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Report RM-187

Climate Change and America's Forests

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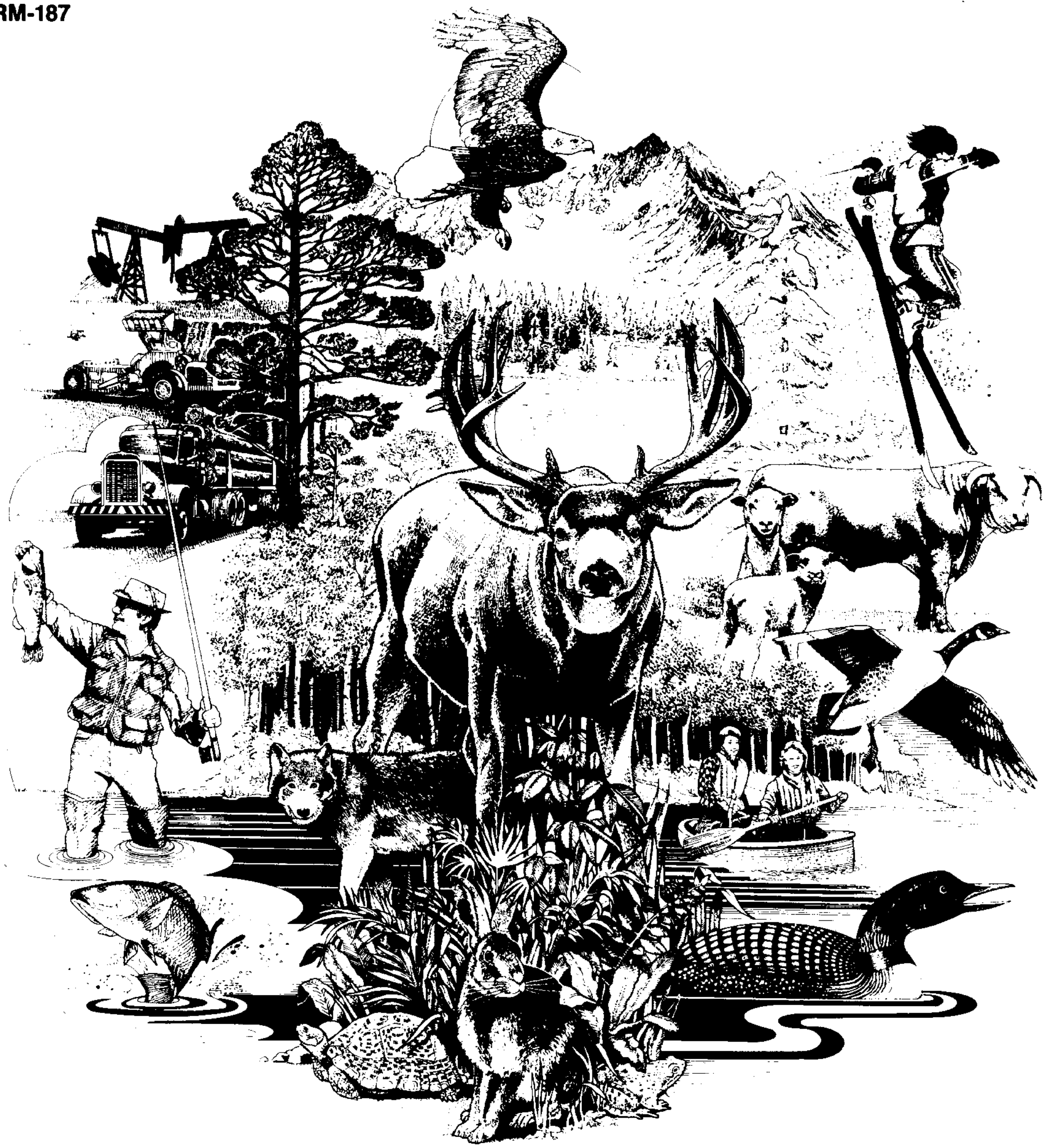

Preface

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA), P.L. 93–378, 88 Stat. 476, as amended, directed the Secretary of Agriculture to prepare a Renewable Resources Assessment by December 31, 1975, with an update in 1979 and each tenth year thereafter. This Assessment is to include "an analysis of present and anticipated uses, demand for, and supply of the renewable resources of forest, range, and other associated lands with consideration of the international resource situation, and an emphasis of pertinent supply, demand and price relationship trends" (Sec. 3.(a)).

The 1989 RPA Assessment is the third prepared in response to the RPA legislation. It is composed of 13 documents, including this one. The summary Assessment document presents an overview of analyses of the present situation and the outlook for the land base, outdoor recreation and wilderness, wildlife and fish, forest-range grazing, minerals, timber, and water. Complete analyses for each of these resources are contained in seven supporting technical documents. There are also technical documents presenting information on interactions among the various resources, the basic assumptions for the Assessment, a description of Forest Service programs, and the evolving use and management of the nation's forests, grasslands, croplands, and related resources.

The Forest Service has been carrying out resource analyses in the United States for over a century. Congressional interest was first expressed in the Appropriations Act of August 15, 1976, which provided $2,000 for the employment of an expert to study and report on forest conditions. Between that time and 1974, Forest Service analysts prepared a number of assessments of the timber resource situation intermittently in response to emerging issues and perceived needs for better resource information. The 1974 RPA legislation established a periodic reporting requirement and broadened the resource coverage from timber to all renewable resources from forest and rangelands.

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Introduction

The timber projections in the Forest Service Assessment assume a future in which the climate follows historical trends and in which changes in timber production and land use are an outgrowth of these trends, not abrupt discontinuities from the past (Darr in press, Haynes in press). These assumptions may not be met if the earth's climate changes rapidly.

Since the beginning of the industrial revolution, the chemistry of the atmosphere has been altered by increases in the concentrations of trace gases such as carbon dioxide and methane. These greenhouse gases trap a portion of the earth's infrared radiation and warm the planet. Further increases in the concentration of these greenhouse gases are predicted to raise the atmospheric temperature by 3 to 5°C within the next 100 years—a time span comparable to the planting-to-harvest interval of many commercial tree species. Major changes in the location and abundance of North American tree species were associated with a similar 5°C warming that occurred over a period of 8,000 years between 15,000 and 7,000 years ago (Bernabo and Webb 1977). This interglacial temperature change is of the same magnitude as the predicted temperature rise, 5°C, but this currently predicted temperature rise is projected to occur in less than 100 years, one one-hundredth of the interglacial time span.

Our perception of change is often associated with seasonal to decadal regional weather changes, such as the summer drought of 1988 or the hot, dry years in the 1980's; and local to regional environmental changes, such as the impacts of acid-rain or urban smog on vegetation. As we begin to understand the earth system, we need to consider long-term changes, such as those changes associated with global climate. There is great uncertainty in the projections of climate change on local ecosystem responses. However, we can say that these factors will play a major role in abrupt changes in the landscape: changes in precipitation and, to a lesser extent, temperature will restrict the persistence of ecological systems; and changes in disturbances, such as fire, insects, and disease, will impose new and different stresses on ecosystems. There is great need to determine the impact of this potential climate change on North American ecosystems and, in particular, our forest resources. Reliable estimates of the magnitude and rate of climate change are needed at many decision levels within society: individuals (e.g., ranchers and farmers), industry (e.g., forestry), and governments (e.g., resource managers and regulators). This document summarizes the current research on the impacts of climate change on America's forests.

The Greenhouse Effect

Scientific Bases for the Greenhouse Effect

The balance between the incoming solar energy and the outgoing energy determines the earth's temperature. A small change in either direction would result in a cooling or warming of the earth. Approximately 43% of the incoming energy is absorbed at the earth surface and this energy warms the land and oceans. A portion of the received energy warms the atmosphere directly through heat transfer. A portion is also reradiated toward space as long-wave infrared radiation. A small percentage of this outgoing long-wave radiation is absorbed by certain trace gases such as carbon dioxide, methane, and water vapor, and this absorption further warms the atmosphere. If the total incoming solar energy is balanced by the total energy returned to space, the temperature of the earth would remain constant. The equilibrium temperature for the earth is currently 15°C.

Recent interest in the greenhouse effect is focused on whether the equilibrium temperature has been disturbed through increases of the greenhouse gases such as carbon dioxide, methane, nitrous oxides, and others (Hansen et al. 1987). Precise monitoring of the amount of carbon dioxide in the atmosphere (Keeling 1984) has shown a steady increase since 1958, the beginning of the record at Mauna Loa Observatory (fig. 1). Comparing these recent data from direct methods with measurements of atmospheric carbon dioxide from indirect methods, such as carbon dioxide in air trapped in permanent ice fields and the analysis of isotopic carbon ratios in tree rings, indicates that before 1850, atmospheric concentration of carbon dioxide was approximately 270 ± 10 parts per million (ppm), as compared to the current level of 350 ppm (Hoffman and Wells 1987). This 25% increase in atmospheric carbon dioxide since 1850 is important because atmospheric concentrations of carbon dioxide are strongly correlated with global temperature. Ice core data extending back 160,000 years (fig. 2) clearly demonstrate this correlation (Fifield 1988, Friedli et al. 1986). Increases in other greenhouse gases such as methane have also been observed (Hoffman and Wells 1987). The increases in atmospheric carbon dioxide are attributable to human activities such as the burning of fossil fuels, deforestation, the burning of forests, byproducts from agriculture such as methane from cattle and rice production, and release of manufactured chemicals such as chlorofluorocarbons, and biotic sources such as the decomposition in forests and carbon cycling in oceans.

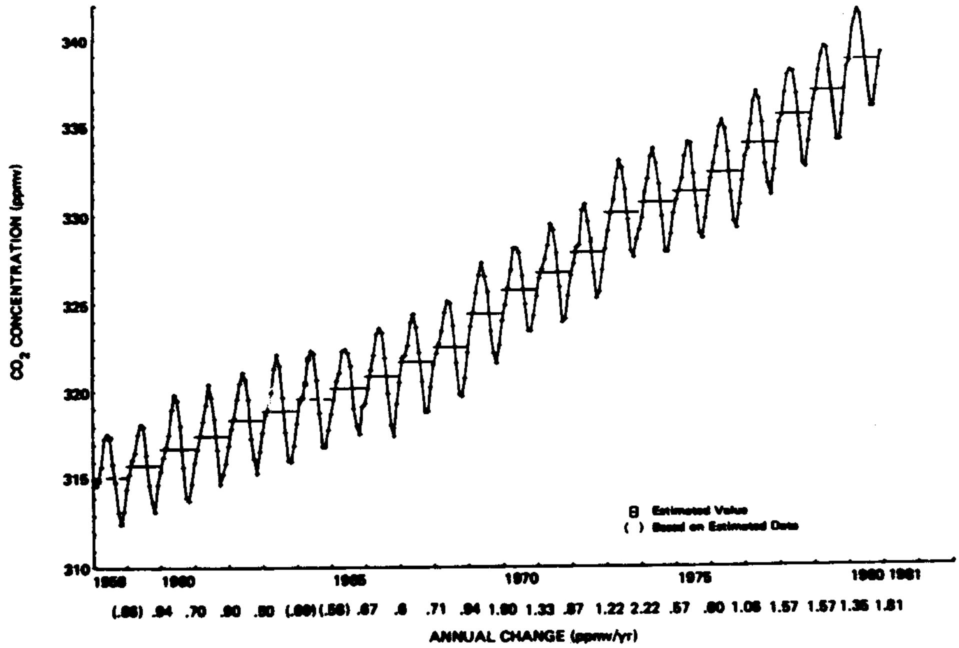

Figure 1.—Mean monthly concentrations of atmospheric CO_2 at Mauna Loa. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere (after National Research Council 1983).

Projections of future concentrations of these greenhouse gases are based on forecasts of energy consumption, energy efficiency, and population growth. Current projections indicate that with present technology and population growth, the concentrations of the greenhouse gases would double by the year 2030, and that even with high levels of energy conservation and efficiency, concentrations would double by 2075 (Mintzer 1987).

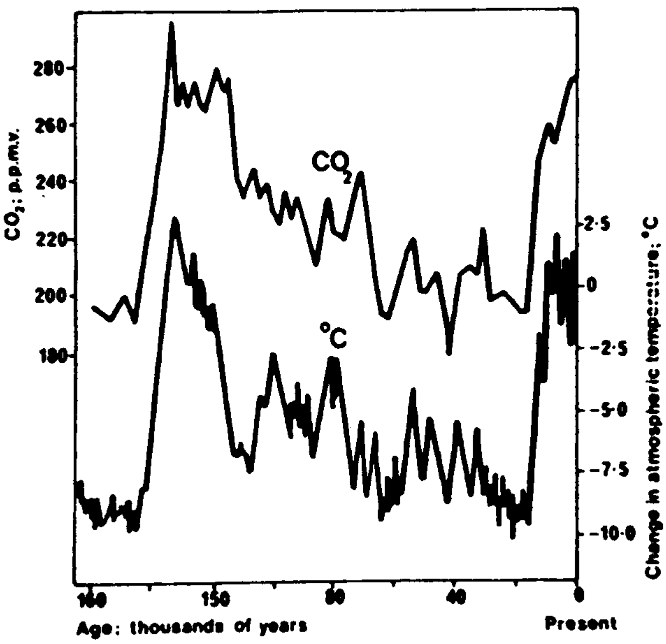

Figure 2.—The Vostock record of temperature from Antarctica, and concentrations of carbon dioxide in the atmosphere (from Fifield 1988).

Quantifying the Atmospheric and Ecological Responses

Modeling the Atmospheric Response

General circulation models (GCM's) are the equations representing the physical concepts of conservation of mass, energy, and momentum. Such models describe the atmosphere and oceans with a large number of discrete points for which forecasts of temperature, pressure, water (for the atmosphere), and salinity (for the oceans) are made. These forecasts permit calculation of clouds, wind, precipitation, and exchange of energy between the biosphere and the geosphere (Dickenson 1982, Schneider 1988).

Major weaknesses and sources of uncertainty in applying these models to predict future ecosystem responses are: (1) coarse spatial resolution, (2) inadequate representation of the role of clouds in the energy balance, and (3) inconsistent prediction of the hydrologic cycle. Spatial resolution of these models is very coarse, 5–7 degrees of latitude and longitude, when compared to ecosystem dimensions. Physical processes associated with small physical dimension phenomenon such as individual clouds cannot be described in these models. Instead, such processes are represented by an expected mean effect on the energy, mass, and momentum budgets. This shortcoming is particularly acute in mountainous regions where ecosystem dimensions are very small and are strongly related to elevation, and where local climate variations are large (Schlesinger 1988).

Representation of clouds in these GCM's is particularly important because of their influence on both incoming solar radiation and outgoing infrared radiation. Intercomparison of the different GCM predictions have attempt-ed to reduce the uncertainty resulting from how clouds influence the model results (Schlesinger 1988), but there is still need for improvement before this problem can be considered resolved (Cess et al. 1989). Effects of clouds on the local energy exchange is three times that predicted from the greenhouse gases (Ramanathan et al. 1989).

How the oceans are depicted affects the prediction of hydrological cycles. In some GCM models, oceans are represented by a shallow ocean in which predetermined sea surface temperatures are used to regulate the atmospheric circulation. In other models, a deep ocean with ocean current to redistribute the heat is used, but these models do not show consistent results (Bryan 1988, Schlesinger 1988).

The four models, Oregon State University (OSU), National Center for Atmospheric Research (NCAR), NASA Goddard Institute for Space Studies (GISS), and the Geophysical Fluid Dynamics Laboratory (GFDL), show a degree of consistency in predicting the future temperature rise and the regional distribution of these temperatures. Also, all four models predict that the global precipitation will increase, primarily because a warmer atmosphere has a higher saturation vapor pressure (Mitchell 1988). Intercomparison of model results for regional precipitation distribution shows far less consistency (Kellogg and Zhao 1988). This lack of consistency is particularly troublesome because the hydrological budget is more important than temperature in determining leaf area, vegetation structure, and the mass of vegetation (Woodward 1987).

The rate at which climate will change is important. If the climate evolves slowly, the biosphere may be able to adapt. Three of these models attempt only to predict the equilibrium climate of the future. Only the GISS model allows the greenhouse gases to increase with time and gives an estimate of the rate of climate change.

Coupling the Biosphere to the Geosphere

Direct, interactive coupling of the biosphere to the atmosphere in global models so that there is a direct exchange of mass and energy (Abramopoulos et al. 1988) will need to be improved dramatically before results useful to resource managers will be available. Current approaches only attempt to describe the heat and water vapor exchange and make little reference to the structure and composition of the ecosystem, to the abundance of individual species, or to any mediating effects of the biosphere on the atmosphere. Heterogeneity of land and water distribution on the surface of the earth contribute to the difficulty of interpreting mean values for climate over a varied region.

Modeling the Ecological Response

Without models that directly link atmospheric processes to ecological processes, climate projections from GCM's are used to construct scenarios as a context in which to examine the behavior of extant ecological models. Attempts to quantify the role of terrestrial biota in the global carbon cycle have their origins in global models of carbon flux (Houghton et al. 1983). Such models have been used to estimate where carbon is stored globally: 617 10^9 tons in vegetation and 1,652 10^9 tons in soils of terrestrial ecosystems (Woodwell 1983), 39,660 10^9 tons in oceans, and 740 10^9 tons in the atmosphere. In addition, these models have been used to estimate the net biotic flux of carbon (carbon release to the atmosphere from deforestation and other changes in land use) which, in 1980, was estimated to be 1.9 $\pm$ 0.99 10^9 tons carbon with only 0.11 10^9 tons carbon released from outside the tropics (Houghton et al. 1987). Models of this type quantify the biotic contribution to atmospheric carbon dioxide and must be compared to models computing the nonbiotic contribution of human activities to atmospheric carbon dioxide (Nordhaus and Yohe 1983). World consumption of fossil fuels contributes nearly 5 10^9 tons ($\pm$10%) per year to the atmosphere with the United States contributing about one-fourth of this emission (Carbon Dioxide Assessment Committee 1983).

Current approaches to modeling the ecological response to climatic change differ by the questions they attempt to answer: physiologically-based plant models, population models, ecosystem models, and regional or global models (Agren et al. in prep.). The response of individual plant processes to climate change is the focus of physiologically-based models. While such models contribute to our understanding of biochemical reactions within plants, these models lack mechanisms to examine interactions of nutrient cycling or species competition at a scale larger than a single plant.

Plant establishment, growth, seed production, and death are simulated in population-community models. Gap-phase models, one example of population-community models, offer a way of predicting future forest species composition under disturbance at a scale that is meaningful to resource managers. These models predict the establishment, growth, and death of individual trees and implicitly account for competition for light, water, and nutrients among trees (Botkin et al. 1972). Such models allow individual species to die and to be replaced by new species that are better adapted to the environment, or that are more competitive for light, water, and nutrients. A major uncertainty in these models is the rate of species dispersal into a region and the lack of explicit dispersal mechanisms (U.S. EPA 1988). In the current models, a species is present or absent, and when present, migrates at the same rate as climate change—an unlikely assumption.

Ecosystem models focus on the biogeochemical processes of fixation, allocation, and decomposition of carbon, and the cycles of nitrogen, phosphorus, sulfur, and other elements. Rates of nutrient cycling may change more rapidly than species composition (days to years versus years to centuries) and, thus, change the environment for species interactions. It is unclear how much climate-induced process-level change (e.g., decomposition) occurs within ecosystems before plant community turnover occurs and, conversely, to what extent species changes drive process-level changes in these systems (Davis 1988). Incorporation of nutrient cycling in gap-phase models in forests (Pastor and Post 1988) suggests that a synthesis of these two approaches will be needed to unravel the likely changes in species abundance and ecosystem processes (Davis 1988).

Recent regional and global models use the coincidence of climate and vegetation zones (correlation) to describe the future distribution of plant communities. The Holdridge Life Zone Classification system (Holdridge 1964) is based on correlating vegetation type (e.g., spruce-fir) to gradients of temperature, precipitation, and the ratio of potential evapotranspiration to precipitation. Historical pollen records can also be correlated with records of past climate, and these correlations can be used to predict future vegetation distributions under a projected climate. All of these approaches are based on the equilibrium relationship between climate and vegetation distribution and can be helpful in determining the global distributions of vegetation under steady state. The assumption of steady state implies that under climate change, the vegetation at a site shifts to the plant community for which the new environmental condition is the optimal climate. If climate zones were displaced geographically, the forest, as it looks now, would migrate with its preferred climate. Such migration may be possible if climate were to change slowly, but under rapid climate change, maintaining an intact forest would be difficult or even impossible because each species in the forest will migrate at a different rate (Davis 1981). This disassociation of species in migrating forests was clearly observed during the early Holocene (Bernabo and Webb 1977).

The major shortcoming of all current approaches is the omission of disturbances such as fire, insects, disease, and pollutants. These analyses do not address potential changes in the frequency and severity of traumatic events and how such changes, in turn, will impact primary productivity, seed production, seedling establishment, and species competition. Insects and animals, particularly herbivores, represent a disturbance that could significantly change species composition as well as nutrient cycling processes of ecosystems under climate change. For example, if hardwoods replace conifers, gypsy moth defoliation will certainly influence primary productivity unless mitigating action is taken (Wingert 1988). Also, if cottonwood (*Populus deltoides*) becomes a more important species for pulp and paper, impact of climate change on melampsora leaf rust (McCracken et al. 1984) must be taken into account (Fosberg 1988).

Increased insect- and disease-caused losses in our nation's forests will become one of the first observed effects of climate change. Evidence can be found in the pest-caused epidemics which now occur as a result of periodic droughts or rainy periods. Changes in climate either through effects on the pest or on the host may increase or decrease pest-caused losses. High temperatures and reduced precipitation cause insect epidemics when these climatic factors stress the tree (host) to the point that the hosts lose their inherent resistance to native pests. Increased moisture can increase losses where disease was limited in distribution and infection was limited by low moisture conditions. Under climate change, currently important pest problems may all but disappear and new epidemics will arise. These pest attacks will often determine the new geographic distribution of tree species under the new climatic conditions.

Fire frequency and severity is also missing in assessing the impact of climate change on forests. Charcoal analyses of sea sediments (Herring 1985) have shown a weak but definite trend of charcoal deposition over the last 50 million years. Charcoal analyses of lake sediments have shown fire cycles and climatically induced changes in fire regimes (Clark 1988). Combining these data with temperature relations (Fifield 1988), we see a weak but positive correlation between temperature and charcoal, suggesting increased fire frequency under warmer climates.

There are few definitive studies of the direct effects of climate change on fire frequency and severity. Direct effects would be the changes in drought frequency, humidity, precipitation, and other weather elements that determine day-to-day variation and interannual variability in fire behavior. Fried and Torn (in prep.) compared the changes in area burned under the current and a double carbon dioxide climate. They found that there would be a two-fold increase in modest-sized fires (a few hundred hectares) and a three-fold increase in fires greater than 1,000 hectares. Fried and Torn (1988) based their studies on an area of the California Sierra Nevada in which the ecosystems are expected to remain unchanged in a future climate.

For many regions, species composition of forests is projected to change. Much of the structure and composition of a forest will remain long after climate change-induced stress has prevented regeneration of those species. New species will take hold during the transition from one vegetation community to another, and a transitional forest will contain elements of both vegetation types. As the structure, composition, and total biomass of the forest change, so will the behavior of fire. A shift on the uplands to hardwood savannahs will likely cause an increase in fire severity in the Lake States (Fosberg 1989).

The size, shape, and distribution of forest land, forest types, and successional stages create a mosaic across the landscape that contributes to the production of wildlife and the use of land for other resources such as grazing. There is concern that the current increasing forest fragmentation will eliminate some species as functioning members of certain regional faunal communities (Flather and Hoekstra 1989). The spatial pattern of land use and vegetation cover influences the migration and dispersal of insects, birds, and animals, and these influences under a changing climate remain to be considered in ecological models. The impacts of changing forest type and the associated changing interspersion on wildlife and other resources have not been addressed.

Forest Changes Under Climate Change

Assessment of the forest resources 50 to 100 years from now as a result of the greenhouse effect has not been done in any systematic fashion. Coverage of the country is not uniform, several estimates were made for some regions and only one estimate for others, and, finally, different methods have been used for different regions. While research is in process on modeling the ecological response to climate change, several existing models have been used to examine GCM scenarios. Gap-phase models have been used to examine changing species distributions in eastern and western forests. Other approaches have included interpreting historical change as an indication of future change. Correlation of modern pollen distribution with climatic data gives a model that can be compared to fossil pollen records under different climates and used to project species distribution into future climates (Overpeck and Bartlein 1988, as described in U.S. EPA 1988).

These ecological models use climate scenarios from the GCM's as inputs in order to quantify the ecological response. Interpretation of these results must consider the uncertainties of GCM climate projections, the potential interactions for disturbances and interactions not currently in the ecological models, and, finally, the uncertainties in the ecological models themselves. In those regions where more than one model or method has been applied, coincidence of prediction may give more support to estimates.

Eastern Forests

Most projections indicate a movement of conifers north with an inward migration of hardwoods from the South, a movement of grassland and savanna types eastward on the western boundary; however, the degree and magnitude of these changes vary. In the New England states under a more severe GFDL-correlation projection, conifers (spruce, northern pines) would retreat into Maine; however, there would not be appreciable change under a milder GISS-correlation scenario (U.S. EPA 1988). Using these same two models, sugar maple shows a similar pattern (U.S. EPA 1988). Using gap models, the New England forests would be replaced by more hardwoods, particularly by oak species from the eastern mid-United States (Botkin et al. 1988; Overpeck and Bartlein 1988; Zabinski and Davis 1988, as described in U.S. EPA 1988).

For the Great Lakes area (U.S. EPA 1988), conifers (spruce) will likely remain in the northern portion of the Great Lakes region and potentially migrate as far north as James Bay with a GISS-correlation scenario. Under a GFDL-correlation scenario, conifers (balsam fir) would be totally lost from the Great Lakes region. Sugar maple would show similar migration patterns under these two scenarios. The gap-phase model simulations show less dramatic changes. Under a GISS-gap-phase model scenario, Botkin et al. (1988) predicted that the boreal forests would disappear by 2040 from the northern Lake States region and that sugar maple, oaks, and other hardwoods would dominate on the drier and better sites in this area, with the potential for increased biomass. On more southerly maple-oak sites, tree biomass would decline 37% to 99%. Solomon and West (1987), using the NCAR GCM, also show hardwoods preferred over conifers, but conifers remained in the region. This simulation predicted a decrease in biomass. Using correlation analysis, Zabinski and Davis (as cited in U.S. EPA 1988) predicted local extinction of tree species such as eastern hemlock and sugar maple in the Great Lakes region. Southern pine species could migrate into the present hardwood forest lands of eastern Pennsylvania and New Jersey (U.S. EPA 1988).

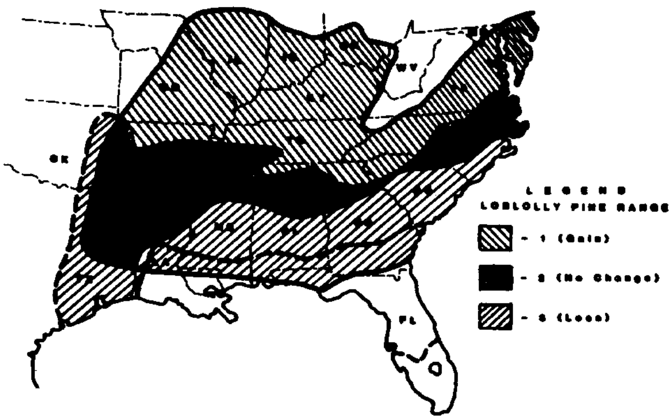

Figure 3.—Projected changes in loblolly range assuming doubled atmospheric CO_2 (after Solomon et al. 1984)

South and Southeast

Most projections indicated a decline of southern forests as we know them, a reduction in the biomass, conversion of some forests to grassland, species regeneration becoming difficult, and a movement of southern pine species north. Using a gap-phase model and GFDL, GISS, and OSU climate scenarios, southern pines would be greatly reduced or eliminated in Mississippi, South Carolina, and Georgia (Urban and Shugart 1988, as cited in U.S. EPA 1988). Biomass would be reduced 30% in Tennessee. An earlier analysis by Solomon et al. (1984) also predicted a marked reduction in Mississippi, Georgia, and South Carolina, and showed loblolly pine invading into Tennessee (fig. 3). Under GFDL-correlation and OSU-correlation scenarios, southern pines extended northward but did not move out of the South and Southeast (Winjum and Neilson 1988).

Miller et al. (1987) described the subtle implications of these projections. The current distribution of loblolly pine is overlain on relatively deep soils, whereas areas into which loblolly is projected to move have a relatively high proportion of shallow, steeply sloping, coarse-textured soils on rocky uplands. Thus, even though the area of the range has increased, productivity is likely to decline because of the marginal productivity of these sites. The seasonal distribution of precipitation and temperature under climate change could also affect the quality of wood for loblolly. An extended period of drought in the northern limits of its range would result in lower-specific-gravity wood and, thus, wood of poorer quality.

West

Projections for the West focused on correlation analysis and, consequently, focused on individual species responses rather than community-level projections. Species responses indicated either movement up an elevational gradient or northward migration. Leverenz and Lev (1987), using correlation and an unspecified GCM, predicted that Douglas-fir (fig. 4) would expand to higher elevations as the lower limit of the continuous winter snowpack climbs upslope. Increased summer drought and rising winter temperatures result in declining importance of Douglas-fir on the east slope of the Rocky Mountains and in the southern limit of its current range.

The range of ponderosa pine (fig. 5) in interior Washington and the eastern slope of the Rocky Mountains would decrease with deficit spring water balances (Leverenz and Lev 1987). While summer drought allows ponderosa pine to expand in California and Oregon, increased temperatures are projected to push ponderosa pine upslope in these states and in Washington, Montana, Idaho, and the middle and southern Rocky Mountains. The southern Rocky Mountains would have major losses in ponderosa pine (fig. 5).

Western hemlock would be restricted to the wetter sites west of the Cascade Mountains. In the northern Rocky Mountains, western hemlock and western larch would be lost in the Idaho panhandle and eastside of Oregon and Washington (Leverenz and Lev 1987). Lodgepole pine would not be effected greatly in its western extent. No estimates were made for redwood or other species. Western larch was projected to increase on better sites, and on sites where fire frequency is increased. On sites where summer drought increases, western larch will be restricted to upslope movement.

Sensitivity of Forest Species Predictions to Uncertainties in the General Circulation Models (GCM's)

The four GCM's predict that the global mean surface temperature rise will range from 2.8°C to 4.2°C (Schlesinger 1988). North American regional and seasonal distributions of these temperature increases differ by as much as 8°C for summer and by 4°C for winter (Schlesinger 1988). Not only does the projected global mean vary, but the implication to regional climate patterns varies by model. When the spatial and seasonal distribution of precipitation is expressed as soil moisture, the southwestern, southern, and southeastern states are expected to be drier during the winter (fig. 6). During the summer, the entire country is expected to be drier (Kellogg and Zhao 1988). However, there are marked differences between each of the model predictions in both winter (fig. 6) and in summer (fig. 7). Areas of greatest discrepancy and, therefore, uncertainty are in winter precipitation for the West Coast, the Great Basin,

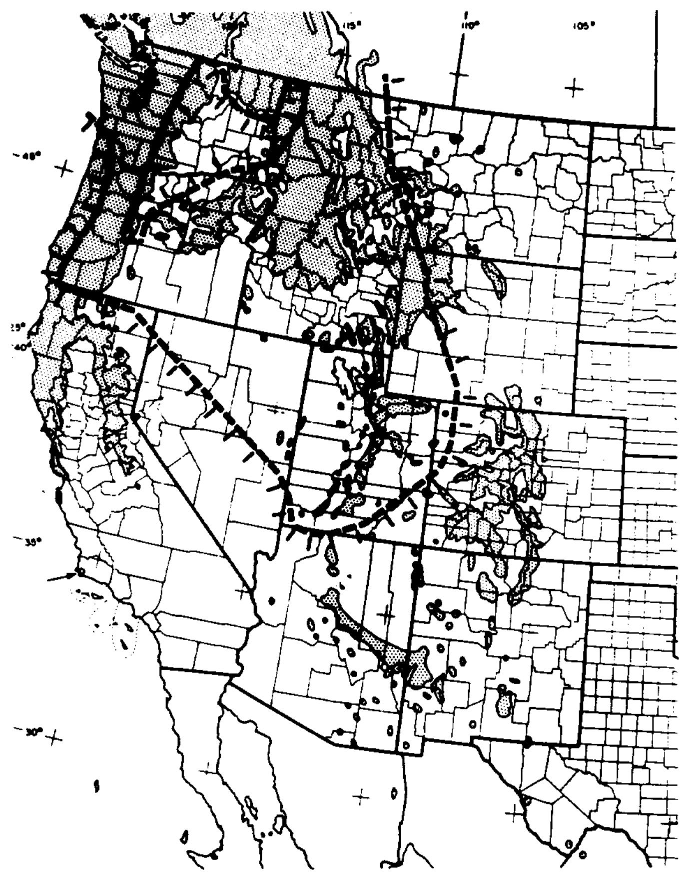

Figure 4.—The current distribution of Douglas-fir and projected distribution under a doubled CO_2 scenario. Hatching is directed toward the zones of decreasing acreages (after Leverenz and Lev 1987).

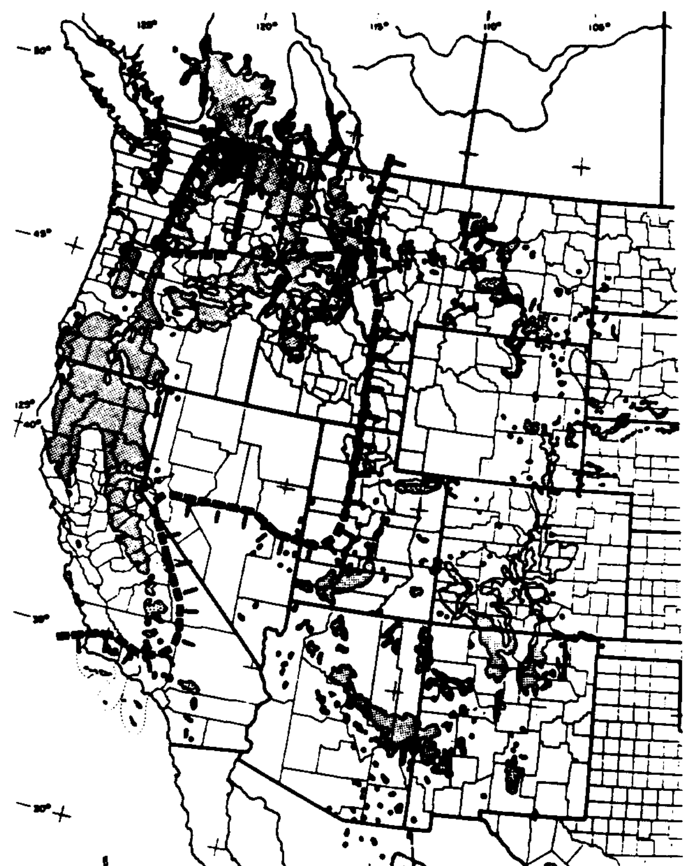

Figure 5.—Current distribution of ponderosa pine and projected distribution under a doubled CO_2 scenario. Hatching is directed toward the zones of decreasing acreages (after Leverenz and Lev 1987).

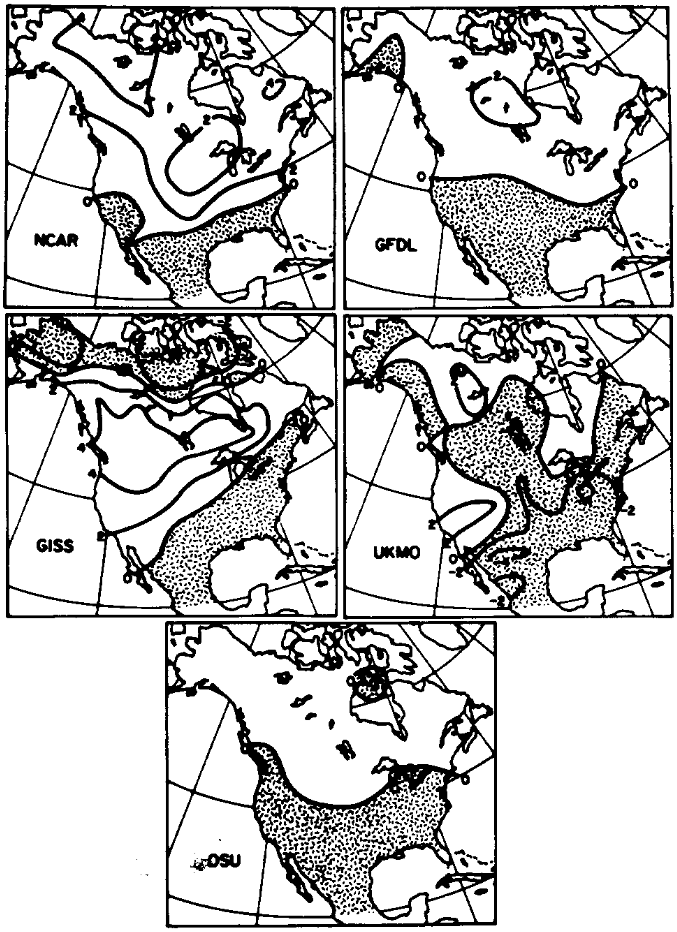

Figure 6.—Increases (clear areas) and decreases (scratches) of winter soil moisture relative to the control when carbon dioxide is doubled (after Kellogg and Zhao 1988).

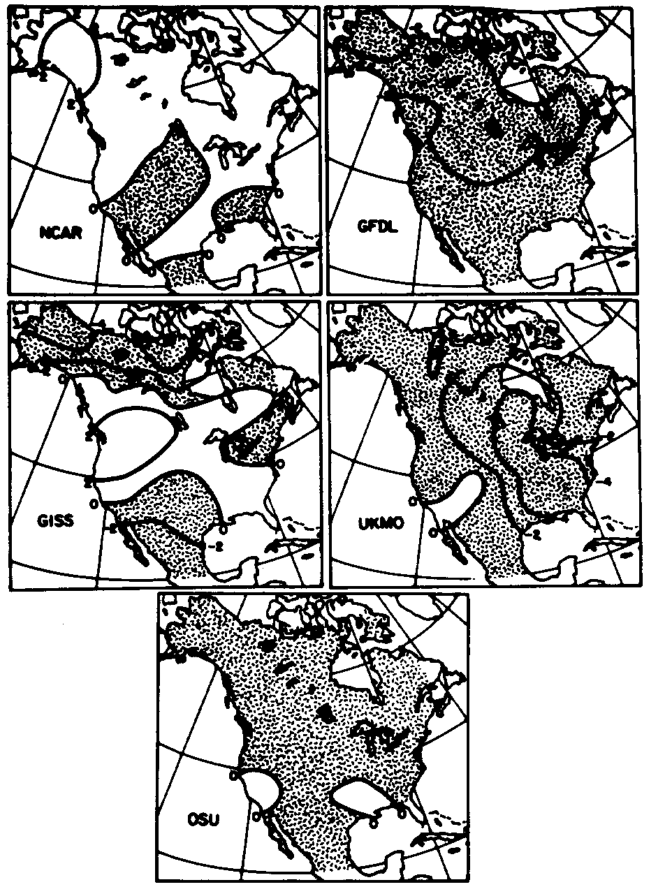

Figure 7.—Increases (clear areas) and decreases (scratches) of summer soil moisture relative to the control when carbon dioxide is doubled (after Kellogg and Zhao 1988).

Rocky Mountains, the Mid-West, and the Northeast. There is greater consistency between the predictions and confidence during the summer.

Natural variations in annual precipitation and mean temperatures have always existed. During the past 100 years, the long-term temperature record for the United States has not shown any systematic change, but has ranged from 10.6°C to 12.8°C (Karl and Jones 1989). Over the last 2,700 years, which includes the Little Ice Age of the 17th century, North America has experienced a natural variability of 1.5°C (Bernabo 1981). Similarly, precipitation has shown large year-to-year variability during the last 2,000 years (Stahle et al. 1988). The Palmer Drought Index shows abnormally dry or wet periods are more common than normal precipitation during periods of change (Stahle et al. 1988).

Given the uncertainty in the predictions, and the natural variability that climate change must exceed before we can detect effects, what can we say about impacts on the ecosystem? Two independent analyses of climate change impact have been completed for the Lake States. Both of these studies used gap-phase models, and both were based on GCM predictions of climate for a doubled carbon dioxide concentration in the atmosphere. The difference between these two predictions is that two different GCM's were used. Solomon and West (1987) used the NCAR model while Botkin et al. (1988) used the GISS model. These two analyses provide us with some measure of the simulated ecological sensitivities to climate change prediction. Differences between the two simulations are that, in one, conifers will be totally replaced by hardwoods and, in the other, conifers will be retained. Also, the two differ in the number of trees per hectare, one showing an increase and the other a decrease. Similarities are that both simulations show a decrease in total biomass. The comparison suggests that some confidence may be placed on prediction of total biomass, but less on the structure and abundance of individual species.

Ecological Uncertainties in the Projections of Climate Change

Current projections of the potential impacts of climate change have limitations because of the omission of some important processes controlling forest production, particularly in response to disturbance or stress. In addition, the physiological responses of individual plants to elevated carbon dioxide under moisture, temperature, or other nutrient limitations remain to be definitively described for natural settings. The fertilization response reported for some species to elevated carbon dioxide levels may be a short-term or transient response, reflecting an adjustment to new and different levels of nutrient availability. As current forest growth is limited by water and/or nitrogen, the impact of climate change will involve not only elevated levels of carbon dioxide, but also changes in the seasonal distribution of precipitation and temperature, both poorly described variables at the regional scale in the current GCM's.

Changes in atmospheric temperature and precipitation will affect soil moisture and soil temperature, two environmental factors controlling the cycling of nutrients in the soil. The rate of nitrogen mineralization has been shown to be positively related to net primary productivity of trees and wood production (Nadelhoffer et al. 1985) (fig. 8). Potential increases in the carbon to nitrogen ratios in aboveground plant parts, such as leaves, would shift the carbon content in litter, resulting in lower quality litter. Declines in litter quality (less relative nitrogen) could decrease mineralization rates and, in turn, productivity of the stand could decline. In other areas, elevated soil temperature and moisture could enhance soil mineralization rates and improve stand productivity. Thus, shifts in the mineralization rates of nutrients could impact forest productivity.

Individual species migrate at different rates; thus, forest vegetation will begin to uncouple as we currently know it and species interactions, which do not currently occur, will begin to play a role in the development of future plant communities. The migration of understory species, important in early-successional stages of forest development and for grazing and browsing animals, could affect the future availability of forage. Potential increased levels of drought will not only reduce vegetation but provide open niches for invading species from nearby geographic regions. Changes in climate are projected

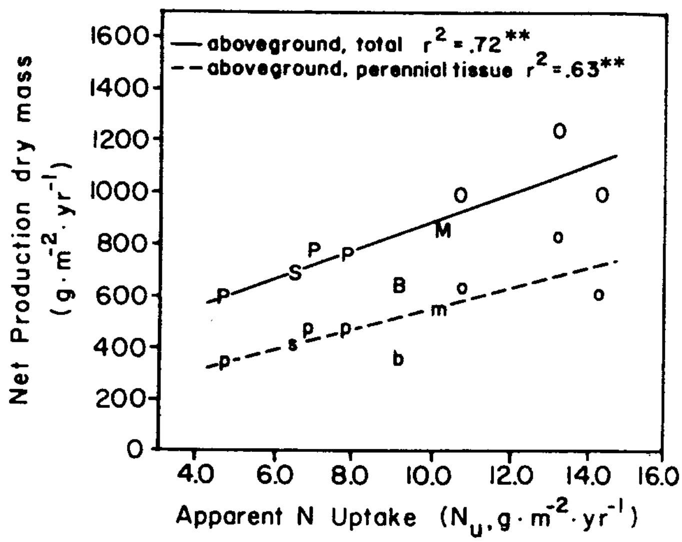

Figure 8.—Aboveground total net primary production (bole and branch plus leaf litter) and aboveground perennial tissue (bole and branch) in relation to annual nitrogen (N) uptake. Symbols designate dominant genera on sites: P = pine, S = spruce, B = birch, M = maple, O = oak. Upper and lower cases designate aboveground production and perennial tissue, respectively. Regression lines through data were significant at the P < 0.01 level (after Nadelhoffer et al. 1985).

to be greatest for the mid-latitudes with only a small increase (1°C) in temperature at the equator. Thus, species diversity in the most diverse plant communities, the tropics, will change less as a result of projected climate change than current land use. Species diversity in the polar and mid-latitudes will likely have the greatest changes. Potentially significant impacts could occur on rare species which are currently found only in refuges located on the basis of their current distribution.

Assessing the impact of resources dependent upon forest production is even more limited. Numerous species of plants and animals are confined to a coincidence of environmental parameters. If jack pine are replaced by hardwoods in northern Michigan (Botkin et al. 1988), the Kirtland's warbler could become extinct. Even though jack pine would fluorish north of the Great Lakes, there is a lack of sandy soil north of the Great Lakes and the Kirtland's warbler nests on sandy soil under jack pine. Similar situations could arise in mountainous areas for other species (Peters 1987). For many reptiles, sex of an individual is determined from temperatures during the egg incubation period. Thus, climate change will affect not only the habitat of the animals but also the energetics and reproduction of their populations. Examples exist where changes in the landscape facilitated an expansion of species previously occupying only a small part of the system. The greatest extent of the Kirtland's warbler occurred after the fire frequency changed dramatically in northern Michigan following settlement in the early 1900's (Whitney 1989). These examples reflect our current understanding of the complicated interactions between plants, animals, and environment in the present ecosystems and suggest subtle interactions not easily determined for the future climates.

The spatial distribution of vegetation across the landscape influences the abundance of wildlife and fish as well as the use of that land for agricultural and forestry purposes. It is difficult to determine changes at the landscape level resulting from climate change and what these changes will imply for land use. A very high percentage of domestic and agricultural water comes from public lands, particularly in the mountainous West. Increased temperatures could be expected to cause early and more rapid snow melt (King et al. 1988). Increased disturbances such as fire will impact the management of that forest and potentially impact water quality (U.S. EPA 1988). With changed seasonal precipitation, the ratios of springwood and late wood will vary from those of today, and frequency of insect and disease outbreaks and the severity of outbreaks will change. Insect- and disease-damaged wood is of lower quality (Becker 1987). The visual impact of forest declines, as well as changing forest species, will impact the recreational use of forest land. And finally, the socioeconomic impacts of changing forest species could include unemployment, community instability, industrial dislocation, and increased net imports of wood products. Changes in what people will expect from the forest will need to be addressed for future climates.

Research to address these questions is ongoing or has been proposed (Bartuska 1989; Committee on Earth

Sciences 1989; Fox and Krebill 1989; Sandberg and Bell 1989; Special Committee for the IGBP 1988; USDA Forest Service 1988a, 1988b). Generally, the main elements of these research programs are: biogeochemical dynamics, ecological systems and dynamics, climate and hydrological systems, the interactions between natural processes and human activities, the study of past natural changes in earth system history, interactions between the earth's surface and the atmosphere, hydrosphere, cryosphere, and biosphere, and solar influences. Forest Service research is aimed specifically at forest and range systems and includes the effect of the atmosphere on ecosystems (changing physical and chemical environments), the effects of ecosystem change on the atmosphere (biogenic emission of gasses, land management influences), long-term changes in ecosystems, and the prediction of ecosystem responses (USDA Forest Service 1988).

The Future

While we have yet to detect the first signals of greenhouse warming, either through direct measurements of temperature or through impacts on forest ecosystems, we need to begin preparing for the inevitable changes. Our policy options are to conserve what we currently have in forest resources, to develop strategies to mitigate the effects of climate change, to adapt to change, or some combination of these three options. Each of these options raises many questions concerning management actions and our understanding of forest ecosystems.

The conservation option is undoubtedly the most difficult to achieve. In those areas where forest productivity will be significantly reduced, many resources will be diminished. While we could conserve some elements, albeit at a high cost, the external force, climate, will ultimately prevail. Different ecosystems will evolve in those areas where the future climate significantly differs from the current situation. Conservation actions might include installation of irrigation systems in plantations, or use of fertilizers to compensate for reductions in growth rates. Solomon and West (1987) suggest that it is uncertain whether it would be possible to maintain the net productivity of commercial forest lands in the United States under climate change. The implementation of such conservation actions raises a policy question of future land use. Which forest types should be conserved, if any, and where should they be conserved? Competition for land use will be strong because other uses, such as agriculture or urban area, will also be adjusting to climatic change.

The second option, that of mitigating the effects of climate change, involves the global community. Energy conservation or use of nonfossil fuel energy will slow global warming. Such actions require a global policy rather than a local land management policy. Energy conservation or use of alternate energy sources can control the rate of greenhouse gases build-up, but cannot reverse the build-up of greenhouse gases that has already occurred in the atmosphere. Vegetation production removes carbon dioxide from the atmosphere and stores some of it as carbon either in wood aboveground or as roots below ground. Through aggressive reforestation and afforestation, we can offset some of the anthropogenic trace gases. To effectively accomplish accelerated tree planting on nonfederal lands would require close coordination and cooperation among federal and state forestry professionals, consulting foresters, and the tree nursery industry to ensure adequate supplies of quality trees of appropriate species were available to private landowners and local communities. Management questions that need to be answered include what tree species and where. Sustained technical assistance would be required to ensure that proper planting, silvicultural treatments, and tree maintenance take place.

The third option, that of adaptation, offers the greatest flexibility in managing forests in a changing climate. Adaptive strategies involve developing new technologies to utilize the resources of the future forest, importing new industries or businesses which are compatible with the resources of the future forests, or relocating existing activities in anticipation of a changing climate. Adaptive strategies also include developing or introducing species which are compatible with the changing climate. Determining these strategies will involve an examination of questions such as how much and which forest land should be managed for timber production, and what kind of forests. What is the role of federal lands—the location of which was based on a previous climate—in the production of resources, such as timber, forage, water quality and quantity, wildlife, fisheries, and recreation? What is the role of private lands in timber and forage production, water quality and quantity, wildlife, fisheries, and recreation? Land management agencies, such as the Forest Service, are faced with great complexity and the challenge of developing appropriate data bases and models that will provide a reliable basis for decisions about what to do in many different ecosystems and locations and under various conditions which involve a wide range of external variables, in addition to the greenhouse gases.

Because forests are complex ecosystems, and because uses of the forests are so varied, there is no set formula which can be prescribed for all forests. Future forest management will undoubtedly contain elements of all three options to address the problems arising from global change. Because of the uncertainties in the current prediction of impact of climate change on America's forests, we will need to continue careful monitoring and surveillance of our forest ecosystems, particularly those components which are highly sensitive to the greenhouse effect in order to refine management strategies. Also, because our current capability to predict impacts is imprecise, we must continue to carry out research on the effects of multiple stresses on our forests in order to assure their health and productivity in a changing atmospheric environment.

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Projections in the Forest Service Assessment assume a future in which changes in timber production and land use are not abrupt discontinuities from the past. These assumptions may not be met if the earth's climate changes rapidly. This document summarizes the current research on the impacts of climate change on America's forests.

Keywords: Greenhouse effect, timber assessment, ecological response

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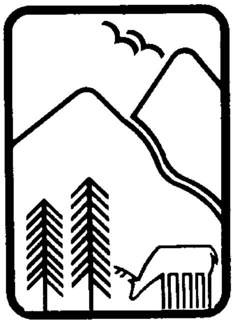
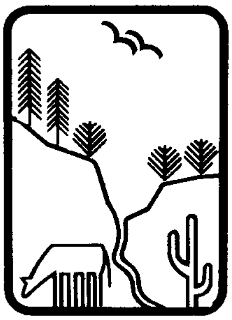
Forest Service

Rocky Mountain Forest and Range Experiment Station



Rocky Mountains



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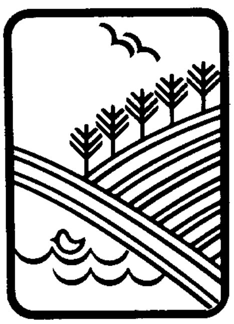

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect Rd., Fort Collins, CO 80526