarios.

4. In our research we used a deterministic dynamic ecological-economic model to simplify complexities in measuring the dynamic change of global timber market and global ecosystems. However, it would be of interest to develop a stochastic dynamic ecological-economic model to explore our main research objectives in a more realistic sense.

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# APPENDICES

# Appendix A

## Supplementary Tables

**Table A-1. Regions and land classes.**

| Regions/characteristics | Ecosystem type | Land class |
|---|---|---|
| Emerging Region | N.A | 1 |
| U.S Pacific Northwest, Normal Access | 5 | 2 |
| U.S Pacific Northwest, Limited Access | 5 | 3 |
| U.S Pacific Northeast, Normal Access | 4 | 4 |
| U.S Pacific Northeast, Limited Access | 4 | 5 |
| Western Canada, Normal Access | 2 | 6 |
| Western Canada, Limited Access | 2 | 7 |
| Nordic Europe, South | 2 | 8 |
| Nordic Europe, South | 3 | 9 |
| Nordic Europe, South | 4 | 10 |
| Nordic Europe, North | 2 | 11 |
| U.S South site I, Normal Access | 3 | 12 |
| U.S South site I, Limited Access | 3 | 13 |
| U.S South site II, Normal Access | 3 | 14 |
| U.S South site II, Limited Access | 3 | 15 |
| U.S South site III, Normal Access | 3 | 16 |
| U.S South site III, Limited Access | 3 | 17 |
| U.S South site IV, Normal Access | 5 | 18 |
| U.S South site IV, Limited Access | 5 | 19 |
| Eastern Canada, Lake (pulp) | 3 | 20 |
| Eastern Canada, Lake (sawlog) | 3 | 21 |
| Eastern Canada, Boreal/Acadia (pulp) | 2 | 22 |
| Eastern Canada, Boreal/Acadia (pulp) | 3 | 23 |
| Eastern Canada, Boreal/Acadia (sawlog) | 2 | 24 |
| Eastern Canada, Boreal/Acadia (sawlog) | 3 | 25 |
| European USSR North, Normal Access | 2 | 26 |
| European USSR North, Limited Access | 2 | 27 |
| European USSR North, Normal Access | 4 | 28 |
| European USSR North, Limited Access | 4 | 29 |
| European USSR South, Normal Access | 3 | 30 |
| European USSR South, Limited Access | 3 | 31 |
| European USSR South, Normal Access | 5 | 32 |
| European USSR South, Limited Access | 5 | 33 |

| | | |
|---|---|---|
| West Siberia North, Normal Access | 2 | 34 |
| West Siberia North, Limited Access | 2 | 35 |
| West Siberia South, Normal Access | 3 | 36 |
| West Siberia South, Limited Access | 3 | 37 |
| | | |
| East Siberia North, Normal Access | 2 | 38 |
| East Siberia North, Limited Access | 2 | 39 |
| East Siberia South, Normal Access | 3 | 40 |
| East Siberia South, Limited Access | 3 | 41 |
| | | |
| Asia Pacific | 8 | 42 |

Note:

1. Ecosystem type of each land class follows classification of biome types given in Haxeltine and Prentice (1996).

2. Nine legends are used in BIOME 3 for the classification of forest types; including 1: Boreal Deciduous Forest/Woodland, 2: Boreal Coniferous Forest/Woodland, 3: Temperate-Boreal Mixed Forest, 4: Temperate Conifer Forest, 5: Temperate Deciduous Forest, 6: Temperate Broadleaved Evergreen Forest, 7: Tropical Seasonal Forest, 8: Tropical Rain Forest, 9:Tropical Deciduous Forest.

**Table A-2. Percentage of forest conservation for each land class.**

| Land class | | Ecosystem type | Percentage of forest conservation |
|---|---|---|---|
| 1 | Emerging Region | N.A | 0.00 |
| 2 | U.S Pacific Northwest, Normal Access | 5 | 7.97 |
| 3 | U.S Pacific Northwest, Limited Access | 5 | 7.97 |
| 4 | U.S Pacific Northeast, Normal Access | 4 | 7.97 |
| 5 | U.S Pacific Northeast, Limited Access | 4 | 7.97 |
| 6 | Western Canada, Normal Access | 2 | 0.00 |
| 7 | Western Canada, Limited Access | 2 | 23.06 |
| 8 | Nordic Europe, South | 2 | 9.50 |
| 9 | Nordic Europe, South | 3 | 9.50 |
| 10 | Nordic Europe, South | 4 | 9.50 |
| 11 | Nordic Europe, North | 2 | 9.50 |
| 12 | U.S South site I, Normal Access | 3 | 0.39 |
| 13 | U.S South site I, Limited Access | 3 | 0.39 |
| 14 | U.S South site II, Normal Access | 3 | 0.39 |
| 15 | U.S South site II, Limited Access | 3 | 0.39 |
| 16 | U.S South site III, Normal Access | 3 | 0.39 |
| 17 | U.S South site III, Limited Access | 3 | 0.39 |
| 18 | U.S South site IV, Normal Access | 5 | 0.39 |
| 19 | U.S South site IV, Limited Access | 5 | 0.39 |
| 20 | Eastern Canada, Lake (pulp) | 3 | 2.92 |
| 21 | Eastern Canada, Lake (sawlog) | 3 | 2.92 |
| 22 | Eastern Canada, Boreal/Acadia (pulp) | 2 | 2.92 |
| 23 | Eastern Canada, Boreal/Acadia (pulp) | 3 | 2.92 |
| 24 | Eastern Canada, Boreal/Acadia (sawlog) | 2 | 2.92 |
| 25 | Eastern Canada, Boreal/Acadia (sawlog) | 3 | 2.92 |
| 26 | European USSR North, Normal Access | 2 | 29.00 |
| 27 | European USSR North, Limited Access | 2 | 29.00 |
| 28 | European USSR North, Normal Access | 4 | 29.00 |
| 29 | European USSR North, Limited Access | 4 | 29.00 |
| 30 | European USSR South, Normal Access | 3 | 29.00 |
| 31 | European USSR South, Limited Access | 3 | 29.00 |

| | | | |
|---|---|---|---|
| 32 | European USSR South, Normal Access | 5 | 29.00 |
| 33 | European USSR South, Limited Access | 5 | 29.00 |
| 34 | West Siberia North, Normal Access | 2 | 16.00 |
| 35 | West Siberia North, Limited Access | 2 | 16.00 |
| 36 | West Siberia South, Normal Access | 3 | 16.00 |
| 37 | West Siberia South, Limited Access | 3 | 16.00 |
| 38 | East Siberia North, Normal Access | 2 | 14.00 |
| 39 | East Siberia North, Limited Access | 2 | 14.00 |
| 40 | East Siberia South, Normal Access | 3 | 14.00 |
| 41 | East Siberia South, Limited Access | 3 | 14.00 |
| 42 | Asia Pacific | 8 | 13.12 |

Note:

1. Percentage of forest conservation for each land class was calculated from scenario five in Yan (1996), except that in the former Soviet Union.
2. For each land class in the former Soviet Union, percentage of forest conservation was selected from Backman and Waggener (1991).

**Table A-3. Commercial inventory of forest with/without conservation for each land class.**

| Land class | | Ecosystem type | Commercial inventory w/o conservation (Millon, hr) | Commercial inventory with conservation (Millon, hr) |
|---|---|---|---|---|
| 1 | Emerging Region | N.A | 6 | 6 |
| 2 | U.S Pacific Northwest, Normal Access | 5 | 4.91 | 4.52 |
| 3 | U.S Pacific Northwest, Limited Access | 5 | 2.50 | 0.23 |
| 4 | U.S Pacific Northeast, Normal Access | 4 | 3.38 | 3.11 |
| 5 | U.S Pacific Northeast, Limited Access | 4 | 5.15 | 4.74 |
| 6 | Western Canada, Normal Access | 2 | 17.7 | 17.7 |
| 7 | Western Canada, Limited Access | 2 | 14.3 | 11.00 |
| 8 | Nordic Europe, South | 2 | 16.7 | 15.11 |
| 9 | Nordic Europe, South | 3 | 2.79 | 2.52 |
| 10 | Nordic Europe, South | 4 | 2.81 | 2.54 |
| 11 | Nordic Europe, North | 2 | 28.14 | 25.47 |
| 12 | U.S South site I, Normal Access | 3 | 16.14 | 16.08 |
| 13 | U.S South site I, Limited Access | 3 | 4.51 | 4.49 |
| 14 | U.S South site II, Normal Access | 3 | 15.97 | 15.91 |
| 15 | U.S South site II, Limited Access | 3 | 4.21 | 4.19 |
| 16 | U.S South site III, Normal Access | 3 | 9.53 | 9.49 |
| 17 | U.S South site III, Limited Access | 3 | 1.29 | 1.28 |
| 18 | U.S South site IV, Normal Access | 5 | 9.46 | 9.42 |
| 19 | U.S South site IV, Limited Access | 5 | 6.81 | 6.78 |
| 20 | Eastern Canada, Lake (pulp) | 3 | 12.6 | 12.23 |
| 21 | Eastern Canada, Lake (sawlog) | 3 | 11.18 | 10.85 |
| 22 | Eastern Canada, Boreal/Acadia (pulp) | 2 | 28.27 | 27.44 |
| 23 | Eastern Canada, Boreal/Acadia (pulp) | 3 | 2.10 | 2.04 |
| 24 | Eastern Canada, Boreal/Acadia (sawlog) | 2 | 25.07 | 24.34 |
| 25 | Eastern Canada, Boreal/Acadia (sawlog) | 3 | 1.86 | 1.81 |
| 26 | European USSR North, Normal Access | 2 | 55.27 | 39.24 |
| 27 | European USSR North, Limited Access | 2 | 40.64 | 28.85 |
| 28 | European USSR North, Normal Access | 4 | 0.066 | 0.047 |
| 29 | European USSR North, Limited Access | 4 | 0.048 | 0.034 |
| 30 | European USSR South, Normal Access | 3 | 28.28 | 20.08 |
| 31 | European USSR South, Limited Access | 3 | 8.340 | 5.92 |
| 32 | European USSR South, Normal Access | 5 | 5.100 | 3.62 |
| 33 | European USSR South, Limited Access | 5 | 1.510 | 1.07 |
| 34 | West Siberia North, Normal Access | 2 | 22.84 | 19.19 |
| 35 | West Siberia North, Limited Access | 2 | 29.27 | 24.59 |
| 36 | West Siberia South, Normal Access | 3 | 13.17 | 11.06 |

| | | | | |
|---|---|---|---|---|
| 37 | West Siberia South, Normal Access | 3 | 8.620 | 7.24 |
| 38 | East Siberia North, Normal Access | 2 | 162.26 | 139.54 |
| 39 | East Siberia North, Limited Access | 2 | 207.93 | 178.82 |
| 40 | East Siberia South, Normal Access | 3 | 28.26 | 24.30 |
| 41 | East Siberia South, Limited Access | 3 | 18.51 | 15.92 |
| 42 | Asia Pacific | 8 | 58.31 | 50.66 |

Note:

1. Commercial inventory data (without conservation) was used given in Sedjo and Lyon (1990) for each land class, except that in the former Soviet Union.

2. For each land class in the former Soviet Union, commercial inventory data (without conservation) was selected from Backman and Waggener (1991)

3. Commercial inventory data (with conservation) was calculated by multiplying percentage of forest conservation tabulated in Table 2-2 and commercial inventory data without conservation.

**Table A-4. The dieback ratio and the regeneration area per year for each land class after climate change.**

| Land class | | Ecosystem type | Dieback ratio | Regeneration area per year (Million, hr) |
|---|---|---|---|---|
| 1 | Emerging Region | N.A | N.A | N.A |
| 2 | U.S Pacific Northwest, Normal Access | 5 | 0.34352 | 0.063280 |
| 3 | U.S Pacific Northwest, Limited Access | 5 | 0.34352 | 0.003220 |
| 4 | U.S Pacific Northeast, Normal Access | 4 | 0.28729 | 0.010663 |
| 5 | U.S Pacific Northeast, Limited Access | 4 | 0.28729 | 0.016251 |
| 6 | Western Canada, Normal Access | 2 | 0.35148 | 0.055629 |
| 7 | Western Canada, Limited Access | 2 | 0.35148 | 0.034571 |
| 8 | Nordic Europe, South | 2 | 0.52571 | 0.006476 |
| 9 | Nordic Europe, South | 3 | 0.81414 | 0.087948 |
| 10 | Nordic Europe, South | 4 | 0.65109 | 0.063681 |
| 11 | Nordic Europe, North | 2 | 0.00943 | 0.047301 |
| 12 | U.S South site I, Normal Access | 3 | 0.00000 | 0.101074 |
| 13 | U.S South site I, Limited Access | 3 | 0.00000 | 0.028223 |
| 14 | U.S South site II, Normal Access | 3 | 0.00000 | 0.100006 |
| 15 | U.S South site II, Limited Access | 3 | 0.00000 | 0.026337 |
| 16 | U.S South site III, Normal Access | 3 | 0.00000 | 0.059651 |
| 17 | U.S South site III, Limited Access | 3 | 0.00000 | 0.008046 |
| 18 | U.S South site IV, Normal Access | 5 | 0.36439 | 0.000000 |
| 19 | U.S South site IV, Limited Access | 5 | 0.36439 | 0.000000 |
| 20 | Eastern Canada, Lake (pulp) | 3 | 0.32275 | 0.183450 |
| 21 | Eastern Canada, Lake (sawlog) | 3 | 0.32275 | 0.162750 |
| 22 | Eastern Canada, Boreal/Acadia (pulp) | 2 | 0.50846 | 0.078400 |
| 23 | Eastern Canada, Boreal/Acadia (pulp) | 3 | 0.45174 | 0.188263 |
| 24 | Eastern Canada, Boreal/Acadia (sawlog) | 2 | 0.50846 | 0.069543 |
| 25 | Eastern Canada, Boreal/Acadia (sawlog) | 3 | 0.45174 | 0.167037 |
| 26 | European USSR North, Normal Access | 2 | 0.35920 | 0.016817 |
| 27 | European USSR North, Limited Access | 2 | 0.35920 | 0.012364 |
| 28 | European USSR North, Normal Access | 4 | 1.00000 | 0.067062 |
| 29 | European USSR North, Limited Access | 4 | 1.00000 | 0.048513 |
| 30 | European USSR South, Normal Access | 3 | 0.11253 | 0.140560 |
| 31 | European USSR South, Limited Access | 3 | 0.11253 | 0.041440 |
| 32 | European USSR South, Normal Access | 5 | 0.37788 | 0.073434 |
| 33 | European USSR South, Limited Access | 5 | 0.37788 | 0.021706 |
| 34 | West Siberia North, Normal Access | 2 | 0.15521 | 0.035639 |
| 35 | West Siberia North, Limited Access | 2 | 0.15521 | 0.045667 |
| 36 | West Siberia South, Normal Access | 3 | 0.00000 | 0.112180 |
| 37 | West Siberia South, Limited Access | 3 | 0.00000 | 0.073434 |

| | | | | |
|---|---|---|---|---|
| 38 | East Siberia North, Normal Access | 2 | 0.14942 | 0.159474 |
| 39 | East Siberia North, Limited Access | 2 | 0.14942 | 0.204366 |
| 40 | East Siberia South, Normal Access | 3 | 0.05955 | 2.863929 |
| 41 | East Siberia South, Limited Access | 3 | 0.05955 | 1.876286 |
| 42 | Asia Pacific | 8 | 0.11464 | 0.079609 |

**Table A-5. The ratio of net primary productivity (NPP) change for each land class after climate change.**

| Land class | | Ecosystem Type | Ratio of NPP change |
|---|---|---|---|
| 1 | Emerging Region | N.A | 1.0000 |
| 2 | U.S Pacific Northwest, Normal Access | 5 | 1.5008 |
| 3 | U.S Pacific Northwest, Limited Access | 5 | 1.5008 |
| 4 | U.S Pacific Northeast, Normal Access | 4 | 1.3525 |
| 5 | U.S Pacific Northeast, Limited Access | 4 | 1.3525 |
| 6 | Western Canada, Normal Access | 2 | 1.2184 |
| 7 | Western Canada, Limited Access | 2 | 1.2184 |
| 8 | Nordic Europe, South | 2 | 1.2228 |
| 9 | Nordic Europe, South | 3 | 1.1233 |
| 10 | Nordic Europe, South | 4 | 1.2218 |
| 11 | Nordic Europe, North | 2 | 1.4504 |
| 12 | U.S South site I, Normal Access | 3 | 1.3010 |
| 13 | U.S South site I, Limited Access | 3 | 1.3010 |
| 14 | U.S South site II, Normal Access | 3 | 1.3010 |
| 15 | U.S South site II, Limited Access | 3 | 1.3010 |
| 16 | U.S South site III, Normal Access | 3 | 1.3010 |
| 17 | U.S South site III, Limited Access | 3 | 1.3010 |
| 18 | U.S South site IV, Normal Access | 5 | 1.3248 |
| 19 | U.S South site IV, Limited Access | 5 | 1.3248 |
| 20 | Eastern Canada, Lake (pulp) | 3 | 1.3189 |
| 21 | Eastern Canada, Lake (sawlog) | 3 | 1.3189 |
| 22 | Eastern Canada, Boreal/Acadia (pulp) | 2 | 1.0187 |
| 23 | Eastern Canada, Boreal/Acadia (pulp) | 3 | 1.1377 |
| 24 | Eastern Canada, Boreal/Acadia (sawlog) | 2 | 1.0187 |
| 25 | Eastern Canada, Boreal/Acadia (sawlog) | 3 | 1.1377 |
| 26 | European USSR North, Normal Access | 2 | 1.1694 |
| 27 | European USSR North, Limited Access | 2 | 1.1694 |
| 28 | European USSR North, Normal Access | 4 | 1.3859 |
| 29 | European USSR North, Limited Access | 4 | 1.3859 |
| 30 | European USSR South, Normal Access | 3 | 1.2029 |

| | | | |
|---|---|---|---|
| 31 | European USSR South, Limited Access | 3 | 1.2029 |
| 32 | European USSR South, Normal Access | 5 | 1.2939 |
| 33 | European USSR South, Limited Access | 5 | 1.2939 |
| 34 | West Siberia North, Normal Access | 2 | 1.2842 |
| 35 | West Siberia North, Limited Access | 2 | 1.2842 |
| 36 | West Siberia South, Normal Access | 3 | 1.3406 |
| 37 | West Siberia South, Limited Access | 3 | 1.3406 |
| 38 | East Siberia North, Normal Access | 2 | 1.5684 |
| 39 | East Siberia North, Limited Access | 2 | 1.5684 |
| 40 | East Siberia South, Normal Access | 3 | 1.1293 |
| 41 | East Siberia South, Limited Access | 3 | 1.1293 |
| 42 | Asia Pacific | 8 | 1.4035 |

**Table A-6. Harvest, access, domestic, and international transportation cost.**

| Land class | Harvest cost ($/hr) | Domestic transportation Cost ($/hr) | Access Cost ($/hr) | International Transportation Cost ($/hr) |
|---|---|---|---|---|
| 1 | 6.00 | 4.50 | 2.63 | 8.50 |
| 2 | 10.00 | 7.00 | 4.00 | 7.30 |
| 3 | 11.00 | 9.00 | 5.00 | 7.30 |
| 4 | 11.00 | 7.00 | 5.00 | 8.50 |
| 5 | 12.00 | 7.00 | 8.00 | 8.50 |
| 6 | 9.50 | 6.65 | 5.70 | 7.30 |
| 7 | 19.00 | 12.35 | 7.60 | 7.30 |
| 8 | 7.20 | 4.80 | 2.80 | 4.50 |
| 9 | 7.20 | 4.80 | 2.80 | 4.50 |
| 10 | 7.20 | 4.80 | 2.80 | 4.50 |
| 11 | 12.80 | 8.80 | 3.20 | 9.00 |
| 12 | 8.00 | 6.00 | 3.50 | 5.00 |
| 13 | 11.00 | 7.00 | 4.00 | 5.00 |
| 14 | 9.00 | 7.00 | 3.50 | 5.00 |
| 15 | 12.00 | 10.00 | 5.50 | 5.00 |
| 16 | 13.00 | 10.00 | 4.00 | 5.00 |
| 17 | 15.00 | 12.00 | 5.00 | 5.00 |
| 18 | 14.00 | 12.00 | 5.00 | 5.00 |
| 19 | 16.00 | 14.00 | 6.00 | 5.00 |
| 20 | 11.40 | 8.55 | 3.80 | 5.00 |
| 21 | 13.30 | 13.30 | 7.60 | 5.00 |
| 22 | 11.40 | 10.45 | 4.75 | 5.00 |
| 23 | 11.40 | 10.45 | 4.75 | 5.00 |
| 24 | 13.30 | 17.10 | 8.55 | 5.00 |
| 25 | 13.30 | 17.10 | 8.55 | 5.00 |
| 26 | 13.00 | 8.00 | 5.00 | 4.50 |
| 27 | 260.00 | 16.00 | 7.50 | 4.50 |
| 28 | 13.00 | 8.00 | 5.00 | 4.50 |
| 29 | 260.00 | 16.00 | 7.50 | 4.50 |
| 30 | 8.00 | 6.00 | 3.50 | 4.50 |
| 31 | 160.00 | 12.00 | 5.25 | 4.50 |

| | | | | |
|---|---|---|---|---|
| 32 | 8.00 | 6.00 | 3.50 | 4.50 |
| 33 | 160.00 | 12.00 | 5.25 | 4.50 |
| 34 | 13.00 | 12.50 | 5.00 | 0.00 |
| 35 | 260.00 | 20.50 | 7.50 | 0.00 |
| 36 | 8.00 | 10.50 | 3.50 | 0.00 |
| 37 | 160.00 | 16.50 | 5.25 | 0.00 |
| 38 | 13.00 | 8.00 | 5.00 | 4.50 |
| 39 | 260.00 | 16.00 | 7.50 | 4.50 |
| 40 | 8.00 | 6.00 | 3.50 | 4.50 |
| 41 | 160.00 | 12.00 | 5.25 | 4.50 |
| 42 | 10.50 | 6.75 | 4.50 | 10.0 |

Note:

Components of cost function are used appearing on Sedjo and Lyon (1990) and Sohngen et al. (1996) to estimate components of cost function in the TSM 2000 for each land class.

**Table A-7. Parameter values of yield functions.**

| Land class | $c^1$ | $c^2$ | $c^3$ | $c^4$ | $c^5$ | $z$ |
|---|---|---|---|---|---|---|
| 1 | 0.1474 | 0.334 | 6.520 | -6.5889 | 6.927 | 650 |
| 2 | 0.1115 | 0.5 | 7.320 | -56.9222 | 10 | 650 |
| 3 | 0.1115 | 0.5 | 7.320 | -56.9222 | 10 | 650 |
| 4 | 0.1115 | 0.5 | 6.770 | -76.2117 | 0 | 650 |
| 5 | 0.1115 | 0.5 | 6.770 | -76.2117 | 0 | 650 |
| 6 | 0.1115 | 0.5 | 6.204 | -37.0169 | 18 | 650 |
| 7 | 0.1115 | 0.5 | 6.204 | -37.0169 | 18 | 650 |
| 8 | 0.050 | 0.3 | 7.457 | -90.0 | 0 | 650 |
| 9 | 0.1115 | 0.5 | 7.100 | -76.2117 | 0 | 650 |
| 10 | 0.1115 | 0.5 | 6.504 | -37.0169 | 18 | 650 |
| 11 | 0.050 | 0.5 | 7.697 | -135.0 | 0 | 650 |
| 12 | 0.1474 | 0.4 | 6.1367 | -10.2576 | 7 | 650 |
| 13 | 0.1474 | 0.4 | 6.1367 | -10.2576 | 7 | 650 |
| 14 | 0.1474 | 0.4 | 6.0739 | -15.3563 | 6 | 650 |
| 15 | 0.1474 | 0.4 | 6.0739 | -15.3563 | 6 | 650 |
| 16 | 0.1115 | 0.5 | 5.9272 | -24.0982 | 3 | 650 |
| 17 | 0.1115 | 0.5 | 5.9272 | -24.0982 | 3 | 650 |
| 18 | 0.050 | 0.5 | 7.697 | -135.0 | 0 | 650 |
| 19 | 0.050 | 0.5 | 7.697 | -135.0 | 0 | 650 |
| 20 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 21 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 22 | 0.1115 | 0.5 | 5.283 | -15.1954 | 15 | 650 |
| 23 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 24 | 0.1115 | 0.5 | 5.283 | -15.1954 | 15 | 650 |
| 25 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 26 | 0.050 | 0.5 | 7.397 | -135 | 0 | 650 |
| 27 | 0.050 | 0.5 | 7.397 | -135 | 0 | 650 |
| 28 | 0.1115 | 0.5 | 6.204 | -37.0169 | 18 | 650 |
| 29 | 0.1115 | 0.5 | 6.204 | -37.0169 | 18 | 650 |
| 30 | 0.1115 | 0.5 | 6.770 | -76.2117 | 0 | 650 |
| 31 | 0.1115 | 0.5 | 6.770 | -76.2117 | 0 | 650 |
| 32 | 0.1115 | 0.5 | 6.235 | -28.4649 | 14 | 650 |
| 33 | 0.1115 | 0.5 | 6.235 | -28.4649 | 14 | 650 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 34 | 0.050 | 0.5 | 7.497 | -135.0 | 0 | 650 |
| 35 | 0.050 | 0.5 | 7.497 | -135.0 | 0 | 650 |
| 36 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 37 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 38 | 0.050 | 0.5 | 7.297 | -135.0 | 0 | 650 |
| 39 | 0.050 | 0.5 | 7.297 | -135.0 | 0 | 650 |
| 40 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 41 | 0.1115 | 0.5 | 6.135 | -28.4649 | 14 | 650 |
| 42 | 0.0 | 1.0 | 4.689 | -1600 | 0 | 650 |

**Table A-8. The portion going to solidwood $\phi_h$ for each land class.**

| Land class | Region/characteristics | Percentage of solidwood (reference) |
|---|---|---|
| 1 | Emerging Region | 30 |
| 2 | U.S Pacific Northwest, Normal Access | 55 |
| 3 | U.S Pacific Northwest, Limited Access | 55 |
| 4 | U.S Pacific Northeast, Normal Access | 55 |
| 5 | U.S Pacific Northeast, Limited Access | 55 |
| 6 | Western Canada, Normal Access | 55 |
| 7 | Western Canada, Limited Access | 55 |
| 8 | Nordic Europe, South | 40 |
| 9 | Nordic Europe, South | 40 |
| 10 | Nordic Europe, South | 40 |
| 11 | Nordic Europe, North | 30 |
| 12 | U.S South site I, Normal Access | 60 |
| 13 | U.S South site I, Limited Access | 60 |
| 14 | U.S South site II, Normal Access | 50 |
| 15 | U.S South site II, Limited Access | 50 |
| 16 | U.S South site III, Normal Access | 45 |
| 17 | U.S South site III, Limited Access | 45 |
| 18 | U.S South site IV, Normal Access | 40 |
| 19 | U.S South site IV, Limited Access | 40 |
| 20 | Eastern Canada, Lake (pulp) | 30 |
| 21 | Eastern Canada, Lake (sawlog) | 50 |
| 22 | Eastern Canada, Boreal/Acadia (pulp) | 30 |
| 23 | Eastern Canada, Boreal/Acadia (pulp) | 30 |
| 24 | Eastern Canada, Boreal/Acadia (sawlog) | 50 |
| 25 | Eastern Canada, Boreal/Acadia (sawlog) | 50 |
| 26 | European USSR North, Normal Access | 30 |
| 27 | European USSR North, Limited Access | 30 |
| 28 | European USSR North, Normal Access | 30 |
| 29 | European USSR North, Limited Access | 30 |
| 30 | European USSR South, Normal Access | 40 |
| 31 | European USSR South, Limited Access | 40 |

| | | |
|---|---|---|
| 32 | European USSR South, Normal Access | 40 |
| 33 | European USSR South, Limited Access | 40 |
| 34 | West Siberia North, Normal Access | 30 |
| 35 | West Siberia North, Limited Access | 30 |
| 36 | West Siberia South, Normal Access | 40 |
| 37 | West Siberia South, Limited Access | 40 |
| 38 | East Siberia North, Normal Access | 30 |
| 39 | East Siberia North, Limited Access | 30 |
| 40 | East Siberia South, Normal Access | 40 |
| 41 | East Siberia South, Limited Access | 40 |
| 42 | Asia Pacific | 80 |

**Table A-9. Carbon contents ($CS_a$, $CS_b$, and $CS_m$) and time period to reach minimal carbon storage ($T_m$ - $T_a$).**

| Land class | Ecosystem type | $CS_a$ ($10^6$ g/ha) | $CS_b$ ($10^6$ g/ha) | $CS_m$ ($10^6$ g/ha) | $T_m$ - $T_a$ (yr) |
|---|---|---|---|---|---|
| 1 | N.A | 120 | 120 | 67 | 10 |
| 2 | 5 | 120 | 120 | 67 | 10 |
| 3 | 5 | 134 | 120 | 67 | 10 |
| 4 | 4 | 120 | 120 | 67 | 10 |
| 5 | 4 | 134 | 120 | 67 | 10 |
| 6 | 2 | 185 | 185 | 175 | 15 |
| 7 | 2 | 206 | 185 | 175 | 15 |
| 8 | 2 | 185 | 185 | 175 | 15 |
| 9 | 3 | 185 | 185 | 175 | 15 |
| 10 | 4 | 120 | 120 | 67 | 10 |
| 11 | 2 | 185 | 185 | 175 | 15 |
| 12 | 3 | 120 | 120 | 67 | 10 |
| 13 | 3 | 134 | 120 | 67 | 10 |
| 14 | 3 | 120 | 120 | 67 | 10 |
| 15 | 3 | 134 | 120 | 67 | 10 |
| 16 | 3 | 120 | 120 | 67 | 10 |
| 17 | 3 | 134 | 120 | 67 | 10 |
| 18 | 5 | 120 | 120 | 67 | 10 |
| 19 | 5 | 134 | 120 | 67 | 10 |
| 20 | 3 | 185 | 185 | 175 | 15 |
| 21 | 3 | 206 | 185 | 175 | 15 |
| 22 | 2 | 185 | 185 | 175 | 15 |
| 23 | 3 | 185 | 185 | 175 | 15 |
| 24 | 2 | 206 | 185 | 175 | 15 |
| 25 | 3 | 206 | 185 | 175 | 15 |
| 26 | 2 | 185 | 185 | 175 | 15 |
| 27 | 2 | 206 | 185 | 175 | 15 |
| 28 | 4 | 120 | 120 | 67 | 10 |
| 29 | 4 | 134 | 120 | 67 | 10 |
| 30 | 3 | 185 | 185 | 175 | 15 |
| 31 | 3 | 206 | 185 | 175 | 15 |

| | | | | | |
|---|---|---|---|---|---|
| 32 | 5 | 120 | 120 | 67 | 10 |
| 33 | 5 | 134 | 120 | 67 | 10 |
| 34 | 2 | 185 | 185 | 175 | 15 |
| 35 | 2 | 206 | 185 | 175 | 15 |
| 36 | 3 | 185 | 185 | 175 | 15 |
| 37 | 3 | 206 | 185 | 175 | 15 |
| 38 | 2 | 185 | 185 | 175 | 15 |
| 39 | 2 | 206 | 185 | 175 | 15 |
| 40 | 3 | 185 | 185 | 175 | 15 |
| 41 | 3 | 206 | 185 | 175 | 15 |
| 42 | 8 | 88 | 88 | 76 | 5 |

Note:

Carbon contents and time periods to reach minimal carbon storage for each land class are estimated from Table 2 provided in Houghton et al. (1983).

**Table A-10. The conversion factors used to calculate carbon storage in each part of the tree.**

| | Wood properties | | | |
|---|---|---|---|---|
| Land class | Specific gravity (*cf1(h)*) ($10^6$ g/m$^3$) | Proportion carbon (*cf2(h)*) | Carbon (above/bole) (*cf3(h)*) | Carbon (whole/above) (*cf4(h)*) |
| 1 | 0.51 | 0.53 | 1.60 | 1.35 |
| 2 | 0.45 | 0.51 | 1.60 | 1.35 |
| 3 | 0.45 | 0.51 | 1.60 | 1.35 |
| 4 | 0.42 | 0.51 | 1.82 | 1.35 |
| 5 | 0.42 | 0.51 | 1.82 | 1.35 |
| 6 | 0.37 | 0.51 | 1.69 | 1.35 |
| 7 | 0.37 | 0.51 | 1.69 | 1.35 |
| 8 | 0.37 | 0.52 | 1.69 | 1.35 |
| 9 | 0.37 | 0.52 | 1.69 | 1.35 |
| 10 | 0.37 | 0.52 | 1.69 | 1.35 |
| 11 | 0.37 | 0.52 | 1.69 | 1.35 |
| 12 | 0.51 | 0.53 | 1.69 | 1.35 |
| 13 | 0.51 | 0.53 | 1.61 | 1.35 |
| 14 | 0.51 | 0.53 | 1.61 | 1.35 |
| 15 | 0.51 | 0.53 | 1.61 | 1.35 |
| 16 | 0.51 | 0.53 | 1.61 | 1.35 |
| 17 | 0.51 | 0.53 | 1.61 | 1.35 |
| 18 | 0.58 | 0.50 | 1.64 | 1.35 |
| 19 | 0.58 | 0.50 | 1.64 | 1.35 |
| 20 | 0.50 | 0.52 | 1.64 | 1.35 |
| 21 | 0.50 | 0.52 | 1.64 | 1.35 |
| 22 | 0.37 | 0.52 | 1.64 | 1.35 |
| 23 | 0.50 | 0.52 | 1.64 | 1.35 |
| 24 | 0.37 | 0.52 | 1.64 | 1.35 |
| 25 | 0.50 | 0.52 | 1.64 | 1.35 |
| 26 | 0.37 | 0.52 | 1.69 | 1.35 |
| 27 | 0.37 | 0.52 | 1.69 | 1.35 |
| 28 | 0.37 | 0.52 | 1.69 | 1.35 |
| 29 | 0.37 | 0.52 | 1.69 | 1.35 |

| | | | | |
|---|---|---|---|---|
| 30 | 0.37 | 0.52 | 1.64 | 1.35 |
| 31 | 0.37 | 0.52 | 1.64 | 1.35 |
| 32 | 0.42 | 0.52 | 1.64 | 1.35 |
| 33 | 0.42 | 0.52 | 1.64 | 1.35 |
| 34 | 0.37 | 0.52 | 1.69 | 1.35 |
| 35 | 0.37 | 0.52 | 1.69 | 1.35 |
| 36 | 0.37 | 0.52 | 1.64 | 1.35 |
| 37 | 0.37 | 0.52 | 1.64 | 1.35 |
| 38 | 0.37 | 0.52 | 1.69 | 1.35 |
| 39 | 0.37 | 0.52 | 1.69 | 1.35 |
| 40 | 0.37 | 0.52 | 1.64 | 1.35 |
| 41 | 0.37 | 0.52 | 1.64 | 1.35 |
| 42 | 0.64 | 0.50 | 1.70 | 1.35 |

Note:

Conversion factors used to calculate carbon storage for each land class are estimated from Turner et al. (1995) and Freedman et al. (1992).

# Appendix B

## Descriptions of Steady-State Ecological Change

## Region I: The U.S. South

1. Geographical Location of Region

Longitude: 95W to 75W
Latitude: 40N to 30N

2. Classification of Region by Forest Type

Mixed hardwood: site IV
Southern pine: site I, II, III.

- Land areas where Mixed hardwood is stocked are associated with Temperate Deciduous (legend number 5) in BIOME 3 ecosystem type
- Land areas where Southern pine, especially loblolly pine, is stocked are associated with Temperate-Boreal Mixed Forest (legend number 3) in BIOME 3 ecosystem type. In particular, the region where Temperate-Broadleaved Evergreen Forest (legend number 6) in BIOME 3 ecosystem type are stocked with long leaf pine and slash pine. Thus, we include the legend number 6 into legend number 3.

3. Steady State Ecological Change

| | Temperate-Boreal Mixed Forest | Temperate Deciduous Forest |
|---|---|---|
| Total Land (Base, $km^2$) | 667236 | 802195 |
| Total Land (Hamburg, $km^2$) | 959549 | 509882 |
| NPP(Base, $g/m^2/yr$) | 1020 | 775.2 |
| NPP(Hamburg, $g/m^2/yr$) | 1327 | 1027 |
| Dieback($km^2$) | 0 | 292313 |
| Regeneration($km^2$) | 292313 | 0 |
| Dieback ratio | 0 | 0.36 |
| Regeneration Ratio | 1.438 | 0.64 |
| NPP Change Ratio | 1.30 | 1.33 |

## Region II: The Pacific Northwest

### The Pacific Northwest (West)

1. Geographical Location of Region

Longitude: 125W to 122W
Latitude: 49N to 37.5N

2. Classification of Region by Forest Type

Douglas fir

- Douglas fir is classified as Coniferous. But land areas where Douglas fir is stocked in West of Pacific North West are associated with Temperate Deciduous (legend number 5) in BIOME 3 ecosystem type.
- This region is highly conserved to protect biodiversities living in this region such as the spotted owl, etc.

3. Steady State Ecological Change

| | Temperate Deciduous Forest |
|---|---|
| Total Land (Base, $km^2$) | 49383 |
| Total Land (Hamburg, $km^2$) | 80912 |
| NPP(Base, $g/m^2/yr$) | 538.9 |
| NPP(Hamburg, $g/m^2/yr$) | 808.8 |
| Dieback($km^2$) | 16964 |
| Regeneration($km^2$) | 48493 |
| Dieback ratio | 0.34 |
| Regeneration Ratio | 1.64 |
| NPP Change Ratio | 1.50 |

**The Pacific Northwest (East)**

1. Geographical Location of Region

Longitude: 122W to 108W
Latitude: 49N to 42N

2. Classification of Region by Forest Type

Ponderosa pine

- Ponderosa pine is associated with Temperate Conifer Forest (legend number 4) in BIOME 3 ecosystem type

- In 49N to 46N, larch is distributed with Ponderosa pine. When we consider inventory stock of this region and the yield function in Sedjo and Lyon (1990), larch could be considered as Temperate Conifer Forest (legend number 4) even if larch is denoted as Boreal Coniferous (legend number 2) in BIOME 3 ecosystem type.

- In 45.5N to 42N, lodge pole is stocked in the high altitude Rocky Mountains area, but in this subregion, lodge pole is extensively conserved; hence it is not harvested for commercial use.

3. Steady State Ecological Change

| | Temperate Conifer Forest |
|---|---|
| Total Land (Base, $km^2$) | 467474 |
| Total Land (Hamburg, $km^2$) | 445769 |
| NPP(Base, $g/m^2/yr$ ) | 343,1 |
| NPP(Hamburg, $g/m^2/yr$) | 464.05 |
| Dieback($km^2$) | 134302 |
| Regeneration($km^2$) | 112597 |
| Dieback ratio | 0.29 |
| Regeneration Ratio | 0.95 |
| NPP Change Ratio | 1.35 |

## Region III: Nordic Europe

1. Geographical Location of region

Longitude: 5E to 30E
Latitude: 70N to 57N

We divide Nordic region into two subregions such that warmer region is the "South" and cooler region is the "North".

2. Classification of Region by Forest Type

- North: Coniferous

  Coniferous is associated with Boreal Coniferous (legend number 2) in BIOME 3 ecosystem type

- South: Coniferous and Mixed

  Coniferous is associated with Boreal Coniferous Forest (legend number 2) and Temperate Conifer Forest (legend number 4) in BIOME 3 ecosystem type,and Mixed wood is associated with Temperate-Boreal Mixed Forest (legend number 3) in BIOME 3 ecosystem type.

3. Steady State Ecological Change

**North**

| | Boreal Coniferous Forest |
|---|---|
| Total Land (Base, $km^2$) | 369155 |
| Total Land (Hamburg, $km^2$) | 416847 |
| NPP(Base, $g/m^2/yr$ ) | 148.3 |
| NPP(Hamburg, $g/m^2/yr$) | 215.1 |
| Dieback($km^2$) | 3484 |
| Regeneration($km^2$) | 47694 |
| Dieback ratio | 0.01 |
| Regeneration Ratio | 1.13 |
| NPP Change Ratio | 1.45 |

**South**

| | Boreal Coniferous Forest | Temperate-Boreal Mixed Forest | Temperate Conifer Forest |
|---|---|---|---|
| Total Land (Base, $km^2$) | 398202 | 66261 | 67258 |
| Total Land (Hamburg, $km^2$) | 200243 | 174202 | 141516 |
| NPP(Base, $g/m^2/yr$ ) | 220.4 | 327.7 | 254.7 |
| NPP(Hamburg, $g/m^2/yr$) | 269.5 | 368.1 | 311.2 |
| Dieback($km^2$) | 209337 | 53946 | 43791 |
| Regeneration($km^2$) | 11378 | 161887 | 118049 |
| Dieback ratio | 0.53 | 0.81 | 0.65 |
| Regeneration Ratio | 0.50 | 2.63 | 2.10 |
| NPP Change Ratio | 1.22 | 1.12 | 1.22 |

## Region IV: Western Canada

1. Geographical Location of Region

Longitude: 135W to 119W
Latitude: 60N to 49N

2. Classification of Region by Forest Type

Softwood

- Softwood is associated with Boreal Coniferous Forest (legend number 2) in BIOME 3 ecosystem type

5. Steady State Ecological Change

| | Boreal Coniferous Forest |
|---|---|
| Total Land (Base, $km^2$) | 805791 |
| Total Land (Hamburg, $km^2$) | 702783 |
| NPP(Base, $g/m^2/yr$ ) | 241.75 |
| NPP(Hamburg, $g/m^2/yr$) | 294.55 |
| Dieback($km^2$) | 283218 |
| Regeneration($km^2$) | 180210 |
| Dieback ratio | 0.35 |
| Regeneration Ratio | 0.87 |
| NPP Change Ratio | 1.22 |

## Region V: Eastern Canada

### Boreal/Acadia Area

1. Geographical Location of Region

### Boreal Area

Longitude: 96W to 60W
Latitude: 60N to 50N

### Acadia Area

Longitude: 68W to 52W
Latitude: 50N to 44N

2. Classification of Region by Forest Type

Softwood

- Softwood is associated with Boreal Coniferous Forest (legend number 2) in BIOME 3 ecosystem type

3. Steady State Ecological Change

| | Boreal Coniferous Forest | Temperate-Boreal Mixed Forest |
|---|---|---|
| Total Land (Base, $km^2$) | 1419175 | 105837 |
| Total Land (Hamburg, $km^2$) | 977576 | 742633 |
| NPP(Base, $g/m^2/yr$ ) | 230.4 | 387.2 |
| NPP(Hamburg, $g/m^2/yr$) | 234.7 | 440.5 |
| Dieback($km^2$) | 721594 | 47811 |
| Regeneration($km^2$) | 279995 | 683977 |
| Dieback ratio | 0.51 | 0.45 |
| Regeneration Ratio | 0.69 | 7.02 |
| NPP Change Ratio | 1.02 | 1.38 |

**Lake Area**

1. Geographical Location of Region

Longitude: 85W to 68W
Latitude: 49N to 45N

2. Classification of Region by Forest Type

Hardwood

- Hardwood is associated with Temperate-Boreal Mixed Forest (legend number 3) in BIOME 3 ecosystem type

3. Steady State Ecological Change

| | Temperate-Boreal Mixed Forest |
|---|---|
| Total Land (Base, $km^2$) | 179931 |
| Total Land (Hamburg, $km^2$) | 311634 |
| NPP(Base, $g/m^2/yr$) | 395.4 |
| NPP(Hamburg, $g/m^2/yr$) | 521.5 |
| Dieback($km^2$) | 58073 |
| Regeneration($km^2$) | 189776 |
| Dieback ratio | 0.32 |
| Regeneration Ratio | 1.73 |
| NPP Change Ratio | 1.32 |

## Region VI: European USSR

1. Geographical Location of Region

Longitude: 30E to 60E
Latitude: 70N to 50N

2. Classification of Region by Forest Type

European USSR is subdivided into four land classes associated with BIOME 3 ecosystem types such as Boreal Coniferous Forest (legend number 2), Temperate conifer Forest (legend number 4), Temperate-Boreal Mixed Forest (legend number 3), and Temperate Deciduous Forest (legend number 5).

3. Steady State Ecological Change

| | Boreal Coniferous Forest | Temperate Conifer Forest | Temperate-Boreal Mixed Forest | Temperate Deciduous Forest |
|---|---|---|---|---|
| Total Land (Base, $km^2$) | 1260884 | 1557 | 845599 | 152540 |
| Total Land (Hamburg, $km^2$) | 849073 | 155508 | 1168141 | 310830 |
| NPP(Base, $g/m^2/yr$ ) | 180.6 | 255 | 309 | 389.9 |
| NPP(Hamburg, $g/m^2/yr$) | 211.2 | 353.4 | 371.7 | 504.5 |
| Dieback($km^2$) | 452909 | 1557 | 95152 | 57642 |
| Regeneration($km^2$) | 41098 | 155508 | 417694 | 215932 |
| Dieback ratio | 0.36 | 1 | 0.11 | 0.38 |
| Regeneration Ratio | 0.67 | 99.88 | 1.38 | 2.04 |
| NPP Change Ratio | 1.17 | 1.39 | 1.20 | 1.29 |

## Region VII: West Siberia

1. Geographical Location of region

Longitude: 60E to 85E
Latitude: 70N to 50N

2. Classification of Region by Forest Type

West Siberia is subdivided into two land classes such that one land class is stocked with Coniferous and the other land class is stocked with Softwood Deciduous.

- Coniferous is associated with Boreal Coniferous Forest (legend number 2) and Temperate Conifer Forest (legend number 4) in BIOME 3 ecosystem types.
- Softwood Deciduous is associated with Temperate-Boreal Mixed Forest (legend number 3) and Temperate Deciduous Forest (legend number 5) in BIOME 3 ecosystem types.

3. Steady State Ecological Change

| | Boreal Coniferous Forest | Temperate-Boreal Mixed Forest |
|---|---|---|
| Total Land (Base, $km^2$) | 1196950 | 354155 |
| Total Land (Hamburg, $km^2$) | 1168435 | 604544 |
| NPP(Base, $g/m^2/yr$) | 144.6 | 279.2 |
| NPP(Hamburg, $g/m^2/yr$) | 185.7 | 374.3 |
| Dieback($km^2$) | 185775 | 0 |
| Regeneration($km^2$) | 157260 | 250389 |
| Dieback ratio | 0.16 | 0 |
| Regeneration Ratio | 0.98 | 1.71 |
| NPP Change Ratio | 1.28 | 1.34 |

## Region VIII: East Siberia

1. Geographical Location of Region

Longitude: 85E to 160E
Latitude: 70N to 50N

2. Classification of Region by Forest Type

East Siberia is subdivided into two land classes such that one land class is stocked with Coniferous and the other land class is stocked with Softwood Deciduous.

- Coniferous is associated with Boreal Deciduous Forest (legend number 1) and Boreal Coniferous Forest (legend number 2) in BIOME 3 ecosystem type. For Coniferous, we included Boreal Deciduous Forest (legend number 1) in Boreal Coniferous Forest (legend number 2). Maps showing vegetation zone in East Siberia (e.g., Backman &Waggener 1991 and Haden-Guest et al.1956) indicate that most of region associated with Boreal Deciduous Forest in BIOME 3 ecosystem type is stocked with Boreal Coniferous Forest (legend number 2).

- Softwood Deciduous is associated with Temperate-Boreal Mixed Forest (legend number 3) in BIOME 3 ecosystem type.

3. Steady State Ecological Change

| | Boreal Coniferous Forest | Temperate-Boreal Mixed Forest |
|---|---|---|
| Total Land (Base, $km^2$) | 6914968 | 99915 |
| Total Land (Hamburg, $km^2$) | 6416182 | 918047 |
| NPP(Base, $g/m^2/yr$ ) | 120.7 | 282.2 |
| NPP(Hamburg, $g/m^2/yr$) | 189.3 | 318.7 |
| Dieback($km^2$) | 1033258 | 5950 |
| Regeneration($km^2$) | 534472 | 824082 |
| Dieback ratio | 0.15 | 0.06 |
| Regeneration Ratio | 0.93 | 9.19 |
| NPP Change Ratio | 1.57 | 1.13 |

## Region IX: Asia Pacific

1.Geographical Location of Region

**Indonesia and Malaysia**

Longitude: 95 E to 120 E
Latitude: 10 N to 5 S

**Phillipines**

Longitude: 120 E to 128 E
Latitude: 20 N to 5 N

2. Classification of Region by Forest Type

Tropical Hardwood

- Tropical Hardwood is associated with Tropical Rain Forest (legend number 8) and Tropical Seasonal Forest (legend number 7) in BIOME 3 ecosystem type. According to BIOME 3 ecosystem type, Tropical Rain Forest and Tropical Seasonal Forest has the same plant functional type. If monthly average available soil moisture is higher than 50 %, Tropical Rain Forest is mapped and if not, Tropical Seasonal Forest is mapped. Thus, we can include Tropical Seasonal Forest into Tropical Rain Forest.

3. Steady State Ecological Change

| | Tropical Rain Forest |
|---|---|
| Total Land (Base, $km^2$) | 1264121 |
| Total Land (Hamburg, $km^2$) | 1254899 |
| NPP(Base, $g/m^2/yr$) | 971.5 |
| NPP(Hamburg, $g/m^2/yr$) | 1363.5 |
| Dieback($km^2$) | 144919 |
| Regeneration($km^2$) | 135697 |
| Dieback ratio | 0.11 |
| Regeneration Ratio | 0.99 |
| NPP Change Ratio | 1.40 |

# VITA

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## EDUCATION

Ph.D. Economics, Major Professor: Kenneth S. Lyon, Utah State University, 2000.

Dissertation Title: *A Dynamic Analysis of the Global Timber Market and Carbon Flux of Forest Under Global Warming: An Integrated Modeling Approach.*

M.A. Economics, State University of New York at Binghamton, 1986.

B.A. Economics, Pusan National University, Pusan, Korea, 1982.

## EXPERIENCE

*Research Assistant*

Research Assistant, Department of Economics, State University of New York, Binghamton, New York (08/1983-05/1986).

Research Assistant, Department of Economics, Utah State University, Logan, Utah (06/1997-10/2000).

*Lecturer*

Lecturer, Department of Tade and Department of Management, InJe University, Kimhae, Korea (03/1987-06/1988).

Taught Principle of Economics, Statistics, Mathematical Economics, Econometrics.

Lecturer, Department of Trade, Pusan National Fishery College, Pusan, Korea (03/1988-06/1988).

Taught International Movement of Capital.

## AWARD

Seely-Hinckley Fellowship, Seely-Hinckley Fellowship Foundation, Logan, Utah (1998).

## CAREERS IN THE GOVERNMENT & NATIONAL ASSEMBLY

Chief Advisor of National Assembly Man, Korean National Assembly, Seoul, Korea (09/1988-03/1990, 05/1991-04/1996).

Chief Secretary of Minister, Ministry of Health and Social Affairs in Korean Central Government, Kwacheon, Korea (03/1990-04/1991).

Member of Korean Government Representatives, 41th Annual International Conference, World Health Organization, Geneva, Switzerland (05/1990).