IMPACTS OF CLIMATE CHANGE ON THE GLOBAL FOREST SECTOR

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Abstract. The path and magnitude of future anthropogenic emissions of carbon dioxide will likely influence changes in climate that may impact the global forest sector. These responses in the global forest sector may have implications for international efforts to stabilize the atmospheric concentration of carbon dioxide. This study takes a step toward including the role of global forest sector in integrated assessments of the global carbon cycle by linking global models of climate dynamics, ecosystem processes and forest economics to assess the potential responses of the global forest sector to different levels of greenhouse gas emissions. We utilize three climate scenarios and two economic scenarios to represent a range of greenhouse gas emissions and economic behavior. At the end of the analysis period (2040), the potential responses in regional forest growing stock simulated by the global ecosystem model range from decreases and increases for the low emissions climate scenario to increases in all regions for the high emissions climate scenario. The changes in vegetation are used to adjust timber supply in the softwood and hardwood sectors of the economic model. In general, the global changes in welfare are positive, but small across all scenarios. At the regional level, the changes in welfare can be large and either negative or positive. Markets and trade in forest products play important roles in whether a region realizes any gains associated with climate change. In general, regions with the lowest wood fiber production cost are able to expand harvests. Trade in forest products leads to lower prices elsewhere. The low-cost regions expand market shares and force higher-cost regions to decrease their harvests. Trade produces different economic gains and losses across the globe even though, globally, economic welfare increases. The results of this study indicate that assumptions within alternative climate scenarios and about trade in forest products are important factors that strongly influence the effects of climate change on the global forest sector.

1. Introduction

The path and magnitude of future anthropogenic emissions of carbon dioxide and other greenhouse gases will be influenced by growth in populations, economies, and technology development, as well as policies to control or reduce fossil fuel emissions (Wigley et al., 1996). The time path of atmospheric carbon dioxide will likely influence changes in climate (IPCC, 1995). Future changes in climate and atmospheric carbon dioxide are likely to affect the productivity of forests

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(Kirschbaum et al., 1996; Mooney et al., 1999; Joyce et al., 2001) and the forest sector (Brown et al., 1996; Solomon et al., 1996). A number of modeling studies have applied equilibrium ecological responses from the doubled carbon dioxide (CO_2) equilibrium climate scenarios to transient forest sector models (Callaway et al., 1994; Joyce et al., 1995; Sohngen et al., 1998; Sohngen and Mendelsohn, 1998; Perez-Garcia et al., 1997; McCarl et al., 2000). These studies have shown that changes in atmospheric CO_2 and climate influence the production, consumption and international trade in timber products through effects on the growth of timber growing stocks. The forest sector responses to these growth effects were also shown to further influence timber stocks through the harvest response. In these studies the climate was assumed to be in equilibrium with the doubled atmospheric concentration of CO_2 and the ecological response was assumed to be in equilibrium with the altered climate. The ecological response was also assumed to be increasing at a constant rate over the time period needed to reach the doubled atmospheric concentration of carbon dioxide. A recent study by Irland et al. (2001) examined the nature of transient climate scenarios on the U.S. forest sector using the dynamic forest sector model, Forest and Agricultural Sector Optimization Model (FASOM). Unfortunately, the above studies did not consider the uncertainties in the transient nature of changing carbon dioxide concentrations and climate on the global forests or the global forest sector.

The global extent of forests changes over time with human use, natural succession and natural disturbances such as fire and disease outbreaks. Currently, forests cover approximately 30% of the land surface, 4.1 billion hectares. Of this area, about 11% is managed for goods and services with the extent of management varying by regions across the globe (Brown et al., 1996, using Food and Agricultural Organization (FAO) data). Consumption of industrial roundwood totaled 1.5 billion cubic meters in 1997 with an approximate value of $150 billion (FAO, 1999). Forest product values are several times larger as lumber, structural panels, engineered wood products, and pulp all utilize this industrial raw material in their manufacturing process. International trade in timber products is approximately $80 billion per year, which comprises about 3% of the world's trade (Laarman and Sedjo, 1992, using FAO data). Globally, conifer species comprise nearly 70% of the world's timber harvest for industrial products (Brooks, 1993). In developing countries, the harvest is predominately nonconiferous species and the use is primarily fuelwood. Analyses of the carbon stored in extant forests indicate that forests currently offset significant amounts of fossil fuel emissions in individual countries (Brown et al., 1996). Interactions between climate change and the world's forest sector have the potential to influence carbon storage of the world's forests (Sedjo et al., 1997). This may have important implications for international efforts to control the concentration of atmospheric CO_2. Thus, it is important to assess how transient changes in atmospheric carbon dioxide and climate may influence the world's forest sector and timber trade into the future.

A previous analysis (Perez-Garcia et al., 1997) on the potential economic impacts of climatic change on the global forest sector was based on equilibrium responses of climate to a doubling of the atmospheric CO_2 as simulated by general circulation models (GCMs). These GCM simulations from the 1980s did not consider the effects of atmosphere-ocean coupling or the effects of atmospheric aerosols. The ecological responses in the analysis were based on equilibrium responses of a terrestrial biogeochemical model that used the climatic scenarios to simulate spatially explicit changes in net primary production (NPP) of global forests at 0.5° resolution (latitude by longitude). The equilibrium responses of NPP were used to define a constant rate of change in growing stock between 1990 and 2040. These changes were used to simulate economic responses of the global forest sector using an economic baseline constructed prior to the recent Asian recession and the fall in consumption and production from the former Soviet republics.

State-of-the-art scenarios of projected climate are currently based on simulations that consider how the time-dependent response of climate is influenced by the effects of the coupling between the atmosphere and ocean and by the effects of atmospheric aerosols (Mitchell et al., 1995). Similar advances have been made with respect to ecological responses. For example, state-of-the-art responses of large-scale carbon dynamics are based on the time-dependent simulations of terrestrial biogeochemical models that are driven by transient changes in climate and atmospheric CO_2 (Kindermann et al., 1996; Xiao et al., 1998; Tian et al., 1998, 1999, 2000; McGuire et al., 2000, 2001; Schimel et al., 2000). These advances in the simulation of climate and carbon dynamics provide the opportunity to simultaneously assess how both climate and terrestrial carbon dynamics may respond to different levels of greenhouse gas emissions (Xiao et al., 1998). In this study, we evaluate the potential economic responses of the global forest sector to different scenarios of climate change produced from alternative levels of greenhouse gas emissions. The economic baseline in the analysis considers the recent collapse of the Asian economy, the fall in production and consumption of wood products in Russia, and their influence on the global forest sector.

2. Methods

2.1. APPROACH

In this study we conducted a set of simulations that represent the first step towards integrating global ecological and economic models to simulate alternative futures of the responses of the forest sector behavior to projected climate change. Our approach is to drive a global ecological model with different climate change scenarios derived, in part, from a global economic model of greenhouse gas emissions, and to use the outputs of the ecological model as inputs to a global model of the forest economies. Time-dependent changes of CO_2 emissions, ocean heat diffusion and aerosol effects are used as inputs to the Terrestrial Ecosystem Model (TEM; see Xiao et al., 1998) for simulating the physiological responses of vegetation carbon to projected climate change. The changes in vegetation carbon simulated by TEM are then used to modify timber supply in the CINTRAFOR Global Trade Model (CGTM; see Cardellichio et al., 1989) for forest products to simulate economic changes in timber supply and the subsequent economic behavior of the forest sector. While our approach in this study does not attempt to achieve full integration or consistency in assumptions among the models, it allows us to explore the types of regional responses in the forest sector that might emerge and provides us with insights for taking the next steps towards achieving more comprehensive integration.

2.2. MODELS USED IN THE ANALYSIS

2.2.1. *The Terrestrial Ecosystem Model*

The TEM is a process-based ecosystem model that makes monthly estimates of important carbon and nitrogen fluxes and pools for terrestrial ecosystems across the globe (Raich et al., 1991; Melillo et al., 1993; McGuire et al., 1992, 1993, 1995, 1997, 2000, 2001; Xiao et al., 1997, 1998). In this study, we used version 4.1 of TEM (Tian et al., 1999), which simulates the time-dependent response of carbon pools in response to time-dependent inputs of climate and atmospheric CO_2 (Melillo et al., 1996; Prinn et al., 1999; Tian et al., 1998, 1999, 2000; McGuire et al., 2000; Clein et al., 2000; Schimel et al., 2000). Regional analyses with TEM indicate that the model simulates the temporal changes in carbon dynamics associated with major regional climate events such as the Dust Bowl of the Central U.S. in the 1930s (Tian et al., 1999), the El Niño Southern Oscillation (Tian et al., 1998, 1999, 2000; McGuire et al., 2001), and the North Atlantic Oscillation (McGuire et al., 2000). We applied TEM globally to examine the vegetation carbon responses of terrestrial ecosystems to three transient scenarios of changes in atmospheric CO_2 and climate from 1990 to 2100. The three scenarios were derived from projections of the Integrated Global System Model (IGSM; see Prinn et al., 1999).

The application of TEM to a grid cell requires the use of data describing monthly climate (precipitation, mean temperature, and mean cloudiness), soil texture (proportion of sand, silt, and clay), elevation, and vegetation types (Pan et al., 1996). Soil texture and vegetation types are used to define the soil- and vegetation-specific parameters for a grid cell. For extrapolating TEM globally, we used spatially explicit data sets organized at a spatial resolution of 0.5° longitude by 0.5° latitude. The natural vegetation classification has 18 upland vegetation types and 13 floodplain and wetland vegetation types (Melillo et al., 1993). The processing of climate data from the IGSM projections for deriving the inputs required by TEM are described by Xiao et al. (1998).

2.2.2. *The CINTRAFOR Global Trade Model*

The CGTM simulates harvests and prices in log and product markets by calculating economic welfare produced by alternative assumptions of forest growth (Kallio et al., 1987; Cardellichio et al., 1989). In a previous study, we used the CGTM to simulate how the effects of equilibrium changes in climate on forest growth influence the global forest sector (Perez-Garcia et al., 1997). In the present study, the CGTM adjusts regional timber supply equations by using the time-dependent changes in vegetation carbon stocks simulated by TEM that are associated with alternative assumptions on carbon dioxide emissions, ocean heat diffusion and aerosol effects. The model then computes the spatial equilibrium of the global forest economy by maximizing economic welfare subject to processing capital and timber growing stock constraints.

CGTM computes market equilibria for all regional forest products markets considering constraints on processing capacity and available wood resources to describe the behavior of the global forest sector. The dynamic structure of the model does not imply inter-temporal market equilibrium because the CGTM does not compute the market solution for all periods simultaneously. Instead, the model captures regional details using 43 log-producing and 33 product-consuming regions year to year adjusting forest products demand, forest inventory and production capacity based on demand end-use factor sub-models, timber supply sub-models of forest management and historical profitability respectively. The specification of the economic model allows us to describe the effects of alternative climatic futures on forest growth, timber supply, processing capacity, consumption of various forest products, and trade in these forest products.

2.3. EXPERIMENTAL DESIGN AND SIMULATION PROTOCOL

To assess the sensitivity of the forest sector to changes in forest growth associated with changes in climate, we used a series of transient climate scenarios and economic scenarios. We create an economic baseline and then impose one of two economic scenarios with one of three transient climate scenarios. We report changes as measured from the economic baseline. The three transient climate scenarios integrate different assumptions about future CO_2 emissions, atmosphere-ocean thermal interactions and aerosol effects as described below. The economic scenarios place boundaries on behavioral assumptions of non-market mechanisms employed in the forest sectors of centrally-planned or otherwise non-market economies.

The three transient climate change scenarios from the IGSM sensitivity study (Prinn et al., 1999) describe possible future climates for the period of 1977 to 2100 using a range of uncertainty in parameters that lead to low and high levels of greenhouse gas emissions under the assumption that no emission control policies are implemented. The projections of anthropogenic emissions of greenhouses gases as derived from the EPPA (Emissions Production and Policy Analysis) model (Yang et al., 1996) were used as input to the combined atmospheric chemistry/climate model for simulating seven transient scenarios of climate change (Prinn et al., 1999). Xiao et al. (1998) used 3 of these scenarios: RRR, HHL, and LLH. Using the standard or 'reference' set of parameters and assumptions in the IGSM generates the RRR scenario. Emissions in the RRR scenario are similar to the IS92a scenarios of the Intergovernmental Panel on Climate Change (IPCC; IPCC, 1995). The HHL scenario is based on higher CO_2 emissions from the EPPA model, slower diffusion of heat into the ocean, smaller effects of cooling associated with atmospheric aerosols, and smaller heating effects associated with the radiative forcing of doubling CO_2. In comparison to the RRR scenario, the HHL scenario leads to larger changes in temperature. In contrast, the LLH scenario is based on lower CO_2 emissions from the EPPA model, faster diffusion of heat into the ocean, larger effects of cooling associated with atmospheric aerosol, and the largest heating effects associated with the radiative forcing of increasing CO_2. In comparison with the RRR scenario, the LLH scenario leads to a smaller change in temperature. Atmospheric CO_2 concentration is 354 ppmv in 1990 and is projected to reach about 745 ppmv in the RRR, 936 ppmv in the HHL, and 592 ppmv in the LLH scenario in 2100. Compared to its value in 1990, global annual mean temperature in 2100 increases by about 2.6 °C for the RRR, 3.1 °C for the HHL, and 1.6 °C for the LLH scenario. Global daily precipitation increases slightly over time for all three scenarios. Global mean annual cloudiness decreases in the RRR and the LLH scenarios but increases in the HHL scenarios.

The transient TEM runs are initiated using non-equilibrium conditions of carbon, nitrogen, and water fluxes and storage in December 1976. The conditions were derived from a TEM simulation driven by the simulated climate data from the 2-D land-ocean climate and global mean atmospheric CO_2 concentration data from ice cores and direct observations over the period of 1850–1976. Because the application of TEM in this study simulates the dynamics of potential mature natural vegetation, the response of vegetation carbon to climate change in mature forests is applied to all age classes in CGTM.

To use the changes in vegetation carbon simulated by TEM for the three scenarios, we aggregated the TEM results by the timber types considered in the CGTM. The forest ecosystem types in TEM were converted to the two timber types of the CGTM (softwood and hardwood) in a manner similar to Perez-Garcia et al. (1997). For several regions plantations that have been introduced and comprise the majority of industrial wood supply do not conform to natural forest types. In these situations we used the simulated changes in carbon vegetation in the appropriate forest types available for the region as the most plausible response for the region. For example, in the southeastern U.S. we used changes in the carbon vegetation for the mixed vegetation type to estimate changes in timber growing stock for softwood plantations.

After identifying the timber type associated with each forest grid considered by TEM, we calculated the proportional annual change in timber growing stock (dI_{Pt}) associated with changes in CO_2 and climate for each grid cell as:

$$dI_{Pt} = (C_{Vt} - C_{Vt-1})/C_{Vt-1} ,$$

where t is the year and C_V is vegetation carbon calculated at the end of December of the year. We averaged dI_{Pt} across all grid cells of a timber type within a timber supply region to determine the mean proportional change in timber growing stock for the region. This index was used to adjust the regional timber supply functions in CGTM from 1985 to 2040, which is the timeframe considered in this analysis.

We explore the economic variability by using two sets of assumptions about harvest behavior similar to our previous work (Perez-Garcia et al., 1997). The first assumption relates to forests in regions at the intensive economic margin. Forests in these regions are characterized by timber producers that are responsive to market prices, i.e., their behavior is characterized by an upward sloping supply curve. Under the intensive margin scenario, we constrain harvests to the economic baseline in all regions where harvesting behavior is not responsive to prices. Examples of non-responsiveness to price behavior include the former Soviet Union and Eastern Europe where large extensive areas of forests exist but political and infrastructure constraints prevent them from expanding harvests even in the presence of higher prices. The second economic scenario relaxes these constraints on extensive margin regions. This scenario assumes that changes in forest productivity lead to changes in harvests in regions that are not sensitive to price. It includes all supply responses from the intensive economic margin scenario as well as shifts in timber supply associated with changes in forest growth in all other regions.

An economic baseline is used to measure the changes in economic variables due to alternative scenarios of climate change and economic behavior. It is an outlook of market conditions under a business-as-usual assumption into the future. The baseline used by the model is modified from Perez-Garcia et al. (1997) by reducing the production and consumption of the former Soviet republics to levels observed from 1993 to 1998 (FAO, 1999) and reducing the growth in demand for wood products in Asian countries in 1997 and 1998. The demand growth for wood products in Asian countries resumes in 2000 with positive GDP growth under the economic baseline until 2040 (Perez-Garcia et al., 1999).

Our analysis first focuses on the changes in vegetation carbon simulated by TEM under the different scenarios of climate change. We then describe the regional changes in softwood and hardwood growing stock tracked by the CGTM under the different climate scenarios. Next, we examine the aggregated economic responses of the major forest sectors in terms of price, harvest and economic welfare changes measured from the economic baseline. Finally, we separately analyze the regional responses of price, harvest, and economic welfare to identify important interactions among climate scenarios, economic assumptions, and global trade in forest products issues.

3. Results

The regional changes in vegetation carbon at 2040, relative to 1985, show the largest response to the HHL scenario (Figure 1), then the RRR (Figure 2), and finally the LLH (Figure 3). The regional change is greatest between the LLH and RRR scenario, whereas the vegetation carbon changes within a region are more often similar between the RRR and the HHL scenarios.

While TEM responses of vegetation carbon vary from less than 2% to greater than 20% over the entire projection period under the three climate scenarios, only under the HHL scenarios do we observe major changes. The changes in vegetation carbon occur mainly in the northern hemisphere, with the larger responses in west-coast regions.

Based on vegetative carbon changes simulated by TEM, the changes in growing stock in the softwood and hardwood sectors simulated by the trade model differ under the three climate scenarios and vary by region and over time. Figure 4 depicts the upper and lower bound of regional responses as percent changes for the study period for softwoods and hardwoods for the three climate change scenarios. While these bounds are depicted as smooth lines, regional transient changes are quite variable year to year. For some regions the time path is not monotonic, decreasing in the early stage of the study period, then increasing. This is particularly true for the LLH climate in softwood and hardwood sectors. This transient response is in contrast to earlier assumptions of a constant percentage growth rate over time (Perez-Garcia et al., 1997).

Globally and under all scenarios, higher growth leads to larger timber growing stocks that lower log prices, increase consumption and improve total economic welfare. Table I presents the aggregate price, harvest and welfare changes observed for the major forest sector regions by 2040. These major forest sector regions include the U.S., Canada, Chile, New Zealand, western continental Europe, Finland, Sweden and Japan. Other regions, such as Russia, are explicitly included under the alternative economic scenarios of intensive versus extensive margins since the difference in economic scenarios is based on the harvesting behavior of regions such as Russia, China and eastern Europe. The price changes are smallest under the LLH scenarios where the potential growing stock response is lowest. The decline in prices is accentuated under the extensive margin scenario as harvests from other regions expand. The results reported in Table I include both softwood and hardwood responses from these sectors.

Total economic welfare, defined as the sum of economic welfare to the timber producer, log processor and product consumer, increases under all climate and economic scenarios by 2040. Economic welfare for the globe increases when productivity adds to timber availability. As we relax our assumption on economic behavior in those markets at the extensive margin, more wood enters the forest products sector lowering prices. The effect continues to raise global welfare over the baseline case. The effects are similar for all three climate scenarios. The

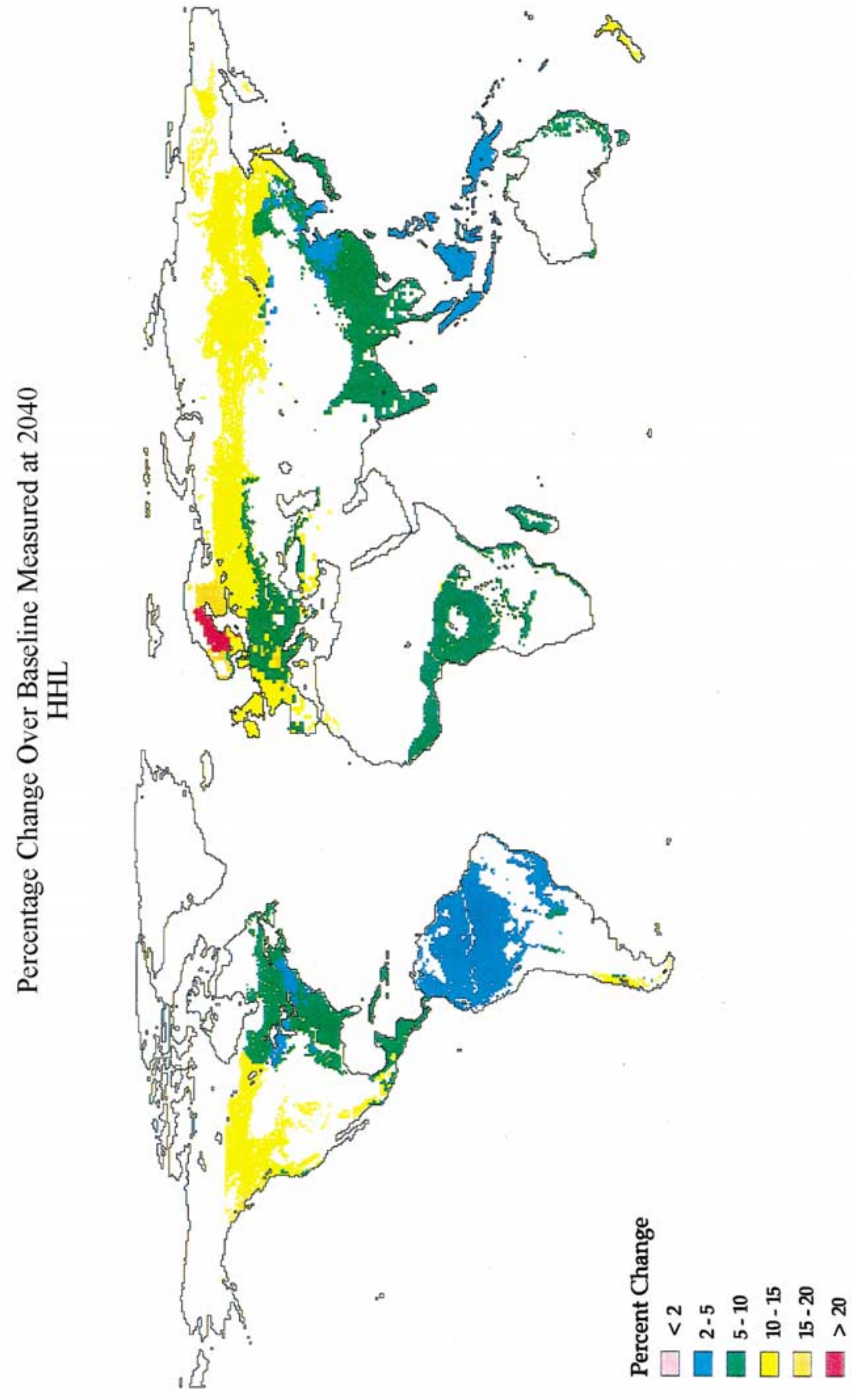

Figure 1. Percentage change in vegetation carbon at 2040 relative to 1985 under the HHL climate scenario.

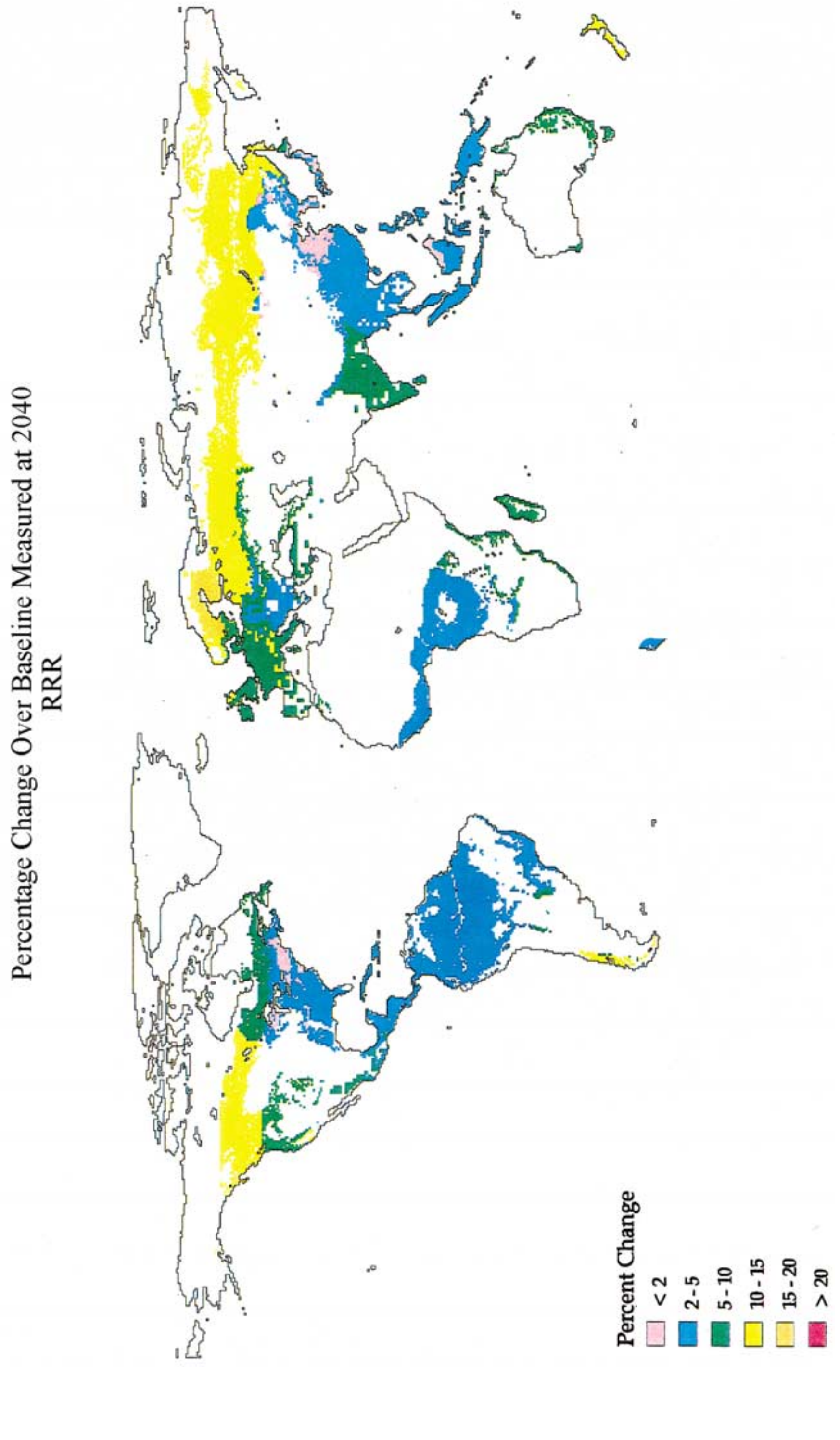

Figure 2. Percentage change in vegetation carbon at 2040 relative to 1985 under the RRR climate scenario.

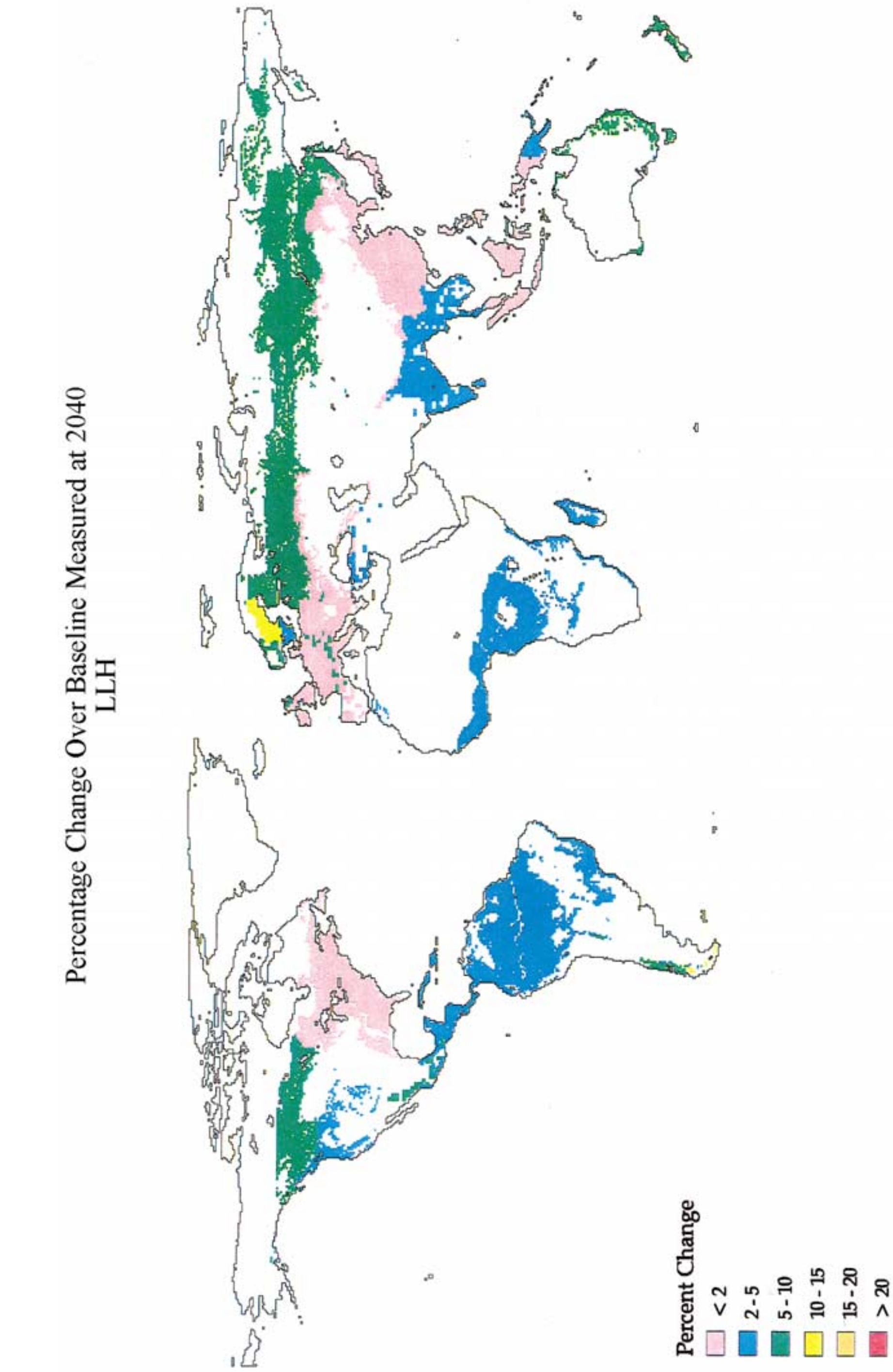

Figure 3. Percentage change in vegetation carbon at 2040 relative to 1985 under the LLH climate scenario.

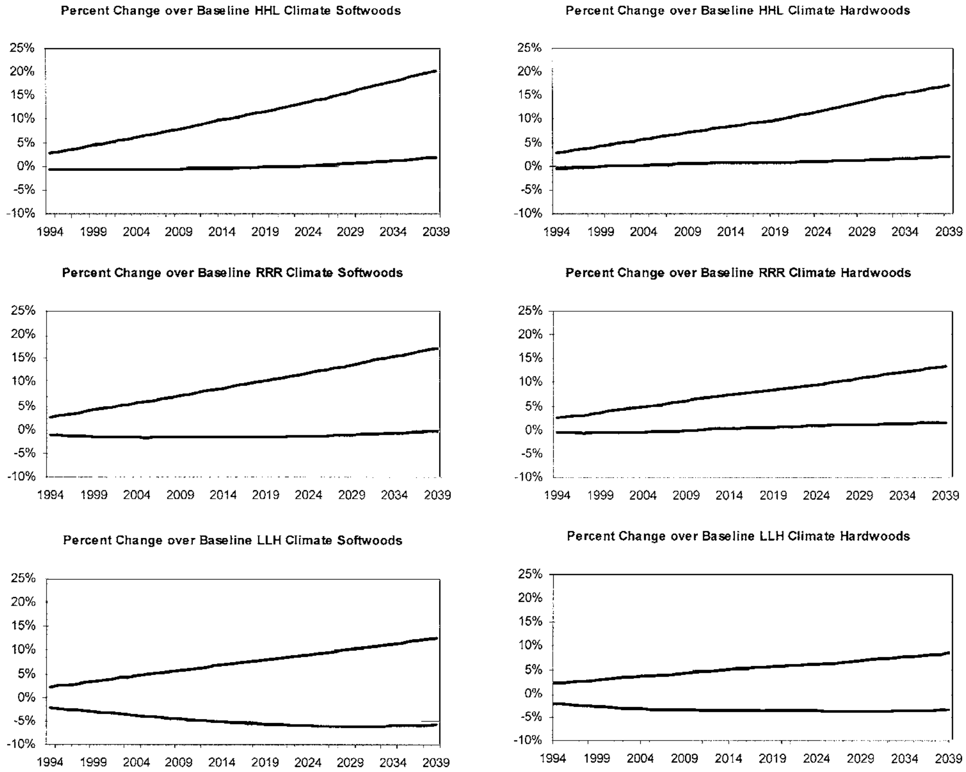

Figure 4. Upper and lower bounds for all regional percentage changes in growing stock relative to baseline growing stock levels under three climates for the softwood (a) and hardwood (b) sectors.

RRR and HHL climate scenarios produce more wood fiber than the LLH climate scenario and their effects are larger.

In all, global price and harvest changes are very small and within probable uncertainties of CGTM projections. The small change is a global aggregate and does not reflect larger variations between regions. The larger range of regional responses demonstrates the importance of trade in forest products. Price changes vary regionally from near zero to slightly over 7%. The ability of regions with lower production costs to successfully increase their harvests due to greater timber availability and trade their surplus timber and forest products produces the large regional variation in price, harvest and welfare measures. As these regions expand production and trade activity they depress prices and force other, higher production cost regions to lower their harvests. These changes in prices and harvests have significant implications for regional welfare changes. We first analyze the regional price responses, followed by harvest behavioral changes in key regions and conclude with a presentation of economic welfare changes in different regions. For the analysis of economic welfare responses, we evaluate the variability in the welfare

Table I

Summary results for selected forest sector markets (measured as changes from the economic baseline)

	Intensive margin	Extensive margin
HHL climate scenario		
Price Change	–2.91%	–3.09%
Harvest change	2.73%	2.45%
Total welfare change	0.41% ($15.0 billion)	0.44% ($15.8 billion)
RRR climate scenario		
Price change	–2.30%	–2.44%
Harvest change	2.36%	2.20%
Total welfare change	0.32% ($11.6 billion)	0.32% ($11.6 billion)
LLH climate scenario		
Price change	–0.83%	–0.86%
Harvest change	1.49%	1.49%
Total welfare change	0.11% ($3.9 billion)	0.04% ($1.8 billion)

Total welfare changes are measured as the cumulative annual net present value discounted at 5% and expressed in 1993 U.S. dollars.

responses among producers, processors, and consumers for different regions to illustrate the regional variability.

Figure 5a shows the price response for several regions in CGTM. The price response is measured as the change in price in 2040 expressed as a percent of the price observed in 2040 for the economic baseline. The percent decline in prices across scenarios is consistent with the expectation that, given demand, an increase in timber availability will produce a decline in prices as the supply function shifts outward. The exception occurs when the growth response in CGTM is lower than the economic baseline as in the LLH climate scenario. Given demand, lower growth leads to a shift inward of the timber supply function, less available timber for harvest, and higher prices. This behavior is evident in the U.S. South and U.S. North (not shown in the figure) regions for the LLH climate scenario. As a result, the price changes observed in 2040 are only slightly negative for the U.S. South by 2040.

The percentage decline in prices is greatest in the Scandinavian region, up to 7%. European prices are forecast to be under less pressure and lower than Asian and North American prices, where demand growth and resource scarcity are greatest (United Nations, 1996). Hence the decline in prices translates to a higher percentage decline relative to other regions. In Europe, the price variation in Scandinavian and west European regions associated with the economic scenarios is as large as

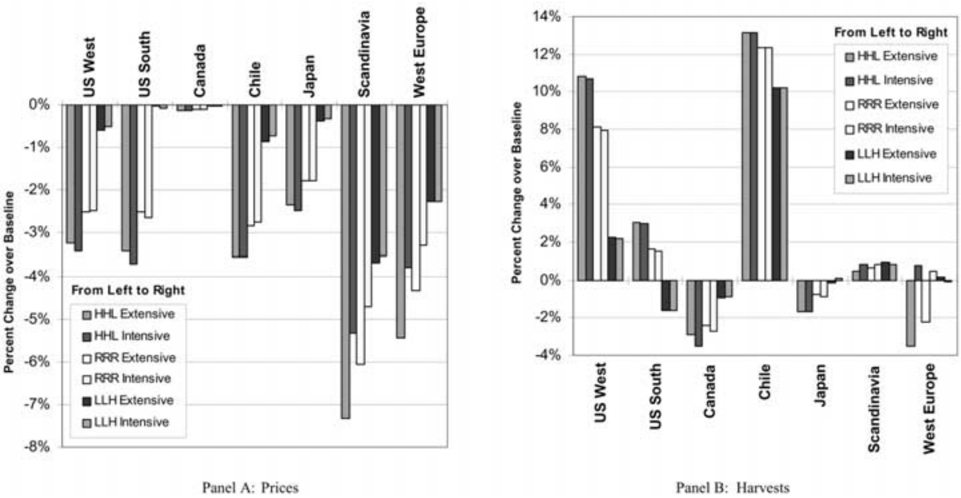

Figure 5. Average sawlog price response (a) and harvest response (b) under three climates and two economic scenarios.

the variation associated with alternative HHL and RRR climate scenarios. This result is not unexpected as harvests from east European countries and the former European republics of the Soviet Union are greater under the extensive economic margin scenario. The eastern European and former republic harvests lower prices under the HHL and RRR climate scenarios in the neighboring regions of western Europe and Scandinavia.

Figure 5b illustrates the change in harvests by 2040 expressed as a percent of the economic baseline harvests in 2040. Harvest responses vary by region. The percent increase in harvest from southern-hemisphere regions is largest under all scenarios. Chile, for example, increases its harvest from 10% to 13% by 2040 over the reference case. New Zealand, not shown on the graph, increases harvest from over 8% to nearly 12%. These two regions are projected to expand harvests significantly under the economic baseline as plantation area expanded during the last two decades. Climate changes further the expansion in timber availability significantly. Other regions also expand harvests. Among other major forest sectors, the US West region and Scandinavia (Finland and Sweden) expand harvests across all scenarios. Scandinavia, with its large potential response of growing stock, expands harvests only slightly, however. The U.S. South, Canada, Japan and western European regions reduce harvests under some of the scenarios analyzed as a result of either the climate-induced changes in growing stock or lower prices or both reasons.

Regional winners and losers define the more significant economic effects from climate change. Table II illustrates how different regions and stakeholders are affected by climate changes. The table presents the value of the cumulative annual changes from the economic baseline in welfare to 2040 discounted at 5% and presented in 1993 U.S. dollars. There are no unambiguous losers or winners across the climate change and economic scenarios. Regional responses are positive for some regions and negative for others depending on the scenario. In addition, within each region different players – timber owners, mill processors and product consumers – are affected differently. As an example, within the U.S., three sub-regions describe the range of effects from alternative views of climate change.

The U.S. North is primarily a wood products consuming region. Both timber owners and mill processors incur small losses. Consumers in the region gain substantially under the RRR and HHL climate scenarios since the region imports a large percentage of forest products they consume taking advantage of greater timber availability everywhere. The consumer gains outweigh producer losses leading to total welfare gains of $5.2 to $7.8 billion by 2040. Under the LLH climate scenarios, consumers in the North show smaller gains.

The U.S. South illustrates a different effect of climate change on the forest sector. The South is the major producer of forest products supplying wood products for its own regional needs and shipping its excess to the North and other regions. Producer welfare is lower for the timber sector under climate change with losses between $5.4 and $4.2 billion. The mill processors benefit in part since they see lower log costs, but lower product prices offset these gains resulting in slightly negative changes in the RRR and LLH scenarios.

Our third U.S. region, the West, is both an exporting region to the rest of the U.S. and Asian-Pacific markets and a major consuming region. Timber producers lose welfare under all scenarios, but less so than the U.S. South. There are small positive changes to mill processors in the West. Under the RRR and HHL climates, consumers have significant positive gains between $5.9 and $8.6 billion. However, under the LLH climate, the consumption sector shows only a small positive gain approaching $1 billion.

Canada represents a region with a dominating production sector, exporting the major part of its forest products to the U.S. and other nations. Lower prices reduce timber producer welfare in Canada. The timber producers adjust their losses by harvesting less, however, resulting in small negative changes in the timber sector. As a result the mill-processing sector has less output from lower timber harvests and lower product prices. In Canada, processors have the largest negative changes in their welfare. Under the HHL climate, these losses reach $17.5 billion. Since the consumer sector is much smaller than the producing sector in Canada, its ability to offset the losses in the milling sector is minimal. Hence total welfare losses are substantial with the exception of the LLH climate scenarios. The losses range from $9.5 to $14.3 billion in the RRR and HHL climate scenarios.

As the lowest wood fiber cost producers in the Pacific Rim markets, Chile and New Zealand represent exceptions to timber owner's welfare behavior. These countries represent regions dominated by wood raw material supplying sectors. They increase their harvests due to greater productivity and offset the loss in welfare due to lower prices. Hence, Chile's and New Zealand's timber sectors have positive gains for its timber owners in all scenarios. The variability associated with the eco-

Table II
Economic welfare changes from baseline: regional results (Million $1993 U.S.)

	Climate and economic scenario					
	LLH		RRR		HHL	
	Intensive	Extensive	Intensive	Extensive	Intensive	Extensive
Canada						
PS log	(141.31)	(150.05)	(408.32)	(403.20)	(501.90)	(469.64)
PS product	(2,079.94)	(1,826.15)	(13,015.07)	(12,153.60)	(17,417.06)	(15,905.72)
CS product	420.71	472.49	2,674.10	3,064.06	3,607.84	4,079.74
Total	(1,800.54)	(1,503.71)	(10,749.30)	(9,492.74)	(14,311.12)	(12,295.61)
Chile						
PS log	4,651.67	2,607.28	3,878.78	1,704.07	3,461.73	1,310.97
PS product	301.07	184.99	394.22	193.35	357.94	198.51
CS product	52.48	285.68	350.86	633.65	473.40	740.39
Total	5,005.23	3,077.94	4,623.86	2,531.08	4,293.07	2,249.87
West Europe						
PS log	(514.66)	(550.80)	(643.81)	(1,135.18)	(713.30)	(1,464.20)
PS product	54.94	144.22	119.89	(308.87)	151.06	(526.80)
CS product	1,097.11	1,927.21	1,701.45	5,141.96	1,996.60	6,796.51
Total	637.39	1,520.64	1,177.52	3,697.91	1,434.36	4,805.51
Finland						
PS log	(244.59)	(70.28)	(353.33)	(222.99)	(407.77)	(297.16)
PS product	99.29	69.64	113.91	(14.37)	120.89	(78.05)
CS product	52.97	163.92	75.76	289.36	87.21	358.37
Total	(92.34)	163.28	(163.65)	52.00	(199.67)	(16.84)
Japan						
PS log	(267.87)	(237.55)	(1,426.67)	(1,354.87)	(2,004.41)	(1,815.15)
PS product	93.07	47.52	324.83	366.57	409.87	545.08
CS product	415.24	188.76	2,524.34	2,303.96	3,591.51	3,102.81
Total	240.43	(1.26)	1,422.50	1,315.66	1,996.97	1,832.75
New Zealand						
PS log	2,334.25	1,197.51	1,850.93	724.93	1,511.43	419.14
PS product	174.24	151.02	333.70	175.41	317.35	167.13
CS product	30.96	6.05	293.56	251.97	394.18	334.01
Total	2,539.46	1,354.58	2,478.19	1,152.30	2,222.96	920.27
Sweden						
PS log	(146.12)	(186.46)	(240.03)	(488.95)	(288.72)	(654.34)
PS product	201.79	264.58	294.23	247.63	342.08	224.43
CS product	72.39	160.00	103.07	307.71	118.78	386.69
Total	128.06	238.11	157.27	66.39	172.14	(43.21)

Table II
(Continued)

	Climate and economic scenario					
	LLH		RRR		HHL	
	Intensive	Extensive	Intensive	Extensive	Intensive	Extensive
U.S. North						
PS log	(171.87)	(278.92)	(757.65)	(725.63)	(979.64)	(864.49)
PS product	(126.42)	(161.83)	(83.99)	(166.55)	(52.91)	(156.24)
CS product	843.87	769.84	6,474.41	6,084.48	8,826.22	8,108.75
Total	545.58	329.09	5,632.76	5,192.30	7,793.67	7,088.01
U.S. South						
PS log	(4,264.76)	(4,204.01)	(5,148.63)	(4,744.64)	(5,443.83)	(4,681.10)
PS product	(977.12)	(1,593.15)	(68.98)	(953.29)	347.10	(620.82)
CS product	929.18	1,546.86	6,937.38	7,500.80	9,449.16	9,762.38
Total	(4,312.70)	(4,250.30)	1,719.77	1,802.87	4,352.43	4,460.46
U.S. West						
PS log	(141.65)	(392.31)	(1,069.55)	(990.57)	(1,451.44)	(1,597.59)
PS product	902.79	756.45	6,354.85	5,927.72	8,623.98	7,898.11
CS product	211.26	470.02	6.84	302.72	26.87	456.77
Total	972.41	834.16	5,292.14	5,239.87	7,199.41	6,757.29

nomic assumptions is large. Timber producers under extensive economic margin assumptions produce greater amounts of wood and undermine Chile's and New Zealand's position to increase their harvests. From the table, total welfare change in Chile ranges from \$2.6 billion to \$5.0 billion depending on the economic and climate scenario. New Zealand's welfare changes are similar but smaller in scale.

In Table II western Europe, a major consumer of wood products, realizes most of its gains in welfare in the consumer sector. Negative changes occur in the timber and processing sectors. The west European region illustrates the significance of the extensive economic margin assumption, where large amount of variation occurs in consumer welfare changes under the two economic scenarios.

4. Discussion

The response of producers and consumers to climate change and the economic scenarios in this study are broadly similar to results in analyses by Sohngen and Mendelsohn (1998) and Irland et al. (2001) using dynamic optimization forestry models. In general, timber inventories rise and price declines, with the consequence that total economic welfare rises. Future price expectations optimally adjust timber investments and rotation age in the dynamic optimization models whereas timber investment is treated exogenously using the timber supply sub-model and varying assumptions on management intensities and projections of forestland area changes in the CGTM. The result suggests further work is needed to understand how perfect price foresight may influence the forest sector through alternative scenarios of climate change.

Trading patterns of a region play important roles in whether the region realizes any economic gains associated with climate change and CGTM is able to examine the influence of regional and temporal trade specifications of log and product markets. Under the intensive economic margin scenario, lower production-cost regions are able to expand harvests. Greater harvests in these areas lead to lower prices and, as a result, harvests decline in some higher production cost regions. The economic response is different for European than for the North American/Asian markets. In the higher latitudes of Europe where the growth response is higher, producers are able to expand harvests. The mill processors in these regions offset smaller revenues from lower product prices through lower wood fiber costs. As a result, the milling sector in Europe generally expands with positive changes in their welfare increasing their use of wood fiber. Combined with the gains to consumers, the European forest sectors are able to improve their total welfare through higher harvests at the expense of the timber owners.

In the North American/Asian markets, low cost plantation wood from Chile and New Zealand expands rapidly in these markets. Timber owners more than offset potential losses in revenues from lower prices by increasing harvests, and in the process, other log producers in the North American/Asia markets are pushed out. Canada and Japan minimize their losses in the timber sectors by reducing harvests, even though the percentage change in potential growing stock response in Canada is high. Although timber losses in the U.S. South region are substantial relative to other regions, they expand harvests. The milling sector is able to minimize its losses by expanding production and meeting higher demand stimulated by lower product prices. As a result sawmillers create the demand for higher harvests from southern forests. Consumer gains in the U.S. South and the North are substantial and lead to large total welfare gains for these regions.

The spatial and temporal variability of climate also influences the trade responses. The LLH climate has a greater impact on the U.S. South region, a major producer of forest products. As a result, the variability in responses observed under the LLH climate is large for the North American/Asian markets, in contrast to the European markets. The LLH scenario also produces an interesting temporal effect. Throughout most of the projection period, the potential growing stock response trend under the LLH climate is either flat or declining for key regions. This temporal trend is different than our previous analysis (Perez et al., 1997) and leads to effects that are substantially smaller by 2040. The result suggests the spatial and temporal aspects of climate change need to be considered in order to properly gauge the cumulative effects on timber growing stocks and the associated economic responses.

Our extensive economic margin assumption produces large effects in the European markets. The east European region is able to affect the market response of the western European region as well as the Scandinavian sector. In contrast, the extensive economic margin assumption has little impact on the North American market, and a large effect on Chile’s and New Zealand’s ability to harvest greater amounts of wood. The non-market economies in China and Russia affect the new southern hemisphere producers more so than the traditional North American timber owners.

In general the climate variations tend to accentuate current trends in economic behavior evident in the economic baseline. As a result, factors affecting the economic trends will tend to have a large effect on the results. This is evident in comparing the results from the present study with past work (Perez-Garcia et al., 1997). The effect of lower demand in Asia from their recent recession and a collapse of the Russian forest sector has led to price declines in three key wood fiber supplying regions of Chile, New Zealand and Scandinavia without the climate change effects. At the same time, regional shortages of timber in U.S. and Canadian Pacific Northwest region has made them higher cost wood producing regions. Climate changes reinforce these trends allowing those regions with current low costs to continue to expand market shares as climate warming increases current low-cost wood fiber availability. The result underlines the importance that current economic conditions play in determining future states of the global forest economy. They suggest a substantial amount of variation is inherent given the uncertainty in projecting the future changes in cost structures and demand for the forest products sector.

In summary, our study indicates that both climate and economic assumptions are important. The path and magnitude of warming in the different climate scenarios varied according to assumptions about the level of greenhouse gas emissions, ocean-atmosphere thermal interactions, and the effects of atmospheric aerosols. Warmer climatic effects are transmitted to the forest sector through changes in growing stock that influence price changes. Overall, the net effect of a warmer climate on global wood markets is a greater supply of wood fiber, lower prices and greater consumption of wood products. The additional wood harvested is significantly less than the change in growing stock associated with climate change as lower wood prices limit the growth of total economic welfare. Total welfare increases with significant regional distributional effects. Consumers gain under climate change at the expense of timber owners who see lower prices. The economic assumptions are important for three reasons. First, inclusion of the recent collapse of the Asian economy and the fall in the production and consumption of wood products in Russia has substantially different effects on the economic responses in comparison to our previous study. Second, expansion of harvests in price-sensitive regions will depend on whether non-market economies expand their timber producing sectors. Finally, temporal aspects are important. They lead to cumulative effects that define the economic behavior. Since forest growing stocks are the result of past cumulative actions, the temporal effects of climatic change influence the path and magnitude of economic responses.

To our knowledge, the analysis in this study represents the first attempt to couple global models of climate dynamics, ecosystem processes, and forest economics in a time-dependent analysis to assess the potential economic responses of the global forest sector to a range of levels of greenhouse gas emissions. Our approach in this study was to examine the economic impacts of the unidirectional flow of information from the range of greenhouse gas emissions that provided alternative scenarios to the atmospheric chemistry/climate model to the ecosystem model to the forest economics model. The study does not represent a full integration of models, however. The study also is limited in its assessment of how uncertainty would affect the results. Uncertainty is a future challenge that may require substantial additional research. Another future challenge with this suite of models will be to provide the emissions model and the atmospheric chemistry/climate model with feedback from the ecosystem model concerning time-dependent changes in terrestrial carbon stocks. Including the role of forest management in this feedback requires a more intimate coupling of the ecosystem model and the forest economics model in which the ecosystem model simulates how carbon stocks in the forest sector are influenced by the harvest responses estimated by the forest economics model. The view of perfect price forecasting may be simulated explicitly with dynamic optimization or treated implicitly with CGTM by projecting future prices and iterating model runs. The expected future price can then be used to adjust forest management investment levels accordingly, which could be incorporated into the timber supply sub-model. Iterations would proceed until a convergence criterion is met. This process may result in a more satisfactory representation of the investment process than currently considered in the present study. The more intimate coupling of the suite of models we considered in this study would allow us to assess the effectiveness of different international strategies that consider the role of forest management in controlling the concentration of atmospheric CO_2. Thus, we believe that the study we describe here represents an important step towards including the role of global forest management in integrated assessments of the global carbon cycle.

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