THE FOREST SECTOR, CLIMATE CHANGE, AND THE GLOBAL CARBON CYCLE – ENVIRONMENTAL AND ECONOMIC IMPLICATIONS.

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ABSTRACT

This paper assesses recent research on climate change, the forest sector, and the global carbon cycle in order to provide a synthesis of recent research results that investigate how climate change may affect the global forest sector. There is evidence that climate change is already affecting forests, but it is likely to have small market impacts in the near term (to 2020). These impacts could grow in the medium term (2020-2060) if climate mitigation is not undertaken. Estimates suggest that 1/7th to 2/3^{rds} of the world's temperate and boreal forests could undergo some type of change in the middle part of the century. The long run impacts (beyond 2060) are difficult to project because they depend on multiple uncertain factors, such as demand growth in forestry and agriculture (e.g., land use), the role that climate change mitigation plays (e.g., by potentially expanding forest area), technological development, and regional climate change impacts on ecosystems. Despite the uncertainty, most economic models suggest that market adaptation can limit the most damaging effects in timber markets. Understanding these important interactions between forests, climate change, and carbon flux remains an important research topic, not only for economists and ecologists separately, but more importantly for the sciences to work together.

INTRODUCTION

The forest sector (i.e., forestry and forest industry, including the use of forest land) plays an important role in the global climate change debate – partly because the sector influences the global carbon cycle, and partly because the sector is influenced by possible global climate change caused by increased concentrations of greenhouse gases, among which CO_2 is the most important. This paper assesses literature examining the impacts of climate change upon the forest sector, focusing on studies that have considered economic impacts and market adaptation. The report also considers how activities in the forest sector - such as mitigation through afforestation, reduced deforestation, and forest management - may affect the global carbon cycle. For the most part, researchers have not considered how mitigation efforts may be influenced by climate change (and vice-versa), so we only briefly discuss the interaction between these two effects in the concluding sections of the paper.

Studies of climate change impacts in the forest sector and studies of adaptation generally link estimates from ecological models to timber models. A number of different types of ecological and timber models have been developed over the years, ranging from local to regional and global. The ecological models provide insights into a host of potential effects that climate change may have on forests, including tree growth effects, carbon fertilization, disturbances and dieback, and other effects (Alig et al. 2004). We draw on this set of results to enhance our understanding of potential impacts on the forest sector in different regions. This paper focuses on a discussion of economic implications in markets. Other environmental issues such as effects on biodiversity, water catchments, wildlife, and recreation are not discussed here, as the uncertainty on these issues seems to be rather high (e.g., Gitay et al. 2001, Kauppi and Solberg 1999).

The paper addresses short, medium, and long run implications, and it considers implications in separate geographical regions, including boreal, temperate, and tropical regions. Institutional factors are also important for forest sector responses (Solberg et al. 1996), but have not been widely addressed in the climate change impacts literature in forestry to date. Thus, it is difficult to make generalizations relating to how institutional factors may affect adaptation and economic responses.

The structure of this paper is as follows. We begin with a discussion about the baseline for future global timber market activity by describing results from several studies that have projected future market conditions. Second, we examine the potential ecological and market effects of climate change impacts in forests, including market-based adaptation to climate change. Finally, we examine the potential economic implications of mitigation activities in forests, including a discussion about the interactions between climate change impacts and mitigation.

BASELINE

To understand the potential impacts of climate change on the forest sector, it is important to have an understanding of the baseline, that is, projections of the forest sector without potential climate change. Many studies that assess economic impacts first estimate baseline conditions, and then compare climate conditions to these baseline conditions to assess potential adjustments and adaptations. Estimates of potential climate change impacts upon the forest sector are best understood in light of how they could alter future market conditions relative to “no climate change” baseline conditions.

Current global timber harvests are approximately 1.6 billion m^3 of industrial roundwood per year (FAO 2005). An assessment of timber market studies suggests that this could rise to 1.9 – 3.1 billion m^3 by 2050, depending on timber demand growth and relative price changes (Solberg et al. 1996). These changes would represent an increase in annual timber harvests of 0.5% to nearly 2.0%. Prices are predicted to increase from 0% to 0.5% per year in real terms. Under all of these scenarios, timber harvest intensities (m^3/ha/yr) in different forests increase, and global harvest intensity is predicted to increase 63% relative to the baseline (Table 1).

An alternative set of scenarios based on the global timber market model described in Sohngen et al. (1999) and updated in Sohngen and Mendelsohn (2007) suggests similar results. The scenarios assume that world-wide population increases from 6.4 to 9.8 billion people over the next 100 years, and that global gross domestic product increases by 1.7% per year on average. In addition, the scenario assumes that technology improves by 1.5% per year in the forest products production function, and that plantation yields rise at 2.5% per decade. Under these assumptions, timber harvests are projected to increase to approximately 2.3 billion m^3 by 2105. Prices are predicted to rise at 0.2% per year. Most of the new timber harvests from this model are predicted for subtropical plantation regions, where technology improvements are increasing the yield of forests substantially over long time periods. In contrast, declining timber harvest intensities are projected for currently inaccessible forests in tropical and boreal regions.

For tropical and subtropical regions, the studies project increases in timber harvests from fast-growing plantations. Most differences between the studies discussed above relate to different predictions of timber harvests from plantations in subtropical regions. The results from the global timber model of Sohngen et al. (1999) project a potentially stronger movement towards subtropical plantation establishment and harvests in future years. For temperate regions, both studies predict increases in timber harvests in the short term. Solberg et al. (1996) do not provide longer-term harvest projections beyond 2050. Sohngen et al. (1999) suggest that temperate regions do not increase timber harvests substantially in the long run. In boreal regions, the global timber model predicts a decline in harvests from these regions over time. One reason for this decline in harvesting activity in boreal regions is that prices are projected to stabilize over time. If prices are remaining constant, incentives to expand infrastructure for harvesting timber in the boreal region are smaller. Solberg et al. (1996) suggests an increase in harvests in boreal regions the short term in part due to price increases, but also due to the fairly large stocks and low costs of accessing stocks in many boreal regions.

These two studies are broadly consistent by suggesting an increasing role for subtropical plantations in global timber supply. They differ on the extent to which this new wood supply will offer alternatives to harvesting natural forests in temperate and boreal regions. However, some of these differences can be explained by the relatively short outlook period for the Solberg et al. (1996) study relative to the longer-term projections provided by Sohngen et al. (1999). Solberg et al. (1996) also offer important insights into institutional factors, such as ownership, rights of use of forestland, and international agreements that may affect future supply of wood from particular tropical countries.

ECOLOGICAL AND TIMBER MARKET IMPLICATIONS OF CLIMATE CHANGE

It is widely recognized that climate change is likely to have strong influences on the structure and function of forests (Watson et al., 2001, Intergovernmental Panel on Climate Change, 2007a). When considering how the ecological effects of climate change translate into economic effects (the interest of this paper), it is convenient to categorize the response into three general areas: forest productivity changes, ecosystem disturbances, and changes in forest species distribution. Productivity changes are adjustments in the productivity of forests which alter the growth rates of timber species (in either a positive or negative way). Changes in disturbance influence the standing stock of trees, and include pest infestations, forest fires, wind-throw, and ice damage. Finally, changes in species distribution result from shifts in climate, which ultimately alter the optimal geographic location of different timber species.

It has long been recognized that there is potential for additional carbon in the atmosphere to enhance the growth of trees (the so-called carbon fertilization effect). Results from modeling studies suggest that carbon fertilization can in turn have a large impact upon the predicted effects of climate change on forest structure and growth (see VEMAP Members, 1996; Cramer et al., 2001). Although earlier model results suggested that CO_2 could enhance global growth rates in forests (e.g., Melillo et al., 1993), more recent results suggest that inter-annual variation in temperature and precipitation could have positive or negative effects on annual growth, depending on the direction of change (Tian et al., 1998; Schimel et al. 2000). Thus, carbon fertilization effects may be limited both by changes in annual weather or by other limiting nutrients (Melillo et al., 1993). The so-called carbon fertilization effect could reach a saturation point for particular species and for ecosystems (Gitay et al., 2001). A recent comparison of CO_2 experiments across a number of sites and timber ages, however, indicates that carbon has a relatively consistent, and positive, effect on net primary productivity (Norby et al., 2005). A recent study may illustrate this evidence. Boisvenue and Running (2006) reviewed historical trends in net primary productivity in forests and found that over the last 50 years most studies have reported increasing growth trends in forests where water is not a limiting factor.

Although tree growth and productivity effects will have clear long-run implications for forests, one of the more important near-term effects could be dieback. Some authors have suggested that climate change could lead to dieback in existing (or future) forests due to water stress, insect infestations, or fires (Shugart et al., 1986; King and Neilson, 1992; Smith and Shugart, 1993; Solomon and Kirilenko, 1997; Bachelet et al., 2003; Bachelet et al, 2004; Scholze et al., 2006). Two causes of dieback appear in the literature. The first is that changes in climate (drying or warming) could make forests more susceptible to insect, fires, and other disturbance agents. Current evidence suggests that climate change may already be causing more intense fires in some regions of the world (Westerling et al., 2006). Climate change could also shift the distribution of climatic variability and climatic extremes (Houghton et al., 1996; Watson et al., 2001).

Predictions of the size and scope of changes in climate or extreme events depend heavily on climate predictions made by climate modelers. The distribution of the climate effects geographically (e.g., where changes in precipitation and temperature occur) and over time is one of the most uncertain aspects of climate modeling, suggesting high uncertainty surrounding the regional distribution of forest dieback effects.

Beyond the direct effects of climate on forests, a related issue is the influence of climate change on the productivity of competing land uses, such as agricultural crop and livestock production. Large changes in productivity of farmland could lead to an expansion, or contraction, of agricultural land. Given the historical inter-relationship between forests and agriculture, shifts in productivity of agricultural land in particular could have large effects on the ultimate distribution of forestland. Current research does not indicate that climate change will lead to large-scale increases in agricultural land at the expense of forests in most temperate regions in the short run (Watson et al., 1996, Alcamo et al., 1997; Alig et al., 2002, Reilly et al., 2003; Gitay et al., 2001). In recent times, most expansion of agricultural land has occurred in tropical forests (FAO, 2005; Houghton, 2003), and these trends are likely to continue over the next 20 years (Watson et al., 2000).

In the next three sub-sections of this paper, we examine the implications of these broad effects for timber markets. We consider both geographic and temporal factors, e.g., where and when the impacts may occur. Although considerable uncertainty still exists with respect to projections associated with climate change, a number of the economic results are fairly robust across the models, and therefore provide some reasonable assurances about the capacity of markets to adapt to change. Our general findings for different regions and time periods are summarized in table 2.

Short Term Climate Impacts (2005 – 2025)

The recent study by Scholze et al. (2006) is perhaps the most comprehensive global assessment to date. The researchers examine potential climate impacts on ecosystems across 16 climate models and 52 different climate scenarios, providing information both on the average potential effect of climate change as well as uncertainty. Uncertainty is inferred by assessing results across the range of climate models and scenarios analyzed. They do not incorporate humans, so their predictions are based on what could happen to forests if humans were not already affecting forests. Their results show that in the short term (next 25 years), forests will likely be a net sink for carbon globally. The risk of forests becoming a source for carbon in the next 25 years, however, is inversely related to global temperature change over the century. For example, in the short-term under a number of the climate scenarios analyzed in the Scholze et al. (2006) paper, the size of the carbon sink in the biosphere becomes larger on average across the climate scenarios if the global average temperature change over the century is >2°C. An increasing sink implies that forest either are expanding in area, or otherwise increasing their stock of carbon. For global average temperature changes <2°C over the century, the biosphere becomes a net source of carbon under some of the climate scenarios. If forests become a source for carbon, then emissions of carbon to the atmosphere from dieback and decay processes are larger on net than forest growth. The short-term results in the paper by

Scholze et al. (2006) contrast with their longer-run results that suggest there is greater probability that forests become a source under larger temperature changes (see below).

Evidence suggests that climate change could have relatively larger near-term effects in boreal regions (Kirschbaum and Fischlin, 1996; Watson et al., 2001). Boreal forests are already characterized by long-term, historical shifts in natural fire frequency that have large effects on forest and carbon stocks (Kurz and Apps, 1999). If climate change alters the natural fire frequency (e.g., Bachelet et al., 2004; Westerling et al., 2006), then there could be fairly substantial impacts on boreal forests in the near term. In addition to potential changes in fire or other disturbance frequency, many ecological models also project a movement of species north with a warmer climate (Solomon and Kirilenko, 1997; Watson et al., 2001). Because boreal regions, except for the Nordic countries and Western Russia, tend to be unmanaged, humans are less likely to be part of the adaptation process, thus slowing the movement of species. Where humans influence regeneration processes, they can speed the movement of tree species across the landscape, and where humans have smaller impacts, forest adjustment processes will be slower (e.g., Sohngen et al., 1998). Slower adaptation could have negative implications for carbon stocks (Solomon and Kirilenko 1997; Nilsson and Shvidenko 2000).

Many of the near-term effects of climate change in boreal forests are likely to occur mostly beyond the accessible margin, so that global markets experience few significant impacts. One reason for this is that native forests in boreal regions are expected to play a smaller proportional role in wood supply over the next 20 years (see Table 1; Solberg et al., 1996; Sohngen et al., 2000). Sohngen and Sedjo (2005) suggest that over the period 2005 – 2025, timber harvest levels are not projected to change substantially in boreal forests of North America, Europe, or Russia. Despite the likely small timber market impacts globally, there could be locally important implications for boreal communities that are dependent on forest resources.

The dynamics of timber markets in temperate regions have been examined more thoroughly than for other regions, particularly in the United States (Sohngen and Alig, 2000). A range of ecological scenarios has been explored for these forests, including changes in annual timber growth, potential dieback, and changes in species distribution. The results indicate that timber supplies from temperate regions would not be dramatically affected in the short run if the primary effects of climate change are changes in the rate of growth of timber. It takes a long time for changes in timber growth rates to have an effect on timber inventories and timber supply (Joyce et al., 1995; Mills and Haynes, 1995; Perez-Garcia, 1997; Joyce et al., 2001; Alig et al., 2002).

Similar results have been found in studies conducted in Europe. Trømborg et al. (2000) used a regional partial equilibrium forest sector model to analyze the market impacts (in a 15- 20 year perspective) of possible accelerating forest growth in Europe. Three scenarios were studied – a base scenario that assumed a 1.4% per year increase in standing stock (this reflects the actual average situation in Europe in 1994), a medium scenario assuming 2.0 % per year increase in growth (i.e., about 43% higher growth than the base scenario), and a high scenario of 2.7 % per year increase in standing stock (i.e., 93% higher growth than the base). The projected impacts of accelerating growth in timber production were found to be fairly small over the next 10-20 years for sawlog and sawnwood markets, whereas pulpwood prices were found to decrease substantially.

Solberg et al. (2003) shows similar results, applying a more detailed partial equilibrium model with respect to forestry, international trade, and forest industry technologies.

More dramatic scenarios have been examined where climate changes substantially over the next 20 years, causing dieback and changes in the distribution of important commercial tree species. Under these fairly dramatic scenarios, climate change could have substantial effects on timber supply in the short term. Specifically, wide-spread dieback, when combined with salvage logging, is projected to increase short-term timber supplies and reduce prices (Sohngen and Mendelsohn 1998). One important uncertainty regarding the effects of dieback in boreal regions relates to global trade. Sohngen et al. (2001) find that timber production in boreal and temperate regions could decline in the near term if climate change causes dieback in boreal and temperate zones, but enhances growth in sub-tropical and tropical regions. Both studies suggest that producers' economic welfare would be reduced by potential dieback, but that they can actively participate in mitigating those effects through salvage, and by changing the tree species they regenerate to those that are better suited to a new climate. Adaptation through regeneration can have important implications for the economic viability of particular forest stands (Lindner, 1999, 2000). The importance of trade is also shown in Kallio et al. (2006), studying the market impacts of a relatively large decrease in European timber supply caused by increased biodiversity protection. The impacts are rather modest because increased imports from Russia offset to a large degree the decline in domestic roundwood supply.

Tropical regions are not expected to experience large immediate impacts from climate change. Currently, natural tropical forests contribute only a small portion of the world's timber harvest, and climate change over the next 20 years is not expected to change this. Many of these same countries, however, are providing increasingly large shares of the world's timber from their plantations. Short-rotation plantation species are expected to be particularly suitable for adaptation during climate change, so that tropical and subtropical countries could potentially benefit from climate change. Sohngen et al. (2001) find that if climate change increases forest productivity in plantations, South American timber harvests could increase by more than 20% over the next 20 years (relative to the baseline) with climate change. The effects in sub-tropical and tropical plantations are directly linked to the size of the change in net growth implied by climate change.

Ecological models do not suggest large near-term additional disturbances in natural tropical forests, and the largest impacts in the near-term on these forests are likely to result from deforestation rather than from climate change (Gitay et al. 2001). Deforestation, although slowing in recent years (FAO, 1999, 2005; Houghton, 2003), is predicted to continue to cause conversion of tropical forests to agriculture (Palo et al. 2000). For example, annual net deforestation rates in tropical areas of Africa and South America are (annual percentage loss in parentheses) 4.0 million ha yr^{-1} (0.7% per year) and 4.2 million ha yr^{-1} (0.7% per year), respectively (FAO, 2005).

Medium Term Climate Impacts (2025 – 2065)

Left unabated, climate change is expected to intensify during the middle of this century (Intergovernmental Panel on Climate Change, 2007b). The most important impacts on forests and timber markets are likely to occur in the medium- to long-term. The Intergovernmental Panel on Climate Change suggests that approximately $1/7^{th}$ to $2/3^{ds}$ of all temperate and boreal forests are likely to undergo some type of ecological change over the century (Watson et al., 1998; Gitay et al., 2001). Those changes could include dieback of existing species (King and Neilson, 1992; Smith and Shugart, 1993; Solomon and Kirilenko, 1997; Bachelet et al., 2004; Scholze et al., 2006 for example), movement of tree species from one region to another region, and accelerating impacts of climate change and CO_2 concentrations on forest growth.

In boreal regions, climate change is generally expected to cause an increase in forest growth and an increase in forest area over the coming century (Cramer et al., 2001; Scholze et al., 2006). Most of the expansion of forests, however, is far to the north, in regions that currently are tundra, and generally considered to be inaccessible. Scholze et al. (2006) suggest that if the average global temperatures change is expected to rise above 3° C over the century, then boreal forests will be at a greater risk of losses due to dieback and disturbance, among other factors. Losses at higher temperatures appear to be driven largely by increases in forest fire activity associated with larger temperature changes (Scholze et al., 2006).

Perez Garcia et al. (1997) relied on ecological studies that suggested rising growth rates in boreal forests. Not surprisingly, their economic model showed an increasing supply of timber from boreal regions over the next 40 years. Heavier timber harvests in boreal forests in turn were found to reduce timber prices, and negatively affect producers' economic welfare in temperate regions. More recent results by Perez-Garcia et al. (2002) also assume that biomass of boreal forests increases, but they find the opposite result for the timber harvest in boreal regions. For example, their study suggests that lower world-wide prices for timber cause a reduction in timber harvests in Canadian boreal forests.

Thus, their results show that economic impacts of lower prices outweigh the benefits of rising forest productivity in boreal regions. The results in Perez-Garcia et al. (2002) are qualitatively similar to those in Sohngen et al. (2001), who suggest that boreal regions become less important over time both in the baseline and during climate change, as global timber harvests shift towards subtropical plantation regions. In combination, these results suggest that boreal forests will continue to become relatively less important globally over the medium term, and that climate change is likely to exacerbate the situation.

Ecological studies suggest a wide range of potential impacts in temperate forests in the medium term. Bachelet et al. (2004) examined impacts in the coterminous U.S. with a single ecological model and two climate scenarios. Their results suggested that total forest biomass could expand under a wetter climate, and forest biomass could contract in scenarios with less moisture. Cramer et al. (2001) considered only a single climate scenario, but a range of ecological models. Their results imply increases in net ecosystem productivity over the century projected by most of the ecological models. The results by Scholze et al. (2006) suggest both increases and decreases in forest area, depending on the climate scenario and the region, with higher temperature changes in the temperate regions. As temperatures increase above 3° C, their results suggest an expansion in forest area, and an expansion in wildfire activity in temperate zones. More wildfires occur partly because there are more forests to burn

It takes some time for forest inventories to reflect the influence of climate change on timber growth, thus economic studies that focus only on changes in productivity of forests, and not on stock effects, show that climate change has larger implications for supply in the medium-term time period than in the short-term (Joyce et al., 1995; Perez-Garcia et al., 1997). McCarl et al. (2000) also show losses accelerating over time if growth effects are negative. Sohngen and Mendelsohn (1998) combined changes in timber growth, dieback from disturbance, and shifts in species range based on VEMAP Members (1996). For all of the ecological and climate scenarios examined, the average effects imply that dieback would occur on an additional 0.7 million ha per year (in the U.S. only) over a 70 year period, forest growth would increase by 5% by 2070, and forest area would increase by 14% by 2150. If forest fires occurred on all areas where dieback occurred, the scenarios suggested a 41% increase in fire activity on average over the current situation. Despite the fairly substantial losses of timber projected during this century due to dieback, salvage was found to reduce the economic losses, and timber supply was found to increase during the medium-term period.

One critical question for timber markets in the medium term lies with regeneration, e.g., which species should be replanted to thrive under new climate conditions. If climate conditions change substantially, landowners in temperate regions will be looking for signals to alter the types of tree species they replant. Whether the signal is strong enough to perceive will have only small effects during the medium term, but will have notable effects on timber supply in the long run. If the more dramatic ecological scenarios involving dieback and tree species change are accurate, getting the answer to this question right will determine the long-run outlook for timber supply from temperate regions.

Scholze et al. (2006) suggest relatively smaller effects in tropical forests than for boreal and temperate regions in the medium and long run, but their results suggest that risks of biome shifts and wildfire disturbance in natural tropical forests are nonetheless substantial. Any changes that do occur in native tropical forests will have relatively small effects on timber markets because these regions do not provide a large supply of industrial timber for markets, and they are not projected to become large suppliers in the future (e.g., Daigneault et al., 2006).

Plantations in subtropical regions--Chile, Argentina, Brazil, South Africa, Australia, and New Zealand--are projected to provide more than 30% of market share in the middle of the century (Daigneault et al., 2006). If climate change drastically alters productivity in these plantations, there could be large timber market impacts. Most of the ecological models consider impacts only in native forests, whereas subtropical plantations tend to be cultivated with non-indigenous tree species. Thus, it is difficult to know exactly how climate change will influence their potential growth under the new climates in which they have been introduced. However, most subtropical plantations focus on very short rotation species (rotation lengths are often less than 20 years, and frequently less than 10 years), so that timberland managers can adjust and adapt rapidly if climate change has dramatic effects. For example, if losses of forests in traditional industrial supply regions of the temperate zone (e.g., U.S., Canada, Europe) become substantial, subtropical plantation species may benefit (see Sohngen et al., 2001).

Long Term Climate Impacts (Beyond 2065)

The long-run effect of climate change on ecosystems will be heavily influenced by the amount of climate change. Scholze et al. (2006) find that for global average temperature changes above 3° C, the natural sink potential in forests declines over the century, with a substantial probability of forests becoming a large source of carbon beyond 2065. One reason for this is the increase in wildfire activity they model, and another reason is the potential shift in biome type. For example, under 38% of the climate scenarios investigated, they predict biome shifts in 10% of existing forests in tropical areas when global average temperature change exceeds 3° C over the century. Under 88% of the climate scenarios they predict biome shifts in 10% of existing boreal forests when global average temperature change exceeds 3° C over the century. For climate change of less than 2° C, 19% and 44% of climate change scenarios were found to cause biome shifts in 10% of existing tropical and boreal forests, respectively. Even for the smaller changes in temperature, potentially substantial shifts could occur in tropical and boreal regions.

The results in Bachelet et al. (2004) illustrate the uncertainty in long-term analysis. They examined only two climate scenarios, one was warmer and wetter over time, and the other was warmer and drier. In the warmer and wetter scenario, forests were found to become a stronger sink over the century, while in the warmer and drier scenario, forests were found to become a strong source by the end of the century. There were strong regional differences within the country in both scenarios. For example, under the more pessimistic climate scenario, the Northeast and Southeast are projected to become strong sources of carbon emissions towards the end of the century, while the West becomes a strong source. For the more optimistic climate scenario, most regions become strong sinks for carbon over the century, although the Northwest becomes a source.

At an aggregate level, different ecological models agree on the overall response in forests (e.g., Cramer et al., 2001). Warming with plenty of additional precipitation will enhance forest productivity, while drying of forests leads to potential losses. These potential losses become more pronounced when global average temperatures exceed increases of 2.5 – 3.0° C. Models do find specific differences in specific regions, and this limits our understanding of where impacts are likely to occur.

For timber markets, the long-term story is one of adaptation. Specifically, one question is whether landowners and land managers will be able to respond to climate, ecological, and market signals adequately during this century. According to the ecological studies, landowners and managers will face a host of hurdles, including changes in forest fire activity, changes in the potential for land to sustain forests, and changes in the rates of growth of tree species. Beyond adaptation on the landscape, the entire forest products industry will need to adapt, for example, by learning to use new tree species in forest production processes. The extent to which the industry responds to climate change will drive signals during the century and will influence the extent of market effects at the end of the century.

One important aspect that has been ignored in most of the literature to date is that the market response will likely influence the ultimate effects that ecosystems experience. Nearly all ecological studies are built on potential vegetation, and none of the models incorporate human management of forests (e.g., Scholze et al., 2006; Bachelet et al., 2004). Forest ecosystems, however, already are heavily influenced by human management. It has long been recognized that foresters respond to changes in disturbance by altering forest management. For example, Reed (1984) and Haight et al. (1995) show how timber rotation ages are adjusted in response to disturbances. Recent economic studies show that there are many opportunities to efficiently manage (not eliminate) forest fires by adjusting timberland management (Amacher, 2004), and by adjusting fire suppression activities (Calkin et al., 2005). In the last 30-50 years, foresters have substantially altered the landscape by shifting forest species types towards more favored market species. For example, in the U.S. South, they have expanded the area of southern pine through planting efforts (USDA Forest Service 1988, Alig and Butler 2004), and globally foresters have expanded non-indigenous plantations by around 2.8 million ha per year (ABARE-Jaako Poyry, 1999; FAO, 2005). To develop a better understanding of both ecological and economic effects, it would seem prudent to build modeling systems that capture both systems and their interactions.

The area of forestland in all regions (boreal, temperate, and tropical) will ultimately depend not only on climate impacts in forests, but also on climate impacts on agricultural productivity. If agricultural productivity declines (increases) as a result of climate change, the area of land devoted to agriculture is likely to increase (decrease) in the long run, inducing additional (fewer) pressures on forests. One global study that includes agricultural and forest impacts predicts that climate change will reduce net deforestation rates over the next century (Alcamo et al., 1997). For example, Alcamo et al. predict that the net rates of global deforestation will decline from 17 million ha per year between 2000 and 2050 without climate change to 14 million ha per year with climate change. Beyond 2050, they predict that climate change could cause net afforestation of 6 million ha per year compared to net deforestation of 0.2 million ha per year during the same time period . Their projection of a gain in forest area arises mainly because agriculture demands less land during climate change.

THE ROLE OF MITIGATION

A different way that climate change could have large effects on forests is through the policies that stimulate mitigation, such as afforestation, reduced deforestation, and forest management. There has been considerable research on the potential for mitigation to help reduce the costs of climate impacts. Metz et al. (2001) suggest that 60-87 Pg C (1 Pg C = 1 billion metric tonnes carbon, or 1×10^{15} grams C) could be sequestered in forests over the coming century, and Sohngen and Mendelsohn (2003) suggest that this amount of carbon could cost up to $187/t C. Such large levels of sequestration would have large effects on land use, potentially increasing the area of forests at the end of the century by 1 billion hectares. Large-scale changes in forest management are also possible.

Studies that examine climate change impacts on the forest and agricultural sectors have not considered the influence of mitigation, and mitigation studies have typically not considered climate change impacts. However, many interactions are likely between mitigation activities and climate change, and vice-versa. First, many integrated assessment models of the climate and economic systems suggest that mitigation efforts in forestry can increase the benefits and reduce the costs of climate policy (e.g., Sohngen and Mendelsohn, 2003; Manne and Richels, 2006). To the extent that forestry mitigation reduces the overall costs of mitigating climate change, policies may be adopted that limit total warming. As shown in Scholze et al. (2006), less warming suggests that the impacts in forests will be reduced in the long-run.

Second, if mitigation in forestry becomes an important component of overall climate change policy, future land uses will change substantially. Within the range of carbon prices of \$60 to more than \$200/t C, Sohngen and Mendelsohn (2003), Sathaye et al. (2006), and Sohngen and Sedjo (2006) suggest that there could be as many as 1 billion more hectares of land in forests by 2100 (or an increase of around 30%). These carbon prices are well within the range of current estimates of the costs of stabilizing future climate (Weyant et al. 2006), suggesting that if forestry is ultimately included as a creditable opportunity, then large land use changes could take place.

The implications of these types of land-use changes for existing ecological models are interesting to consider. For the most part, current ecological models are built on potential forest areas or maps of current land uses (e.g., Cramer et al., 2001; Bachelet et al., 2004; Scholze et al., 2006). For tropical regions, the mitigation efforts described above largely imply reductions in deforestation, thus preservation of existing forest areas in tropical regions. Thus, if reductions in deforestation were included as an option for climate change action, the results of the ecological models for tropical regions would likely be robust because the ecological models already implicitly assume no future deforestation. The limiting factor of course is that climate change could alter the relative productivity of farmland in tropical regions, thus altering the relative costs of reducing deforestation. For temperate regions, the mitigation results imply an expansion of forest land. Ecological models that rely on potential vegetation likely already over estimate climate-change impacts, while those that rely on current distributions of forests likely underestimate climate-change impacts.

Third, results from ecological models examining climate change should influence estimates of the costs of mitigation. Economic modelers thus far have not accounted for climate change impacts when generating marginal abatement cost curves for sequestration. In the face of this limitation, several possibilities exist for whether accounting for climate change impacts would lead to higher or lower estimated costs of mitigation. In the short-term, it was noted above that climate change would have its largest implications in boreal regions, and through growth effects on trees. In regions with positive tree growth effects, climate change would reduce sequestration costs as long as the relative value of agricultural land does not rise too much. In regions with negative tree growth effects, climate change would increase sequestration costs.

In the medium- and long-term, forested ecosystems are likely to be influenced by additional factors, including mortality from forest fires and other disturbances, and changes in the distribution of important tree species. Forest management activities to reduce fire frequency and intensity in forests, so as to conserve carbon in the landscape, could increase mitigation costs. Furthermore, an expansion of forest area due to mitigation suggests more overall hectares burned, which potentially increases the costs of fighting fires. If the geographical distribution of specific tree species changes, or if the geographical distribution of optimal agricultural land changes, as is possible during the medium term, then costs of carbon sequestration could rise due to rising opportunity costs of holding land in forests or search processes associated with finding the right tree species to plant.

In summary, in the short-term, climate change appears to improve the efficiency of mitigation efforts. In the medium- to longer- run, climate change impacts appear to raise the risks associated with mitigation, and consequently raise the costs of avoiding climate change.

Aside from the interaction between mitigation and climate change, if mitigation efforts are undertaken, they are likely to have substantial impacts on timber markets by affecting prices. Over the long-run, most economic studies show that mitigation expands timber supply and reduces timber prices (Sohngen and Mendelsohn, 2003; Murray et al., 2005). However, in the short-term, mitigation could actually increase timber prices if options such as increasing rotation ages are utilized. In fact, if large-scale mitigation efforts are undertaken inefficiently, they could have relatively rapid impacts in timber markets by altering the relative value of forestry and agriculture (Alig et al., 1997; Murray et al., 2004; Sohngen and Brown, 2004).

Thus, while it is possible to increase carbon sequestration in forests through afforestation, the net effects on overall carbon sequestration from large-scale and short-fuse programs may not be as large as anticipated because land markets respond by moving some unprotected forests back into agriculture (i.e. deforestation). Alig et al. (1997), for example, find an approximate 1 to 1 correspondence between hectares that are moved to forests from agriculture and hectares that move the opposite direction, suggesting that large-scale and short-fuse afforestation in the US situation may not be the most efficient method for carbon sequestration. Murray et al. (2004) find similarly large "leakage" effects for some regions of the U.S., while Sohngen and Brown (2004) find smaller, though still potentially substantial, "leakage" effects for tropical regions. More recent efforts suggest that efficient policies with flux constraints or carbon pricing could provide net sequestration, and that these would increase timber supply both in the short run and long run (Adams et al., 1999; Hoen and Solberg, 1994, 1999; Sohngen and Mendelsohn, 2003; Murray et al., 2005).

A related issue that has not been widely examined is the question of substitution between wood and other energy-intensive products like steel, concrete, and aluminum. Energy intensive constraints on carbon (e.g., high carbon prices) would increase the production costs of energy intensive products and thus increase the demand for wood products that substitute for them. Such substitution has a permanent impact on the concentration of atmospheric CO_2. The existing empirical studies indicate that the potential here is rather high (e.g., Buchanan and Levine, 1999; Burschel et al. 1993; Petersen and Solberg 2002, 2003, 2004, 2005; Raymer 2006). However, higher prices for traditional energy products would also spur the demand for bio-energy products, which as noted above, could have substantial impacts upon land-use globally. In particular, large areas of land could be converted from existing forests to support growing needs for bio-energy products based on agricultural crops (Clarke et al., 2006). The development of the so called second generation biofuel technology (using hemi-cellulose for producing bioefuels) will be of special interest here, as it may cause a large shift in demand for forest fiber. The fiber for this purpose does not have to be of high quality and could easily use salvage harvest biomass, thus counterbalancing the impacts to industrial forestry of damages caused by climate change. The development of technology is closely linked to policy instruments – for example, the newly decided EU regulations that 20% of the transport fuels in the EU should by 2020 be based on renewable resources is one main driver for developing the second generation biofuel technology.

CONCLUSIONS

This paper provides a general overview of potential climate change impacts on the forest sector in the short, medium, and long run. The results of our review of the literature suggest that climate change is likely to have small impacts in the near term, out to 2025. Short-term impacts could become large, however, if climate change involves significant changes in regional weather patterns or dieback effects that cause timber stock losses. Existing ecological evidence implies that the earliest signs of climate change will be observed in boreal regions. Changes in boreal regions, however, are likely to have limited effects on global markets, although they could have large consequences for communities located near the impacts.

Climate change impacts are likely to accelerate in the medium- and long -term if mitigation and abatement efforts are not undertaken. Ecological studies suggest that precipitation can offset the effects of warming to some extent, but that there are substantial risks to forests in virtually all regions with global average temperature changes of more than 2.5° C. These risks include additional disturbances (e.g., fires, insect infestations), changes in distribution of species, and conversion of forests to grasslands or other non-forested vegetation types. Because climate models cannot precisely predict how temperature and precipitation will change geographically, it is difficult to know with certainty where the impacts will occur.

Economic studies have shown that if forest productivity increases (decreases), timber prices will likely fall (increase). Large disturbances caused by climate change can have large influences on timber prices. In particular, large salvage efforts following dieback from forest fires would reduce timber prices, with the lower prices benefiting consumers and reducing producers' economic welfare for landowners. The largest effects during climate change may actually result from market adaptation, with temperate and boreal regions losing market share to sub-tropical and tropical regions. These trends already appear to be occurring, so climate change would likely only enhance the movement of industrial timber production from developed temperate regions to developing tropical and sub-tropical regions.

One important potential influence on forests and timber markets that has not been widely examined is the potential effect of changes in agricultural productivity and agricultural policies. Agriculture and forestry compete for the same land globally, and if climate change alters the productivity of agricultural land or global (EU, US, WTO) agricultural policies change, then one would expect a change in the demand for agricultural land. Few models have examined the combined effects of climate change on agriculture and forestry, although the studies that have been conducted do not suggest substantial changes in overall land uses relative to the baseline (Alcamo et al., 1997 and Alig et al. 2002). Using four climate change scenarios from a national climate change assessment in the late 1990s, Alig et al. (2002) find that climate change leads to less projected forest area than without climate change. Less cropland is projected to be converted to forests due to increases caused by climate change in overall agricultural crop production and exports. Projected changes for livestock production and prices depend on the specific climate change scenario (and climate model, e.g., Hadley model), with some variation over regions and time.

Mitigation efforts could have substantial impacts on timber markets, timber prices, and land use during the entire century. Evidence is emerging that forestry can play an important role in overall climate change abatement efforts, but if this role emerges it will entail large changes in how society uses land. These effects include not only changes in the margin between agricultural and forest land, but also increases in the intensity of forest management. No studies to our knowledge have analyzed how mitigation efforts would be affected by the impacts of climate change on forests, however, because climate change is likely to have small, but positive effects on forest productivity in the near-term, climate change could reduce the costs of mitigation efforts. Over the longer-term, mitigation efforts could be more costly to sustain due to climate impacts, particularly if society is not successful in reducing greenhouse gas emissions in the long-term.

One of the most important implications of this synthesis of the literature is that there is little evidence that ecologists and economists have worked seriously together to assess climate impacts in ecosystems. A number of studies have used ecological model results in economic models, but there has been little use of economic models in ecological studies. This is problematic because the scale of human influence on ecosystems is large (e.g., see the Millennium Ecosystem Assessment - http://ma.caudillweb.com//en/Products.Global.Overview.aspx). One would expect the ecological effects to somehow be moderated or influenced by adaptation in markets, with timber producers and consumers behaving in ways that act to limit economic effects. Further, economist and ecologists working together on feedbacks could help advance the analysis of resiliency associated with climate change, both from an ecological and socioeconomic viewpoint. Given that climate change can potentially affect many parts of the global ecosystem and economy, indicators of resiliency would aid in ranking policy responses to climate change. As part of the resiliency analysis, feedback loops would need to be considered. An example is macroeconomic factors that affect forest products markets, such that changing timber values from forestland can affect land-use and the other ecosystem goods and services on that forestland, and those production relationships can be affected by climate change and any adaptation or mitigation responses. Interdisciplinary research could advance resiliency rankings, while recognizing that economists and ecologists often work at quite different scales. For example, many ecologists work at finer scales and focus on functions and processes than economists, which are viewed by some economists as being at a scale that is data-poor and very detailed. Economists can provide analyses that help set the context regarding relative importance of giving more attention to certain feedback loops and ecosystem function resiliency indicators in our global system. Thus, future research is needed to fully integrate ecological and economic models to better understand how forest ecosystems and markets may be affected by climate change. This future research should focus on fully integrating ecological and economic models to better understand how forest ecosystems and markets may be affected by climate change.

Another area that needs additional attention from the research community is the impact of climate change on non-wood forest products and services, such as biodiversity, recreation, edible fruits, and other non-wood products. These are more difficult to assess because our understanding of the demand for these products is incomplete globally, although knowledge is growing, and also because the uncertainty is rather high regarding these ecological effects (Kauppi and Solberg 1999). Most likely, however, impacts on non-wood forest products will vary dramatically from place to place, depending on the nature of climate change (Irland et al., 2000, Loomis and Crespi, 1999; Mendelsohn and Markowski, 1999; Wall, 1998). In particular, industrial wood products are less susceptible to climate change due to global market systems that allow wood trade from region to region. With fewer such established links for non-wood forest products and services, they are likely to exhibit more vulnerability to climate change, at least locally. Impacts on some non-wood products and services, however, would be global regardless of whether or not they are traded across regions (e.g., biodiversity is a global public good, with potentially high public value in all regions).

REFERENCES

ABARE – Jaako Poyry. 1999. Global Outlook for Plantations. ABARE Research Report 99.9. Canberra, Australia.

Adams, D. M., C. A. Montgomery, and T. Naito. 1998. "Input Substitution in the U.S. New Construction Sector: Evidence from a Profit Function Analysis," in Yoshimoto, A. and K. Yukutake (eds.) FORESEA MIYAZAKI 1998, Forest Sector Analysis, Proceedings of International Symposium on Global Concerns for Forest Resource Utilization-Sustainable Use and Management. October 5-8, 1998, SEAGAIA, Miyazaki, Japan. Volume I, pp131-140. Japan Society of Forest Planning Press, University of Tokyo, Japan.

Adams, D.M., R.J. Alig, B.A.McCarl,; J.M. Callaway, and S.M. Winnett. 1999. Minimum cost strategies for sequestering carbon in forests. *Land Economics,* 75(3): 360-374.

Alcamo, J, G.J.J. Kreileman, J.C. Bollen, G.J. van den Born, R. Gerlagh, M.S. Krol, A.M.C. Toet, and H.J.M de Vries. 1997. Baseline scenarios of global environmental change. *Global Environmental Change,* 6(4): 261-303.

Alig, R., D. Adams, B. McCarl, J.M. Callaway, and S. Winnett. 1997. Assessing effects of carbon mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agriculture sectors. *Environmental and Resource Economics,* 9**:** 259-274.

Alig, R., D. Adams, and B. McCarl. 2002. Projecting impacts of global climate change on the U.S. forest and agriculture sectors and carbon budgets. *Forest Ecology and Management,* 169:3-14.

Alig, R.; Butler, B.J. 2004. Projecting large-scale area changes in land use and land cover for terrestrial carbon analyses. *Environmental Managemen*t, 33(4): 443-456.

Alig, R., D. Adams, L. Joyce, and B. Sohngen. 2004. Climate Change Impacts and Adaptation in Forestry: Responses by Trees and Markets. Choices: *The Magazine of Food, Farm and Resource Issues,* Fall:9-11.

Amacher, G.A., A. Malik, R. Haight. 2005. Not getting burned, the importance of fire prevention in forest management. *Land Economics*, 81: 284-302.

Bachelet, D., R.P. Neilson, T. Hickler, R.J. Drapek, J.M. Lenihan, M.T. Sykes, B. Smith, S. Sitch, and K. Thonicke. 2003. Simulating past and future dynamics of natural ecosystems in the United States. *Global Biogeochemical Cycles*, 17(2): 1045

Bachelet, D., R.P. Neilson, J.M. Lenihan, R.J. Drapek. 2004. Regional Differences in the Carbon Source-Sink: Potential of Natural Vegetation in the U.S.A. *Environmental Management*, 33: S23–S43.

Boisvenue, C. and S.W. Running. 2006. Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century. *Global Change Biology*, 12: 862-882.

Buchanan, A.H.. and S. Bry Levine 1999. Wood-based building materials and atmospheric carbon emissions. *Environmental Science & Policy*, 2:427-437.

Burschel P., E. Kursten, B.C. Larson, M. Weber 1993. Present role of German forests and forestry in the national carbon budget and options to its increase. *Water, Air, and Soil Pollution*, 70:325-340.

Calkin, D.E., K.M. Gebert, J.G. Jones, and R.P. Neilson. 2005 Forest Service large fire area burned and suppression expenditure trends, 1970 - 2002. *Journal of Forestry*, 103(4): 179-183.

Cramer, W., A. Bondeau, F. Ian Woodward, I.C. Prentice. R. Betts, V. Brovkin., P.M. Cox, V. Fisher, J.A. Foley, A.D. Friend, C. Kucharik, M.R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, C. Young-Molling. 2001. Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models. *Global Change Biology*, 7: 357-373.

Daigneault, A., B. Sohngen, and R. Sedjo. 2006. Exchange Rates and the Competitiveness of the United States Timber Sector in a Global Economy. In Press: *Forest Policy and Economics*.

Falk, I. and R. Mendelsohn. 1993. "The economics of controlling stock pollutants: An efficient strategy for greenhouse gases." *Journal of Environmental Economics and Management*, 25: 76-88.

FAO. 1999. "State of the Worlds Forests, 1999." United Nations Food and Agriculture Organization. Rome, Italy.

FAO. 2005. Global Forest Resources Assessment 2005: Progress towards sustainable forest management. FAO Forestry Paper 147. United Nations Food and Agricultural Organization. Rome, Italy. (www.fao.org)

Fruhwald, A., and B. Solberg (eds) 1995. Life-cycle analysis – a challenge for forestry and forest industries. EFI Proceedings No. 8, European Forest Institute, Joensuu. 278p.

Gitay, H., S. Brown, W. Easterling, B. Jallow. 2001. "Ecosystems and their services." Chapter 5 of *Climate Change: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change.

Haight, R.G., W.D. Smith, T.J. Straka. 1995. Hurricanes and the Economics of Loblolly Pine Plantations. *Forest Science*, 41(4): 675-688.

Haxeltine, A. and I.C. Prentice, I.C. 1996. "BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types." *Global Biogeochemical Cycles,* 10(4): 693-709.

Hoen, H.F. & B. Solberg 1994: Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *Forest Science,* 40:429-451.

Hoen, H.F. & B. Solberg 1997. CO_2-taxing, timber rotations, and market implications. In: Sedjo, R.A., R.N. Sampson & J. Wisniewski (eds.): Economics of carbon sequestration in forestry. *Critical Reviews in Environmental Science and Technology*, Vol. 27:151-162.

Hoen, H.F. and B. Solberg 1999. Policy options in carbon sequestration via sustainable forest management – an example from the North. In : Palo (ed.) Forest transition and carbon fluxes – global scenarios and policies. World Development Studies No.15:117-132. World Institute for Development Economics Research (WIDER), Helsinki.

Houghton, J.T., L.G. Meira Filho, B.A. Callender, N. Harris, A. Kattenberg, and K. Maskell. 1996. "The Science of Climate Change." Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Houghton, R.A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus*, 55b: 378-390.

Intergovernmental Panel on Climate Change. 2007a. Impacts, Adaptation and Vulnerability. Working Group II Report. (www.ipcc.ch)

Intergovernmental Panel on Climate Change. 2007b. The Physical Science Basis. Working Group 1 Report. (www.ipcc.ch)

rland, L.; D. Adams, R. Alig, C.J. Betz, C. Chen, M. Hutchins, B. A. McCarl, K. Skog, and Brent L. Sohngen. 2001. Assessing Socioeconomic Impacts of Climate Change on U.S. Forest, Wood-Product Markets, and Forest Recreation. *Bioscience*, 51(9): 753- 764.

Joyce, L.A., J.R. Mills, L.S. Heath, A.D. McGuire, R.W. Haynes, and R.A. Birdsey. 1995. Forest sector impacts from changes in forest productivity under climate change. *Journal of Biogeography*, 22: 703-713.

Joyce, L., J. Aber, S. McNulty, V. Dale, A. Hansen, L. Irland, R. Neilson, K. Skog. 2001. Potential Consequences of Climate Variability and Change for the Forests of the United States. Chapter 17 in Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. National Assessment Synthesis Team, US Global Change Research Program. (http://www.usgcrp.gov/usgcrp/Library/nationalassessment/)

Kallio, A.M.T, A. Moiseyev & B. Solberg 2006. Economic impacts of increased forest conservation in Europe: a forest sector analysis. *Environmental Science and Policy,* 491: 9-18.

Kauppi, P. 1999. Forest expansion and carbon fluxes in the North. . In : Palo (ed.) *Forest transition and carbon fluxes – global scenarios and policies*. World Development Studies No.15: 41-50. World Institute for Development Economics Research (WIDER), Helsinki.

Kauppi, P. and B. Solberg 1999. Forests and climate change – ecological and economic challenges. In: Palo, M. and J. Uusivuori (eds): *World Forest, Society and Environment*. World Forests Vol.1:121-126.

King, G.A. and R.P. Neilson. 1992. "The transient response of vegetation to climate change: A potential source of CO2 to the atmosphere." *Water, Air, and Soil Pollution*, 94: 365-383.

Kirschbaum, M.U.F. and A. Fischlin. 1996. "Climate Change Impacts on Forests." Chapter 1 in *Scientific-technical analysis of impacts, adaptations, and mitigation of climate change.* Edited by Watson, R.T., M.C. Zinyowera, and R.H. Moss. Contribution of Working Group II to the Second Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Kurz, W.A. and M.J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications*, 9(2): 526-547.

Lindner M. 2000. Developing adaptive forest management strategies to cope with climate change. *Tree Physiology*, 20: (5-6) 299-307.

Lindner M. 1999. Forest management strategies in the context of potential climate change. *Forstwissenschafliches Centralblatt*, 118: (1) 1-13.

Loomis, J. and J. Crespi. 1999. Estimated effect of climate-change on selected outdoor recreation activities in the United States. Chapter 11 in *The Impact of Climate*

Change on the United States Economy. R. Mendelsohn and J.E. Neumann (eds). Cambridge: Cambridge University Press.

Manne, A.S. and R.G. Richels. 2006. The Role of Non-CO2 Greenhouse Gases and Carbon Sinks in Meeting Climate Objectives. The Energy Journal. 27: 393-404.

McCarl, B. A., D. M. Burton, D. M. Adams, R. J. Alig and C. C. Chen. 2000. Forestry Effects of Global Climate Change. *Climate Research*, 15(3): 195-205.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore III, C.J. Vorosmarty, and A.L. Schloss. 1993. Global climate change and terrestrial net primary production. *Nature,* 363: 234-240.

Mendelsohn, R. and M. Markowski. 1999. The Impact of Climate Change on Outdoor Recreation. Chapter 10 in *The Impact of Climate Change on the United States Economy*. R. Mendelsohn and J.E. Neumann (eds). Cambridge: Cambridge University Press.

Metz, B., O. Davidson, R. Swart, and J. Pan. 2001. *Climate Change 2001: Mitigation.* Cambridge, UK: Cambridge University Press.

Mills, J.R. and R.W. Haynes 1995. Influence of climate change on supply and demand for timber. In *Productivity of America's forests and climate change*, ed. L.A. Joyce. General Technical Report RM-GTR-271. Fort Collins, US Department of Agriculture, Forest Service.

Murray B.C., B.A. McCarl, H. Lee. 2004. Estimating leakage from forest carbon sequestration programs. Land Economics 80(1):109–124

Murray, B.C., B.L. Sohngen, A.J. Sommer, B.M. Depro, K.M. Jones, B.A. McCarl, D. Gillig, B. DeAngelo, and K. Andrasko. 2005. EPA-R-05-006. Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture. Washington, D.C: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

Nilsson, Sten and Anatoly Shvidenko. 2000. Dynamics of carbon budget of the Russian forest sector in 1961-1998 and scenarios for 2010. Abstract in proceedings, *The Role of Boreal Forests and Forestry in the Global Carbon Budget.* Eds., M. Apps and J. Marsden. International Science Conference, Edmonton, Canada, May 8-12, 2000.

Norby, R.J., E.H. DeLucia, B. Gielend, C. Calfapietra, C.P. Giardina, J.S. King, J. Ledford, H.R. McCarthy, D.J.P. Moore, R. Ceulemans, P. De Angelis, A.C. Finzi, D.F. Karnosky, M.E. Kubiske, M. Lukac, K.S. Pregitzer, G.E. Scarascia-Mugnozzan, W.H. Schlesinger,, and R. Oren. 2005. Forest response to elevated CO2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences*. 102(50): 18052-18056.

Palo, M., E. Lehto, and J. Uusivuori. 2000. Underlying causes of deforestation: - modelling causes of deforestation with 477 subnational units. In: Palo, M. and H. Vanhanen (eds.): World forests from deforestation to transition. World Forest Series Vol II: 101-124. Kluwer.

Perez-Garcia, J., L.A. Joyce, A.D. McGuire, and C.S. Binkley. 1997. "Economic impact of climatic change on the global forest sector" In *Economics of Carbon Sequestration in Forestry,* eds. R.A. Sedjo; R.N. Sampson; and J. Wisniewski. Lewis Publishers, Boca Raton.

Petersen, A. K. and B. Solberg. 2002. Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction. Case: Beams at Gardermoen airport. *Environmental Science & Policy,* 5(2): 169-182.

Petersen, A. K. and B. Solberg. 2003. Substitution between floor constructions in wood and natural stone: comparison of energy consumption, GHG emissions, and costs over the life cycle. *Canadian Journal of Forest Researc,h* 33(6): 1061-1075.

Petersen, A. K. and B. Solberg. 2004. Comparison of GHG emissions and costs over the life cycle of flooring materials." *Climatic Change,* 64: 143-167.

Petersen, A. K. and B. Solberg. 2005. Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics* 7(3): 249-259.

Plantinga, A.J., T. Mauldin, and D.J. Miller. 1999. An econometric analysis of the costs of sequestering carbon in forests. *American Journal of Agricultural Economics,* 81(4): 812-824.

Prinn, R., H. Jacoby, A. Sokolov, C. Wang,, X. Xiao, Z. Yang, R. Eckhaus, P. Stone, D. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian, and Y. Liu. 1999. "Integrated global system model for climate policy assessment: Feedbacks and Sensitivity Studies." *Climatic Change*, 41: 469-546.

Raymer, A. K. P. 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy,* **30**: 605-617.

Reed, W.J. 1984. The Effects of the Risk of Fire on the Optimal Rotation of a Forest. *Journal of Environmental Economics and Management* , 11(2): 180-190.

Reilly, J., F. Tubiello, B. McCarl,, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagta, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg and C. Rosenzweig. 2003. U.S. Agriculture and Climate Change: New Results. Climatic Change 57: 43-69.

Sampson, R.N., and R.J. Scholes 2000. Additional human-induced activities-articl 3.4. In: Watson, R.T., I.R. Noble, B. Bolin, N.H Ravindranath, D.J. Verardo, and D.J. Dokken (eds.) 2000. "Land Use, Land-Use Change, and Forestry, 2000." Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge:182-281.

Sathaye, J., W. Makundi, L. Dale, P. Chan, and K. Andrasko. 2006. HG Mitigation Potential, Costs and Benefits in Global Forests. *Energy Journal*, 27:127-162.

Schimel D., J. Melillo, H.Q. Tian, A.D. McGuire, D. Kicklighter, T. Kittel, N. Rosenbloom, S. Running, P. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R. Neilson, and B. Rizzo. 2000. "Contribution of increasing CO2 and climate to carbon storage by ecosystems in the United States." *Science,* 287(5460): 2004-2006.

Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice. 2006. A climate-change risk analysis for world ecosystems. Proceedings of the National Academy of Sciences. 103(35): 13116–13120.

Shugart, H. H., M.Y. Antonovsky, P.G. Jarvis, and A.P. Sandford. 1986. "CO2, climatic change, and forest ecosystems." In *The Greenhouse Effect, Climatic Change and Ecosystems,* eds. B.Bolin; B.R. Doos; J. Jager; and R.A. Warrick. Wiley, Chichester.

Simangunsong, B. and J. Buongiorno. 2000. International Demand Equations for Forest Products: A comparison of methods. *Scandinavian Journal of Forest Economics* (in press).

Smith, T.M., and H.H. Shugart. 1993. The Potential Response of Global Terrestial Carbon Storage to a Climate-Change. *Water Air and Soil Pollution*, 70 (1-4): 629-642.

Sohngen, B. and R. Mendelsohn. 1998. "Valuing the Market Impact of Large Scale Ecological Change: The Effect of Climate Change on US Timber." *American Economic Review,* 88(4): 689 - 710.

Sohngen, B., R. Mendelsohn, and R. Neilson. 1998. Predicting CO_2 emissions from forests during climate change: A Comparison of Human and Natural Response Models. *Ambio.* 27(7): 509-513.

Sohngen, B., R. Mendelsohn, R. Sedjo. 1999. "Forest Management, Conservation, and Global Timber Markets" *American Journal of Agricultural Economics*, 81(1): 1-13.

Sohngen, B. and R. Sedjo. 2000. "Potential Carbon Flux from Timber Harvests and Management in the Context of a Global Timber Market." *Climatic Change,* 44: 151-172.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 2000. Measuring Climate Change Impacts with a Global Timber Model. Working Paper. Department of Agricultural, Environmental, and Development Economics. The Ohio State University.

Sohngen, B. and R. Alig. 2000. Mitigation, adaptation, and climate change: Results from Recent research on U.S. Timber markets. *Environmental Science and Policy,* 3: 235-248.

Sohngen, B. and R. Mendelsohn. 2003. An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics*, 85(2): 448-457.

Sohngen, B. and S. Brown. 2004. Measuring Leakage from Carbon Projects in Open Economies: A Stop Timber Harvesting Project as a Case Study. *Canadian Journal of Forest Research*, 34: 829-839

Sohngen, B and R. Sedjo. 2006. "Carbon Sequestration in Global Forests Under Different Carbon Price Regimes." *Energy Journal,* 27:109-126.

Sohngen, B. and R. Mendelsohn. 2007. "A Sensitivity Analysis of Carbon Sequestration." In *Human-Induced Climate Change: An Interdisciplinary Assessment*. Edited by M. Schlesinger, et al. Cambridge: Cambridge University Press.

Solberg, B., D. Brooks, H. Pajuoja, T.J. Peck, and P.A. Wardle. 1996. "Long-term trends and prospects in world supply and demand for wood and impolications for sustainable forest management – a synthesis." In *Long-term Trends and Prospects in World Supply and Demand for Wood and Implications for Sustainable Forest Management.* Edited by B. Solberg. European Forest Institute Research Report 6. Joensuu, Finland: European Forest Institute.

Solberg, B., A. Moiseyev, and A. M. I. Kallio 2003. Economic impacts of accelerating forest growth in Europe. *Forest Policy and Economics* 5:157-171.

Solberg, B. 1997. Forest biomass as carbon sink -economic value and forest management In: Sedjo, R.A., R.N. Sampson & J. Wisniewski (eds.): Economics of carbon sequestration in forestry. Critical Reviews in Environmental Science and Technology. Vol. 27: 323-334.

Solomon, AM and AP Kirilenko. 1997. Climate change and terrestrial biomass: what if trees do not migrate? *Global Ecology and Biogeography Letters*, 6, 139-148.

Solomon, A.M. and R. Leemans. 1997. Boreal forest carbon stocks and wood supply: past, present, and future responses to a changing climate, agriculture, and species availability. *Agricultural and Forest Meteorology*. 84: 137-151.

Tian, H. J.M. Melillo, D.W. Kicklighter, A.D. McGuire, J. Helfrich, B. Moore III, and C.J. Vorosmarty. 1998. Effect of interannual climate variability on carbon storage in Amazonian ecosystems. *Nature,* 396: 664-667.

Trømborg, E ,. J. Buongiorno and B. Solberg. 2000. The global timber market: Implications of changes in economic growth, timber supply and technological trends. *Forest Policy and Economics*, (1) 1: 53-71.

USDA Forest Service. 1988. The South's Fourth Forest: Alternatives for the Future. USDA Forest Service Forest Resources Report No. 24. Washington, DC.

VEMAP Members. 1995. "Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochemical Cycles,* 9(4): 407-437.

Wall, G. 1998. Implications of global climate change for tourism and recreation in wetland areas. *Climatic Change*, 40: 371-389.

Watson, R.T., M.C. Zinyowera, and R.H. Moss. 1996. Scientific-technical analysis of impacts, adaptations, and mitigation of climate change. Contribution of Working Group II to the Second Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Watson, R.T., M.C. Zinyowera, and R.H. Moss. 1998. The Regional Impacts of Climate Change: An Assessment of Vulnerability. A Special Report of the Intergovernmental Panel on Climate Change Working Group II. Cambridge University Press, Cambridge.

Watson, R.T., I.R. Noble, B. Bolin, N.H Ravindranath, D.J. Verardo, and D.J. Dokken. 2000 (eds). Land Use, Land-Use Change, and Forestry, 2000. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Westerling, A.L., H.G., Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science,* 313 :940-943.

Weyant, J. F.C. de la Chesnaye, and G.J. Blanford. 2006. Overview of EMF-21: Multigas Mitigation and Climate Policy. *Energy Journal*, 27: 1-32.

Table 1: Actual timber harvest in 1995 (million m3), base timber harvest intensity (m^3/ha/year) for different land ownership types, and assumed percentage change in timber harvest intensity by 2020 under two alternative scenarios (adapted from Solberg et al. 1996).

	Temperate Industry	Tropical Plantations	Temperate NIPF	Temperate Public	ROW[1]	Global
1995 TimberHarvest (million m^3 /year)	196	65	419	307	592	1579[2]
1995 Timber Harvest Intensity (m^3/ha/yr)	4.56	2.83	1.93	1.41	0.25	0.54
Base Scenario	21%	112%	30%	42%	40%	50%
Optimistic Plantation Scenario	32%	112%	55%	60%	40%	63%

[1] ROW = Rest of World.
[2] Represents total global timber harvests, not average.

Table 2: Ecological and Economic Implications of Climate Change on the Forest Sector (↑ = increases in indicator; ↓ = decreases in indicator; ↕ = both increases and decreases in indicator likely; double arrows indicate stronger effects likely)

	Short-Term (2005 – 2025)	Medium-Term (2025 – 2065)	Long-Term (2065 – 2105)
Boreal	• ↑ Productivity, • ↑ Risk of fire/natural disturbance • ↑ Salvage; ↑ Timber Supply.	• ↕ Productivity • ↑↑ Risk of fire/natural disturbance • ↑ Expansion of species northward • ↑ Southern range displaced by more southerly forest types. • ↑ Salvage; ↑ Timber Supply	• ↕ Productivity • ↑↑ Risk of fire/natural disturbance • ↑↑ Expansion of species northward • ↑↑ Southern range displaced by more southerly forest types. • ↑ Salvage; ↑ Timber Supply
Temperate	• ↕ Productivity, • ↕ Timber Supply, ↓ Timber Prices	• ↕ Productivity. • ↑ Risk of fire/natural disturbance • ↑ Movement of species northward. • ↑ Salvage; ↑ Timber Supply	• ↕ Productivity. • ↑↑ Risk of fire/natural disturbance • ↑ Movement of species northward. • ↑ Salvage; ↑ Timber Supply
Tropical	• ↕ Productivity, • ↑ Plantation establishment • ↑ Timber supply to world market	• ↕ Productivity. • ↑ Risk of fire/natural disturbance • ↑ Risks to plantations and natural forests • ↑ Salvage; ↑ Timber Supply	• ↕ Productivity. • ↑↑ Risk of fire/natural disturbance • ↑ Risks to plantations and natural forests • ↑ Salvage; ↑ Timber Supply
World Market Effect	• ↑ Supply from rising productivity and the possibility of salvage. • ↓ World Timber Prices • ↕ Producer welfare • ↑ Consumer welfare	• ↑ Supply from rising productivity due to and the possibility of salvage. • ↓ World Timber Prices • ↕ Producer welfare • ↑ Consumer welfare	• ↑ Supply from rising productivity and the possibility of salvage. • ↓ World Timber Prices • ↕ Producer welfare • ↑ Consumer welfare