environment

Forests

& Global climate change

Potential Impacts on U.S. Forest Resources

Herman Shugart
University of Virginia

Roger Sedjo
Resources for the Future

Brent Sohngen
The Ohio State University

Pew Center on Global Climate Change

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Prepared for the Pew Center on Global Climate Change

by

Herman Shugart
University of Virginia

Roger Sedjo
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Brent Sohngen
The Ohio State University

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Approximately one-third of U.S. lands are covered by forests, which makes forest ecosystems prominent natural resources that contribute to biodiversity, water quality, carbon storage, and recreation. Forests also play a significant role in the U.S. economy, and forestry or forestry-related enterprises are the dominant industries in many U.S. communities. Human-induced climate change over the next century is projected to change temperature and precipitation, factors that are critical to the distribution and abundance of tree species.

Forests and Global Climate Change is the ninth in a series of Pew Center reports examining the potential impacts of climate change on our environment and health. A previous report in this series addressed the risks to terrestrial ecosystems posed by climate change. This report details the likely ecological and economic impacts of climate change over the next century on the U.S. forestry sector. Key findings include:

- ***Forest location, composition, and productivity will be altered by changes in temperature and precipitation.*** Climate change is virtually certain to drive the migration of tree species, resulting in changes in the geographic distribution of forest types and new combinations of species within forests. Generally, tree species are expected to shift northward or to higher altitudes. In addition, climate change is likely to alter forest productivity depending upon location, tree species, water availability, and the effects of carbon dioxide (CO_2) fertilization.
- ***Changes in forest disturbance regimes, such as fire or disease, could further affect the future of U.S. forests and the market for forest products.*** Increased temperatures could increase fire risk in areas that experience increased aridity, and climate change could promote the proliferation of diseases and pests that attack tree species. Such disturbances may be detrimental to forests themselves, but may have a lesser impact at the market level due to salvage operations that harvest timber from dying forests.
- ***U.S. economic impacts will vary regionally.*** Overall, economic studies indicate that the net impacts of climate change on the forestry sector will be small, ranging from slightly negative to positive impacts; however, gains and losses will not be distributed evenly throughout the United States. The Southeast, which is currently a dominant region for forestry, is likely to experience net losses, as tree species migrate northward and tree productivity declines. Meanwhile, the North is likely to benefit from tree migration and longer growing seasons.
- ***As a managed resource, the implications of climate change for the forestry sector are largely dependent upon the actions taken to adapt to climate change.*** The United States has vast forest resources and currently consumes less timber than grows within the country each year. If professional foresters take proactive measures to substitute thriving tree species for failing species, to relocate forestry industry to productive regions, and to salvage trees during dieback, the sector may minimize the negative economic consequences of climate change.
- ***A number of challenges currently limit our understanding of the effects of climate change on forestry.*** Existing projections for future changes in temperature and precipitation span a broad range, making it difficult to predict the future climate that forests will experience, particularly at the regional level. The ecological models used to relate forest distribution and productivity to changes in climate introduce additional uncertainty. Thus, current projections could fail to accurately predict the actual long-term impacts of climate change on the forestry sector.

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Executive Summary

Climate change is expected to have far-reaching consequences for forests and, subsequently, timber production in the United States. Although studies have shown that forests have adapted to temperature increases of 2-3°C (3.6-5.4°F) in the past, these changes occurred over thousands of years. Current climate predictions suggest that average global mean temperatures could rise 1.5-5.8°C (2.7-10.4°F) over this century alone. Such rapid changes in a relatively short period of time could affect forests significantly. Understanding how climate change will affect future forests and markets, however, is a complex task. Ecological and economic processes are exceptionally complicated, and understanding how integrated ecological and economic systems will respond to changing climate conditions remains a challenge. In spite of a number of remaining uncertainties, this report describes the many important insights into this process discovered over the last 10-20 years of research.

This report explores the potential effects of climate change on both natural and managed forest ecosystems, which differ significantly in their potential responses to climate change. Managed forests, such as forest plantations, receive significant amounts of human intervention in the form of planting, thinning and other management activities. These interventions have the potential to ameliorate the adverse effects of climate change. However, large areas of forest are considered natural and receive minimal direct human management, and thus may be more vulnerable to the effects of climate change. This duality within the forest sector makes it more difficult to state with precision what the overall economic impacts of climate change on forests will be. Further, the ecological changes caused by climate change could have large implications both for non-market attributes (e.g., biodiversity) and for other economic sectors associated with forests (e.g., recreation and water supply). The economic analysis in this report, however, focuses strictly on timber market impacts.

One of the most important ways that researchers discover clues about how forest ecosystems will respond to climate change is to explore the historical record for data regarding the impacts of past climate changes. This record indicates that individual tree species respond to warming either by changing their ranges or by increasing or decreasing their abundance. More recently, researchers have developed sophisticated models to explore how species distributions may change as climate changes. These changes could include increases or decreases in forest area, changes from one forest type to another, or movements of specific species from place to place.

In addition to species migration, it is important to consider how climate change could affect the productivity of forests (i.e., annual growth in forests). Existing studies show both positive and negative impacts on overall productivity, depending on the climate scenario. Further, some locations could experience higher productivity while others experience lower productivity. For example, forests in the southern

United States are generally sensitive to the effects of drying, and productivity is more likely to decline there, while productivity is generally predicted to rise in the northern United States in response to low to moderate warming.

Understanding how productivity will change is complicated by an incomplete understanding of the effects of higher atmospheric carbon dioxide (CO_2) concentrations on plant growth and ecosystem processes (so-called "carbon fertilization"). Experimental evidence suggests that carbon fertilization is likely to increase individual tree growth. Some evidence also suggests that the CO_2 effect makes trees use water more efficiently, thereby making them less vulnerable to drought. Other evidence, however, suggests that the effects of carbon fertilization decline as trees age and at wider spatial scales where forest losses from other processes become important. Unfortunately, most measurements have been made on individual trees in experimental conditions, and not on entire forest ecosystems. In natural forests, and even in managed industrial forests, enhanced growth in trees could be offset by increased natural mortality elsewhere in the system. This is certainly the case for plantation forests where foresters usually predict increased thinning with higher growth in well-stocked stands.

While more precise regional estimates will be made as climate models provide a fuller understanding of regional climate change, and as ecological impacts become clearer, the existing results suggest that timber production could shift northward. Although some shifting will occur throughout most U.S. forests, the shifts would be strongest if the area suitable for southern softwoods expands northward. Hence, southern forests and markets appear most susceptible to climate change, in part because southern species are sensitive to drying effects, and in part because northward migration would erode the comparative advantage for timber production currently enjoyed by southern producers. Southern forests are also the most important economically since they account for well over one-half of U.S. production.

Changes in the frequency and intensity of disturbances like forest fires, pest infestations, and windthrow (i.e., from large storm events) are likely to have large consequences for the structure of both natural and managed forests. Natural forests, in particular, will be heavily influenced by changes in disturbances. Because disturbance has long been an important issue in forest management, managers have a number of tools available for adapting industrial and other managed forests as conditions change. Large-scale disturbances, however, can have substantial effects on markets. For example, although disturbances can cause substantial forest dieback, such ecological damages have the potential to cause short-term increases in timber supply, depressing timber prices for consumers.

As with agriculture, forest landowners have many options for adapting to the types of changes likely to occur with climate change, such as by salvaging dead and dying timber and by shifting to species that are more productive under the new climatic conditions. The long time lags between planting and harvesting trees, however, complicate the decisions for landowners. Adaptation can also occur at the market level, such as changing the types of species used in producing end products. End products are made from a wider variety of species today than 30 years ago; such adaptations help protect the market from large-scale changes in supply.

The following summarizes the current understanding of the potential impacts of climate change on U.S. forests and timber markets over the next century:

1. Tree species generally are expected to migrate northward or to higher altitudes in response to increased temperatures. While species will adapt over time by moving from one region to another, differential rates of change may cause significant differences in the types of natural stands in the future. Rates will depend critically on (a) how fast seeds migrate into new regions that are climatically suitable for a species after a climate change, (b) changes in the spread of insects and disease, (c) the spread of wildfire in different climates, and (d) human interventions to promote species migration.

2. Forest productivity is expected to change, but the changes could be positive or negative. Forests could become more or less productive, depending on how much climate changes (including both temperature and precipitation), how forests respond to higher carbon concentrations in the atmosphere, whether mortality changes, and whether disturbance-induced dieback increases or decreases. Many of these factors are expected to vary from region to region, suggesting that economic impacts are likely to differ among regions in the United States.

3. The effect of additional carbon dioxide in the atmosphere on forested ecosystems ("carbon fertilization") is complex and uncertain, but it has large implications for understanding how forest productivity will change. Most studies suggest that forest area and productivity will increase if carbon fertilization enhances forest growth, but will decline if carbon fertilization does not occur. Plant-level experiments suggest that carbon fertilization will enhance tree growth, at least for some period of time. Scaling these results up to the ecosystem level is complex, but available studies suggest that carbon fertilization will be limited by competition, disturbance, and nutrient limitations. It is important to continue developing a better understanding of carbon fertilization effects, particularly at the ecosystem scale.

4. Changes in the frequency and severity of forest disturbance, such as storm damage, fires, and pests are likely to affect forest structure and function. The impact on markets, while generally negative, can be ameliorated by salvage. At the market level, salvage associated with disturbances can increase timber supply and reduce prices in the short-term, which benefits consumers. However, increased disturbance and lower prices generally have negative effects on landowners.

5. United States timber markets have low susceptibility to climate change because of the large stock of existing forests, technological change in the timber industry, and the ability to adapt. The United States currently consumes less timber than grows within the country each year, providing a cushion if climate change has short-term impacts on supply. Further, companies already substitute a wide array of species in end products, so that if particular species are negatively affected by climate change, markets can adapt by changing the types of species used in the production of end products. In addition, landowners can assist natural migration of timber by planting southern species in the North.

6. Economic studies have tended to find small negative to positive overall effects on timber production in the United States. While the studies have looked at a wide range of potential climate change effects across species within the United States, the net productivity effects used by the studies have tended to be positive over the long-term. Higher forest productivity translates into increased timber yield, increased timber inventory, increased supply, and lower prices. Lower prices generate overall net benefits, although they primarily benefit consumers at the expense of landowners. Lower forest productivity has the opposite effect.

7. Northern states may gain from climate change if productivity increases and if southern species move north, while southern states may lose production. Producers in southern regions are the most vulnerable to climate change because they have a large share of the nation's current timber production capital, and the highly productive species in that region are sensitive to potential drying effects. Northern states are generally predicted to gain productivity and market share during climate change.

8. Understanding the economic effects of climate change on timber production is limited by scientific understanding of several key factors that control the response of natural and managed forests to climate change. Additional research is needed to enable ecologists and foresters to develop a more robust understanding of future changes in U.S. climate, ecosystem responses to climate change, the relationship between forest productivity and timber yield, and adaptation options available to foresters. Future clarification of these uncertainties will permit more informed assessments of the economic impacts of climate change to the forestry sector.

I. Introduction

Forests are an important part of the American landscape and economy.

The United States is a nation comprised of extensive forestland, and most people in the United States live in forested (or formerly forested) regions. Beginning with the arrival of Europeans in the 17th Century, large areas of forestland on the East Coast were cleared for agriculture. Between 1880 and 1920, population migration and agricultural expansion into the Midwestern and Western United States reduced the area of forestland by an additional 33 percent. Yet, as early as the 1850s, forests began to regenerate on lands cleared earlier in the Northeast (Barrett, 1980). By 1920, the total area in forests began to increase gradually as reforestation surpassed deforestation. Today, about one-third of the U.S. land area, or approximately 737 million acres, is comprised of closed forests (Society of American Foresters, 2000).

From an economic perspective, the forest sector (including both direct harvests and the output of related industries) accounts for approximately one percent of the nation's annual economic output. Regionally and locally, the forest sector is more important than the national statistics suggest: many cities and towns, particularly in the western and southern United States, have mills that provide a significant portion of local income. Although the size of the forest sector, as with the manufacturing sector in general, has declined in relative terms in recent years, it remains an important part of the American economy today.

Many products and services are derived from forests, but this report considers only marketed products. Other services range from the quantifiable, such as the better quality of water flowing from forested watersheds and the role of forests in flood and landslide protection, to the more subtle and even spiritual, such as the protection of the diversity of plants and animals in forest preserves and the beauty of forest wilderness. For more information on these other effects, see the Pew Center report on ecosystem impacts (Malcolm and Pitelka, 2000).

Given the large area in the United States covered by forests and their importance both to the national economy and to many communities, it is useful to explore how climate change may affect forests and the marketed products derived from forests. Climate is perhaps the single most important factor determining where forests exist and consequently where forest industries are located. If, as is predicted by many scientists, climate changes in the future, forest-growing conditions may change, and the forest sector will have to adapt accordingly. For instance, will forests move northward as temperatures increase, and will the forest sector follow this move northward? Will the health of the forest economy be maintained, particularly if some regions have reduced productivity? This study addresses those questions, with particular focus on how climate change may alter the future distribution and productivity of forests and the forest sector.

It is important to understand the ecological and economic impacts of climate change on both managed and natural systems. The classification of forests into managed and natural depends mainly on the stresses placed on forests by direct human intervention. For instance, the many tree plantations in the United States are clearly managed, and wilderness areas maintained on federal forestlands are clearly natural. However, this division into "managed" and "natural" is somewhat arbitrary, because forest management is much more continuous. Most forests in the United States are or have been managed, at least to some extent. In plantations, the composition, spatial patterns, mortality, and regeneration of the trees are controlled almost entirely by human action. Yet, even in natural forests, forest fires are controlled, indicating at least some minimal level of management.

While heavily managed plantation forests are producing an increasing amount of our wood fiber, natural forests remain an important part of the national forest economy. These forests most likely provide a larger share of the non-market services mentioned above. The overall extent of management on forestlands in the United States can be partially assessed by considering ownership and harvest patterns. Private individuals own about 59 percent of forest acreage. Most of this land is not managed intensively. Industry owns the most intensively managed land, but this amounts to only 14 percent of the total forest area. Government owns the remaining 27 percent; however, wood production from this land has declined over the past decade, as harvests from the U.S. national forest system fell from 15 percent of U.S. domestic wood production in the late 1980s to less than five percent today. Today, timber products are increasingly supplied from highly managed plantation forests on private land, but the less intensively managed private and government forests remain an important ecological and economic resource.

Estimating the impacts of climate change on the forestry sector may initially appear to be similar to estimating climate change impacts to agriculture, in which both natural scientists and economists focus on heavily managed agricultural systems (see the Pew Center study on agriculture, Adams et al., 1999). However, estimating the impacts of climate change to forestry is more difficult, because most ecological studies focus on impacts in natural forests, while economic studies of the forestry sector focus on managed forests. The differences between these two types of studies have major implications for predicting the effects of climate change on U.S. forestry, as integrating these two types of information can be challenging. For example, the ecological studies referenced in this report for the most part address natural forests in units that do not directly translate into timber yield, yet the economic studies must nevertheless use these units to estimate changes in yield.[1]

Another difficulty to consider is that impacts in the United States cannot be separated from the global context. The United States is the world's largest consumer and producer of industrial wood. It is also the world's largest importer: 30 percent of the softwood lumber used in the United States is imported from Canada. Although climate change may provide challenges for the timber products industry within the United States, additional market uncertainty may arise if other regions of the world also experience large-scale climate change impacts. This report does not fully examine global implications of climate change, but it does look at a number of aspects as they relate to climate change impacts on U.S. timber markets.

This report begins with a description of the ecological impacts of climate change on forests, both natural and managed systems. This includes discussions about the potential migration of tree species, changes in forest productivity and composition, and changes in disturbance frequencies. The study then considers how these ecological impacts affect markets and the timber industry. A discussion of the major ecological and economic findings to date follows.

II. Ecological Impacts

The close link between climate and vegetation, and hence between climate change and vegetation change, is a central ecological tenet today.

The large-scale boundaries of vegetation often closely follow patterns of climatic variables, particularly temperature and/or moisture (see Stephenson, 1990). Another significant environmental variable is evapotranspiration—the loss of water by plants through their surfaces (transpiration) plus the evaporation of water from the landscape (evaporation). Collectively, these two processes influence the availability of water to plants, and thus their rates of photosynthesis and ultimate productivity. Forests in the temperate and boreal zones are typically found in regions where the demand for water is equal to or less than the supply of water from precipitation. Forests, or at least ecosystems with a strong presence of trees, extend into drier conditions in the subtropics and tropics because they have adapted to dry conditions (Woodward, 1987). There appear to be relatively straightforward physical and chemical explanations for the occurrence of certain features in plants. For example, vegetation appears to be constrained by minimum temperatures that are related to ways that plants adjust biochemically and physically to low temperatures (chilling or freezing) (Woodward, 1987).

Environmental variables are interwoven in relatively complex ways. Warmer temperatures, for example, generally increase plant productivity. However, changes in temperature may interact with other factors. Plants require both water and carbon dioxide (CO_2) for photosynthesis and growth, and plants also use water to maintain heat balance. Warming can cause greater evaporation from soils that limits water availability to plants, potentially causing moisture stress that reduces plant productivity. However, this affect can be ameliorated by increased atmospheric CO_2, which allows plants to use water more efficiently. In addition, plants at different stages in their life cycles often have different levels of resistance to extreme environmental conditions. The range of environmental conditions in which a seed can survive is not necessarily the same as that of a seedling, which in turn may not be like that of the mature plant. Individual plants can often grow vigorously in environments in which they are unable to reproduce. Species often have "sensitive" life stages that, for reasons that are not obvious, limit their ability to survive over large areas.

Given the correlation among climate variables and vegetation patterns, changes in the U.S. climate are expected to cause changes in forests. This expectation is reinforced by two different types of scientific studies: analyses of past climate changes and investigations of the responses of computer models of forest dynamics to changes in climate variables. Both of these studies draw from a rich history of physiological studies, natural history observations, and large-scale ecosystem studies. As is discussed below, most of the current models investigating climate impacts use aggregated results from computer simulation models. These help managers understand potential changes in price trends that may result from climate change, and can thus be useful during investment decisions. However, they do not help managers determine specifically when to harvest stands, when to change species selected for given sites, or how to thin stands to maximize profits.

A. Past Climate Changes

Climate change over the past 10,000 years has been similar in magnitude to that which may result from a future doubling of pre-industrial levels of atmospheric CO_2. The present geological period, the Quaternary Period, is divided into two epochs, the Recent or Holocene (which goes back from the present about 10,000 years) and the Pleistocene (from 10,000 years ago to ~2 million years ago). In the Pleistocene Epoch, there were periodic formations of continental-scale glaciers, giving it the popular name, the Ice Age.

The Quaternary has had a particularly active climate, which has largely shaped the current distributions and patterns of plant and animal species. It is significant that during the Holocene epoch, which began about 10 or 12 millennia ago, the average global temperature is thought to have increased by about 2°C (3.6°F). This warming is at the low end of the range projected for the 21st century by general circulation models (GCMs) in response to greenhouse gas emissions. During the Holocene warming, significant change in forest vegetation occurred, altering forest ecosystems in the following ways:

1. Individual species of dominant plants on terrestrial landscapes changed their ranges with a great degree of independence. Changes in the range of individual tree species have been mapped for eastern North America over the past 14,000 years (Davis, 1981; Webb, 1988). These maps (for example, Figure 1) show the locations of the ranges of species at different times in the past. The maps demonstrate that tree species shifted their ranges in response to the changes in climate over the past several thousand years with a great degree of independence from each other. Different species of trees have had quite distinct changes in their ranges, and have experienced increases and decreases in abundance.

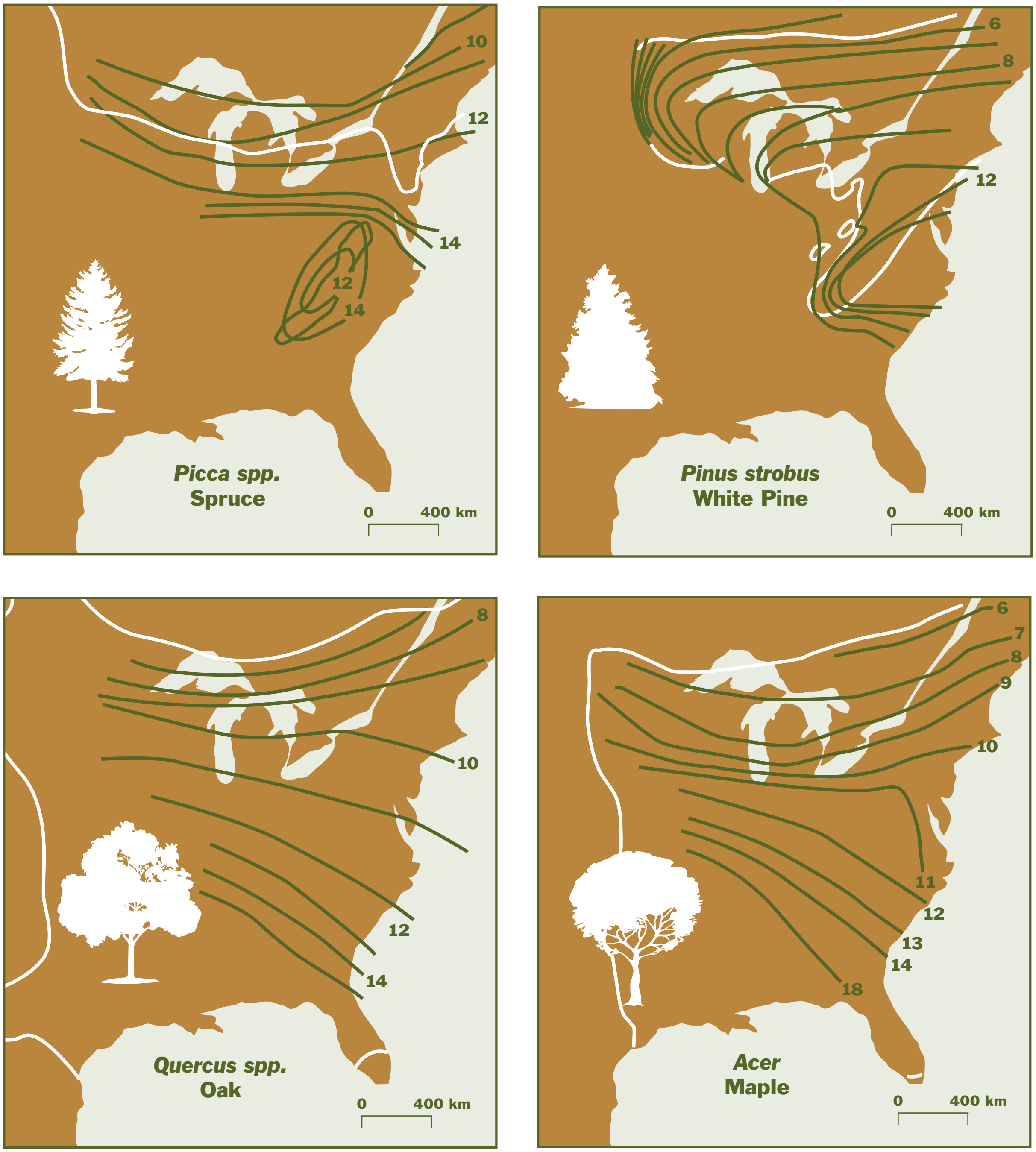
2. Some modern forest ecosystems developed fairly recently. Forest ecosystems not found today both appeared and disappeared in the past. Paleoecological reconstructions of boreal forests indicate that the particular species that comprise these forests have changed greatly over the past 18,000 years (Webb, 1988). These reconstructions reveal unique mixtures of trees and other plants relative to today. Analogous cases can be demonstrated in present-day tropical zones (Haffer, 1987; Whitmore and Prance, 1987; van der Hammen, 1988), temperate zones (Delcourt and Delcourt, 1991), or arctic zones (Lamb and Edwards, 1988).

3. The composition of forest communities changed at specific locations. In the western United States, the shift of tree species ranges was not as pronounced as it was in the East. This is most likely related to some degree to the mountainous topography in the West, which allows species to change elevation (rather than latitude) in response to changes in climate. However, there still is evidence that the forest ecosystems of the West were significantly altered due to past climatic change. For example, Cole (1982; 1985) examined the changes in the distribution of woody plants at different elevations in the Grand Canyon of Arizona and challenged the idea that the plant communities in the western United States moved up and down the elevational gradients as units. Cole found differences in patterns of zonation in response to environmental change over the past 24,000 years.[2] Communities that exist today were not in evidence in the past and vice versa. Species making up the vegetation of each mountain zone changed with a degree of independence from one another.

What one sees in the responses of forests to past climatic change are independent movements of the ranges of important tree species, the formation of new combinations of species to form novel ecosystems, and the disappearance of some types of forest communities. That these significant continental-scale changes occurred in response to what is thought to have been a 2°C (3.6°F) warming is an indication that there will be significant changes in forests caused by future climate change.

Figure 1

Changes in the Ranges of Four Tree Species Since the Last Ice Age



The lines in the maps above mark the boundaries of the species ranges in units of millennia (e.g., 12 indicates the range boundary of the species 12,000 years ago). The changes in the species ranges are in response to climate changes of roughly the same magnitude as that projected over the 21st Century due to climate change. The species clearly displayed marked differences with respect to their migration patterns and rates.

Source: Davis, 1981.

B. Projecting Future Forest Responses to Climate Change

Evaluations of the ecological impacts of future climate change on forests have often been based on the predictions of computer models of forest ecosystems in response to changes in environmental conditions (e.g., NAST, 2000; Gitay et al., 2001). These models are based upon extrapolations of our knowledge of leaf and plant physiology to larger spatial and temporal scales. By and large, they have been developed to represent forests comprised of a mix of species and age classes. The models were primarily designed to understand the underlying causes and patterns of dynamic interactions in forest ecosystems.

Uncertainties about regional climate change in GCMs are an important source of uncertainty in predicting the impacts of climate change on forests. Although GCMs are used to make predictions of regional changes in temperature and/or precipitation, these predictions are not necessarily reliable.[3] Further, there are important phenomena not included in the scale of GCMs that are nevertheless important to regional climate. For example, in the coastal plain of Virginia, if one separates annual rainfall in years with strong hurricane and tropical storm inputs of rainfall from years without such storms, the years with hurricanes have about 1,200 mm of precipitation and those without have 600 or 700 mm (Hayden, 2002). The latter rainfall rate is more typical of prairie ecosystems at the latitude of Virginia. While they may eventually be included (Conaty et al., 2001), hurricanes are not currently incorporated into GCMs.

The potential responses of forest ecosystems to climate change can be conveniently grouped as:

1. Changes in forest location—With a climate change, broad classes of forests comprised of multiple characteristic species could shift to new locations.

2. Changes in forest composition—The composition of species in some forests is different today than in the past. Over time, individual species have changed their ranges with a great degree of independence. For example, species ranges have shifted at different rates, resulting in different distribution patterns, and population sizes have both increased and decreased. Collectively, these processes may result in new combinations of species and forest classes.

3. Changes in forest productivity—Climate change will likely alter future patterns of temperature and precipitation, factors that have a strong influence on forest productivity. In addition, the increase in the concentration of CO_2 in the atmosphere could affect a plant's water balance and rate of photosynthesis, also influencing forest productivity.

These responses to climate change are the result of physiological and ecological processes acting at the leaf-to-plant, stand, and landscape scale (see Box 1). The first two responses (changes in forest location and composition) are very much in evidence in records from the past, but the third, involving productivity, are less known paleoecologically. However, predictions of changes in forest productivity have increasingly dominated assessments of climate effects on forests.

Changes in Forest Location

Several studies evaluating the effect of future climate change on the forests of the United States have used biogeographical models to predict potential changes in the location of forests. The most straightforward of these models are based on observed correlations between climate variables and vegetation classifications. This approach has been applied to predict the distribution of vegetation for past climatic conditions associated with the last glacial maximum (Prentice and Fung, 1990) and to predict future

Box 1

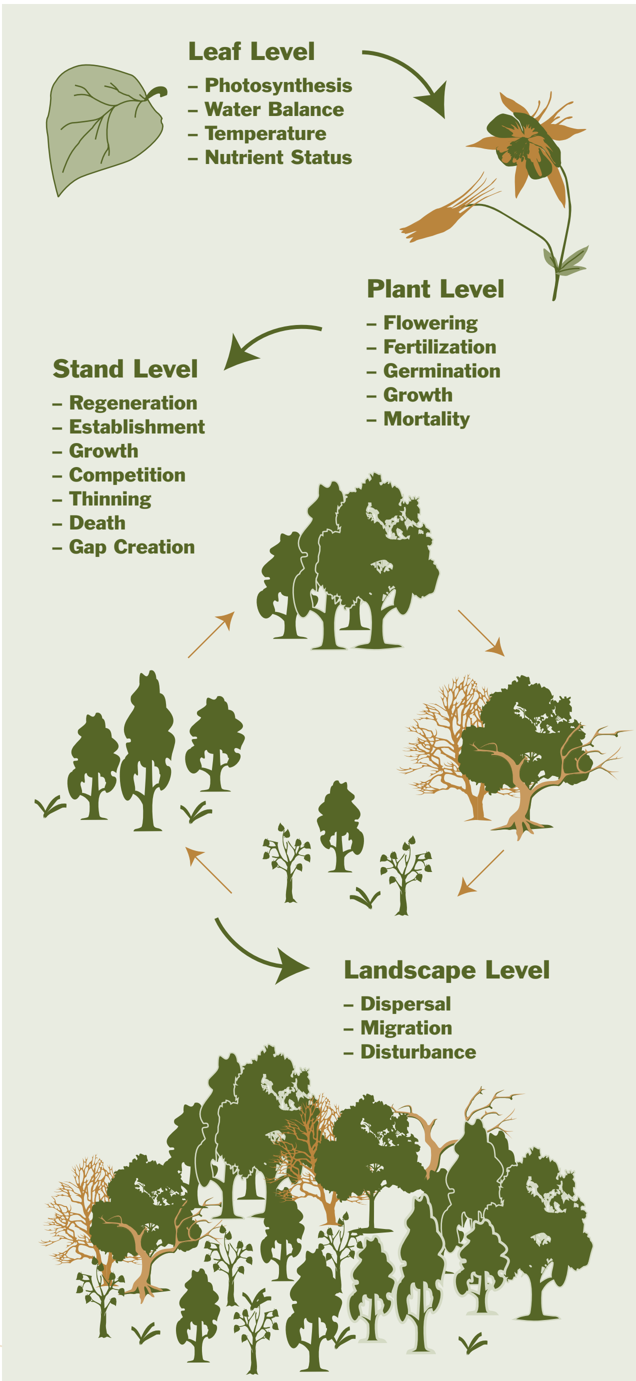
Scale and Forest Response

The response of a forest ecosystem to climate change is a consequence of complex interactions among the components of the forest. Therefore, to understand the effects of climate change on forests, it is essential to appreciate the manner in which forests function at different biological and ecological scales (Shugart, 1998). Woodward (1987), in his classic treatment of climate effects on vegetation, illustrated the importance of understanding that the response of vegetation to climate change varies among different temporal and spatial scales. Forest ecosystems comprise multiple levels of biological complexity (see Figure 2, next page). Response to environmental change arises from processes occurring at the level of the leaf, the whole plant, the stand, and the landscape. Across these organizational levels, response to climate change can have very different magnitudes and even different directions.

Temporal scales are also an important consideration in understanding forest responses to climate change. For example, a change in the ranges of species of different types of plants (herbaceous vegetation, shrubs, trees, etc.) is produced by long-term climatic variation. Late-successional trees require variations in climate over multiple centuries to induce a contraction in their distribution. The expansion of a species' range is induced by climate change that is sustained over somewhat shorter timescales, but still on the order of centuries. However, in neither case do species' ranges change on account of monthly to daily variations in the climate, unless they are sustained for many years. These daily to monthly variations are important for other aspects of plant response (e.g., flowering, germination). At even finer timescales, minutes to seconds, significant variations in the climate strongly impact still other aspects of plants, notably processes involved with tissue-level responses and plant physiology (e.g., stomatal opening, leaf gas exchange).

Figure 2

Scale and Processes at Different Levels of Organization in Forest Ecosystems



climate patterns under conditions of doubled atmospheric CO_2 (Emanuel et al., 1985a; 1985b; Smith et al., 1992a; 1992b; 1995). Neilson (1995), using a more descriptive approach of the factors controlling the distribution of species, identified forest types that appear particularly vulnerable to climatic change across the United States: high-elevation forests in several locations, and drier and older forests in the Northwest and South (see Figure 3).

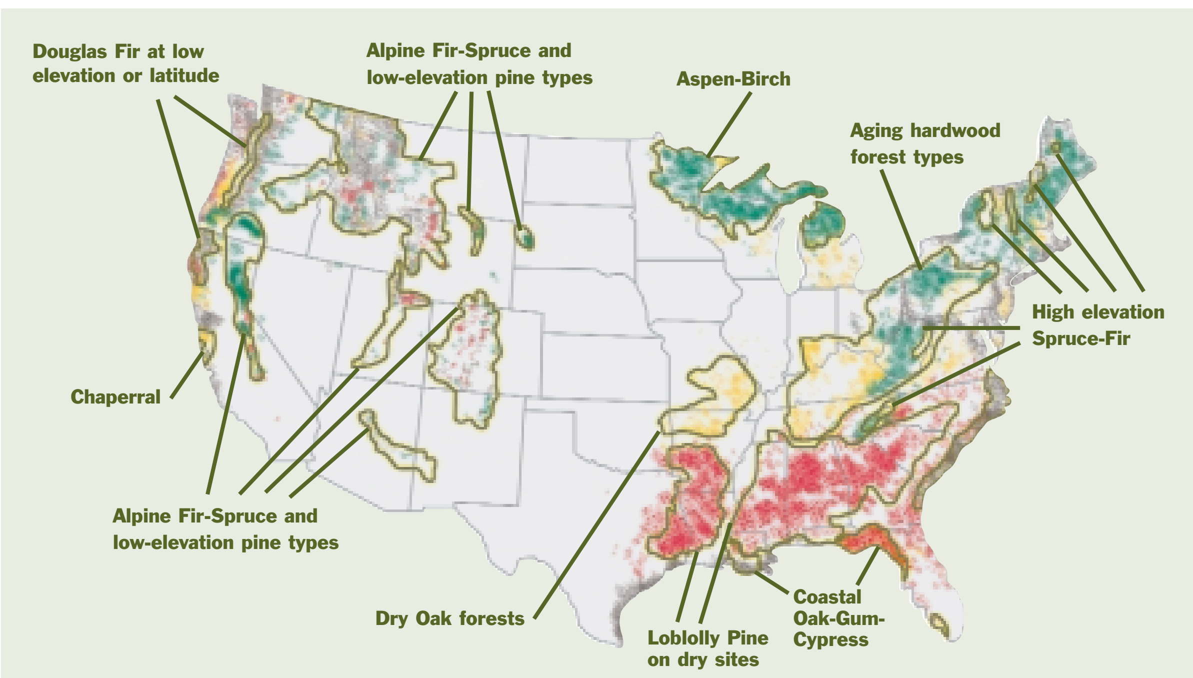
Largely based on the use of analogous approaches, Working Group II of the Intergovernmental Panel on Climate Change noted in 2001 that the boreal forests (generally northern or high-altitude forests, dominated by conifers) are likely to be affected first by climate change (Gitay et al., 2001). An earlier report (Watson et al., 1995) noted an average of about one-third of global vegetation[4] changed in broad vegetation type as a consequence of possible changes in temperature and water availability in response to a doubling of atmospheric CO_2. A substantial fraction of the existing forested area of the world was expected to undergo major changes in broad vegetation types—with the greatest changes occurring in high latitudes and the least in the tropics (Watson et al., 1995). All of these projections are based on the tacit assumption that the correlations between climate and vegetation in the future will be essentially the same as those seen in the present.

Rates of Migration of Tree Species

A critical issue in examining changes in the location of natural forests is the rate at which forests can migrate. Simply put, climate zones may shift faster than forests are able to migrate. This could have implications for the area covered by forests as well as how much carbon is stored in them (Smith and Shugart, 1993). This issue is less important for plantation forests, because foresters can plant seeds or seedlings appropriate for the climatic conditions. However, the timing of growth in many species is determined by day length. Trees shifted from their range often begin growing or initiate budding at inappropriate times (Davis and Shaw, 2001).

Figure 3

Forest Types that Are Vulnerable to Climate Change



Source: MAPPS Forest Cover Model, Neilson 1997; Overlay Graphics, Birdsey and Holt, 1997 (http://www.sgcp.ncsu.edu/nac/forestsector.htm).

Such phenomena as the migration of plant seeds, changes in the spread of insect disease, or changes in the spread of wildfire in different climates are also important for determining changes in the location of forests. These spatial effects require evaluations using computer models that include not only the changes in a forest at a point in time, but also the changes in space. The response of such spatially explicit models have been evaluated in cases of climate change, but the applications are all small-scale case studies, and no continental-scale analysis has been developed (due in no small part to the intrinsic complexity of the models) (see Chapter 12 of Shugart, 1998). The overall result from all these studies is cautionary—the effects of spatial interactions on the biomass dynamics in ecosystem models appear to be potentially quite significant (Shugart, 1998).

The spatial pattern of the response of terrestrial ecosystems to large-scale change, and the potential effects of such spatial phenomena as migration of vegetation, can matter considerably when the dynamics of carbon are considered (Pitelka et al., 1997). Spatial effects such as species migration slow the responses of landscapes to changes. In other model-based investigations, spatial effects can reduce the rate at which species become extinct in response to an environmental change by providing safe locations where a species can persist (at least for a time).

Changes in the Composition of Ecosystems

Models can also provide insight into changes in composition. In particular, two model types—species niche models and individual-tree-based approaches—give us useful insight.

Species Niche Models

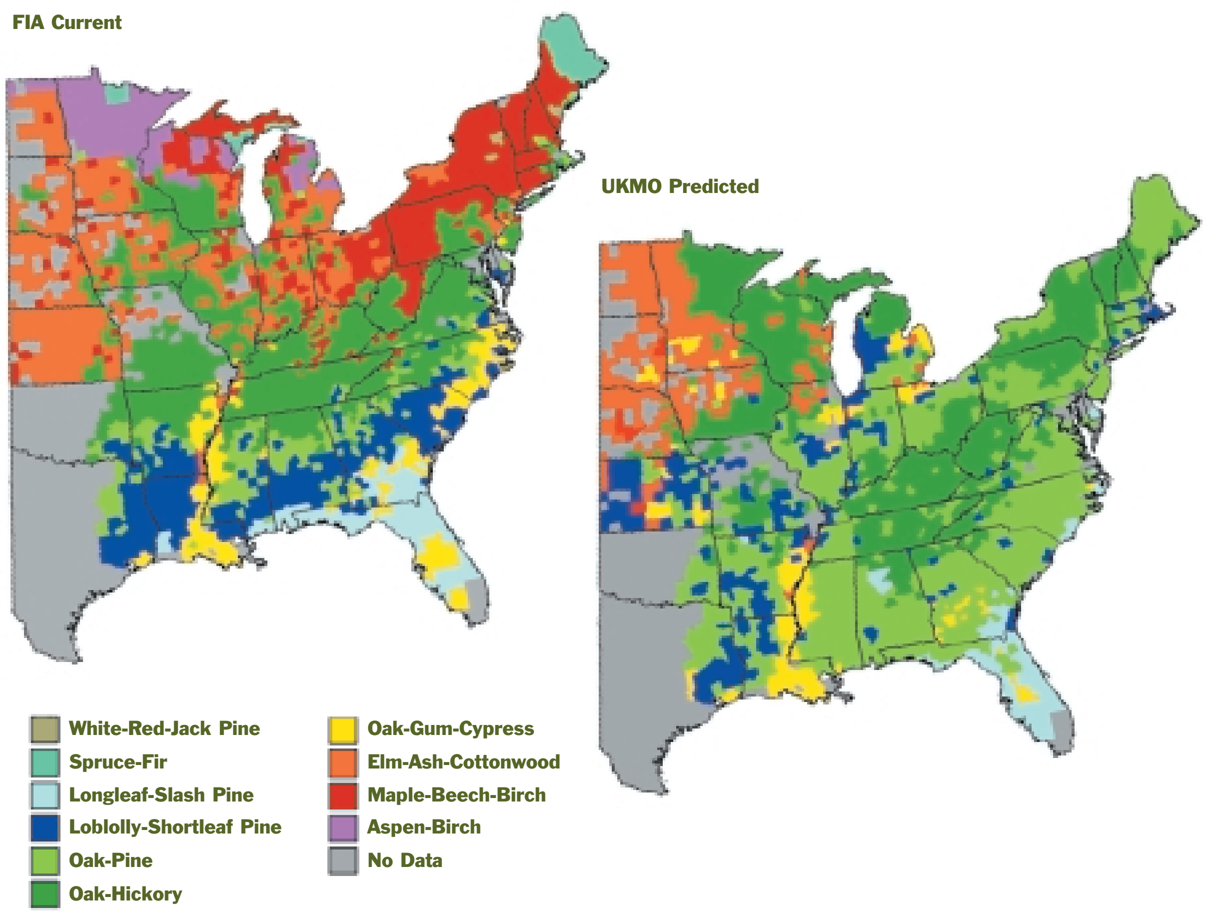
Species niche models use the environmental variables that appear to control the geographical distribution of species as a basis to develop maps of tree species distributions in response to climate change. Since trees have been known to shift their ranges independently of one another during past climate changes (thus changing the composition of forests across the continent), this is a potentially valuable contribution.

Iverson and his colleagues (Iverson et al., 1999; Iverson and Prasad, 2001) recently completed an extremely detailed analysis of the potential distribution and importance of 80 major eastern U.S. tree species using five different GCM scenarios (see also Figure 4 and Iverson and Prasad, 1998; Prasad and

Iverson, 1999). As an example of this approach, Figure 5 (next page) shows the distribution of loblolly pine (*Pinus teada*), the principal forestry species in the nation. The results imply a reduced presence and performance of loblolly pine in the southeastern United States and a shift into Kentucky and northward, where it now does not occur. By estimating shifts in the distribution of all 80 tree types, Iverson and his colleagues were also able to estimate the changes in forest types across the eastern United States (Figure 4).

Figure 4

Changes in the Dominant Forest Types Across the Eastern United States



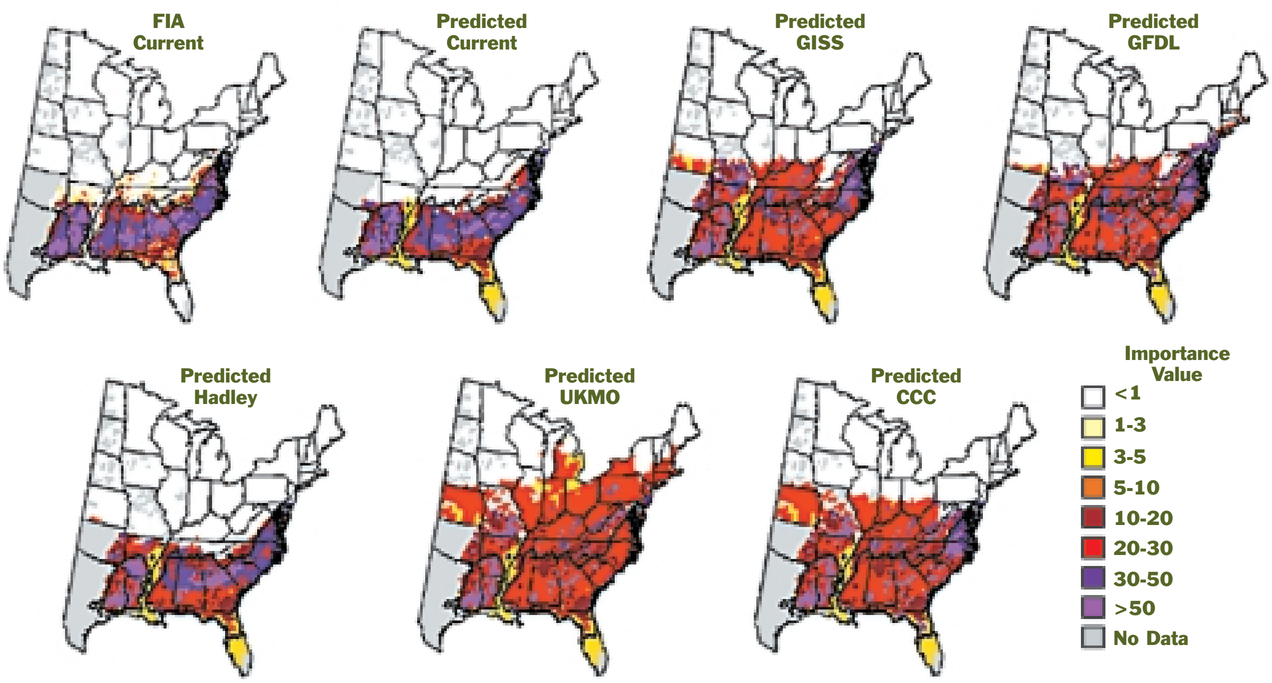
The above maps depict changes in the geographic distribution of major forest types in the eastern United States in response to climate change. Forest type categories were based upon the work of Iverson (1999). Left: Present distribution of forest types from the current USDA/Forest Service inventory (FIA) data. Right: Analogous forest type map generated under the climate conditions predicted by the United Kingdom Meteorological Office (UKMO) for a doubling of atmospheric CO_2.

Source: Iverson et al., 1999.

These changes are significant: the major timber species of the South are displaced northward into what is now a cereal-grain-producing agricultural region (see economics discussion on land use shifts between forests and agriculture), and there is a major shift and reconstitution of the forest communities of most of the eastern United States. Shafer et al. (2001) found similar sensitivities in a number of western tree species to climate change from a variety of different climate change model scenarios, but found that western species would not necessarily migrate northward.

Figure 5

Changes in the Distribution and Abundance of Loblolly Pine Under Five Different Models



The above maps depict the distribution and abundance of loblolly pine under present conditions as well as the predicted distribution and abundance from five climate models for a doubling of atmospheric CO_2. The two maps in the upper left represent an initial comparison between the present observed distribution and abundance of loblolly pine based on forest inventory date (FIA Current) and model predictions (Predicted Current), indicating that vegetation models do a reasonable job of capturing the observed distribution of loblolly pine. The remaining five maps represent the predicted distribution and abundance for loblolly pine in response to a doubling of atmospheric CO_2 for five GCMs (which vary in their projections for future changes in temperature and precipitation). The Importance Value is an indicator of the relative dominance of a species (here loblolly pine) to other species.

Source: Iverson et al., 1999.

Individual-Tree-Based Approaches

Individual-tree-based models[5] are similar to species niche models in considering environment/species interactions, but they also simulate the birth, growth, and death of each individual tree (and their interactions) for a simulated landscape. Neither approach has considered the genetic diversity of the species involved, which is an important limitation because there is genetic variation among individuals across a species' range. A recent review pointed out that this omission is likely to make the climate change evaluations overly optimistic (Davis and Shaw, 2001). Even so, most studies using models that consider the biology of individual species, or even functional groups of species, estimate significant change in response to changes in climate predicted by GCMs.

The individual-tree-based models used to project possible consequences of future climate change typically project significant changes in species composition, vegetation structure, productivity, and standing biomass (Solomon et al., 1984; Solomon, 1986; Pastor and Post, 1988; Urban and Shugart, 1989; Bonan et al., 1990). These applications usually are limited to a local landscape, largely because of a lack of basic information on soils and elevation and other information needed to implement the models over large areas at a high resolution. Thus, these limitations are from a lack of initial data and not inherent to this particular model formulation. Indeed, in some cases, such models have provided subcontinental scale evaluations by assuming a standard soil type and by directly incorporating detailed information of climate variables (Solomon, 1986; Bonan, 1989; Smith et al., 1992a).

In one example of the application of an individual-tree-based model to assess the effects of regional climate change, the effects of several different climate change scenarios were estimated for boreal forests near Fairbanks, Alaska. Fairbanks is in the zone of discontinuous permafrost: north-facing slopes and poorly drained sites have a persistent ice layer in the soil, and are dominated by black spruce (*Picea marina*), one of the few tree species than can grow under such conditions; south-facing slopes have no permafrost and are dominated by white spruce (*Picea glauca*). Using a boreal forest gap model, Bonan (1989) and Smith (1995) investigated the responses of several tree species to several climate change predictions from GCMs for several hundred years on 100 simulated plots near Fairbanks and for conditions associated with north-facing and south-facing slopes. The cold forests of black spruce growing on north-facing slopes were largely unaffected by the climatic warming, but the warmer, white spruce forests of the south-facing slopes were strongly affected by the change in climate (Figure 6). Conditions on the south-facing slopes under climate change were outside the ecological conditions under which the common tree species near Fairbanks are known to be able to persist. For example, for white spruce, the limiting condition appeared to be moisture stress brought on by increases in temperature. Significantly, tree-ring studies a decade after Bonan's work investigated the effects of the recent warmer-than-usual decades on white spruce near Fairbanks and indicated that the warmer temperatures have caused a reduction in productivity due to moisture stress, as predicted by the earlier gap model study (Barber et al., 2000).

Changes in Forest Productivity

Forest productivity directly affects timber yields and other services provided by forests. In most assessments of climate change on forest productivity, computer models that emphasize the biophysical and physiological impacts of climate change on leaves and trees are scaled up to predict forest productivity. An immediate appeal of these assessments is that at least some of the models have mechanisms that involve the direct effects of elevated CO_2 on plant processes as well as the effects of climatic changes involving temperature and water, something for the most part that has not been incorporated in individual species models, although there have been some recent exceptions (Friend et al., 1993; see Chapters 10 and 12 of Shugart (1998) for reviews of other applications worldwide). Because the models used in these assessments draw from plant physiological studies, it is useful to discuss the observational basis for changes in plant function from direct CO_2 effects and some of the issues in scaling these small-scale observations to larger spatial scales and longer time scales.

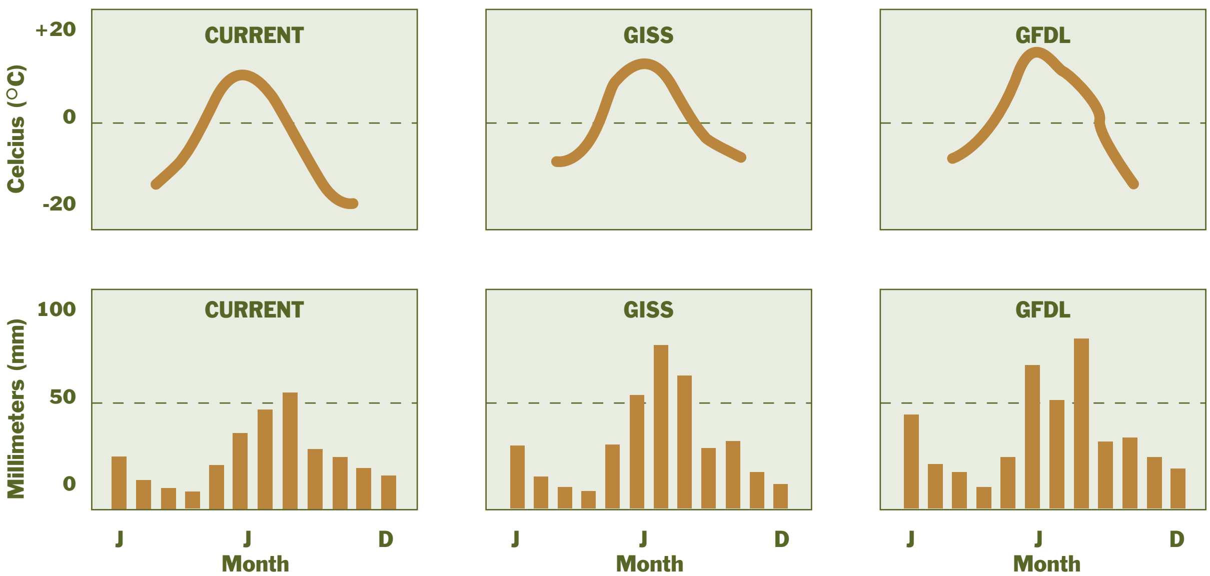
Carbon Dioxide Effects

The biggest challenge in understanding the future forest conditions in a world with greenhouse warming is that the CO_2 levels expected in the future atmosphere are truly remarkable in recent geological time. Because CO_2 is an essential component of the process of photosynthesis that underlies plant productivity, the composition of the future atmosphere is a significant factor in considering the response of future forests.

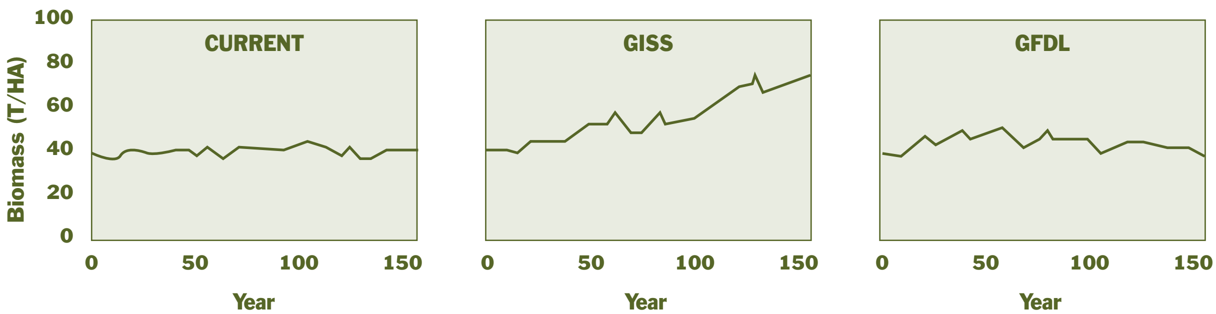
Assessing the potential effects of increased CO_2 in the atmosphere on forest productivity requires appreciating the strongly interactive nature of water, CO_2, and heat in forest canopies. Water use

Figure 6

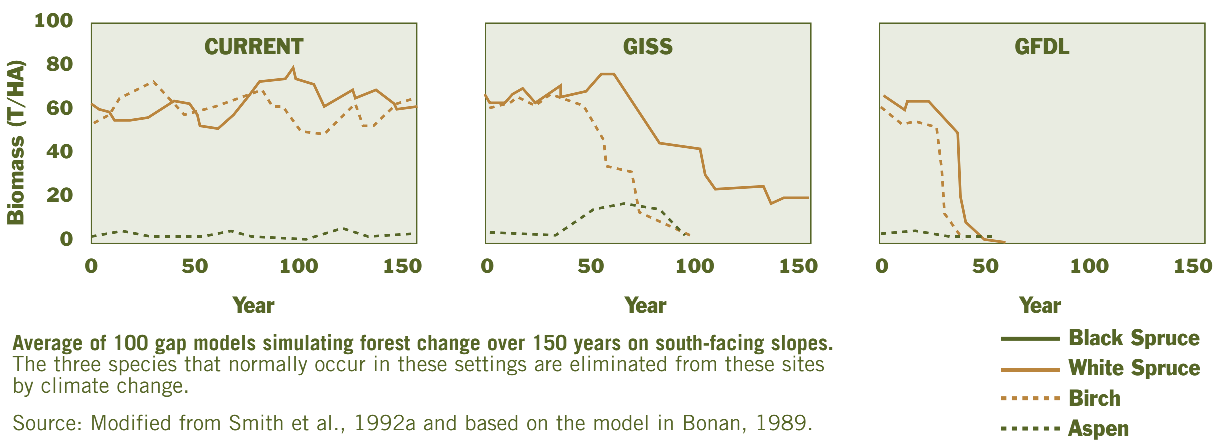
Predicting the Dynamic Response of Forests Associated with the Current Climate and Two Different Climate Change Scenarios for Forests Growing near Fairbanks, Alaska



Scenarios used in the simulation. CURRENT is the present monthly temperature and precipitation for Fairbanks and equivalent information as projected by the GISS (Hansen et al., 1988) and GFDL (Mitchell, 1983) climate simulation models assuming a doubling of atmospheric CO_2. Note the elevated winter temperatures from "greenhouse warming" in both of the climate-change scenarios compared to current conditions.



Average of 100 gap models simulating forest change over 150 years on north-facing slopes. The transition from the current climate to the new climate occurred incrementally over the first 50 years. The only tree species that occurs in these conditions is black spruce (*Picea marina*). Climate change has neutral (GFDL) to positive (GISS) effects on black spruce biomass.



Average of 100 gap models simulating forest change over 150 years on south-facing slopes. The three species that normally occur in these settings are eliminated from these sites by climate change.

Source: Modified from Smith et al., 1992a and based on the model in Bonan, 1989.

efficiency is a commonly used index of how much photosynthesis occurs for a given amount of water. If water use efficiency is high, sufficient water will be available for photosynthesis to maintain growth and productivity. However, if efficiency is low, productivity may be limited by moisture stress, whereby insufficient water is available to maintain photosynthesis. What will be the effect of increased CO_2 on the water use efficiency of plants? A plant's stomata (pores in the leaf surface) open and close to control the diffusion of CO_2 into the leaf and, at the same time, allow water to diffuse out of the leaf. If there is more CO_2 in the air outside the leaf, then the diffusion inward is greater. In this case, more molecules of CO_2 move into the leaf per water molecule moving out of the leaf, increasing the efficiency with which the plant uses water. This allows plants to grow better under drier conditions. However, the heat balance of the plant represents a significant complication that interacts with water use efficiency. The evaporation of water off leaf surfaces has a cooling effect. Thus, even if increased atmospheric CO_2 could potentially allow a tree to keep the stomata of its leaves closed for longer periods, it might still need to continue to leave the stomata open for the purpose of evaporative cooling to maintain heat balance. As a consequence, the improvements in water use efficiency could be offset by the need to maintain heat balance.

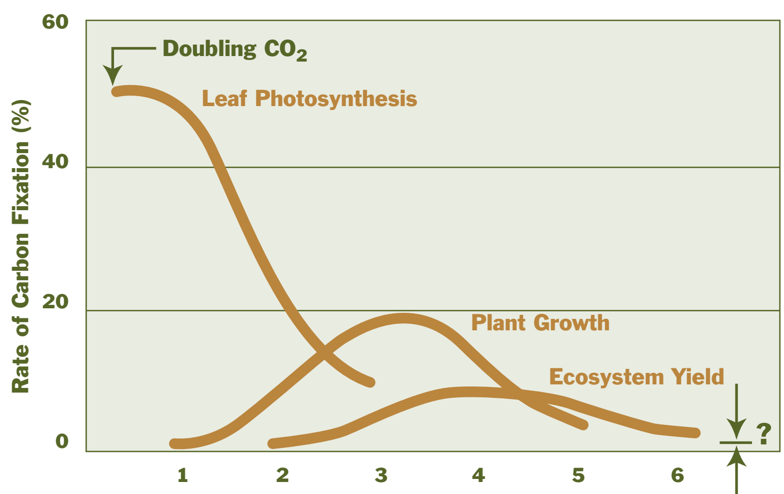
In greenhouse studies of agricultural species growing in single pots under well-watered conditions with adequate nutrients and light but with ambient CO_2 concentrations about double that of today (about 660 ppm), plant growth increases about 40 percent across a variety of young plants, but less (about 26 percent) for tree seedlings and mature plants. If this growth were translated directly to forest growth, the combined effects of a climate warming and elevated CO_2 levels could be quite positive for forest productivity. (However, even this relatively positive case could still produce significant changes in the composition, biotic diversity, and nature of natural vegetation—a significant issue for forest biodiversity). Typically, as the experiments run over longer time periods, the plants grow and their positive response to elevated CO_2 decreases due to crowding in the pot. This "pot effect" is complex in that it occurs even in well-watered and fertilized experiments. A possible implication of the pot effect in reducing growth, as well as the results of experiments with several plants competing in pots, is that as experimental conditions more closely approximate actual field conditions, the less pronounced are the positive effects.

For increased atmospheric CO_2 to significantly increase forest productivity, positive increases in leaf net primary productivity would need to be translated from the level of plants to the level of a forest stand. One would expect increased forest productivity and yield. However, there is a degree of uncertainty as to the magnitude of the positive effect at higher levels of biological organization. Observed responses in plant tissues, plants, and interactive ecosystems demonstrate that the positive effects of increased CO_2 may be significantly reduced in natural systems. Körner (1993) reviewed over 1,000 published papers on the response of plant systems at several different levels (single plant, cultivated plants, natural vegetation) to elevated CO_2. He found that the equivalent positive effects of elevated levels of CO_2 were reduced significantly at higher levels of organization (for example, whole plants rather than leaves) (Figure 7). This same reduction also occurred over intervals of years, weeks, and hours. The causes of these changes in response are potentially many. Likely causes range from the tendency for plants to outgrow their pots in longer-term greenhouse studies and thus slow their growth, to a "down regulation" of photosynthesis in high CO_2 conditions. Thus, the clear implication is that the seemingly positive effects of CO_2 on plant performance observed under laboratory conditions may not directly translate into large improvements in forest ecosystem productivity.

One region where CO_2 direct effects could be significant is the southeastern United States. Many of the GCM simulations over the past decade or longer have indicated significant drying in the Southeast, despite moderate increases in precipitation, because of higher temperatures. An ongoing free-air CO_2 experiment (the Duke University FACE experiment) in this region is documenting the direct effects of CO_2 on a loblolly pine forest growing on small field plots. Based on Körner's (1993) review of the topic, one would expect some

Figure 7

Response of Carbon Gain to Increased CO_2 Concentrations



Over short time scales (hours), a doubling of atmospheric CO_2 concentrations causes a significant increase in leaf photosynthesis and carbon fixation. Over medium time-scales (days-years), the increase in leaf photosynthesis causes a gradual increase in plant growth, followed by a gradual decline. Over medium to long time scales (years-centuries), the increase in plant growth leads to an increase in the overall yield of a forest ecosystem. It is important to note, however, that the response of leaf photosynthesis is much larger than the response at the forest level. The effect of increased CO_2 over time scales greater than a century is currently unknown. (Time scale on the X-axis is in powers of 10; 1=10 hours, 6=~114 years).

Source: Körner, 1993.

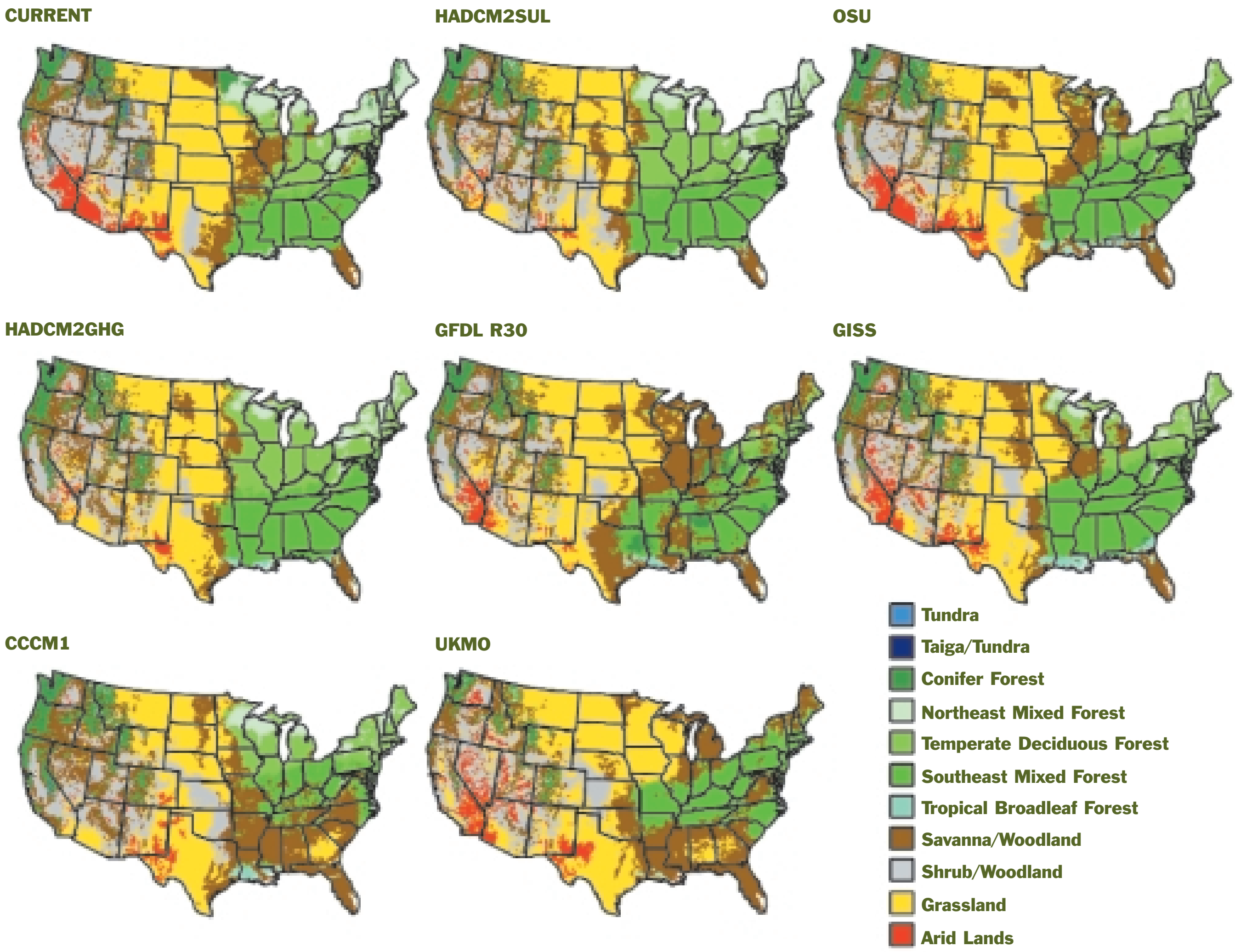
level of increased yield of forests, but the increase should not be as great as the response seen in single trees. An early result (Schlesinger and Lichter, 2001) is the modest response predicted in Körner's review, plus an indication that the increased rate of carbon storage in the forest litter is limited. Other researchers working at the same site (Oren et al., 2001) note that the storage of carbon from increased CO_2 is limited by soil fertility, perhaps a parallel of the "pot effect" seen in laboratory experiments manifested at the level of the forest stand.

The ongoing Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) compares the response of six different ecological models to a doubling (versus pre-industrial levels) of atmospheric CO_2 and several different climate change scenarios for the conterminous United States (VEMAP, 1995; Malcolm and Pitelka, 2000; Figure 8). The six ecological models vary significantly in their input requirements, but include several homogeneous landscape models, particularly in the parts of the project oriented toward dynamic responses. Perhaps not unexpectedly, given the differences in model formulation and resolution, the six models produced rather different results when subjected to large changes in the environment. For example, three of the models simulated changes in vegetation structure across landscapes under climatic warming scenarios and each produced a different result: substantial increase in forest area (MAPSS model), relatively slight changes in forest cover (DOLY model), and a significant decrease in forest area (the BIOME2 model).

A similar variation in net primary production and biomass is predicted by VEMAP's homogeneous landscape models (BIOME-BGC, CENTURY, and TEM). When CO_2 fertilization is not included or set to zero in the model simulations, climate change produces a range of net primary production changes, –6.5 percent to +17.0 percent from the baseline, and total carbon storage changes ranging from –37.6 percent to +4.3 percent, depending on the model and climate change scenario considered. When CO_2 effects are incorporated in the model responses, the simultaneous effects of climate change and direct CO_2 effects range from +1.7 percent to +34.6 percent for net primary productivity and from –32.7 percent to +14.6 percent for total carbon storage (again, depending on model and scenario).

Figure 8

Modeled Vegetation Distributions for the United States



The above maps were generated by the MAPSS vegetation distribution model (10-km resolution), and depict patterns of major vegetation types in the conterminous United States under current conditions and in response to a doubling of pre-industrial atmospheric CO_2 concentrations. The map in the top left corner represents the current distribution of major vegetation types. The remaining seven maps represent the change in distribution of those vegetation types as predicted by different climate models.

Source: Neilson, 1995.

Disturbance Regimes and Productivity

Climate change can be expected to modify the large-scale processes that affect forests in the same manner that the small-scale physiological processes may be altered (Overpeck et al., 1990). Principal among these large-scale changes are alterations in the disturbance regimes of forest ecosystems. Disturbances are significant, often abrupt changes in the environment of an ecosystem, such as wildfires, floods, droughts, and extreme meteorological conditions (e.g., frosts, hurricanes, and extreme winds). Disturbances are the agents of death and destruction; however, they are also part of the natural environment of an ecosystem. The components of a given ecosystem are adapted to different degrees to the disturbance regimen of the ecosystem's environment. The importance of environmental disturbances is that they cause ecological systems to go through substantial, but often predictable, dynamic changes in internal structure, component interactions, and process rates. Because disturbances occur at spatial scales that are larger than those of most ecological studies, and because their recurrence intervals are often longer than the duration of most ecological studies, these disturbance-related changes can be very difficult to quantify.

Thus, the effects of disturbance are often missing or inadequately estimated in calculations of significant ecosystem processes (Aber et al., 2001). The MC1 biogeographical model (Lenihan et al., 1998) includes an empirical fire regime and thus is a first step in including disturbance in a large-scale model (Bachelet et al., 2001). Under warmer climate conditions, the model indicates increased biomass loss from increased wildfires. Wetter conditions in the West lead to larger fires because of fuel build-up during wet years, which gets consumed by fire during dry years. Since wildfire is often a consequence of extreme events, such applications are dominated by conditions in which the uncertainty in the climate change scenario itself is likely to be high.

Since their origination, individual-tree-based models of forests have included disturbances such as fires, flooding, and harvest (see Chapter 8 in Shugart (1998) for examples), and some of these models have been run to consider changes in extreme climatic events, such as hurricane frequency (O'Brien et al., 1992) and flood frequency (Pearlstine et al., 1985). In many of these individual-tree-based model evaluations, increases in disturbance probability generally decreases biomass, increases species diversity, and reduces the percentage of a landscape with mature forest cover. The spatial heterogeneity caused by disturbances and their effect on natural systems are not well incorporated into predictive ecological models used in the assessment of climate change impacts to forests, making this an important topic for additional research in the future.

As ecosystems respond to disturbance, associated changes in energy, moisture, and trace gas transfers between the atmosphere and land surface affect climate and, in turn, the occurrence of subsequent disturbances (Bonan et al., 1992; Henderson-Sellers et al., 1993). One might expect the fire regime of forest systems to be strongly altered by climatic change. Warmer temperatures may cause drier and/or drought conditions in forests that make them easier to ignite and cause them to burn faster. However, wetter conditions could also affect fire regimes by increasing plant productivity, which could increase the vegetation that fuels wildfires. The largest fires tend to occur with extreme weather (hot, dry, and windy), but our lack of knowledge about how extreme weather will change makes it difficult to predict how these disturbances will be affected by climate change.

Fundamental Processes in Models of Productivity

Many of the models used in assessing the interactive effects of climate, CO_2, and forest productivity are based on an assumption that a forested landscape or regional landscape functions as a single, uniform dynamic unit. This is a significant model simplification, but the resultant models are far from "simple." Indeed, they represent a challenge with respect to model parameter estimation and model testing. Usually these models "scale up" the response of ecological processes measured at smaller spatial scales. For example, one might assume that the fluxes of heat, H_2O, and CO_2 associated with the functioning of a single leaf are duplicated by the sum of the responses of the billions of individual leaves in a vegetated landscape. Models based on this assumption often are the ecological models linked to other models of ocean or atmospheric dynamics to assess the relationships among these major earth systems (Ojima, 1992).

The models attempt to represent all the important processes involved with the response of the vegetation to environmental conditions such as climate. In general, the simplifications associated with homogenous landscape models make them unable to simulate large physical changes in landscape vegetation. Representing small-scale processes in homogenous landscape models is also difficult, but such models have the distinct advantage of being able to simulate the direct effects of altered CO_2 levels along with associated climate changes on forest productivity. In general, these simulations indicate that the effects of increased CO_2 mitigate some of the adverse effects of climate change—notably the effects of moisture stress caused by elevated evapotranspiration in some forests.

C. Forestry Practice and Ecological Scale

Understanding the ecological response of forests to climate change is not simply an academic or theoretical consideration, because the ecological response ultimately affects timber yield and thus the economic response of the forestry sector. Scientific forestry has its origins in the management of forest stands to maximize forest productivity and thus yield. Achieving this goal necessitates the consideration of the interactions between tree physiology and forest ecology across varying ecological scales (see Box 1). For example, increased growth at the scale of an individual tree tends to increase that tree's vigor and decrease the likelihood of its death, thereby maximizing its yield. However, at the forest stand scale, an increase in growth of all the trees in the stand produces increased rates of stand thinning, or an increase in the likelihood of tree death, which may or may not decrease stand yield. In the history of forest practice, foresters have expended a tremendous and sustained effort to measure the differences in wood production in stands under different rates of tree growth and stand density.

The resultant compilations of these data are the stand yield tables that are currently the mainstays of forest yield prediction. Such yield tables predict the variables of greatest interest to those wishing to understand the impact of climate change on forests in terms that are immediately germane to forestry and economic effects (board feet, lengths of timber extracted for a harvest, total volume of usable wood). Central to the philosophy of developing yield tables is the observation that the height to which trees grow over an interval of time is an indicator of the quality of a site for growing trees.[6] The volume of timber on a site is a product of how many trees there are on the site and the volume of each tree (which is a function of the height and diameter of each tree). Yield tables can be used to determine if thinning could increase the production of the stand or to know how much the volume of the stand would increase if one delayed harvest. With knowledge of the timber prices, a range of questions can be answered using yield tables, such as, “Is the increase in productivity from thinning worth the costs of thinning?” or “Should a forest be harvested now or after five years when the trees have grown to a size that produces larger, more valuable lumber?”

Yield tables, which are based on decades or even centuries of data, are organized around the concept that any surveyed site can be given an appropriate and unchanging site index, a measure of the volume of timber that can be gained from a particular location. However, yield tables have a number of shortcomings that limit their ability to accurately translate stand characteristics into yield. First, the yield table approach has as its basis the assumption that the climate at a site does not vary (at least not enough to change the site index), a factor that may reduce their ability to predict future stand yields. Changes in temperature or precipitation over years to decades at a site of interest may have an important influence on stand productivity and yield.

In addition, improved tree genetics and new forestry practices (such as forest fertilization and the introduction of commercial tree species) are not factored into yield tables since these practices do not have a sufficient data history. Thus, a model-based approach to understanding the relationship among tree growth, thinning, spacing, and harvest planning has been developed that incorporates additional variables such as species genetics and other forestry practices. Such models are commonly referred to as growth-and-yield models, because their focal issue is the relationship between tree growth and forest yield (i.e., timber and other products). However, like traditional yield tables, published growth-and-yield models do not consider climate change effects for the same reason orbital variations of the earth are not included—these effects are currently considered unimportant with respect to other, more important controlling factors.[7] For example, in evaluating the spacing, thinning, and harvesting of forests over relatively short rotations, climate variations (such as a drought) are perhaps problematic, but do not factor as prominently in the growth-and-yield response of a forest as, say, stand density. Further, climate change most likely would involve model development beyond the empirical databases on which most current forestry approaches are based.

As noted in this report, the models used by ecologists to estimate the effects of climate change on forest location, composition, and productivity are different than the models that foresters use in current practice to predict forest yield. As noted above, this is because the models used by ecologists incorporate climate variables, while the models used by foresters do not. As a consequence, in order to estimate economic effects of climate change on the nation's timber supply, it has been necessary to use the outputs of ecological models that predict the response of forests to different climate change

Box 2

How Useful Are Model Outputs in Estimating Change in Forest Yield?

Allan Auclair, Forest Ecologist, U.S. Department of Agriculture

There remains considerable uncertainty in projecting the impacts of climate changes on forest yield. How useful are the estimates of future forest yields based on process or biogeochemical models such as BIOME-BGC, TEM, and CENTURY? These models simulate, for different scenarios of global warming, the expected changes in net primary production (NPP) or forest carbon uptake. But can these outputs be used as good proxies for changes in yield?

The relation of NPP to stand yield is not simple or linear and remains a problem central to modern "scientific" forestry. It is clear that a 20 percent increase in NPP does not necessarily mean a 20 percent increase in commercial yield. The accuracy of the NPP-yield link is highly variable and depends on the extent to which current models that simulate NPP include the many ecological processes that affect yield. Some examples of these processes include the following. As trees grow faster, they also experience more thinning and mortality as competitive stress increases. Many kinds of losses, such as those caused by insect outbreaks, pest invasions, fire, icing, and windstorms, are highly episodic, difficult to predict, and not part of NPP simulations. Climate change could result in greater weather extremes and increased forest losses. This is not addressed in the current generation of models.

Improvements in stand management and conversion technologies are not modeled. Rigorous protection of plantations from pests and fire can serve to greatly reduce loss. Species and strain selection, artificial regeneration into adapted species, thinning, fertilization, and other silvicultural techniques for achieving high yields can turn potential losses into significant yield and economic gains. Future innovations in wood harvest and processing technologies are difficult to forecast, providing an added complication. The fraction of the original volume "wasted" varies with species, the size and marketability of the trees being cut, the difficulty in harvesting and transport related to terrain and to weather conditions, and methods of harvest and product conversion. While small or young trees grow much faster and are more responsive to climate changes, their effective yield is smaller and less valuable than the larger planks or boards from older trees.

Modelers are addressing the need for better yield prediction through a varied array of new and existing research approaches:

(1) Yield and Loss Monitoring: Long-term records of yield and tree losses on permanent forest plots, such as the USDA Forest Service's forest inventory analysis and forest health monitoring networks scenarios. However, this approach presents a problem because the outputs from ecological models do not necessarily translate directly into harvestable yield (see Box 2), creating uncertainty in the translation of ecological impacts into economic impacts. Despite this problem, the results of ecological models provide interesting insight into how forest supply could be affected by climate change, and the subsequent economic costs and benefits.

Box 2 (continued)

(http://www.na.fs.fed.us/spfo/fhm), are being analyzed in detail. This research is a valuable source of new insight on how climate changes are affecting forest yield.

(2) Long-Term Experiments of CO_2 Enrichment: Hundreds of plant species have been exposed to experimental manipulations of CO_2 concentrations in glasshouse or field chambers and, more recently, in intact ecosystems and forest stands receiving free air CO_2 enrichment (FACE) *(http://www.face.bnl.gov/; http://cdiac.esd.ornl.gov/programs /FACE /face.html)*. In contrast to earlier studies, the FACE experiments on forest stands show a complicated response. There appears to be little evidence that the CO_2 fertilization effect saturates over long periods of time. Rather, the manner in which the extra carbon is distributed within the plant changes. For example, after the first year, the extra carbon was allocated to fine roots and leaves rather than to stem production (or presumably yield), which is no longer being enhanced by CO_2. Although roots and leaves are of great physiological importance to the plant, they are of little use for timber. Therefore, CO_2 enrichment caused continued increase in productivity, but the additional carbon had little effect on yield, and thus NPP could not be used to estimate yield response *(http://www.esd.ornl.gov/facilities/ornl-face/pce1999.htm)*.

(3) Network of AmeriFlux Towers: A series of heavily instrumented towers has been set up to collect and analyze long-term measurements of CO_2, water, and energy exchange in a wide diversity of forest ecosystems in the United States and elsewhere *(http://public.ornl.gov/ameriflux/About/objectives.cfm)*. These instruments will calibrate and verify observed growth (i.e., yield) versus simulated outputs of process-based CO_2 flux models. Monitoring under diverse natural conditions, including pest outbreaks and weather extremes (e.g., drought, storm damage), will enable significant improvements in yield modeling.

(4) New BIOME-BGC Models: Recent versions of BIOME-BGC include the effects of forest fires and extreme climate events such as drought on forest NPP *(http://www.forestry.umt.edu/ntsg/)*.

The use of NPP as a proxy for forestry yield is a provisional step necessitated by the absence of good yield models. At present, however, the task of predicting future forest yields in response to climate change or rising CO_2 still must overcome substantial problems. Resolving these uncertainties will require, in addition to the diverse array of new research efforts identified above, progress on a set of experiments and models dedicated specifically to the NPP versus yield issue.

III. Economic Impacts

In recent years, a number of economists have used results from the ecological models described above to assess how timber markets might respond to climate change. These studies provide a number of insights into the scale of potential changes markets may face, including changes in future availability of timber, location of timber production, timber prices, and profits for landowners and mills. To date, three types of ecological impacts have been systematically examined by economists: yield effects, dieback effects, and species migration.

Yield effects, which measure the impact of climate change on the annual growth of trees, are the most common effects analyzed in impact assessments. Changes in the annual growth of timber ultimately alter timber supply and prices by changing the quantity of timber available on each hectare of forestland. Since ecological models make different predictions about the rate, size, and direction of the climate change impact on forests, economists have used a range of the results available from ecological studies to determine potential changes in the annual growth of timber.

One of the difficulties with predicting how forest growth will change involves translating results from ecological models into estimates that can be used by economic models, namely estimates of changes in annual growth (see Box 2 for a discussion). For market analysis, economists are most interested in the effects on marketable timber species. Economic studies to date have used a variety of indicators from ecological models to determine how climate change affects timber yield. A number of economic studies have assumed that changes in annual growth are proportional to predicted changes in net primary productivity (NPP; Table 1). As noted in Box 2, there are some complications associated with using NPP, and other modelers have chosen to use different indicators, such as total vegetation carbon. There is consequently a wide range of potential ecological changes that have been translated into economic impacts. This sensitivity analysis allows us to assess potential impacts across a range of scenarios.

Table 1

Comparison of **Timber Market Studies**

Study	Market	Method	Climate/Ecological Scenarios	Results
Joyce et al., 1995	United States	Used changes in net primary productivity from the Terrestrial Ecosystem Model (TEM) to predict changes in timber growth rates, timber inventories, and timber supply.	*Number of Climate and Ecological Scenarios:* 2 *Range of Global Climate Change:* *Temperature:* +2.4 to 4.2°C *Precipitation:* +7.8 to 11%	Change in timber growth = +15%, range of –7% to +43% across species.
Perez-Garcia et al., 1997	Global	Used changes in net primary productivity from the TEM to predict changes in timber growth rates, timber inventories, and regional timber supply.	*Number of Climate and Ecological Scenarios:* 2 *Range of Global Climate Change:* *Temperature:* +2.4 to 4.2°C *Precipitation:* +7.8 to 11%	Changes in timber growth for the United States = +10%, range of 0% to +30% across species.
Sohngen and Mendelsohn, 1998	U.S. softwood	Used changes in total vegetation carbon and changes in distribution of timber species from three different models to predict changes in timber supply; changes in the distribution of species were modeled with a dramatic "dieback" scenario, and through a less dramatic "regeneration" scenario.	*Number of Climate and Ecological Scenarios:* 36 *Range of US Climate Change:* *Temperature:* +3.0 to 6.7°C *Precipitation:* +3.0 to 15%	Change in timber growth = +7%, range of –35% to +50% across species. Range of species loss through dieback = 25 to 46%. Range of change in net softwood area = 6 to 38%.
Sohngen et al., 2000	Global	Used BIOME3 model and ecological assumptions similar to Sohngen and Mendelsohn, but used net primary productivity, not total vegetation carbon.	*Number of Climate and Ecological Scenarios:* 4 *Range of Global Climate Change:* *Temperature:* + 1.0 to 3.0°C *Precipitation:* None Given	Change in U.S. timber growth = 17%, range of –1% to +34% across species. Range of species loss through dieback = 0% to 75%. Range of change in net forest area = –2% to –7%.
McCarl et al., 2000	United States	Used assumed changes in U.S. and Canadian production to develop range of scenarios of potential changes in future timber yields for important species based on literature review; used timber model to estimate economic impacts of combinations of these changes.	*Range of Global Climate Change:* None Given	Change in long-term annual timber growth = –6.2% to +13% (in northern United States only).
Irland et al., 2001	United States	Used changes in vegetation carbon predicted from two transient climate models and two transient ecological models to predict decadal changes in timber growth rates.	*Number of Climate and Ecological Scenarios:* 2 *Range of US Climate Change:* *Temperature:* +2.7 to 5°C *Precipitation:* None Given	Change in U.S. timber growth = +0.1% to +0.3% by 2100. Some reductions in growth in early periods.

In addition to considering changes in timber yield, some ecologists have suggested that trees could be affected by dieback and species migration. Estimates of potential changes in the geographic distribution of species are drawn from the biogeographical models described in Section II. These studies suggest that some stocks of existing timber become ill-suited to their current range when climate changes. In these areas, existing timber species are assumed to die back or to continue living, but to be unsuccessful in regenerating naturally. If ecology is considered in isolation, species take many years to migrate from place to place (see Clark, 1998). However, economists model human adaptation and adjustment through forest management practices such as salvage logging and replanting. Foresters, for example, can adapt by switching the tree species planted in a particular area when climate changes. The area replanted depends not only on the ecological conditions, but also on economic conditions such as the costs of replanting and current and future prices.

For the most part, economic studies have attempted to link results from ecological models to economic models, although some studies have developed sensitivity analyses across a range of assumed effects. The studies that rely on ecological models have predominantly used widely available equilibrium ecological results. Equilibrium results assume that both climate and ecosystems stabilize after CO_2 concentrations have doubled (usually assumed to occur around 2060). Although researchers recognize that atmospheric CO_2 will most likely increase beyond a doubling (IPCC, 2001), and that climate and ecosystems will continue to change beyond that, the earlier equilibrium estimates were driven by the models available at the time of the research. Economic studies thus made a variety of simplifying assumptions about the transient changes, the most important of which appears to be that they often assumed that changes would occur proportionally (often in a linear fashion) over the next 60-70 years until CO_2 concentrations doubled, beyond which no further substantial changes would occur.

The main limitation of these equilibrium studies is that they do not provide information on how forests would change over an extended period of time. It is possible that the changes could be negative for a particular period in time and then positive for another period, or vice versa. Recently, atmospheric scientists and ecologists have modeled transient changes (i.e., cumulative changes over time), and economists have begun adopting these results (see Irland et al., 2001).

A number of other issues affect the link between ecological and economic effects. First, as discussed in the introduction, most ecological studies focus on natural forests, while most economic studies focus on managed forests. It is not entirely clear what measures from ecological studies should be used to drive yield changes in economic models. Some studies have chosen NPP (see Box 2), while others have chosen vegetation carbon. These differences could affect modeled economic outcomes if the ecological models predict differences in how NPP and vegetation carbon respond to climate change. Second, increased CO_2 and changes in climate could change the economically optimal age for cutting trees. There is little research on this to date, although changes in rotation ages could have important effects. Third, some of the ecological research discussed above now suggests that the early positive effects of increased CO_2 levels on tree growth could subside or even be reversed in the longer term. As ecologists continue to explore new hypotheses, economic modelers will develop new estimates based on new ecological results.

A. Systematic Examinations of Climate Impacts on Timber Supply

A number of studies have assessed the economic impacts of climate change to the forestry sector. The term "economic impacts" as used here describes changes in the aggregate value of timber market activity. In many studies, aggregate economic impacts are estimated for the United States as a whole. These aggregate economic impacts can be further separated into either regional impacts or into separate effects on consumers and producers. Consumers will benefit if prices fall. Producer impacts are more complicated because they depend on profits. The profits individual landowners receive would generally rise if timber growth increases and fall if timber growth decreases, assuming no change in prices. However, in most of the scenarios described here, climate change has two opposing economic effects on timber producers: timber growth is predicted to rise, and prices are predicted to fall. Producer impacts are the net effect of changes in timber growth and changes in prices.

A brief review of a number of U.S. timber market studies is provided in Table 1. Each study in the table is unique, but they have some general similarities and differences. First, all of the economic predictions assume a future steady-state climate (i.e., climate stabilizes at some future time specified by the model), and the ecological changes are predicted to move toward an equilibrium effect. Forests have large initial inventories and the largest changes in growth are predicted to occur beyond 2050, so all of the models tend to predict small initial impacts, positive or negative, on markets. Even though these impacts become larger as the effects move toward the equilibrium, economists use discounting (which results in near-future effects having relatively more "present value" than effects far in the future) to value the future market impacts, so the studies tend to predict small overall impacts.

Second, many economic models focus explicitly on growth effects (Joyce et al., 1995; Perez-Garcia et al., 1997; McCarl et al., 2000; Irland et al., 2001). Among these studies, the modelers chose different approaches for linking the predictions of ecological models to growth functions in timber models. These differences indicate markets have a wide range of sensitivities to the effects of climate change, although generally if the ecological models predict increases in future growth, timber market studies predict that future inventories will increase (and vice versa if future growth is predicted to decrease).

Third, two of the studies combined changes in growth with potential dieback and species migration (Sohngen and Mendelsohn, 1998; Sohngen et al., 2001). This generated a wider range of potential economic effects. For example, they explored a set of scenarios where forests die back. Even though the models predicted an increase in growth for individual trees, net growth declined across some regions for some time because the losses from dieback outweighed the gains from higher growth.

Fourth, most of the studies are linked directly to climate change scenarios provided by General Circulation Models (GCMs). The studies are based on scenarios drawn from a number of different climate and ecological models. The number of total scenarios and the range of climate sensitivities (temperature and precipitation changes) for each study are shown in Table 1. Note that some studies provide data on effects within the United States, while others provide data only for global climate effects. The only exception is McCarl et al. (2000). While that study makes no explicit links to GCMs or ecological models, it develops a wide range of scenarios based on potential productivity effects possible under climate change.

The studies in Table 1 provide several general results:

- Higher timber growth increases timber inventories, expands the long-run supply of timber, and reduces prices. Lower timber growth reduces timber inventories and supply, and increases prices (Joyce et al., 1995; Perez-Garcia et al., 1997; McCarl et al., 2000; Irland et al., 2001).
- Assuming that species ranges change as suggested by some ecological models, adaptation through regeneration of southern species farther to the north can increase timber supply as faster-growing species replace slower-growing species over large areas (Sohngen and Mendelsohn, 1998).

- Economic impacts are predicted to be increasingly sensitive to reductions in southern softwood timber growth (McCarl et al., 2000). This conclusion supports similar previous studies suggesting that U.S. timber supply is most heavily influenced by how climate change affects growth and yield in the South (see, for example, Joyce et al., 1995; Burton et al., 1998).

- A range of adaptations are possible in timber markets: reducing prices, shifting the mix of species used in the production process, shifting capital from one region to another, and planting new species that are better suited to the new climate. The predicted overall capacity to adapt, however, differs dramatically.

- Rapid, short-term dieback was not found to dramatically reduce timber supply if landowners have salvage possibilities. Dieback signals markets to shift species from one region to another (Sohngen and Mendelsohn, 1998).

- Climate change impacts in other regions of the world will affect U.S. production, although studies disagree on the direction and size of change. One global timber market model finds that U.S. lumber and plywood production increases, although some scenarios show decreases in pulpwood production (Perez-Garcia et al., 1997), while another suggests that U.S. production would decline in the short term, leading to potential economic losses (Sohngen et al., 2001).

In general, these studies tend to predict that the climate changes likely to occur with a doubling of CO_2 will increase national timber supply and lower future timber prices. Sohngen and Mendelsohn (1998) predict that aggregate economic impacts for U.S. timber markets as a whole will be positive, ranging from +1 percent to +12 percent. Irland et al. (2001) predict significantly smaller economic impacts, less than 1 percent, although their aggregate results are all positive. McCarl et al. (2000) make no explicit links to ecological models, but they consider increased growth in northern U.S. forests and decreased growth or no change in growth for southern U.S. forests; their range of economic impacts is –4 percent to +1 percent. These estimates are less optimistic because they assume that southern forests experience either no growth effect or negative growth effects.

All the studies suggest that consumers gain while producers could be harmed if prices decline as a result of climate change-induced increases in U.S. timber supply. However, such price declines would mostly affect existing timberland owners with the most productive forests. For example, the largest losses would occur in the southern United States, where large investments in forestry already have been made and producers experience either lower prices or lower growth, or both. In contrast, producers in northern regions are expected to gain as productivity in that region increases more than in the South. These gains are predicted to be even larger if species migration occurs (either naturally or with human intervention), and landowners in the North can plant faster-growing forests or gain forestlands at the expense of less productive grasslands or savannas in the Northern Plains.

The potential for forest migration is important to consider, although economic analysis of forest migration is complicated. It is unclear, for example, whether or not forestland will expand at the expense of agriculture. Much of the prime agricultural land in this country was originally forestland, and many of

Box 3

The Potential Effect of Dieback and Species Migration on Timber Markets

Sohngen and Mendelsohn (1998) considered direct effects of climate change on the existing stock of trees. They linked ecological predictions from the VEMAP studies with an economic model to project future timber prices and market impacts. The price effects for four of these scenarios are shown in Figure 9. The dieback scenarios assume that existing timber stocks die on the stump, that a proportion of the wood that dies is salvaged, and that the land can be regenerated with new species if ecological models suggest that new species can live in that location. Under dieback, timber supply increases and prices fall as large quantities of timber are salvaged from the dying forests. Dieback thus benefits consumers, although lower prices and lost stock harm producers. Under a more benign scenario, titled "regeneration," forests are not assumed to die back, and there is no loss of stock. Prices are lower in this case because existing, mature trees are not lost to disease and insect infestation. Rather than having to adapt quickly through salvage, under the more benign scenario landowners regenerate new species once the ecological change permits new species to grow in new locations, and once the old species have been harvested.

These results highlight several uncertainties in economic estimates. First, a wide variety of economic impacts are possible because the ecological models generate different economic responses. Some models predict lower prices because they suggest large expansions of the most valuable U.S. timber species, southern pine, combined with increased net primary productivity and timber yield across most U.S. forests. Second, there is uncertainty about how climate change will affect existing stocks (i.e., dieback or regeneration), and these differences can affect price predictions and economic impacts. Dieback causes higher prices relative to the regeneration scenario. While higher prices and salvage can minimize the impacts producers experience if dieback occurs, both producers and consumers would be better off with the regeneration scenario. In general, potential market benefits of climate change are reduced by 10-30 percent when dieback occurs relative to the more benign regeneration scenarios. Third, although salvage logging reduces the effects of dieback in markets, both consumers and producers would be worse off if salvage is more difficult or costly than assumed in the study.

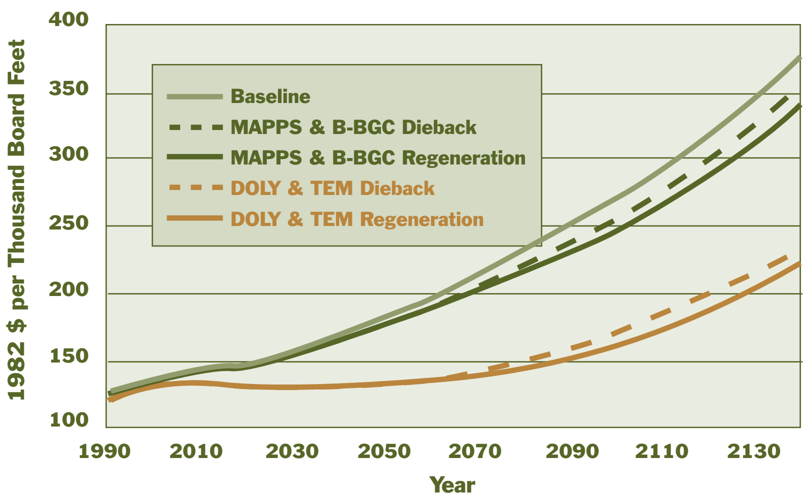
these regions could be suitable for different tree species altogether. For the most part, economic studies assume that forestland will not expand into these prime agricultural regions. Our understanding on this issue is incomplete because forestry may move into areas where forest productivity increases and agricultural productivity decreases. Whether or not markets allow this expansion will depend on price and relative differences in productivity effects between timber and agriculture. To date, researchers have not developed models to explore ecological and economic effects of climate change in both markets.

Migration also can affect the predicted timing of economic impacts. Because dieback and species migration potentially have near-term impacts on forests, studies that investigate these possibilities suggest larger near-term consequences for markets (see Box 3, Figure 9). Studies that consider only growth effects tend to assume that the largest effects occur far into the future (see Joyce et al., 1995; Perez-Garcia et al., 1997; McCarl et al., 2000). This has the effect of reducing the estimates of impacts in markets because most measures of economic impacts involve discounting.

One concern with most economic studies is that they use ecological results that include carbon fertilization effects (i.e., Joyce et al., 1995; Perez-Garcia et al., 1997; Sohngen and Mendelsohn, 1998). If the carbon fertilization effect turns out not to have positive impacts on forest growth and area,

Figure 9

Projections of **U.S. Timber Prices**



The above figure presents projections for U.S. timber prices for a baseline scenario (assuming no climate change) and four scenarios of forest response to a 2.5ºC (4.5ºF) warming and a 7 percent increase in precipitation. DOLY and MAPSS are two different ecosystem distribution models, which model the effects of climate change on forest location. B-BGC and TEM are ecosystem productivity models, which model the effects of climate change on forest productivity. The dieback scenarios predict that existing trees die when the underlying climate changes enough to support a new tree species. The regeneration scenarios assume that existing trees can continue to live and grow in a region as the climate changes, but are unable to reproduce, and thus are eventually lost from a region, but over longer time scales than in the dieback scenarios. The baseline scenario indicates that timber prices are projected to rise well into the 22nd Century, independent of climate change. However, the ecological models all predict that climate change lowers future timber prices (yielding a net economic benefit), although the DOLY model projects that climate change has greater impacts on timber prices than the MAPSS model. Regeneration scenarios yield greater benefits (lower timber prices) than dieback scenarios for both the MAPPS/B-BGC and DOLY/TEM models.

Source: Adapted from Sohngen and Mendelsohn, 1998.

economic impacts would show broader reductions in forest inventories, reductions in timber supply, and higher prices (see discussion on CO_2 fertilization above). It is difficult to assess how different assumptions about CO_2 fertilization would affect the overall results, but the studies that do predict growth reductions for the South (Burton et al., 1998; McCarl et al., 2000) suggest that market impacts appear to be more sensitive to decreases in timber growth than to gains in timber growth.

While many of the studies above use equilibrium results, more recent research captures transient changes. This may have important implications for economic estimates. Irland et al. (2001), for example, capture reductions in near-term (2000–2040) timber yields in some regions followed by long-term (2040–2100) increases in timber yields. Because economic models weigh near-term effects more heavily (because effects over the long-term are discounted), that study predicts smaller positive effects than many earlier studies that simply considered how the changes would occur.

Few studies have explored how a rapidly changing climate may actually affect human adaptation, but existing model results provide some useful information. On the one hand, if growth rates increase rapidly, prices will decline substantially. Although aggregate economic impacts would most likely be positive, producer losses could be substantial even as consumers gain from lower prices. On the other hand, if rapid climate change leads to very rapid forest losses, such as might be caused by fires or disease, or rapid reductions in forest growth, economic losses could be substantial. One set of studies has explored assumptions about potential dieback, as described in Box 3.

The effects of climate change outside the United States are likely to be important for measuring U.S. forest sector impacts. This is particularly important because recent research suggests that production from North America is gradually becoming relatively disadvantaged compared to timber production elsewhere in the world, and economic forces are driving long-term timber production offshore (Sedjo and Lyon, 1996). If timber growth increases in other regions of the world more than in the United States, prices could fall, harming U.S. producers but benefiting consumers (Sohngen et al., 2001). Climate change thus could put pressure on profits for producers of U.S. timber simply by making other regions of the world more attractive for timber investments. Global effects are not likely to reduce timber availability in the United States in the absence of an overall global timber supply reduction, given that we already import large volumes of timber and industrial wood. No major changes in trade law are anticipated, but any action that restricts trade would most likely have negative effects on U.S. consumers.

B. Market Adaptation

As noted previously, the ultimate economic consequences of future climate change on the U.S. forestry sector are dependent upon the management options available to and utilized by foresters to exploit the potential benefits and mitigate the costs of climate change. Economic models generally indicate that the climate change, and subsequent forest response, currently projected over the next century may be beneficial to the U.S. forestry sector as a whole, at least over the range of future climate change and forest response captured by existing economic studies (Table 1). However, the magnitude of such benefits is likely to be dependent upon the successful implementation of adaptation measures by foresters that capitalize on changes in forest location, composition, and productivity. Furthermore, in those regions such as the Southeast, which are particularly vulnerable to climate change, adaptation measures may be critical for mitigating economic losses.

Adapting to Changes in Disturbance Regimes

Climate change could exacerbate large-scale disturbances in U.S. forests—forest fires during hot dry summers, the spread of gypsy moths throughout the eastern United States, and ice storms—or alter the distribution of affected forests. Either way, if forests experience different disturbance patterns (disease, fires, etc.) during climate change, there could be large effects on timber supply and prices, depending on the size, frequency, and location of the disturbances. Furthermore, the indirect effects from climate change, such as those that stress stands and make them more susceptible to existing pests and pathogens, could increase stand mortality.

Although these ecological effects are uncertain, foresters have many years of experience in managing pathogens, pests, and fire, and thus adaptation measures to ameliorate both the ecological and economic consequences of such disturbances are readily available and frequently applied. For example, pest controls and fire suppression can be implemented, albeit at a cost. Even if pathogens, pests, and other stressors become too large to control and stands die back, landowners and mills may be able to adapt through salvage and by substituting species that are less susceptible. However, the economic effects of disturbance and dieback depend on many factors. First, how much of the timber can be salvaged will depend on the damage, accessibility, distance to mills, and the types of mills in an area (Haight et al., 1995). Second, land ownership is an important consideration. For example, the timber on many public lands cannot be salvaged because of administrative restrictions. Thus, the specific distribution of the economic costs and benefits associated with changes in disturbance regimes will depend upon the magnitude of future climate change and the ability of foresters to implement adaptation strategies to offset adverse impacts.

Although natural disturbances can be devastating for individual forestland owners, at the national level, economic models indicate that changes in disturbance regimes could temporarily harm producers while benefiting consumers by reducing timber prices (see Box 3). Modelers typically assume that relatively high rates of salvage are possible in the United States because forests and forest practices are fairly well adapted to handling a number of dieback effects such as fire, disease, infestation, and extreme weather, all of which occur regularly. The resilience of the timber market to past disturbances is important, because it suggests that if the changes are gradual, adaptation to dieback would most likely not be a problem. If the changes are more rapid, however, adaptation through salvage would not be impossible, but the adverse impacts on some forests would certainly be larger.

Adapting to Species Migration

Ecological models suggest that climate change would cause major changes in the distribution of trees and forests. Economic studies suggest that movement of southern pines northward could mitigate the economic effects of dieback in northern regions if slower-growing northern species are replaced with faster-growing southern species. Such redistributions raise overall growth rates for U.S. forests. For example, southern pine plantations grow on average at a rate of 11 m^3/ha/year, compared to northern deciduous trees that grow 2 m^3/ha/year. If climate changes enough to allow southern pines to move northward, landowners in the North could adapt by shifting to pines to raise their returns (Sohngen and Mendelsohn, 1998).

The main economic challenges from species migration lie in two areas. First, landowners would need to be able to shift the types of species they plant to include new species that are better suited to a new climate. If landowners make mistakes by planting incorrect species, timber supply could be adversely affected and welfare could decline. There is no clear economic answer to the question, "Can landowners discern small or large differences in climate and use that evidence to make optimal planting decisions?" However, it is clear that industrial landowners and a number of private landowners, both in the United States and abroad, already experiment with transplanting species (FAO, 1999).

Second, the timber industry (including large industrial corporations and small, family-owned mills) could adapt by adjusting their production processes and capital investments to handle different types of species. These types of adjustments have already been made in pulp production in the South, where increasing quantities of pulp come from hardwood resources because hardwood inventories have increased relative to softwood inventories. Further, increasing quantities of wood products have been manufactured from wood chips that are glued together (i.e., oriented strand board substitutes for traditional plywood). Because these products can be made from a variety of tree species, substitution is likely, although the overall extent of substitution will depend on prices.

Although substitution in the production process may minimize impacts on consumers, species migration can affect both landowners and the landscape. Landowners are likely to intercede and speed up otherwise slow natural migration rates (see above) by experimenting and planting species better adapted for a new climate. Some studies suggest that under gradual climate change, humans could keep pace with climate change by shifting to better-adapted species (Sohngen and Mendelsohn, 1998; Sohngen et al., 2001). It is not clear that rapid climate change would make for a more difficult transition, because rapid climate change could provide more direct signals to landowners that they should adjust their behavior sooner rather than later.

Clarifying the relationship between species migration, forest productivity, and human adaptation through species substitution in production and replanting is an important area of continued research. On the one hand, if forest biomass remains high as trees migrate, landscape level changes in species distribution may have small or negligible effects on markets. In this case, adaptation in timber markets will rely on the timber-processing sector to develop methods of substituting one type of biomass for another. If, however, species migration is slow, and it is combined with dieback that lowers biomass as climate changes, then prices will change more dramatically, and adaptation will rely on land management through salvage and transplanting of species from one region to another.

Role of Naturally Regenerated Forests

Although climate change will undoubtedly affect naturally regenerated and less intensively managed forests, the effects of these changes on timber supply are not likely to be large for a number of reasons. First, the contribution of natural forests to the national timber supply has declined in recent years, and most studies suggest that supply from these forests will continue to decline in the future. For example, national forests and other public lands represent approximately 33 percent of total forestland, but account for about 11 percent of total harvests. In contrast, small non-industrial landowners represent 49 percent of total forestland and supply 61 percent of total timber.

Second, in addition to institutional factors that protect national forests from harvest, economic factors also protect large areas of private land from being harvested. The timber on these lands, often owned in small lots by non-industrial owners, have high harvesting costs or low market quality. These factors make the timber uneconomical at today's prices. If climate change were to reduce timber supply and raise prices, these lands could be harvested to augment supply. The combination of institutional protection of government land and economic protection of large areas of additional private land results in harvests in the United States that are only 60-70 percent of net growth (USDA, Forest Service, 2000). At a biological level, the potential exists for large losses in stock through dieback without imposing a physical constraint on domestic wood production.

Under scenarios of extremely rapid climate change that lead to dramatic dieback and shifts in species ranges, human attempts to facilitate natural forest adaptation may be of only limited success. The success of regeneration techniques aimed at quickly converting the landscape is not guaranteed and the costs could be substantial. Aerial seeding, one technique that could be used for both natural and planted forests, often has limited success. Further, it may well be beyond the realm of what the profit-motivated forest manager is likely to do, except on specific lands, and thus might require governmental actions. The location of natural forests relative to planted forests may also play a role during climate change. Dying natural forests located near planted forests could make the planted forests more susceptible to disease and infestation, further exacerbating the decline. Wildfires beginning in dying natural forests could threaten apparently healthy natural or planted forests that have been somewhat weakened by climate change. Few studies to date have considered these location effects, so it is difficult to assess the scope of potential impacts.

Uncertainty in Regional Impacts

Although current research suggests that timber supply will expand nationally, regional impacts are much more uncertain. There are at least two reasons for this uncertainty. First, climate change predictions are more uncertain at the regional level. A number of climate scenarios, for instance, suggest that the South could experience relative drying effects. The economic results described above are sensitive to these potential drying effects, which typically occur across the existing range of southern pine forests. However, some studies have suggested that the potential for negative economic effects of warming could be compensated for, or offset by, increases in precipitation (Bowes and Sedjo, 1993). Given the importance of the southern United States in producing timber for markets today, it is crucially important to have a better understanding of the sensitivity of different species to climate change to predict market impacts.

Second, economic studies take different approaches, and these different approaches have implications for predictions of regional market effects. Studies that rely entirely on changes in timber yields without considering species migration tend to predict that production remains high in the South. For example, Joyce et al. (1995), Perez-Garcia et al. (1997), McCarl et al. (2000), and Irland et al. (2001) suggest that most production in the United States remains in the South because species do not migrate, and the South experiences moderate increases or decreases in timber growth. Because a large proportion of timber-producing capital and machinery in the United States is currently in the South, it takes exceptionally large increases in timber growth in the North for these models to predict large shifts in production to that region. Alternatively, Sohngen and Mendelsohn (1998) include species migration and disturbance. Although all of the studies tend to predict positive national impacts, Sohngen et al. (2001) predict larger positive benefits for northern regions and larger negative impacts for southern regions than the other studies.

IV. Conclusions

Unlike other sectors, such as agriculture, that are almost exclusively comprised of managed systems, forests are comprised of both natural and managed systems. This makes it more difficult to state with precision what the overall economic impacts of climate change on forests will be. Further, understanding the impacts on forests and timber markets is difficult given the long time lags between the planting and harvesting of trees.

Despite the many practical problems with understanding climate change impacts on forested ecosystems and timber markets, the combination of historical observation, modeling results, and experimental data allows us to draw several conclusions. Future research will certainly revise these conclusions, but the following points summarize the most important findings in the research to date regarding the overall impacts of climate change on forest ecosystems and timber markets over the next century:

1. Tree species generally are expected to migrate northward or to higher altitudes in response to increased temperatures. While species will adapt over time by moving from one region to another, differential rates of change may cause significant differences in the types of natural stands in the future. Rates will depend critically on (a) how fast seeds migrate into new regions that are climatically suitable for a species after a climate change, (b) changes in the spread of insects and disease, (c) the spread of wildfire in different climates, and (d) human interventions to promote species migration.

2. Forest productivity is expected to change, but the changes could be positive or negative. Forests could become more or less productive, depending on how much climate changes (including both temperature and precipitation), how forests respond to higher carbon concentrations in the atmosphere, whether mortality changes, and whether disturbance-induced dieback increases or decreases. Many of these factors are expected to vary from region to region, suggesting that economic impacts are likely to differ among regions in the United States.

3. The effect of additional carbon dioxide in the atmosphere on forested ecosystems ("carbon fertilization") is complex and uncertain, but it has large implications for understanding how forest productivity will change. Most studies suggest that forest area and productivity will increase if carbon fertilization enhances forest growth, but will decline if carbon fertilization does not occur. Plant level experiments suggest that carbon fertilization will enhance tree growth, at least for some period of time. Scaling these results up to the ecosystem level is complex, but available studies suggest that carbon fertilization will be limited by competition, disturbance, and nutrient limitations. It is important to continue developing a better understanding of carbon fertilization effects, particularly at the ecosystem scale.

4. Changes in the frequency and severity of forest disturbance, such as storm damage, fires, and pests are likely to affect forest structure and function. The impact on markets, while generally negative, can be ameliorated by salvage. At the market level, salvage associated with disturbances can increase timber supply and reduce prices in the short term, which benefits consumers. However, increased disturbance and lower prices generally have negative effects on landowners.

5. United States timber markets have low susceptibility to climate change because of the large stock of existing forests, technological change in the timber industry, and the ability to adapt. The United States currently consumes less timber than grows within the country each year, providing a cushion if climate change has short-term impacts on supply. Further, companies already substitute a wide array of species in end products, so that if particular species are negatively affected by climate change, markets can adapt by changing the types of species used in the production of end products. In addition, landowners can assist natural migration of timber by planting southern species in the North.

6. Economic studies have tended to find small negative to positive overall effects on timber production in the United States. While the studies have looked at a wide range of potential climate change effects across species within the United States, the net productivity effects used by the studies have tended to be positive over the long-term. Higher forest productivity translates into increased timber yield, increased timber inventory, increased supply, and lower prices. Lower prices generate overall net benefits, although they primarily benefit consumers at the expense of landowners. Lower forest productivity has the opposite effect.

7. Northern states may gain from climate change if productivity increases and if southern species move North, while southern states may lose production. Producers in southern regions are the most vulnerable to climate change because they have a large share of the nation's current timber production capital, and the highly productive species in that region are sensitive to potential drying effects. Northern states are generally predicted to gain productivity and market share during climate change.

8. Understanding the economic effects of climate change on timber production is limited by scientific understanding of several key factors that control the response of natural and managed forests to climate change. Additional research is needed to enable ecologists and foresters to develop a more robust understanding of future changes in U.S. climate, ecosystem responses to climate change, the relationship between forest productivity and timber yield, and adaptation options available to foresters. Future clarification of these uncertainties will permit more informed assessments of the economic impacts of climate change to the forestry sector.

Endnotes

1. Interestingly, most studies of impacts of climate change on agriculture, such as those described in Adams et al. (1999), use integrated assessments of biological and economic impacts. The studies are constructed so the plant physiologists, zoologists, and hydrologists will estimate outputs in variables such as crop yields, livestock productivity, and water demand and supply that can be directly used (with some manipulation) in economic models. In contrast, studies of forestry have not fully integrated analysis of biological and economic impacts. Ecologists tend to estimate impacts on natural forests and give results in terms of such variables as net primary productivity and carbon storage. These do not directly translate into harvestable yield (see Box 2). Economists have assumed these outputs translate directly into yields. As a result of this, the analyses of forests cannot be considered to be fully integrated.

2. Cole made these findings by cataloguing the contents of the packrat nests (or middens) of different ages and from different locations. The material in the middens collected by a variety of small mammals in arid environments (see Betancourt et al. 1990) can be used to reconstruct local habitat patterns. For example, packrats (*Neotoma spp.*) build their middens from material that they collect within a range of about 30 meters. Material from packrat middens can be dated using carbon 14 techniques and can provide clues to the species of plants that were near the midden at a given time in the past.

3. This is regularly expressed by the atmospheric scientists who have produced the general circulation models, but is sometimes seemingly lost in evaluations of the implications of these models.

4. A global average of one-third, varying by region from one-seventh to two-thirds.

5. Two special issues of *Climatic Change* reviewed the applications of this class of models for climate change assessment. The first is summarized in Shugart and Smith (1996); the second in Bugmann et al. (2001).

6. The site index of a location is the height to which trees could be expected to grow over a time interval (usually close to the time interval over which the trees are expected to be harvested). Yield tables are organized by site index and compiled from regularly remeasured study plots in which trees are planted (or naturally occur) in different densities.

7. Two recent books by the principal practitioners of these approaches do not even list “climate” or “climate change” in their indices.

References

Aber, J., R.P. Neilson, S. McNulty, J.M. Lenihan, D. Bachelet, and R.J. Drapek. 2001. "Forest processes and global environmental change: Predicting the effects of individual and multiple sensors." *BioScience* 51:735-751.

Adams, R.M., B.H. Hurd, and J. Reilly. 1999. *Agriculture and Global Climate Change: A Review of Impacts to U.S. Agricultural Resources*. Pew Center on Global Climate Change, Arlington, VA.

Bachelet, D., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2001. "Climate change effects on vegetation distribution and carbon budget in the United States." *Ecosystems* 4:164-185.

Barber, V.A., G.P. Juday, and B.P. Finney. 2000. "Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress." *Nature* 405:668-672.

Barrett, J.W. (ed.). 1980. "The Northeast region." In *Regional Silviculture of the United States*, John Wiley and Sons, New York, NY, pp. 25-66.

Betancourt, J.L., T.R. Van Devender, and P.S. Martin (eds.). 1990. *Packrat Middens: The Last 40,000 Years of Change*. University of Arizona Press, Tucson, AZ.

Bonan, G.B. 1989. "Environmental factors and ecological processes controlling vegetation patterns in boreal forests." *Landscape Ecology* 3:111-130.

Bonan, G.B., D. Pollard, and S.L. Thompson. 1992. "Effects of boreal forest vegetation on global climate." *Nature* 359:716-718.

Bonan, G.B., H.H. Shugart, and D.L. Urban. 1990. "The sensitivity of some high latitude boreal forests to climatic parameters." *Climatic Change* 16:9-31.

Bowes, M.D., and R.A. Sedjo. 1993. "Impacts and responses to climate change in forests of the MINK region." *Climatic Change* 24:63-82.

Bugmann, H., J.F. Reynolds, and L.F. Pitelka. 2001. How much physiology is needed in forest gap models for simulating long-term vegetation response of forests. *Climatic Change* 51:249-250.

Burton, D.M., B.A. McCarl, N.M. de Sousa, D.M. Adams, R.A. Alig, and S.M. Winnett. 1998. "Economic dimensions of climate change impacts on southern forests." In *The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment*. S. Fox and R. Mickler (eds.). Springer-Verlag, New York, NY.

Clark, J.S. 1998. "Why trees migrate so fast: Confounding theory with dispersal biology and the paleorecord." *American Naturalist* 152:204-224.

Cole, K. 1982. "Late quaternary zonation of the vegetation in the eastern Grand Canyon." *Science* 217:1142-1145.

Cole, K. 1985. "Past rates of change, species richness, and a model of vegetational inertia in the Grand Canyon, Arizona." *American Naturalist* 125:289-303.

Conaty, A.L., J.C. Jusem, L. Takacs, D. Keyser, and R. Atlas. 2001. "The structure and evolution of extratropical cyclones, fronts, jet streams and the tropophase in the GEOS general circulation model." *Bulletin of the American Meteorological Society* 82:1853-1867.

Davis, M.B. 1981. "Quarterly history and the stability of forest communities." In *Forest Succession: Concepts and Application*. D.C. West, H.H. Shugart, and D.B. Botkin (eds.). Springer-Verlag, New York, NY, pp. 134-153.

Davis, M.B., and R.G. Shaw. 2001. "Range shifts and adaptive responses to Quaternary climate change." *Science* 292:673-679.

Delcourt, H.R., and P.A. Delcourt. 1991. *Quaternary Ecology: A Paleoecological Perspective*. Chapman and Hall, London, England.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985a. "Climate change and the broad scale distribution of terrestrial ecosystem complexes." *Climatic Change* 7:29-43.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985b. "Response to comment: Climatic change and the broad-scale distribution of terrestrial ecosystem complexes." *Climatic Change* 7:457-460.

FAO. 1999. *State of the World's Forests*, 1999. Food and Agricultural Organization of the United Nations, Rome, Italy.

Friend, A.D., H.H. Shugart, and S.W. Running. 1993. "A physiology-based gap model of forest dynamics." *Ecology* 74:792-797.

Gitay, H., S. Brown, W. Easterling, and B. Jallow. 2001. "Ecosystems and their goods and services." In *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. J. McCarthy, O. Canziani, N. Leary, D. Dokken, and K. White (eds.). Cambridge University Press, Cambridge, England.

Haffer, J. 1987. "Quaternary history of tropical America." In *Biogeography and Quaternary History in Tropical America*. Oxford Monographs of Biogeography No. 3, T.C. Whitmore and G.T. Prance (eds.). Oxford Science Publications, Oxford, England, pp. 1-18.

Haight, R.G., W.D. Smith, and T.J. Straka. 1995. "Hurricanes and the economics of loblolly pine plantations." *Forest Science* 41:675-688.

Hansen, J., I. Fung, A. Lacis, S. Lebedef, D. Rind, R. Ruedy, G. Russel, and P. Stone. 1988. "Global climate changes as forecast by the Goddard Institute for Space Studies three-dimensional model." *Journal of Geophysical Research* 93:9341-9364.

Hayden, B.P. 2002. Personal communication, University of Virginia, Department of Environmental Sciences, January.

Henderson-Sellers, A., R.E. Dickinson, T.B. Durbidge, P.J. Kennedy, K. McGuffie, and A.J. Pitman. 1993. "Tropical deforestation: Modeling local- to regional-scale climate change." *Journal of Geophysical Research* 98:7289-7315.

IPCC, 2001. *Climate Change 2001: The Scientific Basis*. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, D. Xiaosu, K. Maskell, and C.A. Johnson (eds.). Cambridge University Press, Cambridge, England.

Irland, L., D. Adams, R. Alig, C.J. Betz, C. Chen, M. Hutchins, B.A. McCarl, K. Skog, and B.L. Sohngen. 2001. "Assessing socioeconomic impacts of climate change on U.S. forest, wood-product markets, and forest recreation." *Bioscience* 51:753-764.

Iverson, L.R., and A.M. Prasad. 1998. "Predicting abundance of 80 tree species following climate change in the eastern United States." *Ecological Monographs* 68:465-485.

Iverson, L.R., and A.M. Prasad. 2001. "Potential changes in tree species richness and forest community types following climate change." *Ecosystems* 4:186-199.

Iverson, L.R., A.M. Prasad, B.J. Hale, and E.K. Sutherland. 1999. *An Atlas of Current and Potential Future Distributions of Common Trees of the Eastern United States*. General Technical Report NE-265. Northeastern Research Station, United States Department of Agriculture, Forest Service, Newtown Square, PA.

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.

Körner, C. 1993. "CO_2 fertilization: The great uncertainty in future vegetation development." In *Vegetation Dynamics and Global Change*, A.M. Solomon and H.H. Shugart (eds.). Chapman and Hall, New York, NY, pp. 53-70.

Lamb, H.F., and M.E. Edwards. 1988. "The Arctic." In *Vegetation History*, B. Huntley and T. Webb III (eds.). Kluwer, Dordrecht, Netherlands, pp. 519-555.

Lenihan, J.M., C. Daly, D. Bachelet, and R.P. Neilson 1998. "Simulation of broad scale fire in a dynamic global vegetation model." *Northwest Science* 72:91-103.

Malcolm, J.R., and L.F. Pitelka. 2000. *Ecosystems and Global Climate Change: A Review of the Potential Impacts on U.S. Terrestrial Ecosystems and Biodiversity*. Pew Center on Global Climate Change, Arlington, VA.

McCarl, B.A., D.M. Burton, D.M. Adams, R.J. Alig, and C.C. Chen. 2000. "Effects of global climate change on the U.S. forest sector: Response functions derived from a dynamic resource and market simulator." *Climate Research* 15:195-205.

Mitchell, J.F.B. 1983. "The seasonal response of a general circulation model to changes in CO_2 and sea temperatures." *Quarterly Journal of the Royal Meteorological Society* 109:113-152.

National Assessment Synthesis Team (NAST). 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. U.S. Global Change Research Program, Washington, DC.

Neilson, R.P. 1995. "A model for predicting continental scale vegetation distribution and water balance." *Ecological Applications*. 5:362-385.

O'Brien, S.T., B.P. Hayden, and H.H. Shugart. 1992. "Global change, hurricanes, and a tropical forest." *Climatic Change* 22:175-190.

Ojima, D. (ed.). 1992. *Modeling the Earth System*. University Corporation for Atmospheric Research, Office for Interdisciplinary Earth Studies, Boulder, Colorado.

Oren R., D.S. Ellsworth, K.H. Johnson, N. Phillips, B.E. Ewers, C. Aaur, K.V.R. Schafer, H. McCarthy, G. Hendrey, S.G. McNulty, and G.G. Katul. 2001. "Soil fertility limits carbon sequestration in a CO_2-enriched atmosphere." *Nature* 411:469-472.

Overpeck, J.T., D. Rind, and R. Goldberg. 1990. "Climate-induced changes in forest disturbance and vegetation." *Nature* 343:51-53.

Pastor, J., and W.M. Post. 1988. "Response of northern forests to CO_2-induced climate change." *Nature* 334:55-58.

Pearlstine, L., H. McKellar, and W. Kitchens. 1985. "Modeling the impacts of river diversion on bottomland forest communities in the Santee River floodplain, South Carolina." *Ecological Modelling* 29:283-302.

Perez-Garcia, J., L.A. Joyce, C.S. Binkley, and A.D. McGuire. 1997. "Economic impacts of climate change on the global forest sector: An integrated ecological economic assessment." In *Economics of Carbon Sequestration Forestry: Critical Reviews in Environmental Science and Technology*, R.A. Sedjo, R.N. Sampson, and J. Wisniewski (eds.). Lewis Press, Boca Raton, FL, pp. 123-138.

Pitelka, L.F, R.H. Gardner, J. Ash, S. Berry, H. Gitay, I.R. Noble, A. Saunders, R.H.W. Bradshaw, L. Brubaker, J.S. Clark, M.B. Davis, S. Sugita, J.M. Dyer, R. Hengeveld, G. Hope, B. Huntley, G.A. King, R.N. Mack, G.P. Malanson, M. McGlone, I.C. Prentice, M. Rejmanek, and M. Skyes. 1997. "Plant migration and climate change." *American Scientist* 85:464-473.

Prasad, A.M., and L.R. Iverson. 1999. *A Climate Change Atlas for 80 Forest Tree Species of the Eastern United States*. Northeastern Research Station, United States Department of Agriculture, Forest Service, Delaware, Ohio. Available at http://www.fs.fed.us/ne/delaware/atlas/index.html.

Prentice, K.C., and Fung, I.Y. 1990. "Bioclimatic simulations test the sensitivity of terrestrial carbon storage to perturbed climates." *Nature* 346:48-51.

Schlesinger, W.H., and J. Lichter 2001. "Limited carbon storage in soil and litter of experimental forest plots under elevated CO_2." *Nature* 411:466-469.

Sedjo, R., and K. S. Lyon. 1996. *Timber Supply Model 96: A Global Timber Supply Model with a Pulpwood Component.* Resources for the Future, Discussion Paper 96-15. Washington, DC.

Shafer, S.L., P.J. Bartlein, and R.S. Thompson. 2001. "Potential changes in the distributions of western North America tree and shrub taxa in future climate scenarios." *Ecosystems* 4-200-215.

Shugart, H.H. 1998. *Terrestrial Ecosystems in Changing Environments*. Cambridge University Press, Cambridge, England.

Shugart, H.H., and T.M. Smith. 1996. A review of forest patch models and their application to global change research. *Climatic Change* 34:131-153.

Smith, T.M., P.N. Halpin, H.H. Shugart, and C.M. Secrett. 1995. "Global forests." In *If Climate Changes: International Impacts of Climate Change*, K.M. Strzepek, and J.B. Smith (eds.). Cambridge University Press, Cambridge, England, pp. 146-179.

Smith, T.M., R. Leemans, and H.H. Shugart. 1992a. Sensitivity of terrestrial carbon storage to CO_2 induced climate change: Comparison of five scenarios based on general circulation models. *Climatic Change* 21:367-384.

Smith, T.M., and H.H. Shugart. 1993. The transient response of terrestrial carbon storage to a perturbed climate. *Nature* 361:523-526.

Smith, T.M., H.H. Shugart, G.B. Bonan, and J.B. Smith. 1992b. Modeling the potential response of vegetation to global climate change. *Advances in Ecological Research* 22:93-116.

Society of American Foresters. 2000. *About Forestry*. Available at http://www.safnet.org/about/facts.htm.

Sohngen, B., and R. Mendelsohn. 1998. "Valuing the market impact of large-scale ecological change: The effect of climate change on U.S. timber." *American Economic Review* 88:689-710.

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. Ohio State University, Columbus, OH.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 2001. "A global model of climate change impacts on timber markets." *Journal of Agricultural and Resource Economics* 26: 326-343.

Solomon, A.M. 1986. "Transient response of forests to CO_2-induced climate change: Simulation experiments in eastern North America." *Oecologia* 68:567-79.

Solomon, A.M., M.L. Tharp, D.C. West, G.E. Taylor, J.M. Webb, and J.L. Trimble. 1984. *Response of Unmanaged Forests to CO_2-Induced Climate Change: Available Information, Initial Tests and Data Requirements*. Tech. Report TR009. Carbon Dioxide Research Division, U.S. Department of Energy, Washington, DC.

Stephenson, N.T. 1990. "Climatic control of vegetation distribution: The role of the water balance." *American Naturalist* 135:649-670.

Urban, D.L., and H.H. Shugart. 1989. "Forest response to climate change: A simulation study for southeastern forests." In *The Potential Effects of Global Climate Change on the United States*, J. Smith and D. Tirpak, (eds.). EPA-230-05-89-054, U.S. Environmental Protection Agency, Washington, DC, pp. 3-1 to 3-45.

USDA, Forest Service. 2000. *U.S. Forest Facts and Historical Trends*. Available at http://fia/fs.fed.us.

van der Hammen, T. 1988. "South America." In *Vegetation History*, B. Huntley, and T. Webb III (eds.). Kluwer Academic, Dordrecht, Netherlands, pp. 307-340.

VEMAP (J.M. Melillo, J. Borchers, J. Chaney, H. Fisher, S. Fox, A. Haxeltine, A. Janetos, D.W. Kicklighter, T.G.F. Kittel, A.D. McGuire, R. McKeown, R. Neilson, R. Nemani, D.S. Ojima, T. Painter, Y. Pan, W.J. Parton, L. Pierce, L. Pitelka, C. Prentice, B. Rizzo, N.A. Rosenbloom, S. Running, D.S. Schimel, S. Sitch, T. Smith, and I. Woodward). 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* 9:407-437.

Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds). 1995. *Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group II to the Second Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, England.

Webb, T., III. 1988. "Glacial and Holocene vegetation history: Eastern North America." In *Vegetation History*, B. Huntley and T. Webb III (eds.). Kluewer Academic, Dordrecht, Netherlands, pp. 385-414.

Whitmore, T.C., and G.T. Prance (eds.). 1987. *Biogeography and Quaternary History in Tropical America*. Oxford Monographs on Biogeography No. 3. Oxford Science Publications, Oxford, England.

Woodward, F.I. 1987. *Climate and Plant Distribution.* Cambridge University Press, Cambridge, England.

notes

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Pew Center on Global Climate Change
2101 Wilson Boulevard
Suite 550
Arlington, VA 22201
Phone (703) 516-4146

www.pewclimate.org