CHAPTER 17

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE FORESTS OF THE UNITED STATES

Linda Joyce[1,2], John Aber[3], Steve McNulty[1], Virginia Dale[4], Andrew Hansen[5], Lloyd Irland[6], Ron Neilson[1], and Kenneth Skog[1]

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[1] USDA Forest Service; [2] Coordinating author for the National Assessment Synthesis Team; [3] University of New Hampshire, [4] Oak Ridge National Laboratory; [5] Montana State University, [6] The Irland Group

CHAPTER SUMMARY

Context

Forests cover nearly one-third of the US, providing wildlife habitat, clean air and water, cultural and aesthetic values, carbon storage, recreational opportunities such as hiking, camping, fishing, and autumn leaf tours, and products that can be harvested such as timber, pulpwood, fuelwood, wild game, ferns, mushrooms, and berries. This wealth depends on forest biodiversity—the variety of plants, animals, and microbe species, and forest functioning—water flow, nutrient cycling, and productivity. These aspects of forests are strongly influenced by climate and human land use.

Key Findings

Carbon storage in US forests is currently estimated to increase from 0.1 to 0.3 Pg of carbon per year and analyses suggest that carbon dioxide fertilization and land use have influenced this current storage. Within the next 50 years, forest productivity is likely to increase with the fertilizing effect of atmospheric carbon dioxide. Those productivity increases are very likely to be strongly tempered by local environmental conditions (e.g.,moisture stress, nutrient availability) and by human land use impacts such as forest fragmentation,increased atmospheric deposition,and tropospheric ozone.

Economic analyses when driven by several different climate scenarios indicate an overall increase in forest productivity in the US that is very likely to increase timber inventory, subject to other external forces. With more potential forest inventory to harvest,the costs of wood and paper products to consumers are likely to decrease,as are the returns to owners of timberland. The changes in climate and consequent impact on forests are likely to change market incentives to harvest and plant trees,and shift land uses between agriculture and forestry. These changes will likely vary within a region. Market incentives for forestry are likely to moderate some of the climate-induced decline in the area of natural forests. International trade in forest products could either accentuate or dampen price effects in the US,depending on whether forest harvest activity increases or decreases outside the US.

Over the next century, changes in the severity, frequency, and extent of natural disturbances are possible under future climate change. These changes in natural disturbances then impact forest structure, biodiversity, and functioning. Analyses of the results from climate and ecological models suggest that the seasonal severity of fire hazard is likely to increase by 10% over much of the US,with possibly larger increases in the southeastern US and Alaska and actual decreases in the Northern Great Plains. Although the interactions between climate change and hurricanes,landslides,ice storms,wind storms, insects,disease,and introduced species are difficult to predict; climate changes, changes in these disturbances and their effects on forests are possible.

Analyses of the results of ecological models when driven by several different climate scenarios indicate changes in the location and area of potential habitats for many tree species and plant communities. For example,alpine and subalpine habitats and the variety of species dependent upon them are likely to be greatly reduced in the conterminous US. The ranges of some trees are likely to contract dramatically in the US and largely shift into Canada. Expansion of potential habitats is possible for oak/hickory and oak/pine in the eastern US and Ponderosa pine and arid woodland communities in the West. How well plant and animal species adapt to or move with changes in their potential habitat is strongly influenced by their dispersal abilities and the disturbances to these environments. Introduced and invasive species that disperse rapidly are likely to find opportunities in newly forming communities.

The effects of climate change on socioeconomic benefits obtained from forests will likely be influenced greatly by future changes in human demands, as determined by population growth,increases in income, changing human values,and consumer preferences.

Outdoor recreation opportunities are very likely to be altered by climate change. For example, warmer waters would increase fish production and opportunities for some species;but decrease opportunities for cold water species. Outdoor recreation opportunities in mountainous areas are likely to be altered. Summer recreation opportunities are likely to expand in the mountainous areas when warmer lowland temperatures attract more people to higher elevations. Skiing opportunities are likely be reduced with fewer cold days and snow events. In marginal climate areas,the costs to maintain downhill skiing opportunities are likely to rise which would possibly result in the closure of some areas.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE FORESTS OF THE UNITED STATES

BACKGROUND

Covering nearly one-third of the US, forests are an integral part of the vegetative cover of the nation's landscape (Figure 1). The total area in forests in the US is 747 million acres,which is about 7% of the forestland in the entire world. US forests are distributed in the eastern and western parts of the US, with small stands of forests in the central part located mainly along rivers and streams. The white-red-jack pine forests of New England have supported a timber industry and the northeastern deciduous forests of maples,beeches,birches,and oaks provide the colorful autumn landscapes for tourists. The Mid-Atlantic region is rich in tree species from pine forests and coastal wetlands to northern upland hardwoods such as oak-hickory and maple-beech-birch forest types. The southern forests are also a mix of conifer and deciduous forests. Western forests are primarily conifer forests such as Douglas-fir, fir-spruce, Ponderosa pine and piñon-juniper.

Ownership of forestland varies by region in the US. Over 63% of US forestland is in private ownership. The remaining forestland is in various federal,state, county, and municipal ownerships. Over 50% of the federal land in forests is managed by the US Forest Service. The largest state owner of forestland is Alaska. County and municipal ownerships comprise less than 4% of the total forestland. However, over 2.5 million acres of forestland are managed by these local governments in Minnesota alone. Over 80% of the forestland in federal ownership is found in the west,while most of the forestland held by states is in the northern part of the US. Of the 472 million acres in private ownership, over 60% is found in the eastern part of the US. Forest industry owners account for 14% of the forestland in private ownership,and these lands are found mainly in the southern part of the US (54%).

Current Distribution of Forests in the United States

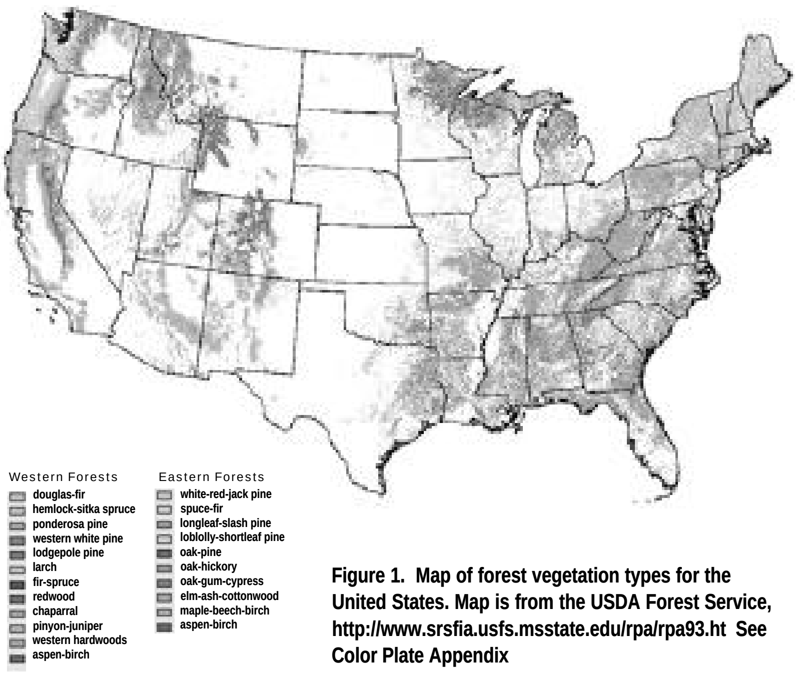


Figure 1. Map of forest vegetation types for the United States. Map is from the USDA Forest Service, http://www.srsfia.usfs.msstate.edu/rpa/rpa93.ht See Color Plate Appendix

Forests are an environment in which people recreate,such as the National Forests and Parks,and an environment in which people live,such as the New England woods,and the conifer forests of Rocky Mountains. Forests provide recreational opportunities such as hiking,camping, fishing,hunting,bird watching,downhill and cross-country skiing,and autumn leaf tours. In addition,many rivers and streams flowing through forests provide fishing, boating,and swimming recreational opportunities. Activities associated with recreation provide income and employment in every forested region of the US and Canada (Watson et al.,1998). Forests provide clean air and water, watershed and riparian buffers, moderate streamflow, and help to maintain aquatic habitats. New York City's water supply is derived from water collected within forested watersheds in a 2,000 square mile area. Forests provide wildlife habitat. Flather et al.(1999) report that at least 90% of the resident or common migrant vertebrate species in the US rely on forest habitats for part of their life requisites. Forests also provide cultural and aesthetic values,carbon storage,and products that can be harvested such as timber, pulpwood, fuelwood,wild game,edible plants,fruits and nuts, mushrooms,and floral products. This wealth from forests depends on forest biodiversity – the variety of plant and animal species – and forest functioning—water flow, nutrient cycling and productivity. These aspects of forests are strongly influenced by climate.

Climate change is one of several pressures on forests encompassed under the broader term,global change. Human activities have altered the vegetation distribution of forests in the US. The arrival of Europeans along the eastern coast initiated the harvest of forests. For example,eastern white pines were highly prized as ship masts for the English Navy. From 1600 to the mid 1800s,the native forests in the eastern US were extensively harvested for wood products as well as to clear land for agriculture and urban uses (Figure 2). While total forestland area has stabilized in the US since the early 1900s,land use shifts still occur where forestland is converted to agricultural or urban use and agricultural or pasture is planted to trees. In some parts of the eastern US,new forests have regrown on abandoned agricultural lands,although forestland in the northeastern part of the US is still less than 70% of its original extent in the 1600s. Forestland in the South occupies less then 60% of the 1600s extent of forestland,and the establishment of pine plantations has placed some 20% of the forestland in this region under intensive management. While western forests have remained relatively constant in area since the 1600s, recent expansion of urban areas and agriculture is fragmenting them. Across the Nation,urban areas have continued to increase (Flather et al., 1999). This expansion of human influences into the rural landscape alters disturbance patterns associated with fire, flooding,and landslides. In addition, human activities can result in the dispersal of pollutants into forests. Increasing atmospheric concentrations of ozone and deposition of nitrogen (N) compounds have profound effects on tree photosynthesis, respiration, water relations,and survival.

Human activities modify the species composition of forests and the disturbance regimes associated with forests. Fire suppression has altered southeastern, midwestern,and western forests. Harvesting methods,such as clearcutting,shelterwood,or individual tree selection,have changed species composition in native forests. The average age of forest stands in the East is less than the average for the West, reflecting the extensive harvesting as the eastern US was settled. Intensive management along with favorable climates in parts of the US has resulted in highly productive forests that are maintained for timber production,such as the southern pine plantations. Native and introduced insects and disease species, such as gypsy moth, chestnut blight,Dutch elm disease,have altered US forests (Ayres and Lombardero, 2000).Trees have been planted far outside their natural ranges for aesthetic and landscaping purposes in urban and rural areas.

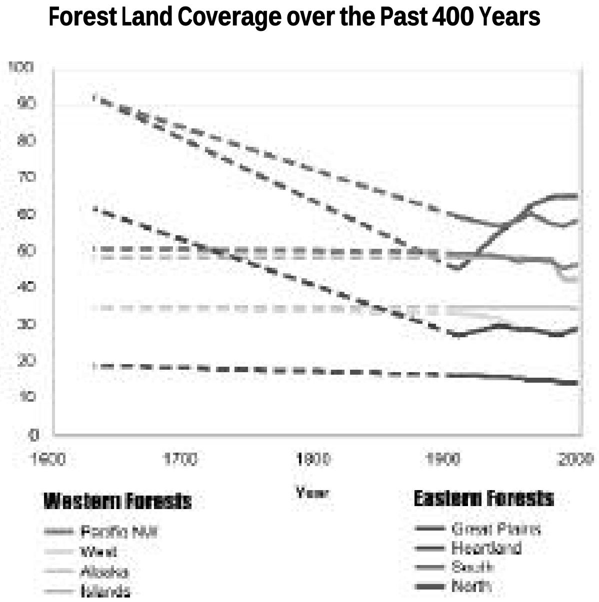


Figure 2. Land area changes in forestland. Data are from Forest Service Resource Bulletin PNW-RB-168, Forest Resource Report No. 23, No. 17, No. 14, the Report of the Joint Committee on Forestry, 77th Congress 1st Session, Senate Document No. 32. Data for 1850 and 1870 were based on information collected during the 1850 and 1870 decennial census; data for 1907 were also based on the decennial census modified by expert opinon, reported by R.S. Kellogg in Forest Service Circular 166. Data for 1630 were included in Circular 166 as an estimate of the original forest area based on the current estimate of forest and historic land clearing information. These data are provided here for general reference purposes only to convey the relative extent of the forest estate in what is now the US at the time of European settlement. See Color Plate Appendix

Population levels,economic growth,and personal preferences influence the socio-economic values associated with forests,and consequently the resources demanded from forests. Per capita consumption of wood in the US has been relatively stable over the last several decades and the future demand for wood products is projected to follow population growth over the next 50 years. Technological development and consumer preferences strongly affect the demand for specific wood and paper products. For example,consumer preference has influenced the increasing amount of recycled material used in fiber over the last several years. Though recreational hunting has been declining,the economic impact is significant;Flather et al. (1999) estimated that, for all wildlife,hunters alone spent nearly 21 billion dollars on equipment and travel in 1996. Other products harvested from forests are more difficult to assign an economic value or to project future demand. Blatner (1997) estimates the harvest of mushrooms from Washington,Oregon,and Idaho forests in 1992 to be valued at about $40 million.

At the global scale, population, economic growth, and personal preferences influence the demands from forests. Wood consumption rose 64% globally since 1961. This increase was strongly influenced by rising wood per capita consumption for fuelwood, paper products, and industrial fiber (Matthews and Hammond, 1999). More than half of the wood fiber produced globally is consumed as fuel in contrast to the US, where fuelwood comprises around 14% of total wood fiber consumed (Brooks, 1993; Matthews and Hammond, 1999). The demands on forests globally are expected to change as the world's populations become increasingly urban. More industrial products and environmental services are likely to influence the management of the world's forests (Brooks, 1993).

CLIMATE AND FORESTS

Climate influences the composition, structure, and function of forest ecosystems, the amount and quality of forest resources, and the social values associated with forests. Native forests are adapted to local climatic features. Where summer drought is typical in the Pacific Northwest, native conifer and hardwood forests have water-conserving leaves (Shriner et al., 1998). Black spruce and white spruce are found in the cold-tolerant boreal forests where winter temperature extremes can reach –62˚ to –34˚C (-79˚ to –30˚F) (Burns and Honkala, 1990). The piñon-juniper forests of the Southwest are drought-adapted.

Changes in the distribution and abundance of plant or animal species reflect the birth, growth, death, and dispersal rates of individuals in a population. Climate and soil are strong controls on the establishment and growth of plants. Climate influences the distribution and abundance of animal species through changes in resource availability, fecundity, and survivorship (Hansen and Rotella, 1999). Changes in disturbance regimes, and competitive and cooperative interactions with other species also affect the distribution of plants and animals. In addition, human activities influence the occurrence and abundance of species on the landscape.

Temperature and Precipitation. The spatial and temporal distribution of water and temperature are the primary determinants of woody plant distributions over the Earth. Air temperature affects physiological processes of individual plants, and over the long-term, the environmental conditions for seed development and germination, population, and community development. Temperature affects fruit and seed yields and quality by influencing factors such as flowering, bud dormancy, and ripening of fruit and cones (Kozlowski and Pallardy, 1997). Changes in air temperature in autumn and spring can also affect hardening and dehardening of tree needles (Guak et al., 1998). Temperature affects ecosystem-level processes such as soil decomposition and mineralization. Indirect effects associated with warming could be larger than the direct effect on plant growth in subpolar biomes where warming of permafrost is likely (Mooney et al., 1999).

Shortages or excesses of water offset the rates of most important processes controlling the biogeochemistry of the major nutrients. In particular, forested wetlands are sensitive to changes in hydrologic regimes. While forest ecosystems generally occupy those regions with low annual water deficits, water limitation in space and time is still critical for overall carbon balances, and is one of the major drivers embedded in the models used to predict global change effects.

KEY ISSUES

The vulnerability of forests to climate variability and change is examined by looking at four key issues: forest processes, disturbance, biodiversity, and socioeconomic benefits.

- Forest processes regulate the flux and apportionment of carbon, water, nutrients, and other constituents within a forest ecosystem. These processes operate at spatial scales from leaf to landscape and control responses of forest ecosystems, such as forest productivity, to environmental factors such as temperature, precipitation, and atmospheric concentrations of CO_2.
- Forests are subjected to disturbances that are themselves strongly influenced by climate. These natural disturbances include fire, hurricanes, landslides, ice storms, wind storms, drought, insects, disease, and introduced species.
- Biodiversity refers to the variety of populations, species, and communities. Climate influences the distribution and abundance of plant and animal species through food availability, habitat availability, and survivorship.
- Forest processes and forest biodiversity are uniquely capable of providing goods such as wood products, wild game, and harvested plants, ecological services such as water purification, and amenities such as scenic vistas and wilderness experiences—the socioeconomic benefits of forests.

Changes in these goods,services,and amenities are influenced by changes in factors that determine their supply — land area,productivity, management,production technology, quality of amenities — and their demand — human population levels, economic growth, and personal preferences.

1. Forest Processes

Current Environmental Changes Include Deposition of Nitrogen and Ozone.
These environmental changes influence the ability of forests to respond to changes in climate (Aber et al.,2001). Tree species have been shown to be sensitive to air pollutants such as ozone and sulfur (S) (Fox and Mickler, 1996;Taylor et al.,1994;US EPA, 1996) and nitrogen (N) deposition has been linked to soil acidification and cation depletion in forests (Aber et al.,1995;Aber et al.,1998). Total deposition of N and associated acidity in the US have increased as much as 10-fold over global background levels as a result of human activity (Galloway, 1995;Vitousek et al.,1997;Matthews and Hammond,1999). Combustion of fossil fuels injects N and S into the atmosphere as simple oxides. The N and S oxides are retained in the atmosphere only for days to weeks,whereas carbon dioxide (CO_2) is retained for decades. Some N and S compounds can be redeposited on the forest surface either in a dry form or, by dissolution into water, in a wet form ("acid rain") (Boubel et al.,1994). The shorter residence time of N and S in the atmosphere results in an intensely regional distribution of deposition,with the eastern US,and especially the Northeast, experiencing the highest levels of both S and N (NADP/NTN, 1997).

With the large reduction in S deposition in the last decade from the controls imposed by the Clean Air Act of 1990,the importance of the acids in precipitation has been reduced. Sources of N vary regionally. Urban areas contribute to increased N deposition in pine forests in southern California (Fenn et al.,1996). Nitrogen deposition as ammonium occurs where fertilizer is applied intensively or where livestock are concentrated in feedlots (Lovett,1994). Agricultural lands and feedlots along the Front Range of the Rocky Mountains in Colorado contribute to increased N deposition in the alpine and forest ecosystems in Rocky Mountain National Park (Baron et al.,1994;Musselman et al., 1996;Williams et al.,1996).

High levels of N deposition can result in negative effects such as soil acidification,causing depletion of nutrient cations (calcium,magnesium,and potassium). Low availability of N in the soil limits forest production. Increases in forest growth in response to N deposition have been reported both in Scandinavia and the US,although the response varies between deciduous and coniferous species (Magill et al.,1997;Aber et al.,1998;Magill et al., 1999).

Ozone is a highly reactive gas. Closely associated with the combustion of fossil fuels,ozone is formed in the lower atmosphere (ground-level ozone) through chemical reactions between nitrogen oxides and hydrocarbons in the presence of sunlight. High levels of ozone occur, generally in summer, when warm,stagnant air masses over densely populated and highly industrialized regions accumulate large quantities of nitrogen oxides and hydrocarbons. Thus, the distribution of ozone concentrations is very irregular in space and time.

Ozone leaves the atmosphere through reactions with plants and soil surfaces along a number of physical and chemical degradation pathways. Ozone concentrations can dissipate in a matter of days when air masses move away from urban areas throughout the eastern US,or from western cities across more remote forested areas,such as from Los Angeles to the San Bernardino and San Gabriel Mountains,California. Ozone tends to remain in the atmosphere when it cannot react with material (e.g. vegetation or soils). Thus,ozone concentrations in eastern Maine can be as high as over urban Boston because ozone-bearing air masses have reached these remote areas with little loss of ozone as they passed over the ocean. High concentrations can occur in relatively remote mountaintop locations because ozone also accumulates at the top of the atmospheric boundary layer where contact with vegetated surfaces is minimal.

Unlike nitrogen and S deposition, which by their nature are slow and cumulative, the effects of ozone on vegetation are direct and immediate, as the primary mechanism for damage is through direct plant uptake from the atmosphere through stomata (small openings in the plant leaf through which water and gases pass into and out of the plant). Ozone is a strong oxidant that damages cell membranes;the plant must then expend energy to maintain these sensitive tissues. The net effect is a decline in net photosynthetic rate. The degree to which photosynthesis is reduced is a function both of dose and species conductance rates, the rate at which leaves exchange gases with the atmosphere (Musselman and Massman, 1999). Analyses suggest that current ozone levels have decreased production 10% in northeastern forests (Ollinger et al., 1997) and 5% in southern pine plantations (Weinstein et al., 1998). Warming of surface air, a consistent feature of the Hadley and Canadian scenarios used in this assessment, is likely to increase ozone and other air-quality problems (see Watson et al., 1996 for analysis of previous climate scenarios), further increasing the stress on forests in areas where air quality is compromised.

Impacts of Elevated Atmospheric Carbon Dioxide and Climate Change on Forest Processes

Experimental exposure of trees to elevated atmospheric CO_2 has shown significant changes in physiological processes, growth, and biomass accumulation (Aber et al., 2001; Mooney et al., 1999). Over a wide range of CO_2 concentrations, photosynthesis has been increased in plants representative of most northern temperate forests (Eamus and Jarvis, 1989; Bazzaz, 1990; Mohren et al., 1996; Long et al., 1996; Kozlowski and Pallardy, 1997). Reviews of the extensive CO_2-enrichment studies have shown variable but positive responses in plant biomass accumulation (Ceulemans and Mousseau, 1994; Saxe et al., 1998; Mooney et al., 1999). In a review of studies not involving environmental stress, biomass accumulation was greater for conifers (130%) than for deciduous species (only 49% increase) under elevated CO_2 (Saxe et al., 1998). The wide range of plant responses reflects, in part, the interaction of other environmental factors and the CO_2 response (Mooney et al., 1999; Stitt and Krapp, 1999; Morison and Lawlor, 1999; Johnson et al., 1998; Curtis and Wang, 1998). A recent field-scale experiment produced significant (25%) increases in forest growth under continuously elevated concentrations of CO_2 for loblolly pine in North Carolina (Delucia et al., 1999). While positive tree responses to elevated CO_2 are likely to be overestimated if abiotic and biotic environmental factors are not considered, most ecosystems responded positively in terms of net carbon uptake to increases in atmospheric CO_2 above the current ambient level.

A significant question is how long these increased responses can be sustained. The observed acclimation or down-regulation of photosynthetic rates (Long et al., 1996; Lambers et al., 1998; Rey and Jarvis, 1998) has been ascribed to a physiological response (accumulation of photosynthetic reserves, Bazzaz, 1990), or a morphological response (changes in trees, Pritchard et al., 1998; Tjoelker et al., 1998b). Declining photosynthetic rates have also been ascribed to the result of a water or nutrient stress imposed on pot-grown seedlings where root growth is limited (Will and Teskey, 1997a; Curtis and Wang, 1998). Down-regulation has been shown in low-temperature systems such as the Arctic tundra, where the initial enhancement of net carbon uptake declined after 3 years of elevated CO_2 exposure (Shaver et al., 1992; Mooney et al., 1999). Down regulation is likely in areas where nutrient availability does not increase along with carbon dioxide. A recent review of large-scale field exposures to carbon dioxide suggested that, though variable, tree response to CO_2 was sustained over these short-term studies (Norby et al., 1999). They also examined the CO_2 response of trees growing near surface vents of deep geothermal springs, and concluded that a basal area increase of 26% was sustained through 3 decades of elevated carbon dioxide.

Under enriched CO_2 conditions, water use efficiency (WUE) has been shown to increase, which results in higher levels of soil moisture. These increased levels of soil moisture have been shown to be a significant factor in increased carbon uptake in water-limited ecosystems (Mooney et al., 1999). While there is still uncertainty as to whether stomatal conductance decreases under elevated CO_2 (Long et al., 1996; Will and Teskey, 1997b; Saxe et al., 1998; Curtis and Wang, 1998), WUE increases either with or without changes in stomatal conductance (Aber et al., 2001). With constant conductance, the higher atmospheric CO_2 concentration results in faster carbon (C) uptake with constant water loss. If conductance is reduced, a tradeoff is established between increased C gain (which is partially reduced by decreased conductance) and decreased water loss (also reduced by decreased conductance). Experimental studies have emphasized leaf-level responses. A physiological response observed at one scale (i.e., leaf) does not necessarily imply that a response will be observed at the larger scale (i.e., canopy, watershed). There is some evidence that the reduction in stomatal conduction of tree seedlings is not seen in mature trees (Ellsworth, 1999; Mooney et al., 1999; Norby et al., 1999).

In the near-term, changes in the physiology of plants are likely to be the dominant response to elevated carbon dioxide, strongly tempered by local environmental conditions such as moisture stress, nutrient availability, as well as by individual species responses (Egli and Korner, 1997; Tjoelker et al., 1998a; Berntson and Bazzaz, 1998; Crookshanks et al., 1998; Kerstiens, 1998). Over the long term, plant species changes within forests will have a large influence on the response of forests (Mooney et al., 1999).

Interactions of Multiple Stresses on Forests

It is crucial to understand not only the direct effects of CO_2, ozone,temperature,precipitation,and N and S deposition on forests,but also the interactive effects of these stresses. For example,if canopy conductance in forests is reduced in response to CO_2 enrichment,then ozone uptake is reduced and the effects of this pollutant mitigated. Drought stress has a similar effect by reducing stomatal conductance. However, if N deposition leads to increased N concentrations in foliage and hence higher rates of photosynthesis and increased stomatal conductance,then the positive effect of increased photosynthesis is partially offset by increased ozone uptake. Reductions in production from ozone damage could possibly speed the onset of N saturation in ecosystems and the attendant development of acidified soils and streams. To project the effects of climate change and other stresses on forests,their interactive effects on forest processes must be understood and integrated into ecological models.

Carbon Sequestration

Globally, an estimated 62-78% of the terrestrial carbon is in forests (Shriner et al.,1998). North American (Canada and US) forests hold 14% of this global total,with large amounts contained in the boreal forests. Estimates of the carbon sequestered annually as a result of climate and carbon dioxide fertilization in US forests were analyzed recently (Schimel et al.,2000) at a value of 0.08 Pg (Pg= Petagrams where 1 Pg = 10^{15} grams) of carbon per year. This analysis focused on the 1980-1993 period. Estimates of carbon sequestration based on forest inventory data were 0.28 Pg of carbon per year, and most of this increase in carbon storage was estimated to be on private timberland (Birdsey and Heath, 1995). Houghton et al.(1999) estimated the increase in carbon stored per year ranged from 0.15 to 0.35 Pg of carbon per year. Schimel et al.(2000) suggest that the larger inventory-based estimates imply that the effects of intensive forest management and agricultural abandonment on carbon uptake in the US are probably equal to or larger than the effects of climate and atmospheric carbon dioxide. A comprehensive approach to account for carbon fluxes to and from the atmosphere is the focus of the recent IPCC Special Report on Land Use,Land-Use Change,and Forestry (Watson et al., 2000).

Projecting the Impact of Climate Change on Forest Processes

A number of studies have examined the climate controls on the distribution and productivity of forests using different types of models (Goudriaan et al., 1999;McGuire et al.,1992;VEMAP members,1995). In this assessment,three types of models were used to project the impact of climate change on forest processes. Biogeochemistry models simulate the gain,loss and internal cycling of carbon, nutrients, and water;with these models,the impact of changes in temperature,precipitation,soil moisture,atmospheric carbon dioxide,and other climate-related factors can be examined for their influence on such processes as ecosystem productivity and carbon storage.Biogeography models examine the influence of climate on the geographic distribution of plant species or plant types such as trees, grasses, and shrubs. Dynamic global vegetation models integrate biogeochemical processes with dynamic changes in vegetation composition and distribution.

An earlier analysis using biogeochemistry models and four climate scenarios (different from this assessment) shows increased net primary productivity (NPP) at the continental scale (VEMAP members, 1995). Carbon storage results vary with the modeled sensitivity to changes in water availability. When the direct effects of carbon dioxide are not included,several analyses indicate a reduction in productivity (biogeochemistry models:VEMAP members,1995) or in vegetation density (biogeography model:Neilson et al.,1998).

In this assessment,three biogeochemistry models (TEM,Century, and Biome-BGC) and one dynamic global vegetation model (MC1) show increases in total live vegetation carbon storage (3 to 11 Pg C) for forest ecosystems within the conterminous US under the Hadley scenario (Table 1). Under the Canadian scenario,the models project changes in live vegetation carbon for forests from a reduction of 1.6 Pg to an increase of 11 Pg C (Pg= Petagrams where 1 Pg = 10^{15} grams). The MC1 model simulates a decline in vegetation carbon of about 2 Pg (Bachelet et al.,2001;Daly et al.,2000). Results for live vegetation in all ecosystems and for live and dead vegetation in both forest and all ecosystems parallel these results. Modeling the changes in species groups and fire disturbance are the primary reasons for the carbon responses in MC1.

In the MC1 projections, regional changes in carbon storage vary greatly across the conterminous US,and reflect the likelihood of disturbances such as

Table 1. Changes in Carbon Storage for the Conterminous US

These results are based on simulations by the VEMAP models (TEM,BIOME-BGC,CENTURY, MC1) using the two transient climate change scenarios described in the text. Baseline period is 1961-1990. Changes are given at decades centered on 2030 and 2095,and for forest ecosystems,and all ecosystems. Values are expressed in Pg (billions of metric tons).

	Hadley		Canadian	
	2030	2095	2030	2095
Forest Ecosystems				
Live Vegetation	0.4 to 4.0	3.0 to 11.1	-1.5 to 2.9	-1.6 to 10.5
Total (Live + Dead)	0.3 to 3.3	3.2 to 10.5	-2.9 to 2.0	-0.6 to 9.4
All Terrestrial Ecosystems				
Live Vegetation	0.4 to 4.7	3.3 to 13.2	-1.2 to 3.8	-1.8 to 13.9
Total (Live + Dead)	0.2 to 4.8	3.4 to 14.5	-0.2 to 4.4	-1.9 to 15.0

drought or fire (Figure 3). Under the Hadley scenario about 20% of current forest area experience some level of carbon loss,while the remaining 80% experience increased storage. Under the much warmer and generally drier Canadian scenario, close to 80% of current forest area experiences a drought-induced loss of carbon. Reductions in carbon storage are projected in MC1 to be especially severe in the eastern and southeastern US,where losses exacerbated by drought or fire approach 75%.

In summary, synthesis of laboratory and field studies and recent simulation experiments indicate that forest productivity increases with the fertilizing effect of atmospheric carbon dioxide and that these productivity increases are strongly tempered by local conditions such as moisture stress and nutrient availability. It is likely that modest warming could result in carbon storage gains in some forest ecosystems in the conterminous US. Under even warmer conditions,it is likely that drought-induced losses of carbon would occur in some forests,notably in the Southeast and the Northwest. These losses of carbon would possibly be enhanced by increased fire disturbance. These potential gains and losses of carbon are very likely to be subject to changing land-use patterns,such as the conversion of forests to other uses.

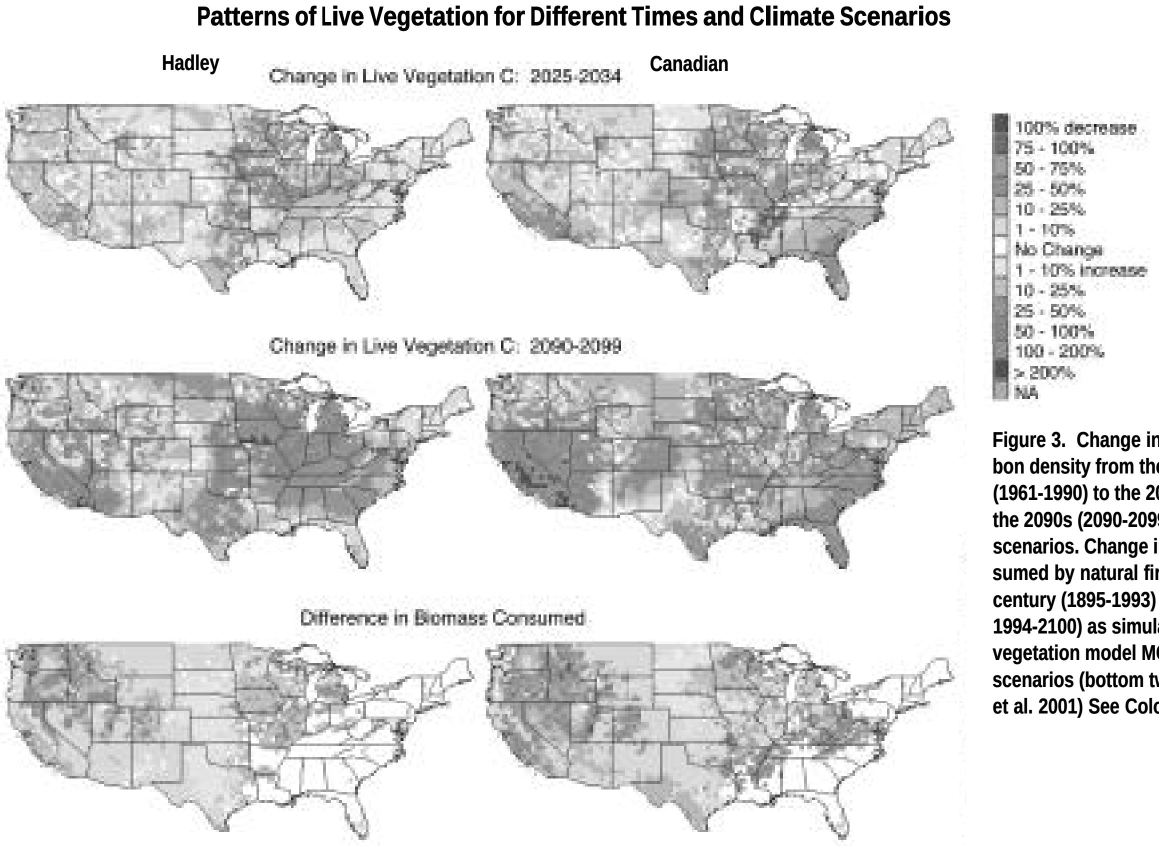
2. Forests and Disturbance

Natural Disturbances Impacted by Climate

Natural disturbances,impacted by climate,include insects,disease,introduced species, fires,droughts, hurricanes,landslides,wind storms,and ice storms. Over geologic time,local, regional,and global changes in temperature and precipitation have influenced the occurrence,frequency, and intensity of these natural disturbances.

Impacts of disturbances are seen over a broad spectrum of spatial scales,from the leaf and tree to the forest and forested landscape. Disturbances can result in:leaf discoloration and reduction of leaf function;deformation of tree structure such as broken branches or crown losses;tree mortality or chronic stress resulting in tree death;altered regeneration patterns including losses of seed banks;disruption of physical environment including soil erosion;alterations in biomass and nutrient turnover; impacts on surface soil organic layers and the underground plant root and reproductive tissues; and increased landscape heterogeneity (patchiness of forest communities). Introduced species (invasives) can affect forest ecosystems through herbivory, predation,habitat destruction,competition, loss of gene pools through hybridization with native species,and disease (either causing or carrying disease). Outbreaks of native insects and disease can result in similar impacts on forests.

At the ecosystem scale,introduced species as well as outbreaks of native insects and diseases can alter natural cycles and disturbance regimes,such as nutrient cycles,and fire frequency and intensity (Mack and D'Antonio,1998). Some tree species have developed adaptations to survive repeated occurrences of certain disturbances over time. Thick bark on some trees allows their survival in



Patterns of Live Vegetation for Different Times and Climate Scenarios

Figure 3. Change in live vegetation carbon density from the historical period (1961-1990) to the 2030s (2025-2035) and the 2090s (2090-2099) under two climate scenarios. Change in the biomass consumed by natural fires between the 20th century (1895-1993) and the 21st century 1994-2100) as simulated by the dynamic vegetation model MC1 under two climate scenarios (bottom two panels) (Bachelet et al. 2001) See Color Plate Appendix

ground-level fires. In western forests, repeated ground-level fires reduce intermediate height vegetation that can serve as fuel between the surface and the crown. Thus,these repeated ground-level fires reduce the occurrence of stand-killing crown fires.

Disturbances can be regional or widespread. Landslide processes exhibit very strong geographic patterns. Pacific coastal mountains are particularly prone to sliding because of weak rocks,steep slopes,and high precipitation from frontal storms in these tectonically active areas. Other disturbances, such as insects,pathogens,or introduced species, are widespread across the US. Many disturbances cascade into others. For example,drought often leads to insect outbreaks,disease,or fire. Insects and disease can also create large fuel loads and thereby contribute to increased fire frequency.

Disturbances can be of either natural or anthropogenic origin (e.g., fire). Many large forest areas have been affected by past human activities,and current disturbance regimes are profoundly different from historical regimes. For example, fire suppression in the fire-adapted western forests has led to increased forest density and biomass, changes in forest composition,and increased outbreaks of insects and disease (Flannigan et al.,2000;Ayres and Lombardero,2000). Some forest types have evolved to depend on the periodic occurrence of the disturbance. Long-leaf pine forests are a fire-climax ecosystem that would not exist if fire were not a part of the Southeast.Nearly 1.5 million acres of prescribed burning and other fuel reduction treatments in 1998 were used to enhance forest health and diversity by restoring fire-dependent ecosystems that have been affected by long-term fire suppression (USDA Forest Service,1998). Natural disturbances interact with human activities such as air pollution,harvest, agricultural and urban encroachment,and recreation.

Impact of Climate Change on Forest Disturbances

Climate variability and climate changes alter the frequency, intensity, timing,and/or spatial extent of disturbances. Many potential consequences of future climate change will possibly be buffered by the resilience of forest communities to natural climatic variation. However, the extensive literature on this subject suggests that new disturbance regimes under climate change will likely result in significant perturbations to US forests,with lasting ecological and socioeconomic impacts (Dale et al.,2001).

Hurricanes. Hurricanes seriously impact forests along the eastern and southern coasts of the US as well as the Caribbean Islands (Lugo,2000). They can inflict sudden and massive tree mortality, complex patterns of tree mortality including delayed mortality, and altered patterns of forest regeneration (Lugo and Scatena,1996). Because most hurricane damage is from floods,effects can be removed from the actual hurricane in distance (heavy precipitation well inland from the coast) and in time (delays involved in water movement,and in mortality resulting from excessive water).Hurricanes can lead to shifts in successional direction,higher rates of species turnover, opportunities for forest species change,increasing landscape heterogeneity, faster biomass and nutrient turnover, and lower aboveground biomass in mature vegetation (Lugo and Scatena,1995).

Hurricane location,size,and intensity are influenced by sea surface temperatures and by regional weather features (Emanuel,1999). Sea surface temperatures (SSTs) are expected to increase,with warmer SSTs expanding to higher latitudes (Royer et al., 1998;Walsh and Pittock,1998). Climate change is also likely to influence the frequency of regional weather events conducive to hurricane formation, although it is not yet possible to say whether hurricane frequency increases or decreases (Royer et al., 1998;Henderson-Sellers et al.,1998;Knutson et al., 1998;Knutson and Tuleya,1999).

Fire. Fire frequency, size,intensity, seasonality, type, and severity are highly dependent on weather and climate. An individual fire results from the interaction of ignition agents (such as lightning,fuel conditions,and topography) and weather (including air temperature, relative humidity, wind velocity, and the amount and frequency of precipitation). Over the 1989-1998 period,an average of 3.3 million acres burned annually in the US, varying from 1 million acres a year to over 6 million,mostly in the west and southeast. Most of the burned acres resulted from human-caused fires.

Two modeling approaches were used to look at the impact of climate change on fire:1) fire severity ratings estimated from future climate (Flannigan et al., 2000),and 2) the interaction of vegetation biomass and climate in establishing conditions for fire (Bachelet et al.,2000).

In the analysis by Flannigan et al.(2000),the future fire severity is projected to increase over much of North America under both climate scenarios and these results are consistent with earlier analyses (Flannigan et al.,1998). The results show great variation for the US and Canada. The warmer and wetter Hadley scenario suggests fire severity increases near 20% for the Northeast and small decreases for the northern Great Plains,with increases less than 10% over the rest of the continent. The warmer and drier Canadian scenario produces a 30% increase in fire severity for the Midwest,Alaska,and sections of the Southeast,with about 10% increases elsewhere. These results suggest a possible increase of 25-50% in the area burned in the US. Temperature and precipitation are not the only climate-related factors that influence fire regimes; for example,lightning strike frequency was estimated to increase 44% under the Goddard Institute for Space Studies general circulation model scenario (Price and Rind,1994). Other factors such as length of the fire season, weather conditions after ignition,and vegetation characteristics also influence the fire regimes. Wotton and Flannigan (1993) found that the fire season would be on average 30 days longer in a double carbon dioxide climate as compared to the current climate for Canada. Wildfire severity was at least as sensitive to changes in wind as to changes in temperature and precipitation in a climate change sensitivity analysis for California (Torn and Fried,1992). Human activities such as fire policies and land use will likely also influence fire regimes in the future (Keane et al.,1998). For example,wildfires on all lands in the western US increased in the 1980s after 30 years of aggressive fire suppression that had led to increases in forest biomass.

The second modeling study examined the influence of climate change on vegetation and the interaction with natural fires (Bachelet et al.,2001). The amount of biomass consumed in fire increased under future climates in analyses with the dynamic global vegetation model,MC1 (Figure 4). In this model, fire occurrence,severity, and size are simulated as a direct function of fuel and weather conditions (Lenihan et al.,1997;Daly et al.,2000,Bachelet et al.,2001). In the western US,increased temperature,steady to increased precipitation,CO_2 fertilization,and increased water use efficiency enhance ecosystem productivity, resulting in more biomass. The highly variable climate of dry years interspersed with wet years and the fuel buildup contributes to more and larger fires in the western landscape. In the eastern US under the Canadian scenario, fires are projected to increase in the Southeast as a result of increased drought stress in forests.

Both approaches suggest the potential for an increased area to be burned with a changing climate.These analyses are based on the physical and biological factors influencing potential fire hazard. Factors such as current land management,land use, and ownership are not considered. Harvest activities and the conversion of forest land to other uses would also alter the amount and kind of fuel.

The rapid response of fire regimes to changes in climate is well established (Flannigan et al.,1998; Stocks et al.,1998),so this response has the potential to overshadow the direct effects of climate change on species distribution,migration,and extinction within fire-prone areas. This possibility of increased fire poses challenges to the management of protected areas such as national parks (Malcolm and Markham,1998) and to the management of forests for carbon storage.

Drought. Droughts occur in nearly all forest ecosystems (Hanson and Weltzin,2000). The primary immediate response of trees to drought is to reduce net primary production (NPP) and water use,which are both driven by reduced soil moisture and stomatal conductance. Under extended severe drought conditions,plants die. Seedlings and saplings usually die first and can succumb under moderate drought conditions. Deep rooting,stored carbohydrates,and nutrients in large trees make them susceptible only to longer, more severe droughts. Secondary effects also occur. When reductions in NPP are extreme or sustained over multiple growing seasons,increased susceptibility to insects or disease is possible,especially in dense stands (Negron,1998). Drought can also reduce decomposition processes leading to a buildup of organic matter on the forest floor.

The consequences of a changing drought regime depend on annual and seasonal changes in climate and whether a plant's current drought adaptations offer resistance and resilience to new conditions. Forests tend to grow to a maximum leaf area that uses nearly all available growing-season soil water (Eagleson,1978;Hatton et al.,1997; Kergoat,1998; Neilson and Drapek,1998). A small increase in growing-season temperature could increase evaporative demand and trigger moisture stress.Using this assumption about leaf area, results from MAPSS, a biogeography model,and MCI,a dynamic global vegetation model,suggest that increased evaporative demands will likely cause future increases in drought stress in forests of the Southeast,southern Rocky Mountains,and parts of the Northwest (Neilson and Drapek,1998;Bachelet et al.,2000). While earlier forest models,often known as 'Gap' models (Shugart,1984) also suggested forest declines,all of a tree's current drought adaptations, such as adjusting growth rates or aboveground-belowground allocations of carbon,had not been incorporated into the analysis (Loehle and LeBlanc, 1996). These adaptations buffer the impact of climate,including drought,on individual trees and forest stands. The current generation of ecological models,such as MAPSS,MC1 and others,have improved upon these process algorithms,including the suggestions from Loehle and LeBlanc (1996).

Biomass Consumed under Two Scenarios of Future Climate

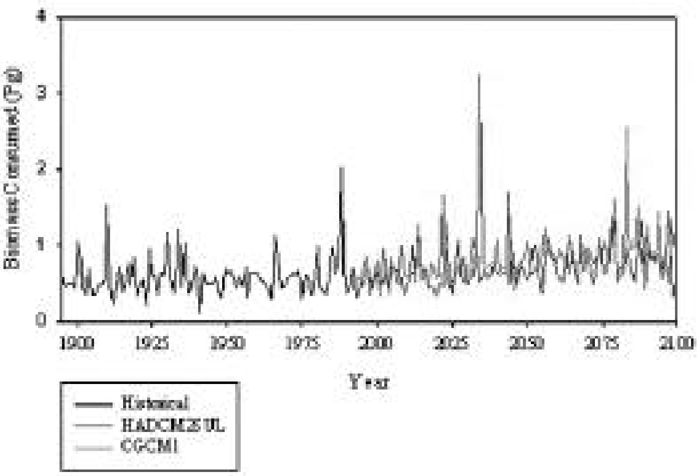


Figure 4. Simulated total biomass consumed by fire over the conterminous US under historic and two future climates; Hadley (HADCM2SUL) and Canadian (CGCM1) scenarios. The fire simulations are for potential vegetation and do not consider historic fire suppression activities. However, grid cells with more than 40% agriculture have been excluded from the calculations (Lenihan et. al., 1997, Daly et. al., 2000, Bachelet et. al., 2001). See Color Plate Appendix

Wind events. Small-scale wind events,such as tornadoes and downbursts,are products of mesoscale weather circumstances (Peterson,2000). These disturbances can create very large areas of damage. For example,an October 25,1997 windstorm flattened nearly 13,000 acres of spruce-fir forest in the Routt National Forest of Colorado (USDA Forest Service Routt National Forest,1998),and a July 4, 1999 windstorm flattened roughly 250,000 acres of forest in the Boundary Waters Canoe Area of Minnesota (Minnesota Dept.of Natural Resources press release 7/12/99). Although small-scale wind events occur throughout the US,the highest concentration of tornadoes occurs across the Central Great Plains states of Oklahoma, Texas,Kansas,and Nebraska.

If climate change increases intensity of all atmospheric convective processes,this change will accelerate the frequency and intensity of tornadoes and hailstorms (Berz,1993). Karl et al.(1995a) found that the proportion of precipitation occurring in extreme weather events increased in the US from

1910 to 1990. Karl et al.(1995b) further suggest that the US climate has become more extreme (in terms of temperature and precipitation anomalies) in recent decades. Further, Etkin (1995) found a positive correlation between monthly tornado frequency in western Canada and mean monthly temperature,and inferred that this relationship suggests increased tornado frequency under a warmer climate. Despite the above indirect inferences about tornado frequencies,and the direct data on thunderstorm trends,there is still inadequate understanding of tornado genesis to directly forecast how climate change will affect the frequency or severity of windstorms in the next century (Peterson,2000).

Ice Storms. Ice storms,also known as glaze events, result when rain falling through subfreezing air masses close to the ground is supercooled so that raindrops freeze on impact (Irland,2000). The National Weather Service (NWS) defines an ice storm as an occurrence of freezing precipitation resulting in either structural damage or at least 0.25 inch of ice accumulation. Ice accumulation can vary dramatically with topography, elevation,aspect, and areal extent of the region where conditions favor glaze formation. While ice storms can occur as far into the southern US as northern Mississippi and Texas,the frequency and severity of ice storm events generally increases toward the northeast (Irland,2000).

Depending on forest stand composition,amount and extent of ice accumulation,and stand history, damage can range from light and patchy to total breakage of all mature stems (Irland,1998). Even though the weather conditions producing ice storms are well understood,it is not known how changes in climate will affect the frequency, intensity, location,or areal extent of ice storms.

Introduced species. Climate,as well as human activities,largely determine the potential and realized distributional ranges of introduced species (Simberloff, 2000). Unsuitable climate at points of arrival restricts the survival of a great majority of introduced species (Williamson,1999). In warmer parts of the US,introduced species comprise a larger fraction of the biota (Simberloff, 1997). Where climate currently restricts invasives, changes in temperature or precipitation may facilitate increased growth, reproduction,or expansion of their ranges. For example,laboratory studies of balsam woolly adelgid (*Adelges piceae*), growing under various temperature conditions,provided the basis for simulations suggesting that temperature-induced changes in the population dynamics of the insect significantly affect Fraser fir (*Abies fraseri*) survival (Dale et al., 1991).

A key feature of most invasive species is that they have the capacity to thrive in disturbed environments through their high reproductive rates, good dispersal abilities,and rapid growth rates (Vitousek et al.,1996). If climate change results in increased disturbances such as fire or drought,these disruptions to ecosystems create just the type of environments in which invasive species are likely to expand rapidly. The interactions among introduced species, native communities,intensively managed forests, human activities that fragment ecosystems, increased atmospheric deposition,and climate change might positively affect the prevalence of invaders,but forecasting specific impacts of invasions remains problematic (Dukes and Mooney, 1999;Williamson,1999).

Insect and Pathogen Outbreaks Outbreaks of insects and pathogens can adversely affect recreation,wildlife habitat, wood production and ecological processes.Over the 1986 to 1995 period,these 4 native insect species damaged annually the following acreages: over 4 million acres for western spruce budworm;less than 1 million acres for eastern spruce budworm;less than 2 million acres for mountain pine beetle;and nearly 12 million acres for southern pine beetle (The Heinz Center, 1999). Within this time period,the acreage affected by any one of these insects could vary from less than half of the long-term average to three times the long-term average. Nearly 13 million acres of southern forests are affected by a single disease,fusiform rust, and 29 million acres of western forests are affected by a parasitic plant, dwarf-mistletoe (The Heinz Center, 1999). Disturbances such as drought and fire influence these outbreaks.

An extensive body of scientific literature suggests many pathways through which elevated carbon dioxide and climate change could significantly alter patterns of disturbance from insects and pathogens (Ayres and Lombardero,2000). Elevated carbon dioxide and climate change could possibly increase or decrease the disturbances of insects and pathogens through direct effects on the survival, reproduction,and dispersal of these organisms. For example,an increase in the interannual variation in minimum winter temperatures could possibly favor more northerly outbreaks of southern pine beetles, while decreasing more southerly outbreaks (Ungerer et al.,1999). It is also possible that climate change would alter insect and pathogen disturbances indirectly through changes in the abundance of their natural enemies and competitors. In addition, climate,and elevated carbon dioxide,influence the susceptibility of trees to insects and pathogens through changes in the chemistry of plant tissues (Ayres and Lombardero,2000).

The short life cycles,high mobility, reproductive potential,and physiological sensitivity to temperature suggest that even modest climate change will possibly have rapid impacts on the distribution and abundance of many forest insects and pathogens. Beneficial impacts could possibly result where decreased snow cover increases winter mortality. Detrimental impacts could possibly result when warming accelerates insect development and facilitates dispersal of insects and pathogens into areas where tree resistance is less. Detrimental impacts could also possibly result from interactions of disturbances. For example, warming could increase outbreaks in boreal forests that would tend to increase fire frequency (Ayres and Lombardero, 2000). Already, the impact of insects and disease in forests is widespread. In 1995, over 90 million acres of forestland in the US were affected by a few species:southern pine beetle,mountain pine beetle,spruce budworm (eastern and western), spruce beetle, dwarf mistletoe, root disease,and fusiform rust. Thus,there are potentially important ecological and socio-economic consequences to these beneficial and detrimental impacts (Ayres and Lombardero,2000;Ayres and Reams,1997).

3. Biodiversity

Land Use Impacts Species, Communities, and Biomes

Global change encompasses a number of events occurring at the continental scale, including climate change, land use change, species invasion, and air pollution. Global change has and will likely continue to affect the abundance and distribution of plants and animals which, in turn, will have considerable ramifications for human economics, health, and social well-being. Organisms provide goods including material products, foods, and medicines. In addition, the number and kinds of species present affect how ecosystems respond to global change. It is the responses of individual organisms that begin the cascade of ecological processes that then manifest themselves as changes across landscapes,biomes, and the globe (Hansen et al., 2001, Walker et al., 1999).

Humans modify the quality, amount,and spatial configuration of habitats. A number of natural community types now cover less than 2% of their pre-settlement ranges (Noss et al.,1994).Examples include:spruce-fir forests in the southern Appalachians;Atlantic white-cedar in parts of Virginia and North Carolina; red and white pine in Michigan;longleaf pine forests in the southeastern coastal plains;slash pine rockland habitat in southern Florida;loblolly/shortleaf pine forests in the west gulf coastal plains;and oak savannas in Oregon. For the species dependent upon ecosystems that have declined in area,such habitat loss can reduce effective population sizes, genetic diversity, and the ability of species to evolve adaptations to new environments (Gilpin,1987). The area involved in land use shifts can dwarf the land area involved in natural disturbances. For example,the area of harvested cropland went from 292 million acres in 1964 to 347 million acres in 1982,and then down to 293 million in 1987. For comparison,the total area burned in fires at 1 to 6 million acres annually is much less than these land area shifts in and out of agriculture. Though the forest remains standing,only five species of insects are estimated to defoliate about 21 million acres each year, on average (The Heinz Center, 1999).

Land use change alters the spatial pattern of habitats by creating new habitats that are intensively used by humans or by reducing the area and fragmenting natural habitats. These changes increase the distance between habitat patches and reduce overall habitat connectivity. Native forests have been converted to agricultural and urban uses, notably in the eastern and midwestern parts of the US. In some cases, forests have regrown on abandoned agricultural lands. Recent expansion of urban areas and agriculture are fragmenting western forests. Nationally, urban areas have doubled in area between 1942 and 1992 (Flather et al.,1999). While urban areas increased most rapidly in the South and Pacific Coast regions,the most influential land use change has been the increase in human population density in rural areas,particularly in the Rocky Mountain and Pacific Coast regions. This expansion alters disturbance patterns associated with fire, flooding,and landslides.Roadways and expansion of urban areas have fragmented forests into smaller, less-contiguous patches.

Loss of habitat and degradation of habitat quality can reduce population size and growth rates,and elevate the chance of local extinction events (Pulliam,1988). The steadily increasing number of species listed as threatened and endangered in the US is currently at 1,232 (USDI, Fish and Wildlife Service,2000). Factors contributing to species endangerment include habitat conversion, resource extraction,and exotic species (Wilcove et al.,1998). The spatial distribution of such factors results in species at risk being concentrated in particular regions of the US,especially the southern Appalachians,the arid Southwest,and coastal areas (Flather et al.,1998),which can be traced back to human population growth and attendent land-use intensification. Land-use intensification has also been found to affect animal communities broadly. Along a gradient of increasing land-use intensification in forested regions of the eastern US,native species of breeding birds are increasingly under-represented and exotic species over-represented (Flather, 1996).

Species that take advantage of anthropogenic habitats,such as some deer, goose,and furbearer species, have greatly expanded in recent years (Flather et al., 1999). Some species of deer (e.g.,white-tailed deer) are now so abundant that the primary concern is controlling their populations. In addition, exotic species have become established and greatly expanded their ranges in the US (Drake et al.,1989).

Impact of Climate Change on Biodiversity

Changes in the distribution and abundance of plant or animal species reflect the birth, growth,death, and dispersal rates of individuals in a population. When aggregated,these changes manifest as local extinction and colonization events,which are the mechanisms that determine a species' range. While climate and soils are strong controls on the establishment and growth of plants,the response of plant and animal species to climate change will be the result of many interrelated processes operating over several scales of time and space. Migration rates, changes in disturbance regimes,and competitive and cooperative interactions with other species will affect the distribution of plants and animals. Because of the individualistic response of species, biotic communities are not expected to respond as intact units to climate change. Community composition responds to a complex set of factors including the direct effects of climate,differential species dispersal,and indirect effects associated with changes in disturbance regimes,land use,and interspecific interactions (Peters,1992).

Some of the best evidence that species'distributions are correlated with changing climates is found for plants (Webb,1992). Recent observations of some species suggest a response to historical changes in climate. Breeding ranges of some mobile species, such as waterfowl,have expanded northward in association with climate warming (Abraham and Jefferies,1997). The breeding dates of both amphibians and birds in Great Britain have shifted one to three weeks earlier since the 1970s in association with increasing temperatures (Beebee,1995;Crick et al.,1997).

The primary focus for this analysis is on the continental-scale response of forest vegetation as reflected in climate-induced changes in the distributions of biomes,community types,species richness,and individual tree and shrub species. Vegetation responses to projected future climate change were assessed by reviewing the available literature and by using the climate predictions of global climate models as input to a set of different vegetation simulation models. Paleoecological studies of climate change impacts on forests provide information about past responses. However, their results are limited with respect to the future because the current size, age, and species composition of temperate forests has been strongly impacted by human activities,and second,global temperatures are predicted to increase at an unprecedented rate (Dale,1997). Although vegetation models incorporating land-use dynamics are under rapid development at local scales,the current state of knowledge does not allow for integrating the effects of land use at the continental scale.

The vegetation models used in this analysis include the following. Two statistical models project the distribution of individual tree species with results aggregated into community types. For the eastern US,the DISTRIB model,which projects potential changes in suitable habitat of 80 tree species, was developed from 33 environmental variables and the current distribution of each tree species (Iverson et al.,1999). The results for 80 species under each climate change scenario were also aggregated to examine potential changes in forest types in the eastern US (Iverson and Prasad,2001). Shafer et al.(2001) developed local regression models that estimate the probability of occurrence of 51 tree and shrub species across North America based on 3 bioclimatic variables:mean temperature of the coldest month, growing degree days,and a moisture index. Changes in species richness of trees and terrestrial vertebrates based on energy theory (Currie,1991) were also analyzed under the different climate scenarios. Species interactions and the physiological response of species to carbon dioxide are not included in these statistical models. In contrast,the MAPSS biogeography model (Neilson,1995) projects biome response to climate as change in vegetation structure and density based on light,energy, and water limitations (VEMAP Members,1995). The potential natural vegetation is coupled directly to climate and hydrology, and rules are applied to classify vegetation into biome types. The model considers the effects of altered carbon dioxide on plant physiology. The analyses for species,communities,and biomes used an equilibrium climate scenario based on the transient Canadian and transient Hadley scenarios. The baseline scenario was the average climate for the 1961-1990 period. The "climate change"scenario was the average of the projected climate for 2070 to 2100. The results of these analyses are given below. The implications of species dispersal and land use change are discussed in the context of these analyses.

Tree Species. The potential distribution of tree species under climate change is modeled using both statistical models (Iverson and Prasad,2001; Shafer et al.,2001) and both climate scenarios used in the National Assessment. These statistical approaches assume that there are no barriers to species migration. Results should be viewed as indications of the potential magnitude and direction of range shifts under a changed climate and not as predictions of change.

For many of the eastern tree species,their possible ranges shift north (Iverson et al.,1999;Iverson and Prasad,2001). Under both climate scenarios,the range of sugar maple (*Acer saccharum*) shifts out of the United States entirely (Figure 5). White oak (*Quercus alba*) remains within its current range but is reduced in importance in the southern parts and increases in the northern parts of its range. A total of 7 of the 80 eastern tree species are projected to decline in regional importance by at least 90%:bigtooth aspen (*Populus grandidentata*), aspen (*Populus tremuloides*),sugar maple,northern white-cedar (*Thuja occidentalis*),balsam fir (*Abies balsamea*), red pine (*Pinus resinosa*),and paper birch (*Betula papyrifera*). The ranges of most species are projected to move to the north, with the ranges of several species moving north by 60 to 330 miles (100 to 530 km). For some species,such as aspen,paper birch,northern white-cedar, balsam fir, and sugar maple,the optimum latitude for their occurrence moves north of the US-Canadian border.

When integrated into community types,southern forest types expand while higher elevation and northern forest types decline in area (Figure 6). The oak-hickory type is projected to expand in area by 34% primarily to the north and east (Iverson and Prasad,2001). The oak-pine type is projected to expand in area by 290% throughout the Southeast. Area of spruce-fir and aspen-birch types is projected to decline by 97% and 92% respectively. These types are replaced mainly by oak-hickory and oak-pine forests. The loblolly-shortleaf pine type is also projected to be reduced by 32% and shifts north and west,being replaced in its current zone by the oak-pine type. The longleaf-slash type is projected to be reduced by 31% in area.

In the western US,the potential future ranges for many tree species are simulated to change,with some species' ranges shifting northward into Canada (Shafer et al.,2001). Simulated future ranges for Western hemlock (*Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*) (Figure 7) are projected to decrease west of the Cascade

Projected Changes in Distribution of Sugar Maple

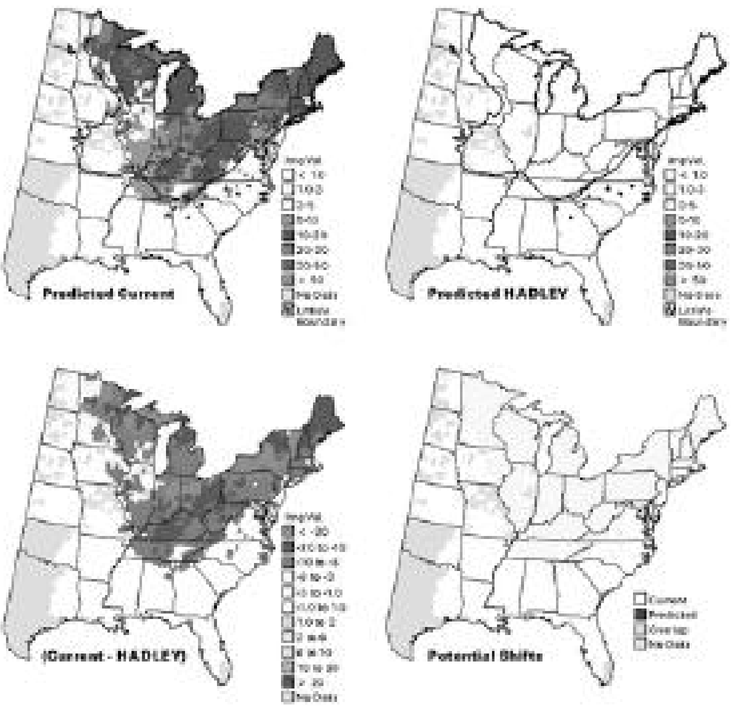


Figure 5. Projected distribution for sugar maple under current climate and the Hadley climate scenario and for the eastern United States, using statistical models developed by Iverson et al. (1999). The Predicted Current map is the current distribution and importance value of sugar maple, as modeled from the regression tree analysis. Importance value is an index based on the number of stems and basal area of both the understory and the overstory. Predicted Hadley is the potential suitable habitat for sugar maple under the Hadley climate scenario. These potential maps imply no barriers to migration. The Difference map represents the difference between Modeled Current and Predicted Hadley maps. The Potential Shifts map displays the modeled current distribution, along with predicted potential future distribution (using the Hadley scenario) and the overlap where the species is now and is projected to be in the future. See Color Plate Appendix

Current and Projected Forest Communities in the Eastern US

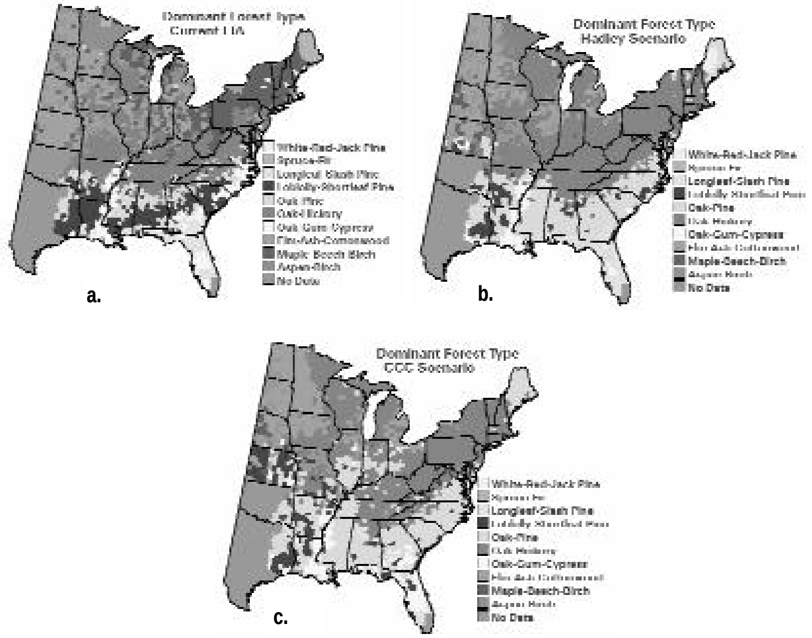


Figure 6. Projected forest communities under (a) current climate, (b) the Hadley climate scenario, and (c) the Canadian climate scenario, based on the results of individual analyses of 80 tree species shifts (see Prasad and Iverson, 1999-ongoing http://www.fs.fed.us/ne/delaware/atlas/index.html) See Color Plate Appendix

Mountains. The potential future range of Western hemlock extends into mountain ranges throughout the interior west while Douglas-fir expands east of the Cascades and Sierras as well as northward along the west coast of Canada into Alaska. The potential future ranges for subalpine conifers such as Engelmann spruce (*Picea engelmannii*),Mountain hemlock (*Tsuga mertensiana*),and several species of fir (*Abies species*) are much reduced in the western parts of the US;however these subalpine species expand to the north along the west coast of Canada and into Alaska. While many of the more mesic and higher elevation species shift northward into Canada,the potential future range of Ponderosa pine (*Pinus ponderosa*) expands within the interior western US.

The complex topography of the western US,combined with its seasonal and regional variations in climate,strongly influences potential future shifts in the ranges of tree species and their likely future abilities to successfully disperse to new habitat (Hansen et al.,2001;Shafer et al.,;2001). Species range shifts in the western US are simulated to occur in all directions whereas in the eastern US,the shifts tend to be northward as temperature increases and westward as precipitation increases. In the western US, several conifer species associated with moderately moist climates shift south and east along the Rocky Mountains with, for example,species typical today of Glacier National Park expanding to the southeast into Yellowstone National Park (Bartlein et al., 1997). Contrasts between eastern and western range shifts can be seen in the simulated future range of Paper birch (*Betula papyrifera*) whose eastern US range limit contracts northward but whose western US range limit expands southward (Figure 7).

Community Richness. The relationship between spatial patterns of climate and richness of trees and terrestrial vertebrate species were used to predict changes in species richness under climate change across North America (Hansen et al.,2001;Currie, 1991;Currie, 2001). The climate relationships with species richness were stronger for temperature than precipitation. Because the climate-richness relationships,including where maximal richness occurs,differ across taxonomic groups,the impacts of climate change will likely also vary across the groups.

Across all scenarios,tree richness is projected to increase in the cooler regions:northern US,the western mountains,and near the Canadian Border (Currie,2001). Because species richness of birds and mammals is currently highest in moderately warm areas and decreases in hotter areas,the model projected species richness for these taxa declines as air temperatures increase. Those scenarios where warming is projected to occur results in a decrease of bird and mammal richness—-a 25% decrease in low-elevation areas in the Southeast,for example. Warming in colder areas (such as mountainous areas) is projected to result in highly variable increases in richness (11% to >100%). Cold-blooded animals such as reptiles and amphibians would benefit from increased air temperatures. Consequently, under the warming climate scenarios,species richness for these taxa is projected to increase from about 11% to 100% over the entire conterminous US.

Flather et al.(1998) identified regions in the US that have high concentrations of the currently designated threatened and endangered species. Species richness was used to explore the potential impact of climate change on taxonomic groups within these hotspots of species endangerment. The projected richness results were overlaid on maps of current hot spots for threatened and endangered species, and the species richness changes within each taxonomic group were evaluated. Within these hotspots,species richness for reptiles and amphibians increased,whereas bird and mammal richness appeared to be much reduced in many of them, especially in the East.

Biome Shifts. The impact of potential climate change on the biogeography of the US is examined using six scenarios that varied in degree of warming (Bachelet et al.,2001). Across the scenarios, forest area is projected to decrease by an average of 11%,with a range of +23% under the moderately warming scenarios to –45% under the hottest scenarios. Northeast mixed forests (hardwood and conifer) are projected to decrease by 72% in area in the US,on average,as they shift into Canada (Neilson et al.,1998). The range of eastern hardwoods is projected to decrease by an average of 34%. Although these deciduous forests shift north, replacing Northeast mixed forests,they are squeezed from the south by Southeast mixed forests or from the west by savannas and grasslands,depending on the scenario. Southeast mixed forests are projected to increase under all scenarios (average 37%). This biome would remain intact under moderately warm scenarios,but would be converted to savannas and grasslands in the South under the hotter scenarios.

Paper Birch and Douglas Fir Tree Distributions under Future Climate Change Scenarios

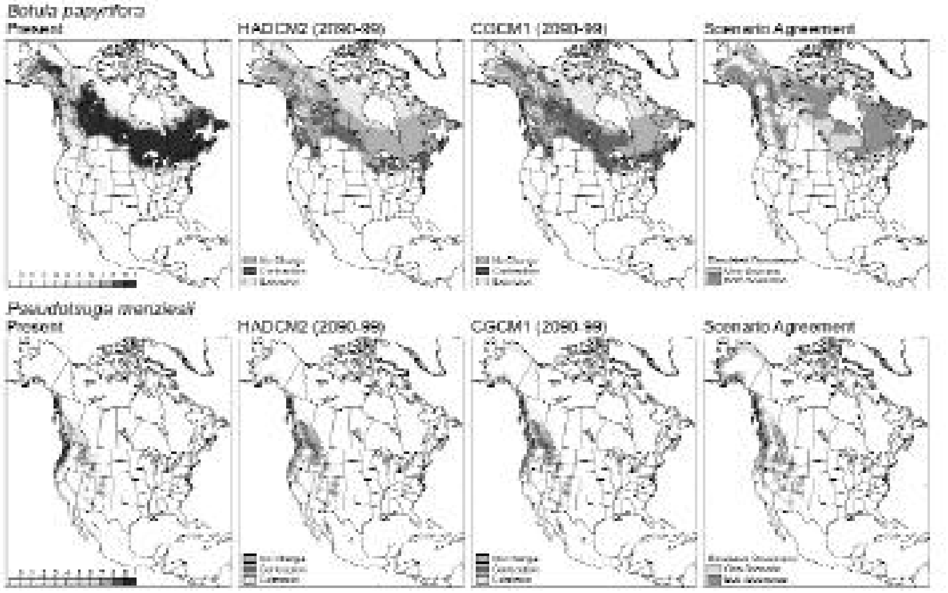


Figure 7. Simulated distributions and scenario agreement for *Betula papyrifera* and *Pseudotsuga menziesii* (after Hansen et al., 2001). Estimated probabilities of occurrence for each taxon simulated with observed modern climate (left panel). Comparison of the observed distributions with the simulated future distributions under future climate conditions as generated by the Hadley (HADCM2) and Canadian (CGCM1) scenarios for 2090-2099 (middle panels). Gray indicates locations where the taxon is observed today and is simulated to occur under future climate conditions; red indicates locations where the taxon is observed today but is simulated to be absent under future climate conditions; and blue indicates locations where the taxon is absent today but is simulated to occur under future climate conditions. Scenario agreement (right panel). Light purple indicates locations where the species is simulated to be present under the future climate of either the HADCM2 or CGCM1 scenario; dark purple indicates locations where the species is simulated to be present under both future climate scenarios. See Color Plate Appendix

Alpine ecosystems are projected to all but disappear from the western mountains,being overtaken by encroaching forests. Under the climate scenarios studied, wet coniferous forests in the northwest decrease in area by 9% on average,while the extent of interior western pines change little. Responses in both wet conifer and interior pine forests show wide variations among scenarios,with expansions under newer transient scenarios (Bachelet et al., 2001).Arid woodlands also are projected to expand in the interior West and Great Plains,encroaching on some grasslands.

Likely Species Shifts, Dispersal, and Land Use Impacts. The locations and areas of potential habitats for many plant and animal species are likely to shift as climate changes. Potential habitats for trees favored by cool environments are likely to shift northward. The habitats of alpine,subalpine spruce/fir, and aspen communities are likely to contract dramatically in the US and largely shift into Canada. Potential habitats that are likely to increase in the US are oak/hickory, oak/pine,ponderosa pine, and arid woodland communities. Most of these results were evident in the results from three independent models:the mechanistic model MAPSS and two statistical models. These results were also relatively robust across the several climate scenarios analyzed,including the Hadley and the Canadian scenarios. The statistical models are highly defensible for this application because of the strong and extremely well-documented relationship between tree species performance and environmental conditions,especially climate and soil.However, statistical models do not incorporate a direct CO_2 effect, which enhances water-use efficiency. Even so,it is well accepted that climate and soils are strong controls on the establishment, growth,and reproduction of many tree species.

How well these species actually track changes in their potential habitats will very likely be strongly influenced by their dispersal abilities and the disturbances to these environments. Good analytical models for dispersal are few. Some native species will very likely have difficulty dispersing to new habitats because of the rapid rate of climate change and the varying land uses along alternate migration routes. For example,aspen communities are currently being reduced by conifer encroachment, grazing,invasive species,and urban expansion. Weed species that disperse rapidly will likely to be well-represented in these new habitats. Hence,the species composition of newly forming communities will likely differ substantially from those occupying similar habitats today.

4. Socioeconomic Impacts

Current Supply and Demand for Amenities, Services, and Goods from Forests

Forests and the forestry sector provide the resource base and flow of amenities, goods,and services that provide for needs of individuals, communities, regions,the nation,and export customers. Harvested products include timber, pulpwood,fuelwood,wild game, ferns, mushrooms, floral greenery, and berries. Recreational opportunities in forests range from skiing, swimming,hiking and camping to birding,and autumn leaf tours. Forest land is also managed to provide clean water and habitat for wildlife.

Environmental conditions and available technology as well as social,political,and economic factors influence the supply of and the demand for forest amenities, goods,and services. Factors that influence supply of these services include forest area, forest productivity, forest management,production technology, and the quality of amenities. Factors that influence demand include population,economic growth and structure,and personal preferences. Changes in these factors also influence supply of and demand for forest amenities, goods,and services. Land-use pressures alter the amount and type of land available for forest reserves, multiple-use forests,commercial recreation, forest plantations, and carbon storage (Alig,1986;Leemans et al.,1996; Solomon et al.,1993). Changes in forest species composition, growth,and mortality alter the possible supply of specific types of wood products, wildlife habitat,and recreation. Assumptions about changes in human needs in the US and overseas also affect the socioeconomic impacts from climate change on US forests (Joyce et al.,1995; Perez-Garcia et al.,1997). Clearly, forest changes caused by human use of forests could exceed those impacts from climate change (Dale,1997).However, climate change could impact many of the amenities, goods, and services from forests (Bruce et al.,1996),including productivity of locally harvested plants such as berries or ferns;local economies through land use shifts from forest to other uses; forest real estate values;and tree cover and composition in urban areas, and associated benefits and costs. In addition, climate-change impacts on disturbances such as fire could increase fire suppression costs and economic losses due to wildfires (Torn et al.,1999). In this assessment,it was only possible to explore the impact of climate change on wood products and recreation in more detail.

North America is the world's leading producer and consumer of wood products. The US has substantial exports of hardwood lumber, wood chips,logs,and some types of paper (Haynes et al.,1995). The US also depends on Canada for 35% of its softwood lumber and more than half of its newsprint. Past, current,and future land uses and management as well as environmental factors such as insects,disease, extreme climate events,and other disturbances affect the supply of forest products. These factors can alter the cost of making and using wood products,and associated jobs and income in an area. Changes in economic viability of wood production influence whether owners keep land in forests or convert it to other uses. Demand for wood products,consumption,and trade is strongly influenced by US and overseas population,economic growth,and human values.While demand for timber needed to make US wood products is projected to grow at about the same rate as population over the next 50 years,the demands for products and the kinds of timber harvested will be affected by technology change and consumer preferences. For example,use of recycled paper slows the increase in the amount of timber harvest needed to meet increasing demands for various paper products.

The combinations of resources,travel behavior, and population characteristics vary uniquely across the regions of the US. Participation in outdoor activities is strongly related to age, ability and disability, race,education,and income. These factors influence the types of recreation opportunities available and in which people participate. Approximately 690 million acres of federal lands are used for recreation,of which 95% are in the West. State and local governments manage over 54 million acres,of which 30 million (55%) are in the East (Cordell et al.,1990). Most of the downhill skiing capacity is in the western US while most of the cross-country skiing capacity is in the East.The number of people participating in recreation is expected to continue to increase for many decades. The importance of recreation opportunities near urban areas is rising as US preference shifts from long-distance vacations to frequent close-to-home trips (Cordell et al.,1990). A little over 14% of private lands are open to recreation,but this amount is declining as lands are converted to other uses or access is restricted. Projected increases in per capita income will likely contribute to higher demand for snow-related recreation,although land- and water-based activities will continue to dominate total recreation patterns (USDA Forest Service, 1994).

Potential Impact of Climate Change on Timber and Wood Product Markets, and Recreation

Adaptation in forest land management and timber markets. The possible degree and uncertainty in the flow of value from forests — goods,services, and amenities — is influenced by the combined (and individual) uncertainty in changes in climate, forest productivity, and the economy. Comparisons of earlier with more recent analyses indicate that differences in assumptions,modeling structure,and scope of analysis such as spatial scale significantly affected the socioeconomic results. For example, an early study of Scandinavian boreal forests concluded that increased warming would benefit higher latitude regions (Binkley, 1988); yet when the global trade patterns were analyzed,other regions with lower production costs benefited most (Perez-Garcia et al.,1997). Early analyses (e.g.,Smith and Tirpak,1989) that did not include economic forces concluded there would be significant damage to US forests. When active forest management was included in a previous economic analysis,timber markets adapted to short-term negative effects of climate change by reducing prices,salvaging dead and dying timber, and replanting species appropriate to the new climate (Sohngen and Mendelsohn,1998). The total of consumer and producer benefit (surplus) remained positive.

For this assessment,the dynamic optimization model FASOM (Adams et al.,1996,1997;Alig et al., 1997,1998) was used to evaluate the range of possible projected changes in forest land area,timber markets,and related consumer/producer impacts associated with climate change (Irland et al.,2001). The range of scenarios considered alternate assumptions about 1) climate (the Hadley and the Canadian scenarios),2) forest productivity (the TEM and CENTURY biogeochemistry models),and 3) timber and agricultural product demand (determined by population growth and economic growth).

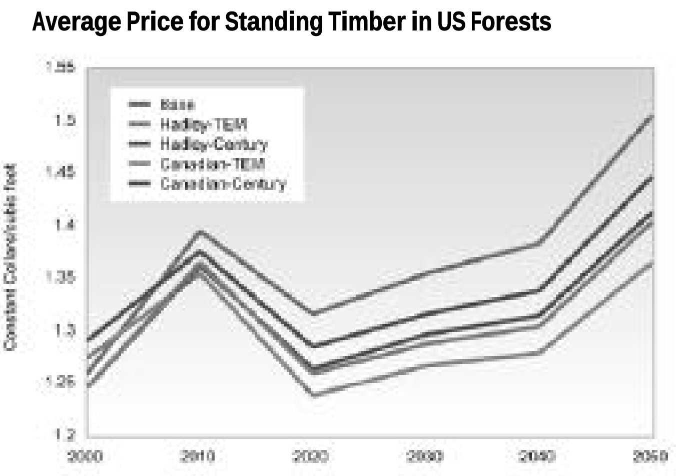


Figure 8. Prices for standing timber under all climate change scenarios remain lower than a future without climate change (baseline). Prices under the Canadian scenario remain higher than prices under the Hadley scenario when either the TEM or the CENTURYmodel are used. (Irland et al., 2001). See Color Plate Appendix

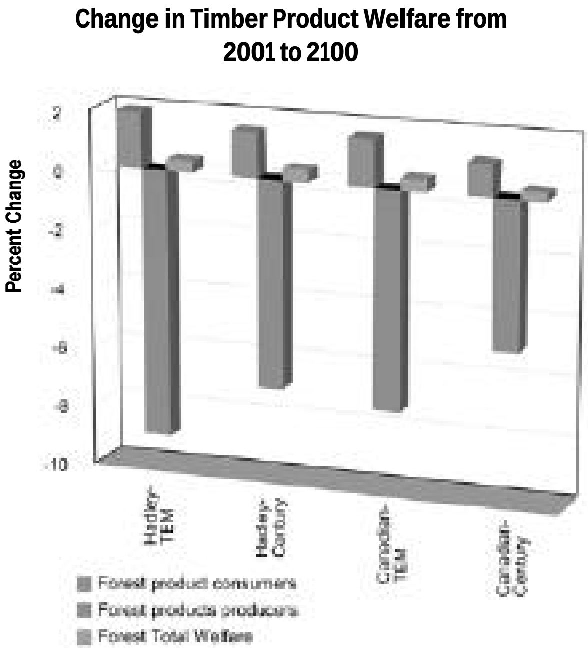


Figure 9. Increased forest growth overall leads to increased wood supply; reductions in log prices decrease producers' welfare (profits), but generally benefit consumers through lower wood-product prices. Welfare is present value of consumer and producer surplus discounted at 4% for 2000-2100. (Irland et al., 2001). See Color Plate Appendix

Analyses of these particular scenarios indicate that forest productivity gains increase timber inventories over the next 100 years. This increased wood supply results in reductions in log prices,which,in turn,decrease producers'profits. At the same time, lower forest-product prices mean that consumers generally benefit (Figure 8). The net effect on the economic welfare of participants in both timber and agricultural markets was projected to increase in all scenarios from between 0.4 to 0.7% above the current values (Figure 9). Land would likely shift between forestry and agricultural uses as these economic sectors adjusted to climate-induced changes in production. Although US total forest production generally is projected to increase in these analyses, hardwood output is higher in all scenarios whereas softwood output increases only under moderate warming. The extent of these changes varies by region. In these analyses,timber output increases more in the South than in the North,and sawtimber volume increases more than pulpwood volume.

While previous studies and this analysis differ in the degree of market and human adaptation,one general conclusion is that timber and wood product markets will likely be able to adjust and adapt to climate change (Irland et al.,2001). Assumptions about changes in population,land use,trade in wood products,consumption of wood products, recreation patterns,and human values are highly uncertain on a century time scale. For example,if human needs from forests increase over the next 100 years and imports are limited,the socioeconomic impacts of climate change on forests would be greater than if needs are low or products can be imported from areas where climate increases forest growth. Thus, assumptions about change in human needs in the US and overseas,and about climate change effects in other parts of the world,are likely to be the major factors that determine socioeconomic impacts on the US.

Recreation. Outdoor recreation will likely be altered as a result of changes in seasonality of climate,and air and water temperatures (Irland et al., 2001). Secondary impacts of environmental changes,such as increased haze with increased temperatures,and degraded aquatic habitats under changing climates,will also likely affect outdoor recreation opportunities. Because recreation is extremely broad and diverse in its environmental requirements (Cordell et al.,1999),it is difficult to generalize about the impact of climate change across recreation as a whole (Wall,1998). Change in benefits to consumers,as measured by aggregate days of activities and economic value, vary by type of recreation and location (Loomis and Crespi,1999; Mendelsohn and Mackowiki,1999). In some cases, recreation in one location will be substituted for recreation in other locations. For example,temperature increases will likely extend summer activities such as swimming and boating in some forest areas, and substitute to some degree for such activities in more tropical areas. Effects on fishing opportunities will likely vary with warming waters increasing fish production and opportunities for some species while decreasing habitat and opportunities for cold water species.

Recreation is likely to expand in mountainous areas where warmer temperatures attract more people to higher elevations. Skiing is an important use of forested mountain landscape and is sensitive to the climate in the mountains. Competition within the skiing industry is strong,with successful ski areas attracting customers by providing high-speed lifts, overnight accommodations,modern snowmaking and grooming equipment,and other amenities. Small ski areas often cannot compete and many have closed or have been annexed by adjacent larger areas (Irland et al.,2001). Climate change will likely alter the primary factors influencing the ability of a ski area to make snow;namely temperature, water availability, and energy. Higher winter temperatures could possibly increase the amount of snow melting,the number of rain events,and decrease the opportunities for snowmaking while increasing the need for machine-made snow. The efficiency of snowmaking declines as temperature warms. The cost of making snow is 5 times greater at 28˚F (–2 ˚C) as at 10˚F (–12 ˚C). The annual electricity usage at Maine’s Sunday River ski area is approximately 26 million kilowatt-hours (Hoffman,1998),at a cost of nearly 2 million dollars per year and most of this energy is used for snowmaking. On the other hand,higher winter temperatures and more rain events together could possibly result in increased water availability for snowmaking and perhaps increased visitation with fewer extremely cold days. Changes in the geographic line of persistent subfreezing winter temperature could possibly alter the location of winter recreation by affecting the feasibility of snow-making,such as in the southern Appalachian Mountains. While the impacts of climate change on the US ski industry remain speculative,ski areas operating in marginal climates are likely to be seriously affected.

ADAPTATIONS: FOREST MANAGEMENT STRATEGIES UNDER CLIMATE CHANGE

A major challenge in developing strategies for coping with the potential effects of climate change on forest processes and subsequent values is that the magnitude and direction of such changes at the local level remain highly uncertain. In addition, potential climate-induced changes in forest processes must also be put into context of other human-induced pressures on forests, which will likely change significantly over future decades and centuries. Finally, such strategies must be considered in terms of their economic viability. Strategies for coping with climate change could include: 1) active forest management to promote forest adaptation to climate change, and 2) assistance to urban and rural communities to adapt to changing forest conditions.

Active Forest Management under Climate Change

Current forest management capabilities provide initial guidance on how to manage forests under a future changing climate. The value of the forest, any changes in natural disturbance regimes, and the available environmentally and economically acceptable management options influence the coping strategies for forests. One way forests may be aided in adapting to climate change is to take steps to decrease other forest stresses, such as atmospheric deposition. Strategies for coping with disturbances in forests will vary regionally.

If climate change results in alteration of such disturbance regimes as fire, drought, or insects and disease, managers could try to cope with these impacts by influencing forest ecosystems prior to the disturbance, mitigating the forest disturbance itself, manipulating the forest after the disturbance, or facilitating the recovery process. Prior to the disturbance, the ecosystem could be managed in ways that alter its vulnerability or ability to enhance recovery from a disturbance. For example, trees susceptible to ice or wind storms could be removed, as is common in cities. Density and spacing of tree planting could be altered to reduce susceptibility to drought. Species composition could be changed to reduce vulnerability of forests to fire, drought, wind, insects, or pathogens. Management could be designed to reduce the opportunity for disturbance to occur. Examples include: limiting the introductions of non-native species; burning restrictions; and prescribed fires to reduce fuel loads. While manipulations of fuel type, load, and arrangement could protect local areas of high value, fuel management may not be complicated for larger landscapes. Some disturbances, such as fire, insects, disease, and drought can be managed through preventive measures, or through manipulations that affect the intensity or frequency of the disturbance. For example, fire, insect, and disease controls are examples of managing to reduce the impact of a disturbance for high-valued forests. Mitigation measures, such as irrigation, might temporarily support specific gene pools until new and stable environments are identified. Recovery efforts can focus either on managing the state of the system immediately after the disturbance, or managing the ongoing process of recovery. Recovery can be enhanced by adding structural elements that create shade or other safe sites necessary for reestablishing vegetation or that serve as perches for birds (and thus places where seeds would be dispersed). Alternatively, late successional species might be planted to speed up succession.

There will likely be surprises in how changes in climate alter the nature of forest disturbances and the forests themselves. A monitoring program could determine the influence of climate change on forests and the natural disturbance regimes. Programs for monitoring the impact of forest disturbances currently exist for insects, pathogens, and fire. However, few surveys quantify the extent and severity of damage from wind, ice storms, and landslides. Further, reserve areas such as wildernesses, are not currently monitored. Information from monitoring programs could then be used to update risk assessments in management plans and prescriptions in an adaptive management sense (Walters, 1997) or to assess the regional vulnerability of landscapes (O'Neill et al., 2000). A risk ranking system could identify aspects of the forest most susceptible to severe repercussions from disturbance under a changing climate.

Human Adaptation to Forest Changes under an Altered Climate

While recent studies have suggested that human activities associated with markets will likely allow for adaptation to ecological changes by changing land use practices, production and use technologies, and consumption patterns, it may be important to examine the breadth of possible adaptations. As forest conditions change costs of goods, services, and amenities, investors, producers, and consumers will likely shift investments and consumption decisions. However, it is possible that separate effects on producers and consumers of timber products, especially in different regions, could be large and in opposite directions.

Helping human communities to adapt to changing forest conditions could include reducing potential socioeconomic impacts by mitigating carbon buildup in the atmosphere. Carbon buildup in the atmosphere can be slowed by changing forest management and forest industry technology to increase net carbon sequestration. Carbon storage in forests could be increased by reducing the conversion of forests to other land uses, setting aside existing forests from harvest, or reducing forest fires (Birdsey et al., 2000; Sampson and Hair, 1996). Carbon storage could also be increased by converting other land uses to forests and by enhancing forest management. Improvements in forest industry technology could enhance sequestration by allowing substitution of wood products where appropriate for products requiring more energy and carbon emissions in production and use, and increasing the use life of products and recycling of products allowing more carbon accumulation in forests (Sampson and Hair, 1996).

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Linkages between Forest Processes, Air Quality, and Climate Change. It is crucial to begin to understand not only the direct effects of CO_2, ozone, temperature, precipitation, and nitrogen and sulfur deposition on forests, but also the interactive effects of these stresses. Physiological impacts propagate through forest ecosystems by altering competitive interactions among individuals and species, litter characteristics, and soil processes. These impacts and interactions feed back to affect physiological processes, nutrient cycling, and hydrology. These interactions stress the need for integrated ecological research to improve our understanding of these forest dynamics.

Responses of Terrestrial Animals to Changing Climate, and Trace Gases. The response of trees to climate, soils, and other biophysical controls is relatively well-documented, in comparison to other plants or animals. For native species, and the interaction of introduced species and natives, understanding the combined effects of climate, carbon dioxide concentration, and nutrients such as nitrogen on terrestrial vertebrates and invertebrates is severely lacking. The response of vertebrates and invertebrates to soils and other biophysical controls is also lacking. Research is needed to combine models of impacts of climate change and other factors on forest pests (insects and pathogens, introduced species) with models of range and abundance changes of host species.

Integration of Climate and Land Use Change into Biodiversity, Ecosystem Structure, and Higher Trophic Level Models. Climate and land use interact in ways that influence biodiversity, implying that these factors cannot be considered in isolation (Hansen et al., 2001). Climate and land use jointly influence species distributions through alteration of dispersal routes and changes in habitat through changes in disturbances such as wildfire, flooding, and landslides. Land use may modify the local climate through changes in transpiration, cloud formation and rainfall, and increased levels of drying. Land use models include socio-economic variables such as human population size, affluence, and culture (Alig, 1986); however, the influence of climate on land use and land use impacts on climate are not considered. Global and local climate projections simplify the feedbacks between land use, vegetation, and climate. Integrated models of land use and climate are needed to predict the interactions of these two influences on biodiversity.

Understanding the Interactions of Current Forest Disturbances and Climate. Basic information on the disturbance — frequency, intensity, spatial extent — and the climatological conditions that initiate these current forest disturbances are currently not available for a number of forest disturbances. For example, the genesis of ice storms is well-understood, but the nature of the ice accumulation in relation to storm characteristics is not well-understood. Similarly, the understanding of what specific climatological conditions lead to the formation and occurrence of small-scale wind events is inadequate. Analyses suggest that future climate variability may push fire and hurricanes outside of the well-studied historical conditions that initiate them and control their intensity and frequency. For most disturbances, there is a need for better understanding of the interactions between climate variability, disturbance frequency, and spatial patterns. Once the relationships between weather, climate, and forest disturbances have been quantified, the occurrences of such disturbances could be predicted to help minimize their impact.

Quantifying the Impact of Disturbances on Forest Structure and Function. A key aspect of managing the forest before, during, or after disturbances is an understanding of the disturbance impacts on forests. For disturbances such as fire, the impact has been studied extensively. For others such as ice storms, insects, diseases, and introduced species, a more complete understanding of impacts is necessary before we can manage for the disturbance, or explore the interactions of multiple disturbances. Research might identify herbivores and pathogens that are likely to be key agents of forest disturbance in the next 50 years. Integrated continental surveys would help to determine the sensitivity of different types of pests and diseases to environmental change and their potential for increased outbreaks at the margins of their existing ranges.

Trees and forests have developed adaptations by co-evolving with disturbances. Research exploring the utility of these adaptations under a changing climate would be valuable. For example,more work in understanding the inherent genetic variation within particular species is needed to assess the resilience of both unmanaged and managed forests. Research on how genetic traits can be manipulated to increase resistance to specific stresses through biotechnology, expanded tree breeding programs, and seed banks would also be useful for adapting to change in areas where extensive planting is used.

Information to Manage Forests under Multiple Disturbances. Capabilities to manage forests currently, as well as under future potential climate change, rest on the understanding of how forests respond to multiple disturbance events,and how one event affects the response to subsequent disturbance. Fire and biological disturbances such as insects,pathogens,and introduced species have significant interactions. A better understanding of these interactions would improve the ability to make long-range predictions about the fate of forest succession and ecosystem dynamics,and would lead to better predictions of conditions under which one event affects the response to a subsequent one.

Human Adaptation in Response to Climate Change Impacts on Forests. Research needs include better links between ecological models and economic models,and improvements in ecological models to capture human adaptation activities. Enhancing these linkages may require additional information about the interface between ecological processes and management objectives. Continued evaluation is needed of climate change impacts on a wide range of forest goods and services such as water supply, carbon storage,nonwood forest products,as well as timber and recreation. For example,an improved understanding is needed of how extreme weather events affect timber yields,salvage activity, and timber markets. When stakeholders associated with forest operations in the Mid-Atlantic region were surveyed,more than 20% reported major impacts on their forests from heavy rains,high winds,or ice storms (Fisher et al.,2000). Increased forest operation costs associated with extreme weather events were noted by all managers regardless of their forest management objective. New generations of combined vegetation/economic models should incorporate a range of adaptation mechanisms – for example investments in new/altered management strategies and in new technologies.

Research needs also include more applied research on how adaptation could occur based on how it has occurred in the recent and historical past (McIntosh et al,2000). Previous marketing and recreational studies typically examined human behavior against many attributes including a set of environmental attributes. These studies have shown that people adapt behavior to environmental events such as fish advisories,smog alerts, beach closing, fish catch rates,and nitrogen deposition. This wealth of information could be used to examine market and recreational choices to climate change phenomena. Further, this information would be the basis to begin testing the sensitivity of human adaptation to different climate scenarios.

US Trade Flows. The US forest sector operates within a global market. Information is needed on how climate change will alter US trade flows in wood and harvest in the US, versus harvest overseas. As mitigation alternatives are identified,the costs,benefits,and the distribution of costs and benefits must be evaluated. Trade flows can be sensitive to fairly modest shifts in exchange rates and price levels,to a degree that can be important for regions within a nation.

Longer-term Socioeconomic Impacts on Consumer and Producer Benefit/Costs. Improvements in methods are needed that value long-term changes in resource conditions and consumer and producer benefits/costs. While it has been shown that human migration patterns are sensitive to climate and climate change,a larger social question remains: will climate change phenomena cause larger socioeconomic changes than demographic or macroeconomic phenomena?

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Forest Sector Assessment Team
John Aber*,University of New Hampshire
Steven McNulty*,US Department of Agriculture, Forest Service
Darius Adams,Oregon State University
Ralph Alig,US Department of Agriculture, Forest Service
Matthew P.Ayres,Dartmouth College
Dominique Bachelet,Oregon State University
Patrick Bartlein,University of Oregon
Carter J. Betz,US Department of Agriculture, Forest Service
Chi-Chung Chen,Texas A&M University
Rosamonde Cook,Colorado State University
David J. Currie,University of Ottawa,Canada
Virginia Dale,Oak Ridge National Laboratory
Raymond Drapek,Oregon State University
Michael D. Flannigan,Canadian Forest Service
Curt Flather, US Department of Agriculture, Forest Service
Andy Hansen,Montana State University
Paul J. Hanson,Oak Ridge National Laboratory
Mark Hutchins,Sno-Engineering,Inc
Louis Iverson,US Department of Agriculture, Forest Service
Lloyd Irland,The Irland Group
Linda Joyce,US Department of Agriculture, Forest Service
María Lombardero,Universidad de Santiago,Lugo, Spain
James Lenihan,Oregon State University
Ariel E.Lugo,US Department of Agriculture, Forest Service
Bruce McCarl, Texas A&M University
Ron Neilson,US Department of Agriculture, Forest Service
Chris J. Peterson,University of Georgia
Sarah Shafer, University of Oregon
Daniel Simberloff, University of Tennessee
Ken Skog,US Department of Agriculture, Forest Service
Brent L.Sohngen,Ohio State University
Brian J. Stocks,Canadian Forest Service
Frederick J. Swanson,US Department of Agriculture, Forest Service
Jake F. Weltzin,University of Tennessee
B.Michael Wotton,Canadian Forest Service

* signifies Assessment team chairs/co-chairs