

The Forest Sector in a Climate-Changed Environment—A Briefing Paper

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Summary

Across the globe and in the U.S., it is anticipated that forest resources in rural and urban settings will be affected by climate-change induced impacts to forest growing conditions, including CO₂ fertilization and disturbance regimes. These changing forest conditions are projected to trace through to changes in management regimes, production practices, and, potentially, the uses of timberlands within the forest products sector. In this paper, we report the results of studies that have used economic models to trace changes in forest growth as result of climate change to changes in behavior within the forest products sector. We also provide a discussion of the importance of urban forests, some potential impacts to urban forests from increased disturbance as result of climate change, and associated research needs.

In the studies considered here (and in the current reports from the Intergovernmental Panel on Climate Change), forest productivity, globally and across the U.S., is projected to increase in aggregate under climate change. In the U.S., growth increases are projected to be fairly small (e.g., 1 to 3 percent per decade relative to the baseline), with increases generally projected for the North and West regions in most climate scenarios. Forest growth in the South is projected to decline in several climate scenarios because of projected limited water availability in an increased temperature environment. Although growth is projected to increase in aggregate, dieback of existing trees, increased disturbance in the U.S. South and West, and shifts in the location of some forest types are also projected to in many studies.

Under climate change, and when forest yields increase, timber harvest rotations in the U.S. are projected to increase slightly in the coming decades compared to baseline projections. When forest yields decrease, such as is projected in some scenarios for the southern U.S., timber rotations are projected to shorten. Timber rotations may also shorten if producers become concerned that the risk from dieback or disturbance is too great. Concurrent to an increase in timber rotation length, timber harvest volumes are projected to increase in aggregate. Globally, the greatest increases are projected for the lower Mid-latitude forests. In the U.S., slight increases in timber harvest are projected in most regions, with the West projected to have the greatest increases in one study. Under a lower emissions/lower temperature scenario considered in one study, timber harvests were reduced in the U.S. South. Harvests in Canada are projected to decline under climate change. One study projected a general increase in sawtimber production in the U.S. but a decline in pulpwood production under climate change.

As result of increased supply, timber prices are consistently projected to decline in the models considered here. Global prices are projected to decline by up to 3 percent relative to baseline projection in the coming decades. The greatest price reductions in the coming decades were projected for Scandinavia and the smallest price declines were projected for Canada. For the U.S., price declines were not found to differ between regions in the existing models. Increased dieback because of climate change had some impact on projected price changes, but did not change the overall relationship.

There are important uncertainties to consider when interpreting the results of existing studies of climate change impacts on the forest sector, including the potential for increased dieback and the capacity of the private forest landowners to respond optimally to changing climate. Increased dieback from climate change is explicitly modeled in only one of the existing studies. The extent to which climate change will increase dieback and disturbance is largely unknown, although a number of studies now project increased levels of wildfire and insects and disease outbreaks under climate change. To some extent, increased dieback and disturbance is likely to be mitigated or adapted to in future forest management actions. A significant increase in dieback and disturbance relative to historic patterns could yield changes in the forest products sector that differ from current model projections. Additional research efforts that quantify how increased dieback and disturbance will affect the forest products sector will help to address this uncertainty.

The U.S. timber industry is experiencing a general reduction in capacity (e.g., milling infrastructure), a move away from vertically-integrated companies (i.e., a forest product company owns the mill as well as the timberland) to a business model where timber is obtained from lands owned by other corporations and private entities, and production is regionally concentrated. Additionally, the proportion of forestland owned by non-industrial forest landowners, including those who often have no forest management plan and objectives other than timber production, is increasing. The degree to which product producers and timberland owners are positioned to optimally respond to changing forest conditions is somewhat in doubt. The present situation of the timber producers and land ownership could lead to changes in the forest sector from climate change that are not

consistent with the projections reported here. However, strategies developed by land agencies and conservation organizations that recognize these challenges may improve the mitigation and adaptation behavior of the timber producers and landowners.

Approximately 80 percent of the U.S. population lives in urban areas and the urban forest is estimated to encompass some 3.8 billion trees. Trees provide a number of ecological services to urban ecosystems and cultural benefits to urban residents. Trees have regularly been found to increase the values of residential properties. Recent outbreaks of insects and diseases, as well as other disturbances, have been costly and damaging to urban forests in many locations. A primary concern for the future is the potential for climate change to increase the frequency and severity of disturbance to urban forests. Between 2009 and 2018, treatment in the eastern U.S. for the emerald ash borer, an invasive beetle that has damaged extensive urban forest areas, is projected to cost more than \$1 billion.

There are a number of opportunities for additional research examining how climate change might influence the forest sector. First, it would be useful to update the existing studies using the most recent climate expectations and economic models. Second, global trade is an important factor in the forest sector and additional research that better captures the recent dynamics of global forest products trade will be useful. Finally, it appears increasingly likely that the U.S. will pursue some additional climate policies that may affect the forest sector. Additional research to examine how the forest sector responds to concurrent changes in climate conditions, adaptation actions, and comprehensive climate

policies (e.g., a carbon cap and trade system, increased demand for woody biomass for biofuels) will help to provide more comprehensive projections of the future forest products sector.

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Introduction

Policies adopted to address climate change will influence the extent, composition, and management of future forests. At the same time as policy is causing forest changes, climate change itself is expected to yield changes to environmental conditions, influencing the characteristics and growth of forests in rural and urban settings. In response to changes in forest productivity, timber producers will likely change management regimes, production practices, and, potentially, the uses of timberlands. Similarly, climate-induced changes in composition and health of urban forests may change the service flows that urban residents receive from those forests. The effects of climate policies on the potential future conditions of forests are discussed in other reports. The focus of this paper is how the forest sector may change in response to future altered climate conditions. To accomplish this, we rely on a number of U.S. studies, including those that utilize economic models to trace changes in forest conditions to responses in forest sector markets and timber production.

A number of studies have focused on changes in ecological processes in forested ecosystems as result of an altered climate (e.g., Joyce 1995, Joyce and Birdsey 2000, Iverson et al. 2008, Latta et al. 2010). Economic studies, including the ones discussed in this paper, extend that ecological research by explicitly including human activities (e.g., the demand for forest products by consumers, the desire to live in amenity-rich settings) in analyses of projected future forest conditions and landscapes. In the U.S., especially on private lands, landscape conditions reflect human activities (e.g., land-use change), forest

management (e.g., silviculture systems), and the demands for products (e.g., timber) and services (e.g., recreation opportunities) from natural environments. The models described in this briefing paper focus on land-use changes involving forests, forest management activities, and the demand for timber products. The impacts of climate change on other forest products and services, such as recreation opportunities, have been discussed to a limited extent elsewhere (e.g., Irland et al. 2001).

The next section briefly describes the observed changes in climate and projections of future climate conditions as identified by the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC). Further description of these expectations are available in IPCC reports (Field et al. 2007, IPCC 2007) and a short briefing paper for policy makers developed by the Pew Center (Pew Center 2007). We then briefly discuss the projected changes to forests from changes in climate conditions. Although the literature on this subject is extensive and at times contradictory, we present a brief summary and rely on others (e.g. Joyce and Birdsey 2000, Field et al. 2007) to give this topic more comprehensive treatment. Next, we describe the approaches that economists have adopted to trace expected changes in forest growth through to impacts on the forest sector, including on forest management. Following that, we discuss the factors believed to be important in influencing future timber availability, relying often on the inputs to the forest sector studies included in this synthesis. Following that, we describe the modeled impacts on timber production, prices, forest management, and other factors as estimated from the existing models. Next, we describe the projected welfare impacts to wood product consumers and timber producers as result of climate change. In

the penultimate section we examine some of the benefits received by society from urban forests and potential impacts of global change on those forests. Finally, we close with a number of conclusions drawn from the models considered here and several opportunities for future research.

Observed Climate Changes and Projections for the Future

One challenge to projecting future forest conditions is the uncertainty surrounding future climate. Published summaries of work being completed by the IPCC indicate that warming of the planet is now “unequivocal” (IPCC 2007, Pew Center 2007). Between 1955 and 2005, temperatures in North America increased moderately, with the increases becoming greater as one moves northwestward from the Southeast, towards Alaska and northwestern Canada (Field et al. 2007). Whether this warming is currently yielding changes in natural systems is less certain, with expert opinions indicating even likelihood and unlikelihood that some impacts of climate change on natural systems are now beginning to emerge. Looking forward, the IPCC has concluded that average global temperature increases over the 21st century are expected to range from 1.8 to 4.0 degrees centigrade (IPCC 2007, Pew Center 2007). In North America, average temperature increases are projected to be 1 to 3 degrees centigrade by 2040, increasing to 2 to 3 degrees centigrade late in the century (Field et al. 2007). For land areas, warming is anticipated to be greatest over the high northern latitudes. The IPCC has determined it is “very likely” (> 90 percent probability) based on evidence there will be an increase in the frequency of hot extremes, heat waves, and heavy precipitation (IPCC 2007). Uncertainty

in these projections increases as anticipated global conditions are downscaled to regional conditions. The IPCC deemed it was “very likely” that precipitation will increase at high latitudes and “likely” (> 66 percent probability) to decrease in most subtropical regions. Areas in the southern and southwestern U.S. are considered to be in the subtropical zone. Precipitation in U.S. is projected to decrease in the southwest but increase elsewhere (Field et al. 2007). Further, the IPCC reports “high confidence” (80 percent agreement) that areas such as the western U.S. will experience a decrease in water availability as a result of climate change (Pew Center 2007). In some areas, such as the West, precipitation may increasingly be in the form of rain rather than snow, decreasing snowmelt water availability (Field et al. 2007). The current IPCC climate scenarios each project continued increases in greenhouse gases (GHG) (including CO₂) over the next several decades. However, GHG emissions in recent years have been below projections because of the global economic downturn.

Climate Change and Forest Impacts

At the most general, forest responses to climate change are expected to involve changes in forest location, the combinations of forest species and classes on the landscape (i.e., forest compositions), and growth rate and timber yield (Shugart et al. 2003). These expected changes result largely from climate-change induced changes in temperature, precipitation, and atmospheric CO₂ levels as well as a general lengthening of the growing season. Although these general relationships are fairly accepted, there remains a fair amount of uncertainty about the forest conditions in specific regions likely to result from

climate change. Much of this uncertainty relates to ecosystem complexity, the variety of ecosystem conditions involved, and the ability of ecosystems to adapt (including through human intervention). In one example of uncertainty because of complexity, there is a lack of agreement on the extent to which increases in atmospheric CO₂ will have a fertilizer effect on plants (e.g., Norby et al. 2005, Reich et al. 2006, Thornton et al. 2009, McKinley et al. 2009). Some believe that while increased CO₂ promotes plant growth, over large areas limitations in other inputs to plant growth (e.g., nitrogen or water availability) may reduce these increases. For example, nitrogen is required for tissue growth and, even in the presence of elevated CO₂, limited nitrogen may limit increased growth rates (e.g., Joyce 1995).

Uncertainty in ecosystem response also results from the range of environmental conditions projected from the global circulation models (GCMs) commonly relied on for economic studies. Generally, however, tree physiology and growth are expected to be altered by increases in atmospheric CO₂ concentration and changes in temperature and water availability conditions (Field et al. 2007). How these changes interact with the limiting factors and existing ecosystem processes and linkages will differ by region. Over large areas, it may take many decades for the impacts of climate changes on forests to be evident. However, localized impacts (e.g., warming in sensitive alpine ecosystems) may be evident much faster.

Bosworth et al. (2008) describe a number of uncertainties related to how future forest conditions may be influenced by climate change. First, there is potential for forest

condition changes to result in feedbacks that may mitigate or enhance forest changes. For example, increased forest growth or migration of forests into areas largely nonforested may reduce surface albedo—increasing the localized warming that influenced initial growth increases or migration (see Chapin et al. 2002 and Thompson et al. 2009 for discussions). Second, increases in ozone, which can damage tree leaves and slow growth, may offset any increases in growth as result of increased atmospheric CO₂, water availability, or growing season. Third, the impacts that increased vigor of invasive weeds, responding to improved growing conditions, may have on stand productivity is uncertain. There is some evidence that invasive weeds, similar to trees, respond well initially to increased levels of CO₂ (Ziska 2003). The items identified by Bosworth et al. (2008) are not explicitly incorporated in the economic studies considered here.

Conceptual Linkages between Climate Conditions and the Forest Sector

To project how future climate conditions may impact the forest sector, economists must link expected forest changes to the inputs and parameters used in forest sector economic models. Conceptually, future climate change could impact both the existing timber stands (the existing “stocks” of resources) as well as the future incremental growth rates of existing and new timber stands (the “flows”) (Sohngen and Sedjo 2005). Mortality, as a result of fire or insect disturbances or long-term changes in environmental conditions, may result in losses in the existing stocks of forests. At the same time, the “flows” of future incremental growth in forest stands may increase or decrease as a result of the changes in growing conditions (e.g., temperature, precipitation, CO₂) from climate

change. Impacts on the stocks and flows of forest resources, along with other factors such as changing management practices, will combine to yield the future forest conditions. Stated differently, climate change is expected to impact current forests through magnified disturbance regimes (e.g., fire, insects, and disease) and future forests through changes in growth rates, mortality rates, and seed production for future forests (especially in unmanaged stands) (Alig et al. 2004b). Combined, these factors will influence future forest conditions and forest management activities.

Humans (as consumers) are connected to forested ecosystems through the market (e.g., timber) and non-market (e.g., recreation opportunities) products and services we receive from forests. Changing forest conditions impact the supply of timber available for use in the production of wood products. Changes in supply of wood products trace through into short-term changes in the prices of wood products, all else being equal. Increases in the price of wood products may reduce the consumption of wood products generally and the substitution from some wood products (e.g. dimensional lumber) to others (e.g., engineered wood products) or to non-wood products (e.g., steel 2X4s). Conversely, declines in wood product price would likely increase the consumption of wood products, all else being equal, and possibly result in the substitution of wood products for non-wood products.

In addition to changes in the behavior of consumers that result from changing forest conditions, producers of wood products and timber may change their practices in response to changing forest conditions. Timber producers may alter their management

strategies to take advantage of changing growing conditions and timber markets. For example, if incremental growth rates experience a marked increase, timber producers may extend rotation lengths to take advantage of additional revenue from growth that could be generated, net of forest management costs. Manufacturers may alter the types of products they produce in response to changes in the forest supply (e.g., a greater reliance on producing dimension lumber relative to engineered wood products or vice versa). Over longer timeframes, the wood products sector may change their timber processing infrastructure and material handling systems in response to changes in the flow and quality of supplied timber.

Model Operation

Two general approaches have been adopted to examine the potential impacts of climate change on the forest sector using economic models. The first general approach uses the output of GCMs to inform changes to the forest growth rates (the flows) and forest extent and disturbance (the stocks) used as inputs in the economic model. Often an intermediate model is used to translate the changing environmental conditions identified in the GCM to changes in net primary productivity (or other parameters) that can be used to modify inputs in the economic model (e.g., Joyce 1995, Perez-Garcia et al. 2002). In all the cases described in this study, timber yields in the economic model are modified to reflect the changing growing conditions under climate change (i.e., the flows) (e.g., Joyce 1995, Alig et al. 2002, Perez-Garcia et al. 2002, Sohngen and Sedjo 2005, Sohngen et al. 2001, Irland et al. 2001). A limited number of studies have also changed input parameters for

existing stocks to reflect dieback of existing stands as result of climate change (e.g., Sohngen and Mendelsohn 1998, Sohngen et al. 2001). The timing of the expected climate conditions is important because most forest sector economic models project conditions for many decades into the future. Typically, in the studies considered here, the GCM has been used to depict climate conditions mid-21st century (e.g., 2065) in the equilibrium that would result with atmospheric CO₂ at some projected future increased level (e.g., 625 parts per million, ppm) (Shugart et al. 2003) (e.g., Mills and Haynes 1995, Sohngen and Mendelsohn 1998, Perez-Garcia et al. 2002). A linear trend between now and those estimated future conditions is then often used as input to the intermediate model or as direct changes in the growth and yield parameters. A limited number of studies have estimated decadal conditions from GCMs as inputs to an ecosystem model and economic model (e.g., Irland et al. 2001).

The second approach to examining the impacts of climate change on forests using economic models is to utilize sensitivity analysis rather than explicit inputs from GCMs or ecosystem models (e.g., McCarl et al. 2000). Rather than using the output of GCMs and intermediate models to identify new values for inputs and parameters under a changed climate in the economic model, the sensitivity analysis approach examines a range of new values for model inputs and parameter values. The response to these changes in inputs and parameters is then used to identify likely responses of the forest sector to changes in forest characteristics such as growth and yield. If the range of input values considered is large enough, a sensitivity analysis approach is useful in that it can provide “sideboards” on the likely future changes in the forest sector in response to

climate change. The sensitivity approach is accommodating to changing expectations on forest growing conditions because a range of future conditions have already been simulated.

Anticipated Timber Availability Factors under Climate Change

There are a number of factors that will influence the availability of timber in a climate-changed environment. Perhaps most recognized is the anticipated changes in growth and yield of timber (the flows described above) as result of climate change. However, several other factors could impact the availability of timber, including land-use changes, shifts in species distribution shifts, dieback associated with heat, drought, and increased disturbance, and land ownership patterns.

Changes in Growth and Yield

In the studies considered here, over broad geographic areas, climate change is anticipated to increase the growth and yield of timber (e.g., Alig et al. 2004b, Sohngen et al. 2001, Joyce 1995). In the study by Irland et al. (2001), timber growth in the U.S. was projected to increase by 1 to 3 percent per decade relative to the baseline projections under all the scenarios considered. In their global analysis, Sohngen et al (2001) projected global forest productivity increases of 29 and 38 percent relative to the baseline by 2145, for the UIUC and Hamburg climate scenarios available at the time. The increases projected for North America (17 percent) by 2145 were less than the global increase because the higher latitudes are projected to suffer some losses to productivity from climate change. In

addition to the productivity increase, Sohngen et al. (2001) project an increase in yield of timber (accounting for shifts of productive southern species northward) in North America, of between 34 and 41 percent by 2145. Perez-Garcia et al. (2002) assume a direct relationship between forest carbon and forest productivity and they project forest carbon increases in the West Coast U.S. of between 2 and 15 percent and from less than 2 to 10 percent in the East by 2040, with increasing forest carbon under higher CO₂ emissions/hotter temperature scenarios. In Perez-Garcia et al. (2002), softwoods were projected to have a greater positive response to climate change than hardwoods.

Changes in growth and yield are projected to differ by U.S. region, with the Northeast generally projected to benefit. The South is projected to lose productivity under some scenarios because of a combination of warmer temperatures but decreased water availability. Alig et al. (2002) estimated that growth rates in the Northeast would increase, such as 0.3 percent annually for oak/hickory, but growth rates would decline across the South. Sohngen and Sedjo (2005) state the South appears to be the most “vulnerable region” in terms of forest growth and the forest sector because of climate change. Additionally, those authors suggest that the northern conifer forests and those in the Mountain West are most susceptible to damage because of a changing growing environment and increased disturbance.

Land-use changes

Most studies thus far have assumed that the total area of land in agriculture and the total

area of land in forests will remain about the same even as climate changes. Although the total area of land in agriculture and forestry may indeed remain relatively constant over time, climate change could alter the distribution of land uses over time. Given that forest areas could be affected and the potential human and social consequences of these impacts, it is important to consider and assess the implications of climate change on the distribution of U.S. land uses.

Differential impacts of climate change in agriculture and forestry could lead to land-use shifts as one possible adaptation strategy by landowners. For example, if climate change results in relatively higher agricultural productivity per acre, some acres may be converted from forests to agricultural use. Such changes would alter the supply of products to national and international markets, changing the prices of forest products and the economic well-being of both producers and consumers. If climate change affects yields and costs of production for forest stands and agricultural crops, land could shift between forestry and agricultural uses as these two sectors adjust to climate changes. Given that the agricultural and forestry sectors sometimes compete for the same land, thus shifts in productivity of agricultural land could affect the ultimate distribution of forestland, and vice versa.

Using four climate change scenarios from the national assessment of climate change, Alig et al. (2002) found that less forested area was projected under four climate scenarios relative to the base case (no climate change). Furthermore, less cropland and more pasture land were projected to convert to forests under all scenarios. With their modeling

of the forest and agricultural sector and exogenous estimates of productivity impacts at the time, Alig et al. (2002) provided regional results. Although climate change is likely to affect the margin between forestry and agriculture in specific locations, aggregate productivity changes in forestry appear to outstrip aggregate productivity changes in agriculture.

Economic impacts of climate change on land use distribution could also involve human migration patterns and impact the area of urban and developed areas by region. Regional patterns of growth and decline in the United States have shifted population and property value to more vulnerable areas (van der Vink et al. 1998), and concerns about climate change and severe weather events could alter coastal settlement patterns. A large amount of uncertainty surrounds any such movement of population and land use impacts.

In addition to effects from adaptation, climate change policies may involve mitigation actions that can markedly impact the land use distribution in a region. Although outside the scope of this chapter, Alig (2010) in a subsequent chapter in this volume summarizes recent results from studies that have examined possible implications for land use in the U.S. of different policies that would promote reduced deforestation and active afforestation on former agricultural land to increase net carbon sequestration as part of climate change mitigation strategies.

Species Shifts

Changes in forest type and tree species distributions could have a number of ecological and forest sector consequences. Within regions of the U.S., the forest sector has developed infrastructure and management systems based on current forest type distribution and dominant market species. Changes in forest type and species distribution may, over the long-term, lead to changes in the equipment used in the harvesting and processing timber and in forest management practices. Shifts in the distribution of species in response to changing habitat conditions may occur as result of natural migration of species in response to changes in growing conditions or, perhaps more likely, as result of changes in forest management and the tree species selected for reforestation or afforestation. Changes in tree species distribution could include land-use changes if forests move to land currently used for agriculture or other uses.

Modeling the projected shift in suitable habitat over the next century or more, Iverson et al. (2008) projected shifts northeastward of many eastern tree species. Some species were projected to move up to 500 miles under the highest emissions/hottest temperature scenario considered. In addition to shifting suitable habitat location, the area of suitable habitat for individual tree species may also change. About half of the species considered by Iverson et al. (2008) were projected to have an increase in habitat area. Both oak and pine species were projected to experience increases in habitat area, with a stretch toward the northeast. Losses in habitat area in the U.S. were projected for those northernmost forest types, including the maple-beech-birch, spruce-fir, and aspen-birch types (Fig. 1.). Those forest types are projected to have expansions in suitable habitat area in Canada. The types of shifts identified by Iverson et al. (2008) are reflected generally in the inputs

in some of the economic models considered here (e.g., Sohngen et al. 2001). Iverson et al. (2008) note that it is very unlikely that expanding tree species would widely colonize newly-suitable habitat without human intervention.

Dieback and Disturbance Regimes

In addition to the changes that may occur in the flow of resources, the stocks of current resources may be reduced through dieback that results because of climate change.

Dieback is typically modeled as a reduction in the suitability of growing conditions or as increased mortality from more frequent or more severe disturbance. Dieback from growing condition change is anticipated to result from increased heat and reduced water availability. The southern U.S. is thought to be the U.S. area with the greatest potential to experience limited water availability and heat induced dieback in timber over the next several decades, although increased growth is projected later in the decade as managers respond to changing environmental conditions (e.g., Alig et al. 2004b).

The IPCC has expressed high confidence that the North American forest sector will likely be sensitive to changes in disturbance regimes from climate change (Field et al. 2007).

Increases in disturbance are most frequently projected for the western U.S. via more frequent or severe wildfires and insect and disease outbreaks (e.g., Bosworth et al. 2008).

Citing the research of others, the IPCC suggests that the period of high risk for wildfire ignitions could increase by 10 to 30 percent and burned area could double under climate change (Field et al. 2007). Gan (2004) found that the infestation risk of the southern pine beetle may increase by 2.5 to 5 times under changed climate conditions. If southern pine

shifts northward, the increase risk might be 4 to 7.5 times higher than present risk.

Research completed in the Pacific Northwest has found that increased winter temperature and spring precipitation have contributed to the occurrence of Swiss needle cast disease (Stone et al. 2008). Anticipated continued increases in temperature and precipitation from climate change are expected to lead to increasing spread and severity of that disease. Increased disturbance under climate change also includes the potential for increased frequency and magnitude of wind events (e.g., windthrow) and ice storms, which are more often associated with eastern forests.

Disturbance events can be modeled through changes in the existing stocks of forest resources. Historical dieback patterns are implicit in the growth and yield functions used to project future forest volumes. In the economic modeling literature, few studies account for dieback events that depart from historical patterns. However, the IPCC has stated (Field 2007) “very high confidence” (i.e., > 90 percent agreement in statement) that disturbances are currently increasing relative to historic patterns and will continue to increase. Currently, Sohngen (e.g., Sohngen and Mendelsohn 1998, Sohngen et al. 2001) has the most explicit inclusion of additional dieback anticipated from climate change. Under the assumptions adopted in Sohngen et al. (2001), 75 percent of the trees killed from dieback are available for timber salvage at their current volume. Future increases in value that would have occurred for the killed stocks are lost in the Sohngen et al. (2001) treatment.

One potential positive outcome of dieback is that timber producers can replant affected stands with species or varieties appropriate for the new growing conditions (e.g., Joyce 2007). Sedjo and Sohngen (1998) point out that although extensive dieback could result in “substantial damage” if forests were unable to provide their current levels of ecosystem services, natural systems tend to respond quickly to disturbance. Additionally, if dieback were to increase significantly from historic levels, we could expect increased human intervention to mitigate at least some of the impact of that disturbance. This pattern has been exhibited in the increased attention to fuels treatment and expansion in fire suppression capacity as result of previous years’ increases in wildfire costs and burned acres. In later sections, when possible, model results are discussed both with and without dieback outcomes.

Public and Private Timberland Ownership

The patterns of forest ownership may also factor into future timber availability under climate change conditions. Land ownership may influence timber availability because of differential impacts to growing conditions on lands in differing ownership groups and because different ownership groups may respond in divergent ways to changes in forest growing conditions. Private timberlands provide the vast majority of the timber currently produced in the U.S., with much of the timber coming from private lands in the South (Adams et al. 2006). If climate change were to have greater negative impacts on growth and yield on private lands, this could magnify the consequences for U.S. timber production. Currently, the economic studies considered here do not explicitly incorporate land ownership patterns into projections of climate change growth and yield; however, in

general, most timber is assumed to come from privately-owned timberlands (e.g., McCarl et al. 2000, Irland et al. 2001).

Differential impacts by land ownership from climate change in the U.S. are most likely in topographically rich landscapes, but could occur anywhere with systematic spatial patterns of land ownership. In many areas of the western U.S., private lands are concentrated at lower elevations and public lands are concentrated at higher elevations. If climate change has a differential impact on the growing conditions of low-elevation forests, the private/public pattern of land ownership in the West could impact future timber production. In Washington and Oregon, Latta et al. (2010) have projected that private forestlands at low elevations would experience declines in productivity, while the higher elevation forests (in public ownership) would experience productivity increases. If such systematic differences are not adequately captured in economic models, gains in timber production, as estimated from the models, could be reduced because private timberlands provide most of the timber but suffer under climate change. However, because the West is most likely to experience systematic ownership differences in forest growing conditions from climate change and the East currently accounts for the majority of U.S. timberland and timber production, the impact of systematic ownership patterns on projected timber production is probably minor.

Private individuals and corporations own forestland for a variety of reasons. Individuals who own timberland tend to do so for reasons other than timber production, such as aesthetics, privacy, and recreation (Smith et al. 2009). Private individuals are much less

likely to have written forest management plans. Corporations tend to manage land for financial returns, including returns from timber production. Because their ownership objectives and management capacities differ, the responses of private individuals to changes in forest conditions may be different from private corporations. It is possible, that private corporations may respond aggressively with mitigating activities to changing forest conditions and disturbance, while private individuals respond more passively. None of the modeling studies considered here differentiates growth and yield changes or dieback magnitude under climate change by type of private ownership. In considering mitigating behaviors and future conditions, it is useful to consider that different strategies for responding to climate change (e.g., planting newly-suitable species, responding to increased disturbance regimes) may need to be tailored for the different private ownership groups.

Timber Management under Climate Change

With climate change, forest management activities by producers, including choices of planting stock, thinning regimes, and harvesting practices, could be changed to take advantage of both new growing conditions and changes in forest sector markets (Alig et al. 2004b). For example, private timberland owners suffering production declines as result of climate change (and wishing to maintain current production levels) would need to intensify management systems (e.g., planting improved stock or conducting more aggressive thinning or fertilizing activities) (Latta et al. 2010). Conversely, landowners facing increased productivity may need to change management regimes to accommodate

increased growth or to take advantage of other market opportunities (e.g., carbon offset payments). In addition to forest management activities during the rotation, harvesting choices (e.g., rotation ages, silviculture systems) could also be modified in response to changing growing conditions or forest product markets (Alig et al. 2004b).

Timber Rotation Lengths

In general, the yields of forests communities in North America are expected to increase because of the fertilization effect of CO₂ and a longer growing season (Field et al. 2007). In those places where timber yields increase, timber production is generally projected to increase and stumpage prices are projected to decline. This results in lengthened timber rotations relative to current practice (McCarl et al. 2000, Irland et al. 2001). Timber rotation is the length of time producers allow timber to grow prior to harvest. If the opposite climate impact occurs and forest productivity declines, rotation lengths are expected to shorten, particularly over the short-term. Rotation lengths shorten because timber supply is reduced (leading to increased stumpage values) and the annual growth of trees (representing the opportunity cost of foregoing future additional stumpage value) is less than under previous growing conditions. Additionally, timber rotation lengths could shorten if disturbance regimes increase markedly, reducing timber supply, or because producers choose to harvest sooner to avoid risk of timber losses to disturbance.

For the U.S. South, where productivity losses appear to be most likely to occur (although not certain), McCarl et al. (2000) project that a 1 percent reduction in growth would shorten rotation length in that region by about 0.2 percent for the first 20 years after yield

reduction, regardless of what happens to forest growth in other U.S. regions. Two decades post-change, McCarl et al. (2000) project rotation lengths in the South would decrease further, with a mostly linear continued shortening in length as decades progress. If yields in southern U.S. forests were unchanged and northern forest yields increased, rotation lengths in the South were projected to remain largely unchanged (McCarl et al. 2000). In the North, rotation lengths were expected to increase under changes in growth and yield by about 0.1 percent for the first 25 years under almost all scenarios (McCarl et al. 2000). However, when there is no change in timber growth in the South and the North experiences an increase in timber growth, rotation lengths were projected to remain largely unchanged in the North (and the South).

Harvest Levels

Under climate change, Perez-Garcia et al (2002) project that the global forest sector will increase harvest levels by 1.5 to 2.7 percent above the baseline by year 2040. The authors note these global changes are very small, but some regional changes are greater. The southern hemisphere accounts for the greatest increases in harvest levels. For example, timber harvest in Chile was expected to increase by between 10 and 13 percent by 2040 relative to the baseline depending on the scenario (Fig. 2). New Zealand was projected to increase harvest by 8 to 12 percent relative to the baseline. In the U.S., the West was projected to increase harvest between 2 and 11 percent, with the greatest increases projected under the hottest/highest emission scenarios (Perez-Garcia et al. 2002). The U.S. South is projected to increase harvests under the moderate and high heat/emissions scenarios but reduce harvest under the lowest heat/emissions scenario. This projected

reduction reflects reduced prices because other global regions are able to take greater advantage of changing growing conditions and increase timber production. Canada is projected to reduce harvest levels by up to 3 percent relative to the baseline under all scenarios (Perez-Garcia et al. 2002).

The results of the global study completed by Sohngen et al. (2001) are generally consistent with those of Perez-Garcia et al. (2002) for projected harvest levels over the next several decades. Sohngen et al. (2001) project a 5 to 6 percent increase in harvests globally (relative to the baseline and depending on scenario) for the 1995 to 2145 period. Sohngen et al. (2001) also show that most of the gains in timber harvest, over the next several decades, occur in the low Mid-latitude forests, particularly in South America (10-19 percent) and India (14 to 22 percent). In the near decades, Sohngen et al. (2001) project that North American harvests (Canada and U.S. combined) will decline by about 1 percent. This decline reflects some of the assumed dieback in the Sohngen et al. (2001) model and the general productivity losses projected for Canada. Global timber harvests in the later half of the century are projected to have a more substantial increase, relative to the baseline, of between 18 and 21 percent. These later gains reflect the increased productivity of forests and increased demand for wood products in response to decreased prices. Most of this later-century increase is driven again by the low Mid-latitude forests; however, North American harvests are projected to be about 14 percent above the baseline during that period.

In one of the initial studies examining the effect of climate change on the U.S. forest sector, Mills and Haynes (1995) projected that U.S. harvests would increase by 1 to 3 percent by 2040 relative to the baseline under climate change. The authors report that most of the projected increase took place several decades after climate-induced growth increases began. Regionally, Mills and Haynes (1995) projected that harvest levels would increase in the South and West (with slightly greater increases in the South owing to model assumptions) but decrease in the North. These projected increases in harvest levels in the South and West are consistent with the finding of Perez-Garcia et al. (2002) in their moderate and high emissions/temperature scenarios. In the Mills and Haynes (1995) study, harvest shifted towards regions with established production capacity and lower costs of production. Industry timberlands, relative to non-industrial lands, experience the greatest gains in timber harvest in the Mills and Haynes (1995) study. In the Pacific Coast states, harvest levels were projected to decline on nonindustrial lands, although industry timber harvest was projected to increase. Irland et al (2001), using a dynamic optimization model also found that total U.S. timber harvests would increase slightly under climate change, regardless of the climate change scenario. The South has the most consistent harvest gains across the climate scenarios modeled by Irland et al. (2001).

Timber Price Changes

In general, forest sector prices are expected to decline as a result of climate change (e.g., Irland et al. 2001, Sohngen et al. 2001, Perez-Garcia et al. 2002, Sedjo and Sohngen 1998). In the Sohngen et al. (2001) study, global timber prices, under all scenarios (including those with dieback) decline relative to the baseline (Fig. 3). Prices are

projected to depart from the baseline in a mostly linear fashion between the present time and 2050. In the presence of dieback, prices in Sohngen et al. (2001) are slightly closer to but still below the baseline. Although dieback mitigated the price changes to some extent, the modeled dieback did not dramatically change the general relationship between climate change and timber prices. In the Sohngen et al. (2001) model, the greatest departures from baseline prices were projected to occur post 2060. In the first 20 years of the Sohngen et al. (2001) simulation, prices remain close to the baseline projections, allowing timber producers in low Mid-latitudes to take advantage of climate-change induced yield increases and increase output.

In the Perez-Garcia et al. (2002) model, global timber prices under climate change are projected to be 0.8 to 3.1 percent below the baseline projection in 2040. These timber prices are projected to translate through to wood product prices. Perez-Garcia et al. (2002) point out, as with the projected harvest changes described above, projected global price changes are minimal, although there are larger regional changes. As the climate scenarios represent more hotter temperatures/higher emissions, prices are projected to decline farther below the baseline because timber productivity continues to increase in modeled scenarios.

For the U.S., Perez-Garcia et al. (2002) project price declines in the U.S. South and West ranging from less than 1 to about 3.5 percent (Fig. 4). Under the smallest temperature changes, projected U.S. price declines are 0.5 percent or less. Similar patterns are expected for the U.S. North. In the Perez-Garcia et al. (2002) model, the greatest price

declines were projected for Scandinavia and Western Europe (not shown). Studies only completed for the U.S. have found slightly greater projected price declines than those projected in the global models. In a study by Mills and Haynes (1995), stumpage prices are projected to decline by 6 to 35 percent under climate change scenarios (Joyce 1995). In a later study, Alig et al. (2002) project prices for sawtimber to decline by 3 to 6 percent relative to the baseline for the period 2020 to 2050 under climate change.

The price impact results of the sensitivity analysis by McCarl et al. (2000) depart slightly from the other studies. For the U.S., prices for timber are projected to slightly decline, relative to the baseline, in scenarios where the South experiences no change in growth and the North increased productivity. This pattern of growth change is one possible outcome of climate change. If the South experienced a 1 percent loss of productivity and the North experienced a corresponding gain in productivity, McCarl et al. (2000) project that prices would increase slightly (less than 1 percent). In cases where both U.S. regions experienced a loss in productivity, greater price increases were projected. Note that the McCarl et al. (2000) study includes forest sector imports only from Canada, potentially limiting the price-mitigating effect of forest sector imports. In the Sohngen et al. (2001) and Perez-Garcia et al. (2002) models, low Mid-latitude timber producers would be the primary gainers (and timber exporters) under climate change and Canada would suffer production losses.

Because softwoods are projected to have greater increases in productivity than hardwoods (e.g., Perez-Garcia et al. 2002) in response to climate change, softwood prices

may experience greater price declines (Mills and Haynes 1995). Regionally, Mills and Haynes (1995) projected that softwood stumpage prices might experience the greatest declines in the U.S. South and Pacific Coast regions. The other studies considered here do not report results separately for hardwoods and softwoods, often because the model results are similar for the two forest types (e.g., Irland et al. 2001, McCarl et al. 2000).

Climate change is projected to generally lead to faster growing trees that become larger in a shorter period of time. Further, at least one study (Mills and Haynes 1995) suggests that softwoods may experience a disproportionately positive response. These factors combine to suggest some potential differences between sawtimber and pulpwood production in a climate-changed environment. Pulpwood is typically produced from trees that are too small or not of high enough quality to produce sawtimber. In the northern U.S., much of the pulpwood is produced from hardwood species. As climate change produces trees that can become larger more quickly, potentially displaces hardwoods north to Canada, and potentially yields feasible growing conditions in the northern U.S. for productive southern pine species, the production of pulpwood is projected to decline. Irland et al. (2001) project declines in pulpwood harvest of approximately 3 percent during the 2020 to 2050 period, regardless of which climate scenario is considered. Because of decreased production, pulpwood prices are projected to increase during this period (Irland et al. 2001). In the 2000 to 2020 period, Irland et al. (2001) project that pulpwood prices would remain generally unchanged. Note that even with pulpwood price increases and sawtimber price declines in the 2020 to 2050 period, sawtimber prices are still high

enough and timber growth rates fast enough to increase sawtimber production and decrease pulpwood production.

Consumer and Producer Welfare under Climate Change

The basic relationships between changes in forest productivity and consumer and producer welfare are fairly straightforward and consistent among the studies considered. As Sohngen and Sedjo (2005) state, "...if climate change makes forests more productive, then timber prices will fall, consumers will benefit (consumer welfare will rise relative to the baseline) and (forest product) producers will lose (producer welfare will decline from the baseline)." The opposite will occur if climate change makes forests less productive. In nearly all results, under a positive change to forest productivity, total welfare (the net combination of consumer and producer welfare) in the U.S. is projected to slightly increase from the baseline because the gains to consumer welfare are greater than the losses to producer welfare. Alig et al. (2002) project U.S. total welfare increase of between 0.05 and 0.18 percent. Using a global economic model, Sohngen et al. (2001) estimated total welfare in North America would increase by \$55 to \$65 billion, depending on the climate scenario and not accounting for any potential forest dieback. The greater total welfare gains in Sohngen et al. (2001) can be traced to the projected global increase in timber supply, which leads to even larger consumer surplus gains relative to the baseline.

Although welfare gains are projected in aggregate for the U.S. as a whole, some locations and groups may suffer losses. Within the U.S., the South and West regions and timber and wood product producers are projected to suffer welfare losses under some climate scenarios. In the Perez-Garcia et al. (2002) model, total welfare is positive under climate change relative to the baseline in the U.S. North and West (Table 1). Both regions are major consumers of wood products and the gains to those individuals overcome losses to producers. However, the U.S. South is currently the major timber producing region in the U.S. (Adams et al. 2006) and because timber producers suffer losses relative to the baseline, that region is projected to experience total welfare losses under a climate scenario of 592 ppm CO₂ in 2100 and a temperature rise of 1.6 degrees Celsius. Under higher CO₂ and temperature levels, Perez-Garcia et al. (2002) project greater gains in consumer surplus in the South, offsetting producer losses and yielding small gains in total welfare. However, in scenarios where the South experiences net gains in total welfare, that region's gains are about 1/3 to 1/2 as large as the gains experienced in the North or West.

In the Perez-Garcia et al. (2002) model, consumers in all U.S. regions experienced a gain in welfare regardless of climate scenario (Table 1). Conversely, log producers in each U.S. region were projected to experience losses in producers' surplus, relative to the baseline, because of declines in timber prices as result of gains in yield. Wood product producers in the West were projected to experience slight gains in surplus relative to the baseline. In the other regions, wood product producers are projected to have surplus losses under nearly all scenarios. The only exception to that pattern is a projected slight

gain in wood product producer surplus in the southern U.S. under the highest CO₂ scenario.

Because, in part, consumers can change their purchasing behavior and choose substitute goods, the welfare of producers is about 10 times as sensitive to changes in growth and yield (such as in response to climate change) as consumer welfare (McCarl et al. 2000). If existing stands suffer mortality because of changes in climate conditions and increased disturbance, producers experience greater losses. Sohngen and Sedjo (2005) project that producers' surplus in North America could decline by \$1.4 to \$2.1 billion per year relative to the baseline in a scenario where existing stocks are subject to dieback. In a scenario without dieback, producer losses are about 30 percent less (Sohngen and Sedjo 2005).

Globally, Perez-Garcia et al. (2002) projected small total welfare changes of between 0.4 percent (\$1.8 billion) and 0.44 percent (\$15.8 billion) in response to climate change. Sohngen et al. (2001) found slightly larger changes in global total welfare, relative to baseline projections, of 3 percent (\$113 billion) if dieback occurs to 6.7 percent (\$251 billion) without dieback. In both cases, as found in the U.S.-only models, global welfare gains result from the lower cost of wood products to consumers that overcome welfare losses to producers. Sohngen et al. (2001) project the largest gains in consumer welfare will accrue to North America, Europe, and the former Soviet Union (Table 2). Producers in South America and the Asia/Pacific region are projected to experience the greatest gains in welfare relative to the baseline. Producers in the U.S. are projected to experience

the largest nominal losses relative to the baseline (however the authors do not report the percentage change).

Timing of Welfare Changes

The welfare measures reported above are in net present value terms. That is, they are the sum of welfare changes from the baseline for all the future periods in the economic simulation, discounted to the present day. Through the discounting, changes that occur in earlier decades have more weight than changes in later decades. In any one period in the future, the welfare changes experienced by producers and consumers may differ from that projected for the entire simulation period. For example, although producers are projected to suffer losses when the whole simulation period is considered, they might experience gains in welfare in some decades. The expected temporal patterns of welfare changes are uncertain.

Climate Change and Urban Forests

In addition to the possible effects of climate change on the U.S. forest products sector, climate change may have significant impacts on urban forests. Although the projected effects of climate change on rural forests have been discussed extensively elsewhere, fewer studies have summarized the potential impacts to urban forests from climate change. The potential impacts on urban forests are important because approximately 80 percent of the U.S. population lives in urban areas and this proportion will increase in the decades ahead. This section briefly reviews the extent and value of urban forests,

documents threats to urban forests, and suggests how climate change may affect those threats.

The urban forest (i.e., all trees and associated natural resources within urban areas) of the U.S. is an extensive and valuable natural resource. Nowak et al. (2001) estimate 3.8 billion trees grew in 108,500 mi² of urban area in the coterminous U.S. in the 1990s. Urban and developed areas are projected to exceed 193,000 mi² by the year 2030, with almost half of this urban growth taking place in forested areas (Alig et al. 2004a, Nowak and Walton 2005). Urban forests provide a wide range of benefits, including protection against soil erosion, provision of habitat for wildlife, improvement in local air quality, reductions in the urban heat island effect, energy savings through building shading and insulation, carbon sequestration, and reductions in storm-water runoff (e.g., Dwyer et al. 1992, McPherson et al. 2005). Urban tree cover also provides cultural benefits that lead to improved quality of urban life as trees may improve the scenic quality of a city neighborhood, provide privacy, reduce stress, and shelter residents from the negative effects of undesirable land uses (e.g., Dwyer et al. 1991, Westphal 2003).

It is difficult to put an economic value on the environmental and cultural benefits of urban forests because most of those services are not traded in markets. Nevertheless, some of the benefits of urban forests may be capitalized into the values of residential property, and hedonic property price models document those values based on property characteristics and home sale prices. Summarizing studies of home sales in several U.S. cities, Sander et al. (2010) conclude that increasing proximity to forested areas and

increasing tree cover are associated with increasing home sale price. For example, in Grand Rapids, Michigan, housing lots that directly bordered a forest preserve sold for 19 to 35 percent higher prices than other lots (Thorsnes 2002). A North Carolina study found that increasing forest cover by 10 percent on a forest parcel increased home sale price by an average of \$800 (Mansfield et al. 2005). A Minnesota study found that a 10 percent increase in tree cover within approximately 328 feet of a home increased home sale price by \$1,371 and within 820 feet increased home sale price by \$836 (Sander et al. 2010). The positive impact of trees on home sale price together with the size of the U.S. housing stock (115 million housing units in 2000) (Radeloff et al. 2010) suggest that the total impact of trees on residential property value in the U.S. is very large.

Invasive insects and pathogens are among the greatest threats to urban forests and can have substantial economic effects. In a comprehensive study of the economic impacts of biological invasions of forests in the continental U.S., Aukema et al. (2010) conclude that local governments and homeowners are the sectors sustaining the greatest economic damage, which includes expenditures for treatment, removal, and replacement of infested trees and reductions in property value associated with tree mortality. These governmental and residential expenditures represent transfers of wealth between sectors (such as from homeowners to tree removal firms), and impacts on residential property values represent wealth that is lost from the economy. For example, emerald ash borer (*Agrilus planipennis* Fairmaire), a phloem-feeding beetle native to Asia and introduced in the U.S. in the 1990s, is projected to cause average annual expenditures of more than \$1 billion for treatment and replacement of trees by local governments and homeowners in the

eastern United States from 2009-2018 (Kovacs et al. 2010a). Residential property value losses associated with EAB damage are projected to exceed \$340 million annually (Aukema et al. 2010). Sudden Oak Death (*Phytophthora ramorum*), a non-indigenous forest pathogen that causes substantial mortality in coastal live oak and several other oak tree species on the Pacific Coast of the U.S., is projected to cost \$6 million per year in treatment, removal, and replacement costs and \$105 million per year in property value losses to single family homes (Kovacs et al. 2010b).

Wildfire is another significant threat to urban forests with substantial economic effects. The wildland urban interface (WUI) is the area where houses meet or intermingle with wildland vegetation, including trees, shrubs, and grass (Stewart et al. 2007). According to recent estimates, the WUI encompassed 11 percent of the land area (276,100 mi²) and 38 percent of the housing units (44.3 million) in the contiguous U.S. in 2000 (Radeloff et al. 2005). In western and southeastern states, where wildfires burn the most area, 45 percent of the housing units are in the WUI (11.1 and 4.1 million units, respectively) (Hammer et al. 2009). Although wildfire risk varies widely, the presence of homes in fire-prone vegetation increases the risk of loss of life and property and increases fire prevention and suppression costs. For example, wildfires in the WUI of Southern California destroyed 3,079 structures in 2007 and suppression costs to the state totaled nearly \$300 million (Hammer et al. 2009).

Conclusions

Although there remains uncertainty in the physiological and disturbance responses of U.S. forests to climate change, there is general agreement in results from currently-available studies examining the impact of climate change on the forest sector. Broadly, the model results included here indicate that the forest sector (both globally and in the U.S.) is fairly resilient to changes in forest stocks and growing conditions resulting from the modeled climate change scenarios to date. Although there are projected to be impacts to forest production, forest sector prices, and consumer and producer welfare, changes are generally projected to be small. Currently the forest sector (globally and in the U.S.) is operating in a manner that reflects a diverse arrangement of resources, processing capacity, and consumer demand. Climate change would likely impact those arrangements and, over time, economic theory and the output of economic models suggest the forest sector would adapt accordingly.

The northern U.S. is generally projected to experience productivity increases with climate change. However, some of this increase may coincide with a displacement of some currently important northern species (northern hardwoods and spruce/fir forest types) north to Canada because of changing growing conditions. Concurrently, changing growing conditions may make way for some productive southern pine species to be planted in portions of the U.S. North. The western U.S. is generally expected to see gains, particularly in the timber-important Pacific Coast states. However, the West is also generally the focus of concerns related to increased disturbance, in the form of increased wildfire or insects and disease outbreaks, because of climate change. Whether these disturbances will be mitigated by human intervention or depart significantly from the

general long-term historical levels remains to be seen. Within the U.S., the South is generally considered the region most likely to suffer growth losses because of changing climate conditions. Dieback and increased disturbance mortality may also impact existing forest stands in that region.

The economic studies considering the impact to the forest sector from climate change are generally consistent in projecting, in model inputs, that climate change will lead to aggregate yield increases globally and for portions of the United States. These yield increases will lead to increased timber production, which will result in price declines. Timber harvest increases in the U.S. are most consistently projected for the northern and western regions. The U.S. South is projected to have increased harvest under some scenarios and decreased harvest in others. In one study, the South is projected to remain near baseline harvests levels only in a scenario when that region's productivity remains stable and the North increases productivity. In another study, the South is projected to increase harvest under the hottest temperature/highest emission scenarios but reduce harvest under the lowest temperature/lowest emissions scenario. The global models indicate that much of the increased global timber productivity will come from producers in the low Mid-latitudes who are able to respond quickly to changing growing conditions and are expected to experience some of the largest growing condition improvements. An increase in timber harvests is projected to occur fairly quickly in the decades post growth change, followed by a small slow-down and then a long, sustained increase.

Climate change is projected to result in welfare changes for consumers of wood products and producers of timber. The studies considered here are generally consistent in projecting that total welfare, net of forest product consumers and timber producers, will increase relative to the baseline. However, the South and West U.S. are projected to suffer total welfare losses under some scenarios and timber producers are projected to experience welfare losses in most scenarios. Wood product consumers are projected to gain in nearly all the scenarios considered. The temporal pattern of welfare changes by decade post-climate change is largely unknown.

The current projections for the forest sector under climate change are based on existing studies that were completed using the information and models available at the time. One important uncertainty in considering the existing model results is the impact that unaccounted for dieback or increased levels of disturbance may have on the expected responses of the forest sector to climate change. Historic levels of dieback and disturbance are represented in the growth and yield functions used in the models. Additional levels of dieback (including that possibly from disturbance) were included in the Sohngen et al. (2001) study. In that analysis, increased dieback did change model output but did not change the general relationships between climate change and forest sector outcomes. For example, under the dieback scenarios, timber prices were still projected to decline with climate change, although this change was mitigated slightly by the modeled dieback. If the dieback or disturbance experienced under climate change is greater than that captured in the models, actual impacts to the forest sector may differ from model results.

Although the total area of land in agriculture and forestry may remain relatively constant over time, climate change could alter the distribution of rural land uses and affect forest area over time if climate change affects yields and costs of production for different land use alternatives. Given the potential human and social consequences of these impacts, it is important to extend and enhance modeling tools to assess the implications of climate change on the distribution of land uses in the United States. Another uncertainty is how climate change may affect human migration patterns and thereby areas of urban and developed uses and areas of rural land uses such as forest that may be converted to developed uses, including those of coastal areas. Another research area is the relationship between human settlement patterns and vulnerabilities to natural disasters. In terms of risks and hazards, natural disasters have many varied consequences, including damage to forest ecosystems and human communities. Recent trends in land use and housing growth not only create stresses on natural ecosystems, they also increase society's vulnerability to natural hazard. Global climate change has also been indicted in recent catastrophic weather events, and although scientific opinion is mixed regarding its role in current patterns, scientists agree that there is potential for significant change in the future. However, in the short run, i.e., over the past 50 years, the likelihood of natural hazards has been relatively stable but losses in the U.S. have increased because our vulnerability to these hazards has increased (Alig et al. in press). More houses and more wealth concentrated in regions of the country facing significant hazard levels describe the trend in the U.S. over the past 50 years.

Another uncertainty is how timber producers and private and public landowners will respond to changing forest growing conditions. Currently, the U.S. timber industry is experiencing a general reduction in capacity (e.g., milling infrastructure), a move away from vertically-integrated companies (i.e., a forest product company owns the processing mill as well as the timberland) to a business model where timber is obtained from lands owned by other corporations and private entities, and production that is regionally concentrated. Combined, these factors may make it difficult for the timber industry to adapt to and mitigate climate change impacts on forests, particularly in the short-term. Private landowners own forests for a variety of reasons and those owners may not adopt adaptation and mitigation activities that promote continued or improved timber production, potentially reducing future timber availability from private land. However, it is possible that expanded programs by land agencies (e.g., the State and Private Forestry Branch of the USDA Forest Service) and conservation organizations could improve the implementation of adaptation and mitigation activities for timber production by private landowners. The results of current studies assume that producers will adopt forward looking, optimal responses and significant departures from this assumption may yield unanticipated impacts on the forest sector.

Given the extent and value of urban forests, an area of research that deserves more attention is projecting the effects of climate change on threats to urban forests, including invasive forest insects and diseases and wildfires. Climate change will likely increase the frequency and intensity of these disturbances and we need to quantify the associated costs and losses, including government and homeowner expenditures for prevention and

mitigation activities and homeowner losses in property value. Documenting these potential costs and losses associated with disturbances to urban forests will add to our growing understanding of the overall effects of climate change on forests.

There are a number of opportunities for further research examining the impacts of climate change on the forest sector. First, because most of the existing studies were completed several years ago, it would be useful to update those analyses using the most recent climate projection and economic models. Second, additional studies that quantify how increased disturbance and dieback and sub-optimal responses by timber producers and landowners affect model projections would help to identify how these uncertainties might impact the forest sector under climate change. Third, the expectation is that global trade will increasingly be important and economic models that better account for the dynamics of global trade will be useful as climate change is projected to have diverse positive and negative effects on timber growth and yield in different portions of the globe. Finally, the existing studies have examined the forest sector impacts from climate change in isolation. In future studies, it will be important to examine how the forest sector responds to concurrent changes in climate conditions and comprehensive climate policies (e.g., a carbon cap and trade system, increased demand for woody biomass for biofuels). For example, the climate scenarios considered here suggest that timber harvest will increase in response to improved yields. However, it is not known how that relationship would be affected if forest carbon offsets are also valued. It is probable that the combination of improved forest yields and a carbon value would have an impact on timber harvest levels (and ultimately consumer prices) not represented in current modeling.

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Metric Equivalents

When you know:	Multiply by:	To get:
Miles (mi)	1.609	Kilometers
Feet (ft)	.3048	Meters
Cubic feet (ft ³)	.0283	Cubic meters

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Table 1—Projected net present welfare changes (\$ millions 1993) in U.S. regions under three climate emissions/temperature scenarios. Projection period 1985 to 2040. Adapted from Perez-Garcia et al. (2002).

	High	Moderate	Low
US North			
Log producers	-922.1	-741.6	-225.4
Product producers	-104.6	-125.3	-144.1
<u>Consumers</u>	<u>8,467.5</u>	<u>6,279.4</u>	<u>806.9</u>
Total	7,440.8	5,412.5	437.3
US South			
Log producers	-5,062.5	-4,946.6	-4,234.4
Product producers	-136.9	-511.1	-1,285.1
<u>Consumers</u>	<u>9,605.8</u>	<u>7,219.1</u>	<u>1,238.0</u>
Total	4,406.4	1,761.3	-4,281.5
US West			
Log producers	-1,524.5	-1,030.1	-267.0
Product producers	8,261.0	6,141.3	829.6
<u>Consumers</u>	<u>241.8</u>	<u>154.8</u>	<u>340.6</u>
Total	6,978.4	5,266.0	903.3

Table 2—Projected changes in the net present value (\$ billions 1990) of welfare for consumers and producers under climate scenarios with and without forest dieback. Projection period 1995 to 2145. Adapted from Sohngen et al. (2001).

	North America	Europe	Former USSR	China	South America	India	Asia- Pacific
Scenarios without dieback							
Consumer welfare	80.3	44.5	37	17.2	17.5	4.2	26.2
<u>Producer welfare</u>	<u>-24.7</u>	<u>5.6</u>	<u>-0.2</u>	<u>5.5</u>	<u>2.3</u>	<u>1.6</u>	<u>-7.5</u>
Total welfare	55.5	50.1	36.8	22.7	19.8	5.7	18.7
Scenarios with dieback							
Consumer welfare	35	19.5	16.2	7.7	7.8	1.9	11.8
<u>Producer welfare</u>	<u>-39.3</u>	<u>25.8</u>	<u>-24.6</u>	<u>8.6</u>	<u>14.7</u>	<u>3.8</u>	<u>3.3</u>
Total welfare	-4.3	45.3	-8.4	16.4	22.6	5.7	15.1

Figure captions

Figure 1—Projected forest type shifts in the eastern U.S. as result of climate change. Data source: Climate Change Tree Atlas: http://www.nrs.fs.fed.us/atlas/tree/ft_summary.html

Figure 2—Approximation of projected harvest levels in 2040 under three CO₂ emission/temperature scenarios. Adapted from Perez-Garcia et al. (2002).

Figure 3—Projected timber prices under baseline and four climate change scenarios, including two with forest dieback. Adapted from Sohngen et al. (2001).

Figure 4—Approximation of projected log price changes in 2040 under three CO₂ emission/temperature scenarios. Adapted from Perez-Garcia et al. (2002).

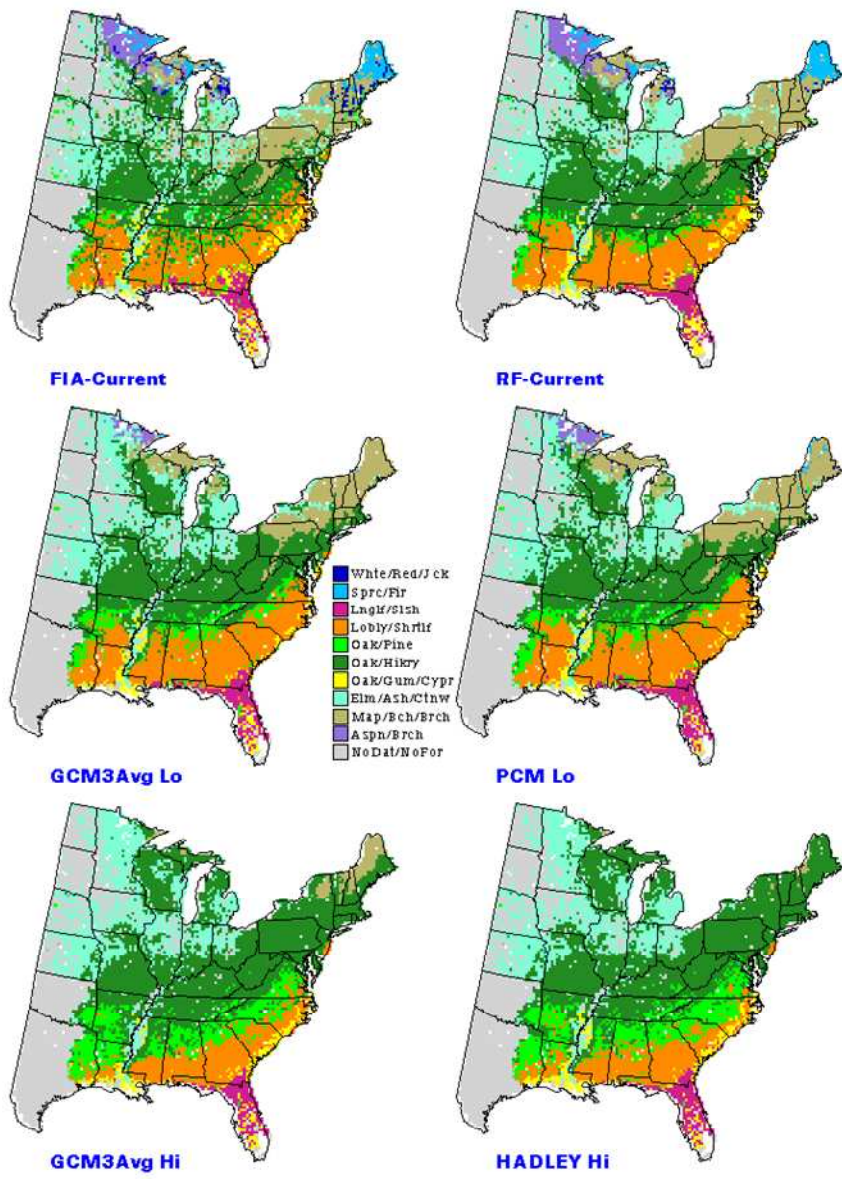


Fig. 1

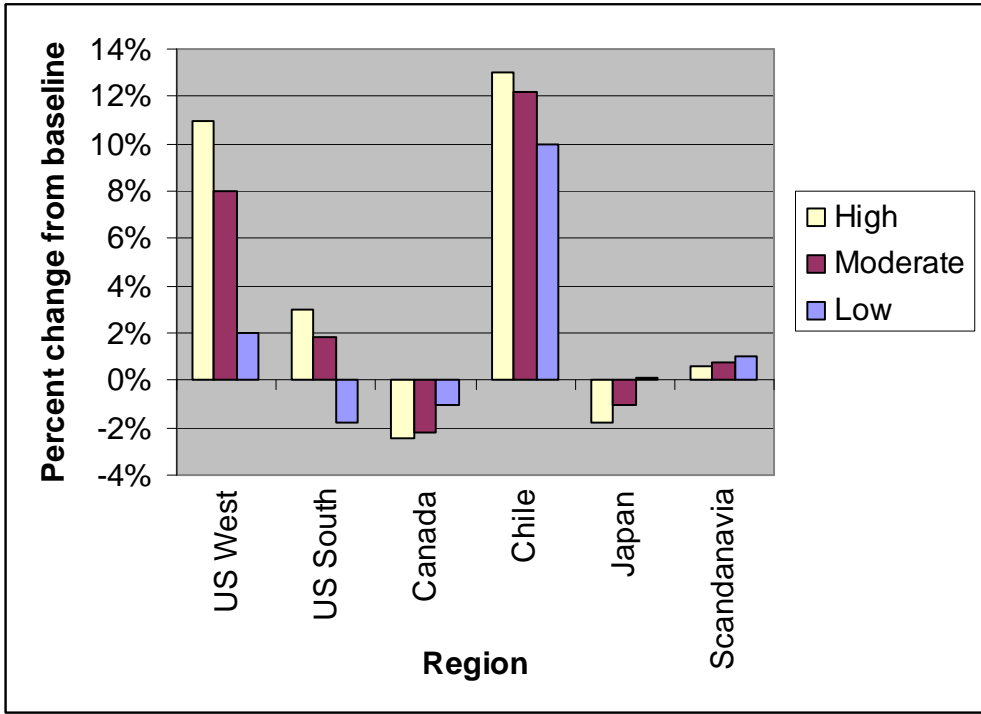


Fig. 2

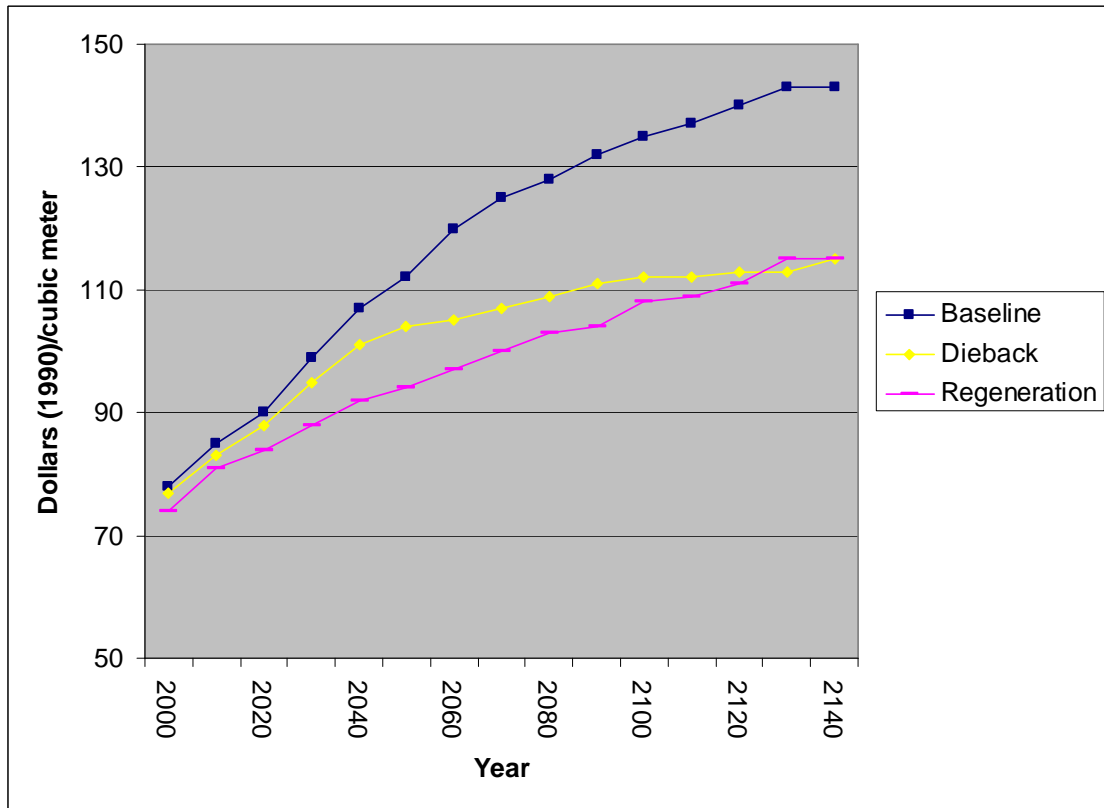


Fig. 3

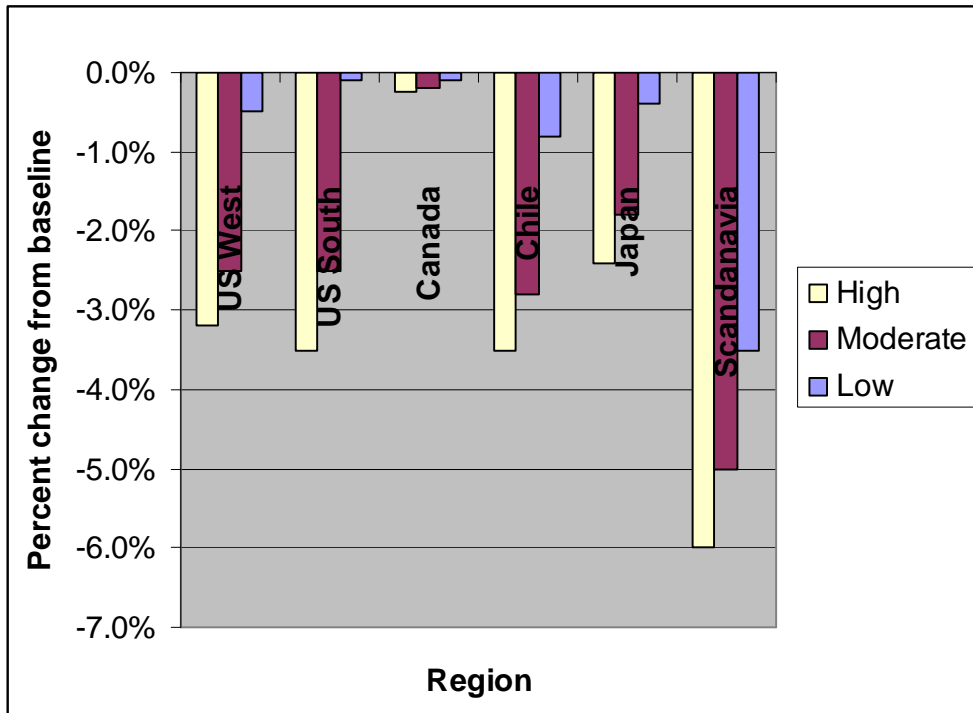


Fig. 4