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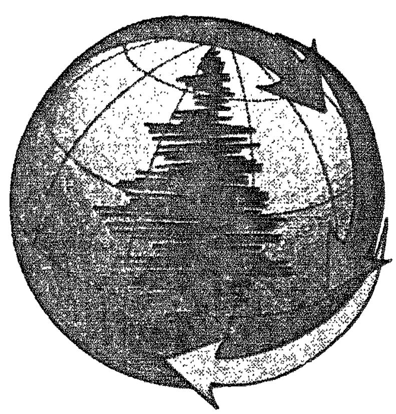
USDA Forest Service Global Change Research Program Highlights: 1991-95



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USDA Forest Service Global Change Research Program Highlights: 1991-95

Edited by

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The authors who submitted manuscripts for publication in this document were responsible for technical review and editing of the content. We appreciate the efforts of all who participated in this process. In addition, various individuals reviewed drafts of the entire document. We are grateful to those who provided substantive comments: Carolyn Sieg, Alan Lucier, Gerard Hertel, David Peterson, and Marla Emery.

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Program Objectives

By the end of the next century, the global average temperature is expected to have increased by 1.0 to 3.5° C (1.8 to 6.3° F), according to the Intergovernmental Panel on Climate Change. As carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases increase, so too will the impacts of air pollution, increased ultraviolet (UV-B) radiation, and intensified land use. One inevitable result will be rapid ecosystem changes. These changes will compel society to make important and far-reaching decisions regarding the management and allocation of natural resources to adapt to and mitigate global change. As the steward of more than 191 million acres of national forests and grassland, the USDA Forest Service is committed to making informed decisions and responsibly implementing them.

The Forest Service Global Change Research Program (FSGCRP), as described in the most recent program plan, provides the scientific basis to address three broad questions concerning global change and forest ecosystems (USDA For. Serv. 1992):

1. What processes in forest ecosystems are sensitive to physical and chemical changes in the atmosphere?
   Or in policy terms: Is there a problem?

2. How will future physical and chemical climate changes influence the structure, function, and productivity of forest and related ecosystems, and to what extent will forest ecosystems change in response to atmospheric changes?
   Or in policy terms: How serious is the problem?

3. What are the implications for forest management and how must forest management activities be altered to sustain forest productivity, health, and diversity?
   Or in policy terms: What can be done about the problem?

Through participation in the U.S. Department of Agriculture's Global Change Research Program, the FSGCRP is a part of the U.S. Government's Global Change Research Program (USGCRP). The USGCRP has been developed under the direction of the Executive Office of the President, through the National Science and Technology Council (NSTC) and its Committee on Environment and Natural Resources (CENR). The FSGCRP also maintains extensive contacts with international and private programs and, thus, contributes to global change science worldwide.

Program Elements

In order to meet its objectives of providing a sound scientific basis for policy and management decisions, FSGCRP research focuses on four scientific program elements and two crosscutting activities. Scientific program elements include: (1) atmosphere/biosphere gas and energy exchange, (2) ecosystem dynamics, (3) disturbance ecology, and (4) human activities and natural resource interactions. Crosscutting activities include assessment and modeling, and data quality assessment. The national program is implemented through regional programs.

Atmosphere/biosphere Gas and Energy Exchange Research

Atmosphere/Biosphere Gas and Energy Exchange research examines the way in which climate and atmospheric chemistry shape and are shaped by the biological world. This research is conducted at scales from the regional to the extremely local, and is focused on: (1) the carbon cycle and carbon budget with particular attention to the transfers of carbon between soils, water, the atmosphere, and the biosphere; (2) greenhouse gas (CO_2, CH_4, N_2O, H_2O) exchanges with terrestrial ecosystems; and (3) regional and local climate change scenarios. The objective of this research is to understand the flow of gases and energy between the atmosphere and the biosphere, anticipate ways this flow might change, and identify means by which land use and forest management strategies might contribute to mitigating and adapting to global change.

A number of methodologies are applied to this program element. Measurements of the atmosphere adjacent to plants and plant communities are currently being made to determine biogenic gas fluxes—especially CO_2 and CH_4. Soils are monitored to determine trends in carbon storage and to develop an understanding of the processes that control the flux of carbon between soils, aquatic systems, the atmosphere, and the biosphere. Mechanistic models for individual species, functional groupings, and specific ecosystems are under development to describe processes of carbon sequestration and allocation, water balance, and gas exchange. The models also predict changes in responses resulting from natural and human induced stresses. Biogeochemical soil models that couple climate to nutrient budgets, soil organisms, soil structure, function, and productivity are being developed. A modeling framework will connect existing and new models at the variety of scales necessary to predict ecosystem responses to climate changes and climate responses to ecosystem changes.

Ecosystem Dynamics Research

The Ecosystem Dynamics research component focuses on the response of terrestrial and aquatic ecosystems—forest, range, and wildland; wetlands, lakes, and rivers—to global change. The objective of this research is to understand and anticipate the ecosystem changes that will result from altered environmental conditions and to understand the sensitivity of key ecosystem processes and components to different levels of stress. Ecosystems Dynamics research employs a variety of techniques and methodologies that are dependent on the scale of inquiry. So, it has been divided into three sub-elements according to scale:

Basic Plant Processes—To understand basic plant processes, chamber experiments are conducted to determine plant responses to altered physical environments—enhanced CO_2, O_3, and acidic deposition; changes in temperature and moisture availability; and increased insect stress. Controlled experiments provide data on genetic resilience to stress and adaptability of individual plants to changing environments.

Ecosystem Processes—To understand ecosystem processes, long-term investigations of hydrology, soils, and forest communities are conducted in experimental forests and watersheds maintained by the Forest Service and cooperators. Additional extensive observations are made along environmental gradients and across ecotones. Paleoecology is used as an historical base for forest health and productivity. Sensitivity of the mechanisms of nutrient cycling by microbes and small soil animals to global change is also studied.

Regional Impacts—At the regional scale, ecosystem models and resource production models are used to synthesize and extrapolate the results of experimental and observational research. Such models help us understand and predict how ecosystem productivity and vegetation distribution may respond to global change.

Disturbance Ecology Research

Fire, insect, and disease disturbances can profoundly affect the health and productivity of ecosystems. In some regions, O_3 and acidic deposition interact with other factors to change how ecosystems behave. Large-scale disturbances may even become natural disasters, as did the Yellowstone fires of 1988 and the northeastern gypsy moth epidemic. Global climate projections suggest that drought cycles, precipitation patterns, temperature extremes, strong winds, and intense storms may change in the future. These climatic factors drive both the occurrence and severity of fire, insects, and disease episodes. To assess the potential impact of disturbance changes on forest ecosystems, the FSGCRP addresses three categories of disturbance: fire, insects and diseases, and air pollution.

Fire research focuses on changes in frequency and severity of fire weather resulting from global atmospheric changes, the processes by which fire affects the current equilibrium between climate and ecosystems, and the net result of new fire regimes on production of trace gases and particulate matter in the atmosphere. Research has been initiated to analyze changes in fuel buildup and fire hazard as well as to predict wildland fire activity and emissions with global change. Historical fire occurrence, determined from fire scars on both live and dead trees, provides a record of fire frequency and severity over a long period of time. Coupling these data with dendroclimatological and other paleoecological pollen data gives a history of fire in transitional ecosystems and its associated climate relations, which are used to project future conditions. Understanding the role of both human-caused and natural fire in ecosystems provides information on how ecosystems recover from major disturbances. Interactions between humans and fire—such as suppression activities, planned use of fire and the urban/wildland interface—are sensitive to climate and are also assessed.

Insect and disease research focuses on how climate change influences the frequency and severity of insect and disease outbreaks. Their importance as a disturbance influence on ecosystems and how those disturbances accelerate ecosystem change are emphasized. In addition, insect and disease epidemics are studied because they may serve as early warnings of changes in ecosystems. Research also addresses the direct effects of climate change on pest organisms as well as how insect and disease organisms function to influence host species stressed by climate and air pollution.

Air pollution, particularly O_3 and acid deposition, affects ecosystems across the Eastern United States and parts of the West. The FSGCRP participates in monitoring networks and modeling activities to estimate and predict O_3 and acidic deposition at many locations. In addition, there is a need to understand how these disturbances interact with other atmospheric changes such as increased CO_2, and with insects and diseases, to influence ecosystem dynamics.

Human Activities and Natural Resource Interactions Research

This element addresses the ways in which global change will affect human activities and how human activities—through agriculture and resource management—will affect global change. The Human Activities and Natural Resources Interactions research program conducts research in three problem areas:

(1) Assessment of ecosystem change impacts. Research to identify and assess the effects of forest ecosystem responses to climate change on communities and society.

(2) Evaluation of forest policy options. Identification and evaluation of policy options in rural and urban forestry for mitigating and adapting to the effects of global change.

(3) Implications for forest management. How to integrate risks associated with potential climate changes into rural and urban forest management decision processes.

Implementation of these activities requires that models currently used to assess the forestry sector be enhanced to include geophysical, biological, and human systems. Research underway in ecological systems and dynamics will provide the basis for modifying empirical relationships in planning models so that the effects of climate change on resource productivity can be incorporated into the decisionmaking process. There are also linkages with greenhouse gas flux and process models that describe and predict terrestrial carbon and greenhouse gas exchanges. Additional needs include evaluations of changing landowner objectives and associated effects on management decisions, as well as better methods for evaluating nonmarket resource values.

Assessment and Modeling

Results from experimental studies, monitoring, and modeling research are essential for guiding future resource management decisions. Periodic assessments provide information to administrators for consideration in policy making. The FSGCRP develops, evaluates, and applies models to address both the impact of global change on forests and the role of forests in a changing environment.

The modeling activities are designed to: (1) improve the understanding of how forest management activities and resource outputs will be affected by a changing climate; (2) improve the understanding of carbon cycling in trees, forest soils, and wood in service; (3) evaluate alternative response strategies and options for mitigation and adaptation by predicting system responses to both global change stresses and management actions; (4) provide an improved characterization of forest and rangeland ecosystems for economic/policy models; (5) aid in the synthesis and integration of research results and help identify weaknesses in system understanding.

The FSGCRP and the Resources Planning Act (RPA) assessments have a common goal of assessing current and future resource trends. The RPA assessments follow a longstanding Forest Service tradition of assessing the past, current, and future state of forests. A substantial body of expertise, information management, and modeling systems are in place to support the assessment process. Assessments typically include: (1) a description of the current status of the resource, (2) a projection of supply of and demand for resource outputs, (3) social, economic, and environmental implications of the projections, (4) management opportunities to improve the resource situation, and (5) a description of Forest Service programs and responsibilities. The results of the RPA assessment are used as the factual basis for formulating future renewable resource management programs.

Data Quality Assessment

FSGCRP data quality assessment activities ensure that the data produced for the program are of known and documented quality. It is the goal of data quality assessment to ensure that all environmentally related measurements may be carried out such that uncertainty statements can be made. The objectives of data quality assessment are: (1) to document data quality through statistically supported quantitative and qualitative assessments; (2) to ensure comparability of data collection for field and laboratory procedures within and between research projects; (3) to establish criteria for the development and evaluation of models, historical data bases, and socio-economic assessments.

The essential features of data quality assessment consist of quality management, quality assurance, and quality control. Quality management establishes program-wide policies and procedures that ensure adequate documentation and data quality for all field, analytical, and modeling activities. Quality assurance (QA) implements these policies by establishing and monitoring quality control (QC) procedures including the identification of variability and follow-up control recommendations to improve the accuracy and precision of measurements. QC procedures are implemented by scientists within each project and are designed to produce a sustained reduction of error and document systematic error within statistically defined limits. All three activities comprise the FSGCRP total quality management philosophy in which management policies, research planning, and operating methodology are fully integrated within the national program.

Literature Cited

U.S. Department of Agriculture, Forest Service. 1992. **Forest Service Global Change Research Program - program plan update.** PA-1497. Washington, DC: U.S. Department of Agriculture, Forest Service. 36 p.

SUMMARY OF NATIONAL RESEARCH PROGRAM HIGHLIGHTS: 1991-95

This section highlights the research studies sponsored wholly or in part by the FSGCRP. A more detailed presentation of the studies can be found in the regional section of this report and in the cited literature.

Atmosphere/biosphere Gas and Energy Exchange

Regional Climate Modeling—Although general circulation models (GCMs) operate at a coarse spatial resolution of approximately 5° latitude and longitude, they are the basis for regional and local climate change predictions. Researchers have derived baseline climate data sets and projections for the United States at a resolution of 1/2° latitude and longitude to improve the regional representation of climate-change predictions. Special studies in the South have analyzed the output of several GCMs[1] to show that the equilibrium temperature increase could range from 3.6 to 6.7 °C in that region. Additional variables have been added to the climate data sets for portions of the West to represent surface winds and humidity, which control the rate of moisture and energy exchange between plants and the atmosphere. In the North, high-resolution climate models and interpolation methods have been used to estimate current or prospective climate for specific areas.

Baseline Trends in U.S. Carbon Budget—Increases in biomass on U.S. forest lands over the last 40 years have added 281 million metric tons per year of stored carbon. This increase is enough to offset 25 percent of U.S. emissions for the period, and account for a significant portion of the "missing" carbon in evaluations of the global carbon cycle. Projections show additional increases of approximately 177 million metric tons per year through 2040. Increasing amounts of carbon in harvested wood, the effects of increasing atmospheric CO_2 on ecosystem productivity, and large reforestation programs may all have a measurable effect on the rate of carbon sequestration.

Effects of Warming on CH_4 Release from Minnesota Peatlands—Peatlands store huge amounts of C, more than 30 times that found in typical upland sites. Peatlands release CH_4, a greenhouse gas with high warming potential. Studies in Minnesota show that extended growing seasons and warmer soil temperatures would increase CH_4 release from peatland by 50 to 80 percent, thereby adding to future warming potential.

Ethanol from Wood—New processes for fermenting xylose sugar from hardwoods significantly increase the yield potential of ethanol, an alternative to gasoline and diesel fuel. Only a few species of yeast ferment xylose effectively, and by using a mutant strain of this yeast, we are able to increase ethanol production by 50 to 100 percent. Because ethanol is derived from a renewable resource, its use displaces fossil fuels thereby reducing atmospheric emissions of CO_2.

Chemicals in Wood Finishes—Widespread changes in the paint industry are necessary to meet air standards under the new Clean Air Act. Many paint and stain manufacturers will have to change formulations to meet the required decreases in volatile organic compound (VOC) content in wood finishes. New formulations with low VOC content have been tested and found to comply with emissions standards.

Ecosystem Dynamics

Basic Plant Processes

Adaptability of Larch—Investigations on larch have shown that conifers can change their genetic makeup rapidly in response to changes in the environment. Genetic maps of the DNA from larch seeds grown under two temperature conditions show a strong segregation in certain marker locations, and show different growth responses, indicating selection for alternative traits under different growth environments. This research suggests that some tree species may adapt quickly to environmental change, which would lower the risk of adverse impacts to forest ecosystems should climate change proceed rapidly. Most models of species distribution and composition changes do not include species adaptability as a factor because very few studies of this nature have been conducted.

Reproductive Biology of Southern Species—Exposure of hardwood and pine trees to elevated levels of CO_2 and increased temperatures demonstrated significant changes in the timing of pollen release and seed maturation. Pollen release occurred almost 2 weeks earlier and time of seed maturation was lengthened on treated trees. The number of seeds were reduced, but the size of the seeds increased in trees with elevated temperatures and CO_2. There was no impact on seed viability. These studies demonstrate that changes in reproductive biology should be considered when assessing the effects of global change on the natural migration of hardwood and pine species and in genetically improved plantations.

Increased CO_2 and O_3 Affect Physiology and Growth of Eastern Species—White pine, trembling aspen, and yellow-poplar grown from seedlings to early maturity in controlled environments responded very differently to elevated O_3 levels, alone or in combination with elevated CO_2 levels. Experiments with yellow-poplar showed the expected response—increased CO_2 partially compensated for reduced growth caused by O_3 exposure. Experiments with O_3-sensitive aspen clones showed that increased CO_2 did not compensate for growth reduction caused by O_3 exposure; rather, the growth reduction was greater when the trees were exposed to both O_3 and CO_2. Experiments with white pine have been inconclusive. Knowledge of how trees may grow in the future environment allows managers to choose

[1]These GCM outputs did not include the effect of aerosols.

appropriate species or genotypes to plant in areas of high exposure to O_3.

CO_2 Affects Growth of Loblolly Pine—After 3 years of exposure to elevated temperatures and CO_2, net photosynthesis of mature loblolly pine increased by 40 to 100 percent, and leaf area increased by 33 percent. These increases are attributed to elevated concentrations of CO_2 rather than warming. A temperature increase of 2°C had little effect compared to the growth stimulation effects of increasing CO_2. Other experiments have shown that increasing water, nutrients, and CO_2 have additive effects that indicate a potential for increasing forest productivity. Under climate change scenarios, increases in temperature combined with decreases in precipitation could reduce or reverse the prospect for increasing growth in the extreme margins of the range of the southern pine forest.

Photosynthesis Response of Western Conifers to CO_2—During the past century, atmospheric CO_2 concentration has risen by about 60 ppm. Results from controlled experiments with immature trees suggest that this magnitude of increase in CO_2 should have increased photosynthetic rates of western conifers. To look for evidence of such a response under natural growing conditions, scientists studied the composition of stable carbon isotopes in tree rings for several western conifer species. Inferences from these data show that photosynthesis rates have remained constant over the past 80 years. Higher levels of CO_2 may not have the expected effect when increased gradually under natural conditions that may include other simultaneous environmental changes.

Cold Hardiness of Western Conifers Under Increased CO_2—Temperate and boreal woody plants must become hardy enough in the fall to withstand cold winter temperatures. Doubled CO_2 had little effect on cold hardiness of radiata pine, but increased autumn and spring hardiness of Douglas-fir, which suggests that it could be adapted at higher elevations in the future. Doubled CO_2 increased hardiness of ponderosa pine in autumn and decreased it in the spring. In the future, ponderosa pine may become susceptible to late spring frosts.

Winter Injury to Eastern Red Spruce—Exposure to acidic clouds, common at high elevations in the Northeast, reduces the cold tolerance of red spruce foliage, predisposing it to winter injury. The exact mechanism causing the damage has eluded researchers, but foliar damage follows several possible combinations of acid exposure, rapid temperature change, and extreme cold. Although reports of winter injury seem to be more common since 1960, there is little evidence that red spruce has suffered any unusual rate of growth decline or increased mortality as a consequence.

Ecosystem Processes

Warming Effects on Soils—Temperature and precipitation are known to affect the rate at which organic matter decays and is broken down into mineral components in northern forest soils. Heating the soils of spruce-fir and northern hardwood forests by 5°C increased fine root growth, litter decomposition, and CO_2 emissions. How these changes would interact with the physiological responses of plants to increased CO_2 and O_3 is unclear. Ecosystem-scale experiments and coupling of ecosystem and plant models will lead to better predictions of ecosystem responses to multiple environmental changes.

Nitrogen Saturation in the Northeast—Long-term studies at a commercial spruce-fir forest in Howland, Maine, and at a high-elevation spruce-fir forest on Whiteface Mountain, New York, have shown that most of the nitrogen (N) deposited in rainfall and cloud droplets is retained in the ecosystem. However, sites in high-deposition areas of the Middle Appalachian region are beginning to show signs of N saturation based on long-term monitoring of experimental watersheds. Nitrogen saturation could lead to reduced forest growth and increased nitrate pollution of fresh water supplies and marine ecosystems such as the Chesapeake Bay.

Nutrient Availability in Red Spruce Forests of the Northeast—Long-term studies in the Adirondack Mountains of New York and the White Mountains of New Hampshire have documented a substantial decline (50 % or more) in calcium (Ca) in the organic soil layers of red spruce forests since the 1930's, which coincides with the period of increased acidic deposition. Acidic deposition also increases the availability of aluminum (Al) in the rooting zone, which can damage plants. If continued over a long period of time, the decline of available Ca coupled with increased availability of Al could cause decreased productivity and decline/dieback of red spruce. We have identified mechanisms that reduce the availability of Ca in soils, and are beginning to understand how Al operates as a stress factor in red spruce. Identifying indicators of Al stress, as well as understanding how acid deposition affects soil processes, may lead to identification of susceptible sites and treatment options.

Effects of Global Change on Tree Competition in the South—Competition studies were conducted to mimic regeneration of pure seedling stands of loblolly pine and sweetgum, and mixed stands of both species under different levels of soil moisture, nitrogen availability, and CO_2. Higher concentrations of CO_2 increased the total biomass of both species: 33 percent for sweetgum and 14 percent for loblolly pine. In mixed stands, the balance of competition between these species, as measured by total biomass, was not altered by higher concentrations of CO_2. These findings differ from reports by other researchers measuring individual trees in pure stands, which concluded that sweetgum was a stronger competitor when grown with increasing concentrations of CO_2. Global change-induced alterations in regeneration and species competition across the range of southern pines must be considered when assessing future stand productivity and sustainability.

Prospective Regional Impacts

Distribution of Ecosystems—A model of location, volume, and area of forest types under differing climate and land-use scenarios has been developed to anticipate where major vegetation life forms will change and whether the changes will be gradual or catastrophic. The Mapped Atmosphere Plant Soil System (MAPSS) model provides an essential link to other models that predict changes in regional forest inventories and associated economic impacts. Simulation using the MAPSS model under alternate future climate scenarios demonstrates the following potential changes:

Potential Vegetation Redistribution—Under a scenario of increased temperature and decreased precipitation, simulations of vegetation redistribution show increases in forest area and a large shift from high-density forest to low-density woodland. The loss in timber volume associated with reductions in density could be as high as 57 percent when averaged across all forest types.

Cool Temperate Forests—Forests that are constrained to cool climates, such as northeastern hardwoods and high-altitude forests in the West, could be lost or reduced significantly in size under some climate senarios. Soil characteristics at high altitudes may restrict expansion of forests to high elevations.

Warm Temperate Forests—Forests in warm regions are potentially sensitive to increased drought and temperature stress if climate warms and/or precipitation decreases. This effect could be partially or totally offset by increased water-use efficiency, a physiological response to increased atmospheric CO_2. MAPSS simulations have identified the southeastern mixed pines and hardwoods and the western Douglas-fir regions as most at risk from drought stress. In the West, the Southern Coast and Cascade Ranges are particularly sensitive to drought stress. Under climate change scenarios, these closed forests could be replaced by woodlands or savannas, possibly with similar species composition.

Uncertainties in Model Projections—The three most important factors that make these projections uncertain are: differences among the GCM scenarios, the direct effects of elevated CO_2, and the mechanisms and degree of coupling between the canopy and the atmosphere. These projections are also partially inconsistent with evidence from experiments, particularly in the South, which show positive effects of increased CO_2 that are not substantially constrained by interactions with other stresses.

A Model Intercomparison Study—Under a project called VEMAP (Vegetation Ecosystem Model Analysis Project), three biogeography models and three biogeochemistry models were parameterized to simulate the response of 21 different U.S. vegetation types to climate change scenarios. The biogeography models were equally able to simulate current vegetation distribution, and the biogeochemistry models were equally able to simulate the net primary productivity and carbon pools of the different vegetation types. However, the models exhibited very different levels of sensitivity to scenarios of global warming. MAPSS was the most sensitive with respect to temperature effects on forests, and also was the most sensitive to the direct effects of CO_2. The comparison activity helps the developers understand model strengths and weaknesses in representing key processes, especially since many assumptions must be made when simulating the behavior of complex ecosystems. Model comparisons are not a substitution for model validation (which is impossible for this scale of analysis), but they do help analysts consider uncertainty in evaluating projected changes.

Long-term Ecosystem Change in the Interior West—Studies of woodrat middens containing organic material preserved in the dry southwest climate show that communities and ecosystems are far less stable than previously assumed. Over the millennia, climate changes have had major influences on species adaptation, migration, or both. Knowledge of the trajectories of change will help managers understand the likely outcomes of their activities.

Treeline Changes in Colorado—Treelines represent clear boundaries between ecosystems (ecotones). Based on tree-ring-width chronologies of Englemann spruce, a rapid change in the elevation of timberline in Colorado about 750 years ago has been identified. No unusual growth increases were seen in recent years, suggesting that no current movement is underway that might be associated with climate change.

Regional Impacts of Global Change in the Northeast—Data from long-term research plots highlight the difficulty of attributing changes in forest productivity or composition to specific causes when many factors simultaneously influence the systems. Natural succession, disturbance, drought, and human activities, past and present, are dominant factors affecting forests in the Northeast. Increasingly sophisticated computer models facilitate analysis of the effects of environmental change at the regional scale. For example, using average O_3 exposures recorded from 1987 to 1992, very preliminary estimates show that annual NPP may have declined from 2 to 17 percent, with the greatest reductions in southern New York and New England.

Climate Change Impacts on the Great Plains—Global climate models predict that summer soil moisture in the Northern Great Plains will decline under CO_2-induced warming. Analysis of data from a 100-year period has revealed a relationship between climate anomalies in the Great Plains and the well-known Southern Oscillation events in the Pacific Ocean. The ability to predict these phenomena several months in advance will help managers make better informed decisions.

Disturbance Ecology

Environmental Changes—We have made substantial progress in our ability to characterize past and future changes in air pollution and acid deposition at regional to local scales. We have developed high-resolution models to estimate past, current, and future deposition of chemicals for any location in the Eastern United States. For example, large areas of the Eastern United States receive substantial quantities of N (20-30 kg/ha) deposited primarily as dissolved nitrate and ammonia in rainfall. The pattern of N deposition varies substantially over short distances depending on topography and rainfall distribution.

High Resolution Climate Models in the Interior West—Researchers are developing high resolution models to study the impact of climate and fire in the Northern Rockies. High resolution, not available in global models, is necessary to analyze impacts at the landscape scales important to land managers. Increasing the resolution of a climate model from 50- by 50-km grid cells to 10- by 10-km grid cells resolves important topographic features that impact temperature, precipitation, and other climate variables that affect forests. Validation of the 50- by 50-km grid model shows reasonable prediction of recorded temperature, but overprediction of precipitation.

Historical Insect Population Distributions—We have collected and are compiling maps of the population changes of five of the most important forest insect pests in the United States: gypsy moth, eastern spruce budworm, western spruce budworm, southern pine beetle, and mountain pine beetle. These maps will be used in population dynamics models to predict long-term changes in insect populations affected by climate change.

Ozone Effects on Southern Pine—Experimental evidence indicates that O_3 pollution, widespread in the South, reduces growth in some southern pines. Studies on pine seedlings exposed to a range of O_3 concentrations and levels of water deficit showed that water deficit was clearly the factor most limiting growth and physiology. However, there were significant O_3-induced tree responses that occurred in the moderate and severe soil-water-deficit conditions. Reductions in foliage biomass and tree growth as a result of O_3 exposure complicates analyses of expected impacts of climate change on southern forests, but will certainly be a factor.

Multiple Stresses and Insects—Studies of aspen foliage from plants treated in exposure chambers have shown that increased CO_2 and O_3 change the chemical composition of the foliage, which in turn influences both its resistance to insect attack and its nutritional value for insect growth. Using plant material from open-top chamber experiments, researchers discovered that elevated O_3 generally increased insect growth, and that elevated CO_2 generally decreased insect growth. An increase in foliage volume expected under increased CO_2 may be partially offset by increased insect feeding, thus reducing the potential increase in tree growth. Likewise, a decrease in foliage volume from O_3 damage may not reduce plant growth as much if insects consume less foliage than trees without O_3 damage.

Wind and Atmospheric Deposition Affect Western High-Elevation Ecosystems—High-elevation ecosystems are particularly vulnerable to atmospheric deposition and climatic change. Research at the Glacier Lakes Ecosystem Experiments Site in Southeast Wyoming addresses the effect of these changes on terrestrial and aquatic components of the ecosystems. Detailed maps of wind speed and direction, and snow depth, have shown that these variables are strongly affected by topography. Snow depth is a good indicator of atmospheric deposition. Areas of deeper snow have higher amounts of chemicals. During snowmelt, there is a surge of chemicals into lakes that are normally free from detectable nitrate and phosphate levels, and acidity increases slightly. How these chemical changes affect ecosystem processes is unknown but currently under study.

Wildfires in the East—Research on synoptic-scale circulation patterns in the middle troposphere has shown distinct weather patterns associated with the most severe wildfires in the East. Large-scale changes in the normal atmospheric circulation patterns as a result of global climate change have the potential for changing the frequency and intensity of wildfires, especially in drought-prone areas. Until the resolution of GCMs improves substantially, however, predictions of changing fire frequency for any specific region of the United States will remain speculative.

Southern Pine Beetle (SPB)—An improved regional-scale forest process model has been developed to predict how forest growth and soil water use will affect SPB populations, and assess how SPB populations are affected by present and future climatic variations. The population response will likely depend on the magnitude of average monthly temperature change.

Human Activities and Natural Resource Interactions

The President's Climate Change Action Plan—Results from U.S. Carbon Budget Models (FORCARB and WOODCARB) have contributed to the development of alternate forest management and timber utilization policies for offsetting greenhouse gas emissions as part of the President's Climate Change Action Plan. Basic information about carbon changes over time for different forest management intensities, and for converting agricultural land to forest, can account for 10 percent of the needed reductions in the President's Plan.

A National Integrated Model—An integrated modeling framework first developed for RPA assessments was used to address the effects of four different scenarios of climate change on forest productivity, market responses, and carbon storage. This framework was implemented to link climate change scenarios, an ecosystem model, a forest sector model, and a carbon accounting model. A summary of the results reported in the 1995 RPA Assessment Update:

Expected Changes in Productivity, Timber Harvest, and C Storage—Under the scenarios studied, the largest increases in productivity were in northern forest types, while southern forest types showed only small increases or decreases in productivity. Increases in productivity were not followed by increases in harvest at the national scale because the market responds to many other economic factors besides timber supply. There was some redistribution of harvest among regions, ownership categories, and fiber types. Continuing strong demand for wood products keeps net growth about equal to removals over the long run, eventually driving the current net gains in carbon storage to zero. Long-term changes in C storage indicated that private timberlands will become a source of CO_2 for all but the most optimistic climate change scenario.

Mitigation Opportunities Using Wood Products—Changing forest products and production methods offer opportunities to reduce or offset emissions of greenhouse gases. Researchers have studied energy conservation, reduction of volatile organic compounds in wood finishes, use of biomass as an alternative to fossil fuel, and sequestration of carbon in wood products.

Management Opportunities and Markets—Intensive studies of soil properties, root growth, and crown physiology under different silvicultural treatments demonstrate the effects of stand manipulation on key processes. Management tools could be used to manipulate carbon fixation in forest stands to either offset the negative affects, or capture the positive affects of global climate change on forest productivity. Mitigation activities would likely have some effect on regional and national timber markets.

REGIONAL RESEARCH PROGRAMS

The Forest Service contribution to global change research is unique because of its extensive land base and long history as both a land management and research agency. With more than 191 million acres of forest and range land, Forest Service scientists have access to terrestrial and aquatic ecosystems from Alaska to Puerto Rico and from Hawaii to Maine. With experimental forests and watersheds established as early as 1908, scientists also have access to data sets that permit comparison of ecosystem trends over the better part of a century. In addition, the Forest Service regularly conducts a comprehensive assessment of forest resources that couples land resources, land use, and economic considerations.

While the primary emphasis of the U.S. Government's global change research efforts to date has been on large-scale atmospheric and oceanic processes, the effects of global change will be felt most acutely at the local and regional levels. To ensure a cohesive, ecosystem-based approach to its research, the FSGCRP is conducted through five regional programs and a national program office located in Washington, D.C. (Fig. 1). Each regional program addresses the national program elements to provide an understanding of the specific implications of global change for the region and contribute to the broader national and international body of knowledge.

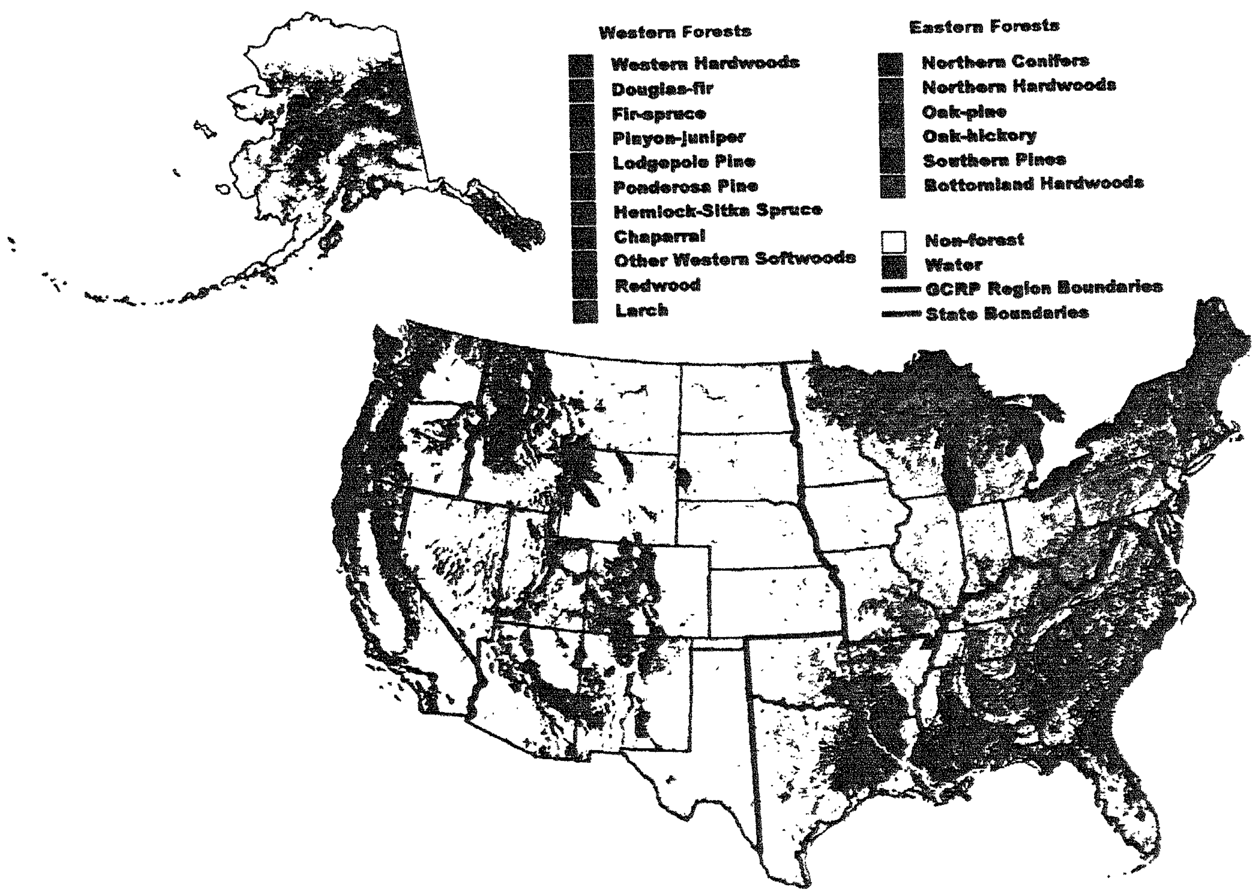


Figure 1.—Organization of the Forest Service Global Change Research Program, including major forest types by region.

NORTHERN GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

Research in the North has begun to unravel some key questions about how environmental changes will impact the productivity and health of forest ecosystems, species distributions and abundance, and associations of people and forests. Initial research was focused on basic process-level understanding of tree species and forest ecosystem responses to environmental stress. Chemical pollution stresses received equal emphasis with climate change concerns.

At the most basic plant level, research has highlighted some of the mechanisms that determine how physiological processes respond to combinations of factors that affect northern forest trees. We have experimented with increases in carbon dioxide (CO_2) and ozone (O_3), and investigated the impacts of ambient levels of nitrogen (N) and acidic deposition. These primary factors are expected to have continuing effects on forests. Less certain but still of concern are anticipated changes in temperature and precipitation that may be induced by increasing concentrations of greenhouse gases. We are currently engaged in a research strategy to scale up experiments from highly controlled chamber studies of seedlings, saplings, and mature trees to more realistic experiments and observations on whole ecosystems using open-air exposure systems and gas exchange measurements. Basic physiological research, combined with experimental and observational research at the ecosystem level, will lead to understanding of the causes of observed changes in forest health and productivity of northern forests, including prospective changes in growth and biomass, species composition, pest outbreaks and mortality, C allocation and storage, water quality and yield, and wildlife habitat.

Because of these potential changes, there is a need to develop effective management practices to protect forest health and productivity on both public and private lands. Landscape-scale studies have an important integrating function directed at understanding how changes in the physical and chemical climate affect the abundance, distribution, and dynamics of species, populations, and communities. Social interactions and economics research are directed at understanding how the use of trees and forests by people will be influenced by potential changes in forest ecosystems due to global change (adaptation), and how human activity can initiate or alter the processes of change (mitigation). Modeling is employed in all research program areas to integrate study results, to provide understanding and prediction of global change effects on forest ecosystems, and—along with landscape-scale studies—to provide an important bridge to assessment, resource management, and policy. Assessment and policy activities will ensure that research results and assessments are transferred to sound management practices and interpreted into policy options.

The Northern Program is an active participant in regional and national assessments of resource conditions and trends, with a focus on how forest health and productivity may be affected by global change. A large part of this effort requires development and application of the modeling tools needed to make such assessments, to provide scientific input for national assessment efforts, and to develop and analyze policy options for local, regional, and national decisionmakers.

Atmosphere/biosphere Gas and Energy Exchange

Minnesota's Peatlands Hold Clues to Impacts of Global Warming

Peatlands in the northern hemisphere store huge amounts of C—about one-third of the world's soil C, which is equivalent to two-thirds of the C in the atmosphere. Carbon deposited in peatlands decomposes into CO_2 or methane (CH_4) and is emitted into the atmosphere. Minnesota's peatlands are at the southern limit of the northern hemisphere's distribution of peatlands, so may offer a glimpse of what could happen if the vast areas of colder peatlands to the north were significantly warmed.

Peatland soils store more than 30 times the amount of C than upland soils in a typical landscape in Minnesota (Fig. 2). Studies in Minnesota have shown that longer growing seasons and warmer soil temperatures would increase CH_4 release by 50 to 80 percent. Because CH_4 has strong radiative properties, it is possible that an increase in the rate of methane release over a large area of colder peatlands would create a positive feedback with the atmosphere and further increase warming. Sulfate deposition, however, tends to suppress CH_4 release, so in some areas of high air pollution the warming effect would be less.

Ecosystem Dynamics

Some Tree Species Adapt Quickly to Environmental Stress

Some tree species are well adapted to extreme environmental conditions. Under a changing environment, adaptation may be a significant alternative survival strategy to migration for some species. Successful adaptation or migration, or both, of a species may depend on how rapidly environmental conditions change.

Investigations on larch show how rapidly conifers can change their genetic makeup in response to changes in the environment. Genetic maps of the DNA from larch seeds grown under two temperature conditions show a strong segregation in certain marker locations, and show different growth responses, indicating selection for alternative traits under differing growth environments (Greenwood and Hutchison 1995). The environment induces selection of different alleles in genetically identical populations of trees.

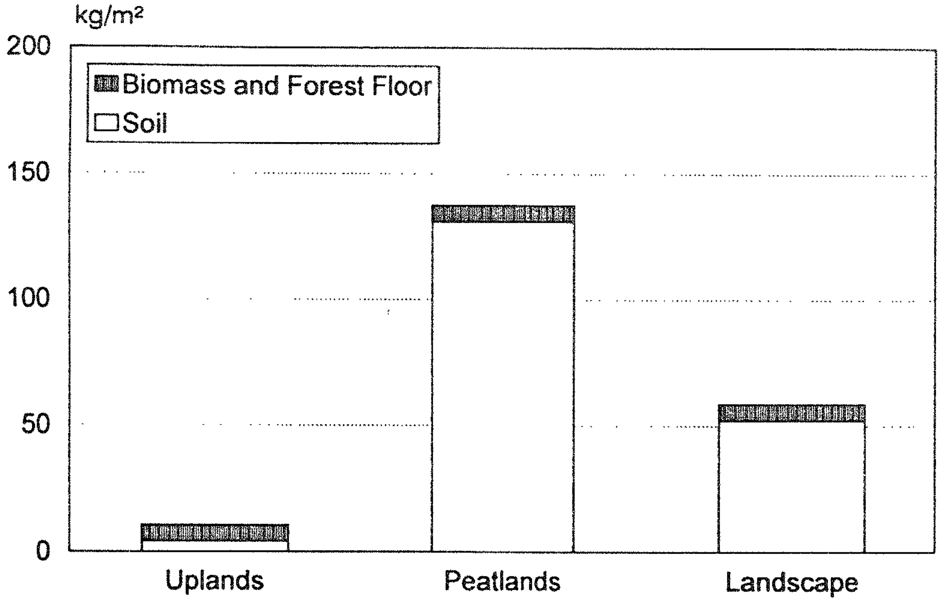


Figure 2.—Carbon storage in the landscape and broad land types of Cedar Creek, Minnesota (Bell et al. 1995).

Eventually, identified genetic markers can be correlated with tree stress responses. This correlation would allow managers to select and propagate trees with adaptive traits for changing climatic conditions. A better understanding of the effect of breeding environment on plant performance may allow managers to select seed sources tailored to the expected environment in which a tree will grow over a long rotation.

How Trees Adapt to Drought

Comparative studies of temperate and tropical tree species are yielding new insights into the mechanisms by which trees adapt to drought. Under drought stress, the negative pressure created by transpiration exceeds the availability of water, causing the water column within the tree to break (cavitate) and create air-filled pockets in the xylem. The adaptability of many species to water stress can be explained in terms of differences in the vulnerability of the xylem to cavitation. There is also a link between xylem vulnerability to cavitation and the physiology of stomates, the leaf openings through which gases are exchanged during photosynthesis and respiration. It is well known that high CO_2 induces stomatal closure and reduces plant water needs, but effects on plant structure and internal water relations are not well understood (Tyree and Alexander 1993).

Understanding how trees adapt to drought and other simultaneous stresses will eventually allow managers to improve the match between species or genotypes and the site conditions, especially during the critical stand regeneration period after harvest (Van Sambeek et al. 1995). The survival of trees is strongly affected by their ability to tolerate drought.

Multiple Interacting Stresses Produce Surprising Tree Responses

Trees and ecosystems are subjected to many environmental stresses that vary in space and time. Although simple experiments may show the effect of a single factor, it is the timing and intensity of interactions between multiple factors that determine how a tree responds to environmental change. There are also genetic factors that determine sensitivity to stress and adaptability to a new environment, so that different tree species respond differently. Also, individuals of the same species may respond differently. Predicting the response of an ecosystem composed of many species is complicated by this variability of individual organisms.

In several multi-factor, multi-year experiments using large outdoor exposure chambers, white pine, trembling aspen, and yellow-poplar grown from seedlings responded differently to elevated O_3 levels, alone or in combination with elevated CO_2 levels (Isebrands and Karnosky 1995; Rebbeck 1995). Aspen is highly sensitive to ozone and shows strong genotypic differences (Fig. 3). Ozone reduces biomass production and root growth; addition of CO_2 does not compensate for the reduction. There has been a negative interaction between CO_2 and O_3 for aspen photosynthesis. By contrast, white pine and yellow-poplar were not adversely affected by experimental exposure to O_3, and their growth was stimulated by the simultaneous addition of CO_2. The responses change over time, suggesting that the trees may be adapting to elevated CO_2 and O_3.

Similar multi-factor experiments involving CO_2, water stress, and N deficiency also show complex plant responses. For

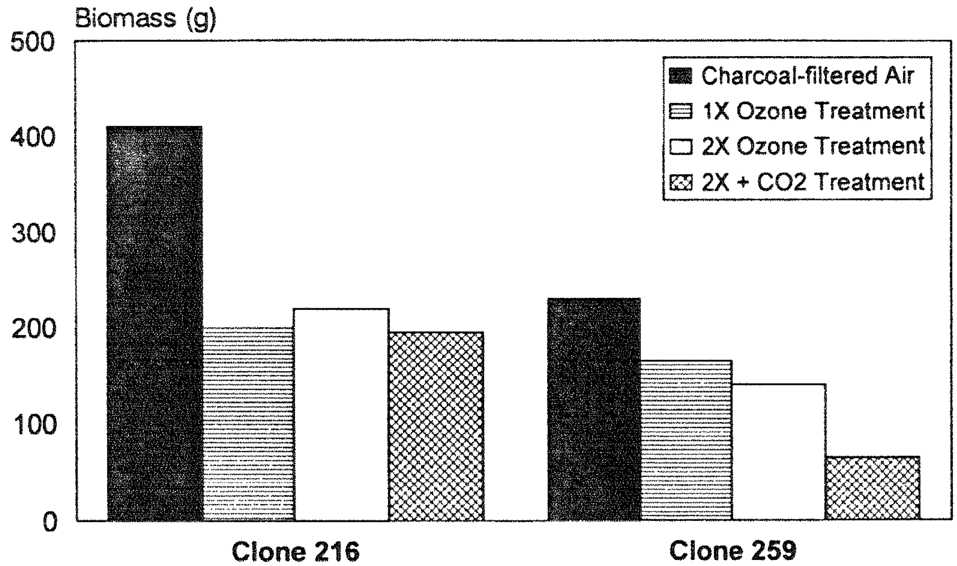


Figure 3.—Stem biomass of aspen clones exposed to various O_3 and/or CO_2 treatments for two years (Karnosky et al. 1995).

example, for northern red oak, increased CO_2 seems to compensate for water stress when nitrogen is not limiting.

The results of multi-factor experiments show the difficulty in generalizing the response of complex ecosystems from single factor experiments on a limited number of species. To help understand the relationships among the many interacting factors, physiological process models allow us to integrate diverse information from experiments. Such models operate at various scales, from the leaf to the tree to the whole ecosystem.

Managers and policy analysts should carefully evaluate broad conclusions based on small-scale experiments, many of which involve immature trees studied for short periods. However, the studies on aspen strongly indicate that selection of clones for plantations should be based on resistance to O_3 in areas of the Lake States where ambient exposure is likely to be high.

Acid Deposition Linked to Increased Winter Injury in Red Spruce

Damage to the foliage of red spruce during the winter is observed periodically in the North. Reports of winter injury have increased since 1960. Several studies have shown that exposure to acid mist, common at high elevations in the Northeast, reduces the cold tolerance of red spruce foliage, predisposing it to winter injury. In experiments with simulated acid cloud water, exposing plants to acid mist at pH 5.6 and pH 3.2 reduced their cold tolerance by 3 to 5°C (Fig. 4).

Midwinter dehardening followed by extreme cold or rapid freezing (rather than reduced tolerance to cold temperature) may also cause winter injury (Strimbeck et al. 1995b). In laboratory experiments and field studies, rapid freezing causes the same damage symptoms as observed in the field after winter injury events. There were strong elevation and aspect patterns to damaged trees after severe injury during the winter of 1992-93, suggesting that solar radiation plays a role in rapid temperature changes.

Foliage exposed to acid mist has lower amounts of calcium (Ca) in the tissue. There is some disagreement concerning the role of Ca in the sensitivity of tissue to cold. Attempts to mediate reductions in cold tolerance by adding Ca to the soil in short-term experiments have not been successful. There is some uncertainty regarding the role of older, weathered soils that have depleted levels of Ca vs. newer glaciated soils that have abundant available Ca.

Although the link between acid deposition and increased susceptibility to winter injury has been demonstrated in experiments, the impact on red spruce at different field sites is still under study. Effective management practices have yet to be identified.

Litter Decomposition is Affected by Environmental Impacts on Insects and Soil Organisms

Decomposition of tree litter is an important part of ecosystem nutrient cycling. Understanding the effects of environmental change on rates of decomposition, either directly or through the activity of insects or soil organisms, helps us understand and predict how global change will affect C and N cycles, and ecosystem productivity. Decomposition affects the release of greenhouse gases to the atmosphere, and concurrently, the amount of C and N stored in ecosystems.

A series of studies has highlighted how environmental factors affect some of the insects and soil organisms that perform valuable decomposition functions. Elevated CO_2 and available light have variable, species-dependent effects on insect and microbial activity (Kaufman et al. 1995; Strand et al. 1995). Acidic deposition affects microbial biomass,

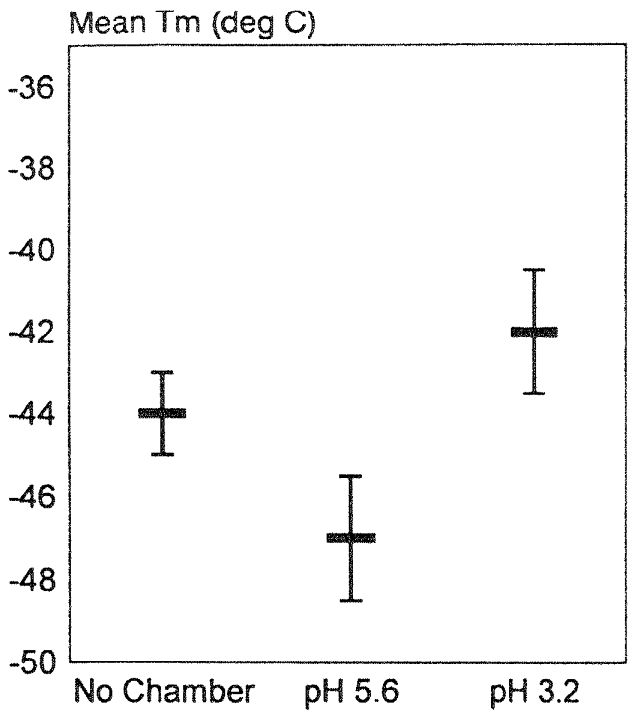
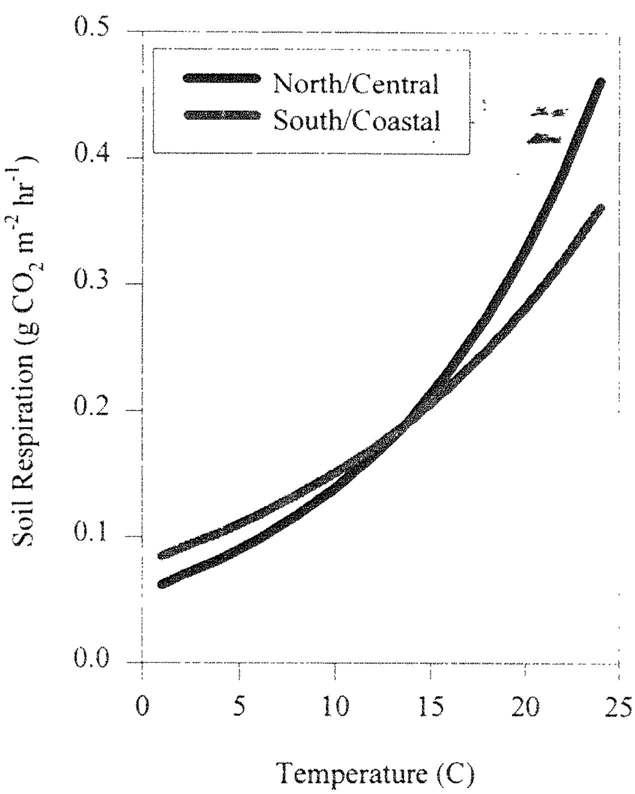


Figure 4.—Cold tolerance of red spruce by mist treatment. Mean Tm is an estimate of cold tolerance. There is approximately 5°C between pH 5.6 (above ambient) and pH 3.2 treatments (Strimbeck et al. 1995a).



macroinvertebrates, and decomposition of leaf litter in streams (Engstrom et al. 1995). In urban and suburban areas, litter decomposition is affected by temperature and earthworm activity (Pouyat et al. 1994, 1995).

These studies, and those described in the next section on warming effects, strengthen our understanding of the basic processes that are likely to be affected by global change. In turn, these ecosystem changes will affect C and N compounds that are released to the atmosphere.

Warmer Temperatures Affect C and N Dynamics in Northern Forest Soils

Climate—particularly temperature and precipitation—affects the rate at which organic matter decays and is broken down into its mineral components. This has led to much debate about the potential effects of global warming on northern temperate and boreal forest soils, especially since soils are major reservoirs for C, N, and other nutrients necessary for forest growth and productivity. Air pollution, particularly acid deposition, may also affect the availability of certain nutrients such as calcium and magnesium. The purpose of several major experimental and observational studies of forests in the Northeast and Lake States is to determine the impact of expected environmental changes on major element cycling.

The response of a commercial spruce-fir forest soil to a warmer climate was investigated by increasing the forest floor thermal regime by 5°C with the use of buried heating cables (Rustad et al. 1995). Results to date have shown that fine root growth, litter decay, and CO_2 emissions are greater in the heated plots than the unheated plots. It is likely that increased microbial decomposition and root respiration caused these changes. A similar soil heating study in a northern hardwood forest produced similar results: increases in CO_2 flux, litter decomposition, and N mineralization (McHale et al. 1995). Germination of white pine seeds increased but there was no change in germination of eastern hemlock seeds in response to heating.

From observations along a series of short climate gradients in Maine, investigators concluded that temperature is a strong predictor of soil respiration and net N mineralization, though there are regional differences in the derived relationships (Fig. 5).

A gradient study in Michigan was established in 1987 to examine the effects of climate and atmospheric deposition on forest productivity and ecosystem processes in the Great Lakes Region (Pregitzer et al. 1995). At hardwood study sites along a climate and pollution gradient, fine roots dominated total biomass

Figure 5.—Soil respiration as a function of temperature based on data from a Maine gradient study. For North/Central Maine, R = exp(-2.84 + 0.0862*T). For South/Coastal Maine, R = exp(-2.52 + 0.0627*T) (Simmons et al. 1995).

and N litter inputs to the soil. Differences in microbial respiration, N mineralization, and S mineralization were related to differences in temperature between the sites. Leaching of important nutrients such as Ca and magnesium (Mg) seem to be related to pollutant deposition.

These studies suggest that global warming would affect forest productivity, species composition, and carbon sequestration in forests of New England and the Lake States. These and similar experiments help answer some key questions about CO_2 flux and nutrient availability under a changing climate, and provide data to use in predictive models of the effects of regional climate change.

Nitrogen Deposition Is Retained and Sulphur Deposition Exported in Northeastern Study Sites

Continuous, long-term measurements of climate variables, atmospheric deposition, throughfall chemistry, and soil solution chemistry provide a basis for evaluating changes in chemical deposition and effects on forest processes. Nitrogen deposition is of particular importance in the Northeast. Although most temperate forests are considered N limited, there is a growing concern that chronic N deposition can lead to the contrasting condition of excess N or N saturation. Excess N interferes with normal soil processes and can reduce productivity, and may also be exported from the forest in streams and rivers, with undesirable effects on water quality. Sulphur (S) affects vegetation in the Northeast primarily as sulfuric acid, a major component of acid deposition.

At a commercial spruce-fir forest site in Howland, Maine, S deposition has decreased over a 6-year period while N deposition has remained relatively steady (Fig. 6). There was a net retention of N in the soils, attributable to N-deficiency in the ecosystem. Outputs of S in streamwater decreased in proportion to decreasing atmospheric inputs.

The effects of elevation on deposition and nutrient cycling were studied over an 8-year period at a high-elevation spruce-fir forest on Whiteface Mountain, New York. There are large (four- to fivefold) differences in deposition of S and N over an elevational range of 600 to 1275 m. The differences are attributed to higher levels of cloud water deposition at higher elevations (Fig. 7). Most of the N is retained in the ecosystem, except a small amount is exported in streamwater. This may signal the early stages of N saturation. Sulphur output varies with the level of S input, similar to observations at Howland.

These long-term observations of chemical inputs, transformations, and outputs in forest ecosystems allow us to analyze changes that result from the recent revision of the Clean Air Act. They also facilitate understanding of the critical role of N in ecosystem productivity, interactions with other stresses such as increasing CO_2 and O_3, and the role of N fertilization in the global C cycle. Of particular importance are prospects for N saturation and eventual export of nitrate, a significant pollutant of drinking water and marine systems, from northeastern watersheds.

Nutrient Concentrations Are Declining in Areas Sensitive to Acid Deposition

Several long-term studies in the Adirondack Mountains of New York and the White Mountains of New Hampshire documented a substantial decline since 1950 in Ca and Mg in the organic soil layers of red spruce forests. Evidence of changing Ca and Mg availability is also present in wood (Shortle et al. 1995). Chemical analysis of wood cores from the northeastern United States and from Siberia have documented trends in Ca and Mg concentrations that are consistent with changes measured in the soil. There is a strong correlation between these changes in the forest and historical changes in acid deposition, which increased substantially about 1950.

It has been suggested that reduced availability of Ca and Mg could cause decreased productivity and decline/dieback of red spruce in the Northeast, especially on calcium-deficient soils. Establishing a cause-effect link between acid deposition, soil chemistry, and tree health was one of the major challenges of the National Acid Precipitation Assessment Program (NAPAP). Research has continued on these important soil-mediated effects of acidic deposition by establishing an interdisciplinary team of scientists to examine changes in soil chemistry, root health, and wood chemistry throughout sites in the Northeast (Fig. 8).

Chemical analyses from the 12 sites have documented increased leaching of Ca and Mg from the soil, a decreased amount of Ca and Mg avaliable to tree roots, and corresponding changes in Ca in wood. These changes are initiated by acid deposition. Acid deposition leaches Ca from the soil, and can cause aluminum (Al) to become soluble. Soluble Al may be brought to the surface soil and the rooting zone of red spruce by upward water movement (Lawrence et al. 1995b). Elevated concentrations of Al inhibit the uptake of Ca and Mg by the roots, and can be toxic if concentration becomes too high.

Decreased availability of Ca and Mg and increased availability of Al cause stress in red spruce and make the trees more vulnerable to winter injury, defoliators, and root rot. High elevation spruce-fir sites have shown the greatest impact, and although lowland spruce-fir forests have been less obviously impacted, the same chemical processes are occurring and there is reason to expect that impacts may become more apparent over time.

The team is seeking to discover early indicators of stress in red spruce trees so that managers have an early warning of impending decline/dieback. The team is also evaluating possible mitigating effects of additions of Ca. Results of this major study will assist land managers in maintaining healthy forests over a large area of red spruce forest in the Northeast.

Can We Predict or Detect Species Migrations?

Predictions of the effects of global warming on the ranges of individual tree species indicate northward shifts of up to 800 km. These predictions are based on the correlation between

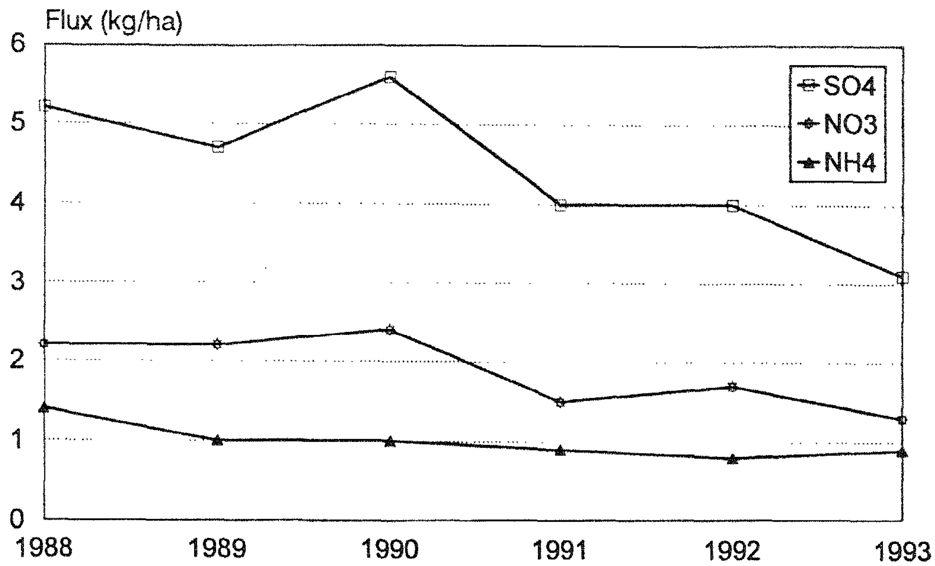


Figure 6.—Trends in atmospheric deposition of N and S in precipitation recorded at Howland, Maine over a 6-year period (McLaughlin et al. 1995).

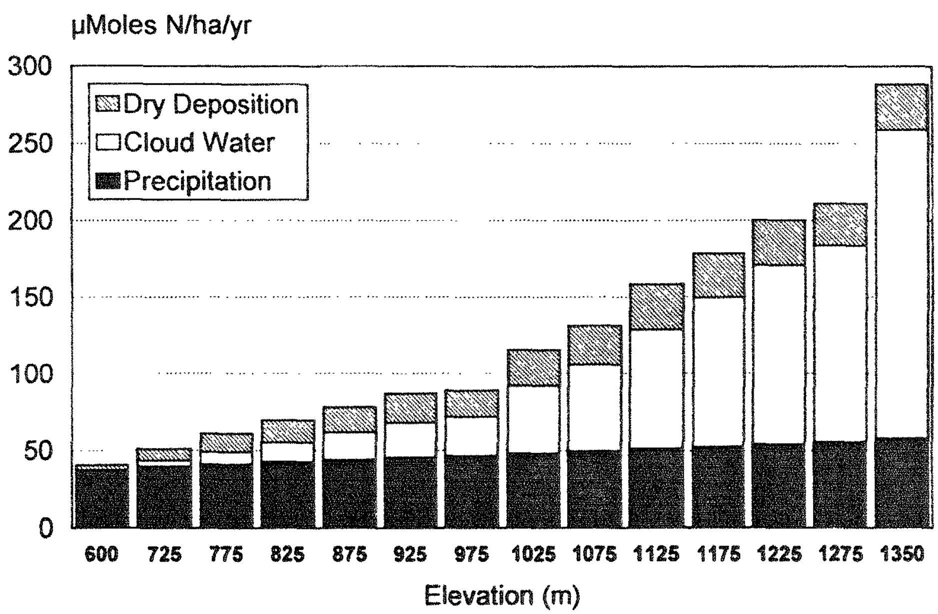


Figure 7.—Model estimates of the total annual deposition of N to the forest canopy on Whiteface Mountain, New York (Miller et al. 1993).

a range of species occurrence and the current climate. The models do not account for many other factors that may affect species distributions. Estimates of the maximum rate of tree migration from historical records (15-50 km per century) suggest that most species could not keep pace with the predicted rate of climate change. Keeping pace would require a migration rate of more than 10 times the past rates. Following this logic, many have speculated that rapid climate change could cause tree species to grow under environmental conditions that are not optimal for growth during transition to a new climate (a transient response), which could cause growth reductions, declines in tree health, or abnormal rates of tree mortality.

Historical rates of distribution shifts may be misleading because human land use has fragmented most landscapes, making it even more difficult for many species to move into new areas (Fig. 9). On the other hand, humans have unprecedented capability to assist in the process of species establishment and so could substantially increase the natural rate of seed dispersal.

We have remeasured long-term, permanent sample plots with the objective of detecting changes in species composition associated with disturbance, acid deposition, and climate change. Establishment of sample plots along an elevation gradient in New Hampshire, and remeasurment of forest inventory plots over a 24-year period in Maine, show that species composition changes are strongly associated with past land use changes, obscuring any signal of changing composition associated with climate (Solomon and Leak 1994). A separate study covering a 60-year period on the Bartlett Experimental Forest in New Hampshire showed that the primary factor affecting species composition was natural succession, followed by management activities and wind damage (Leak and Smith 1996). A study in Ohio did not support the hypothesis that high levels of acid deposition caused growth decline and mortality in oaks after a severe drought (LeBlanc and Haack 1995).

These and other studies highlight the difficulty of attributing observed changes in forest composition to specific causes when there are many factors simultaneously influencing the systems. Natural succession, disturbance and drought, and past and present human activities seem to be dominant factors affecting forests in the Northeast. Detection of changes in species composition as a consequence of warming or other environmental change would require intensive monitoring of sites that would be most sensitive to small perturbations.

Ozone May Reduce Regional Ecosystem Productivity

We are synthesizing, on a regional basis, the different responses of trees, stands, and landscapes to multiple environmental stresses. We developed or studied a number of models with the goal of integrating a cluster of biological models operating at various spatial and temporal scales with models of physical and social systems.

In one study we adapted a well-known ecosystem process model, PnET-II, to estimate the effects of O_3 on forest productivity over the northeastern United States. The productivity model is applied to regional data bases within a geographic information system. The model simulates physiological processes at the ecosystem scale and applies the predicted changes to landscapes composed of a grid of cells classified by vegetation attributes, climate parameters, pollution exposure, and so on.

We assumed that the only effect of elevated O_3 was a reduction in photosynthesis. Using average O_3 exposures from 1987-92, we estimated that annual Net Primary Productivity (NPP) was reduced from 2 to17 percent, with the greatest reductions in southern New York and New England where O_3 levels and potential photosynthesis were greatest (Fig. 10).

No Evidence of Widespread Decline in Productivity of Sugar Maple

Since the 1980's, small stands of sugar maple have declined in New England and Canada. Extensive monitoring has failed to substantiate reports of widespread decline, yet the issue continues to surface because maple is so important in many ways: wood, maple syrup, aesthetics, and wildlife.

In 1991 we recovered records of research plots measured in the late 1950's in northern hardwood stands of Vermont's Green Mountains. The purpose of the original study was to examine relationships between site index and site characteristics. It was hypothesized that remeasurement of these same plots and replication of the original analyses would uncover any significant changes in productivity that might have occurred over the 33-year period. About half of the plots had been harvested, allowing tests of additional hypotheses about the effects of disturbance.

The investigators found current growth to be equal to or better than growth 33 years ago, with shade tolerant species such as sugar maple increasing to a greater degree than shade intolerant species. This is consistent with expected stand dynamics. In the undisturbed plots, stands grew essentially as predicted from the 1957-59 data. For a given d.b.h., sugar maple was slightly (but not significantly) taller in 1990-92 than in 1957-59 (Fig. 11). For maple stands that were harvested, there was apparently no effect on total carbon stored in the soil.

Disturbance Ecology

Physical and Chemical Environmental Changes

Environmental changes become important to policy makers and land managers at regional to local scales at which risks to specific ecosystems and associated groups of people can be identified. We have made substantial progress in our capability to estimate past trends and project future changes in climate, air pollution, and acid deposition at regional to

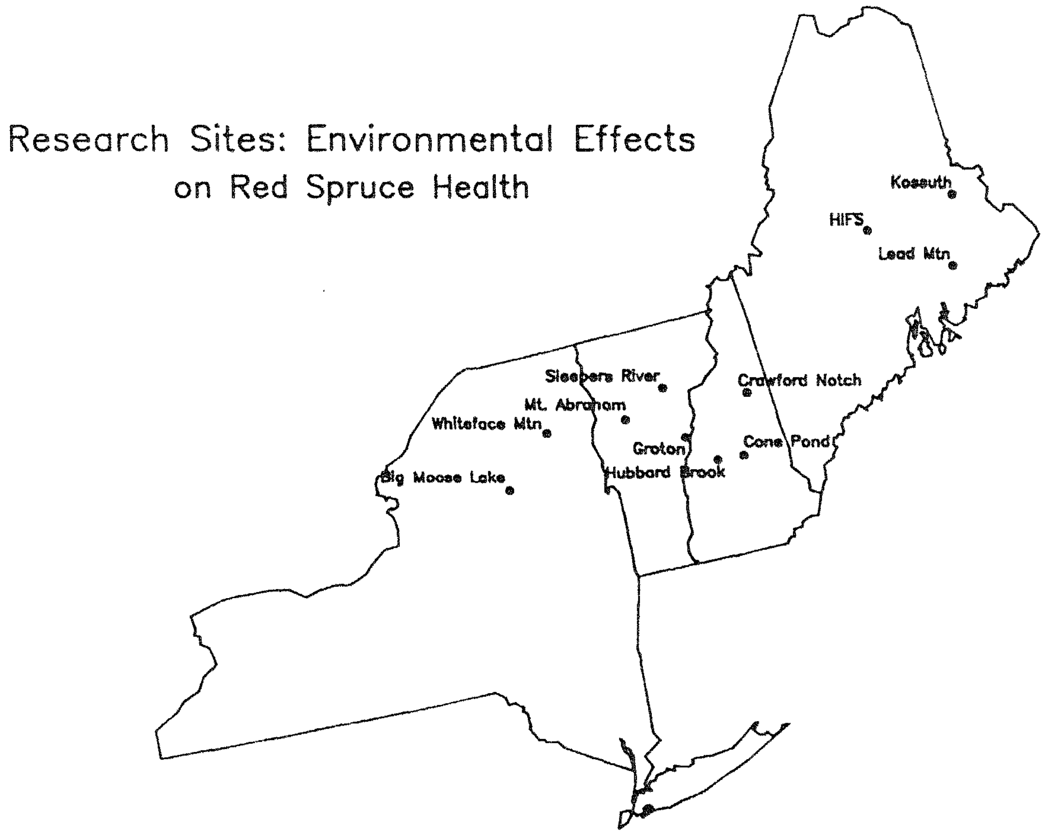


Figure 8.—Network of intensive research plots established to study the effects of environmental change on red spruce health (Lawrence et al. 1995a).

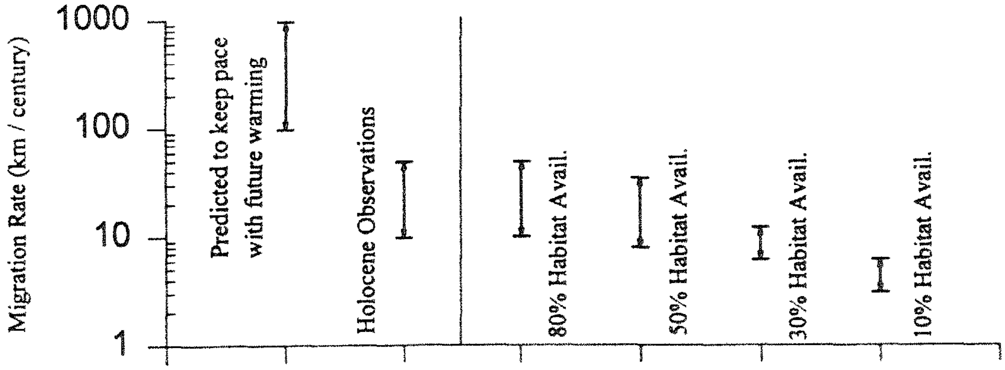


Figure 9.—A schematic diagram of variation in tree migration rates comparing: (1) rates that would be required to keep pace with climate change; (2) observations of Holocene migration rates; and (3) varying levels of habitat availability in a simulated landscape (Schwartz 1995).

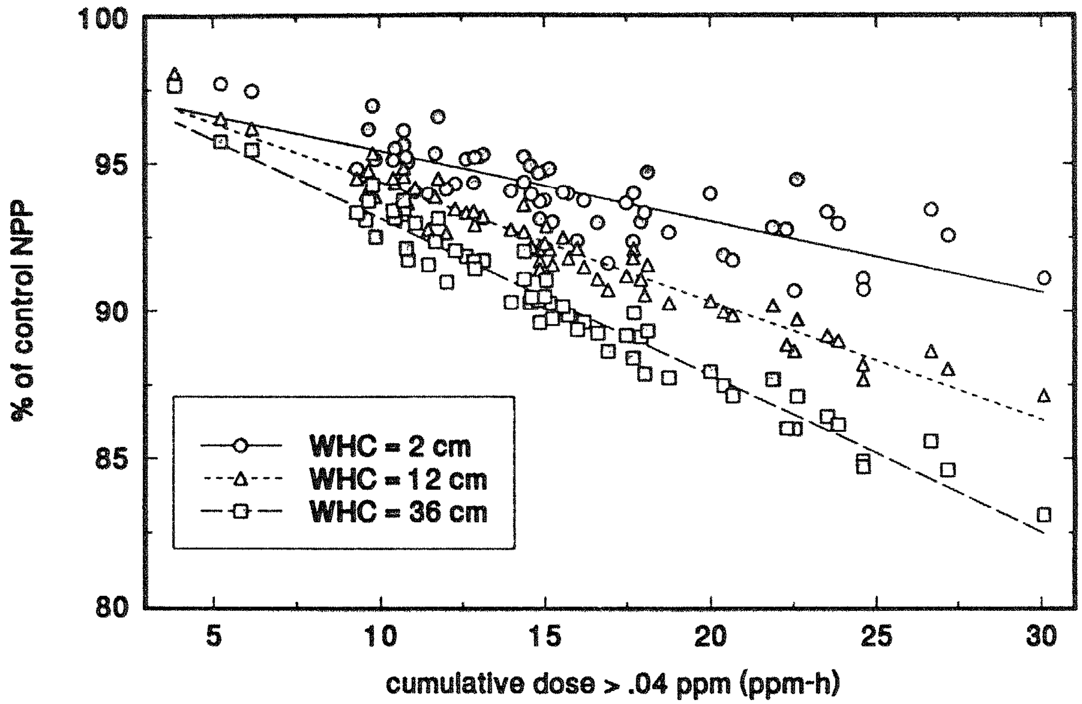


Figure 10.—Predicted change in annual NPP at 64 sites across New England and New York in response to O_3 levels from 1987-92. Predictions are shown for three levels of soil water holding capacity to show how the response changes from well-watered (WHC = 36) to drought-stressed (WHC = 2) conditions (Ollinger et al. 1995).

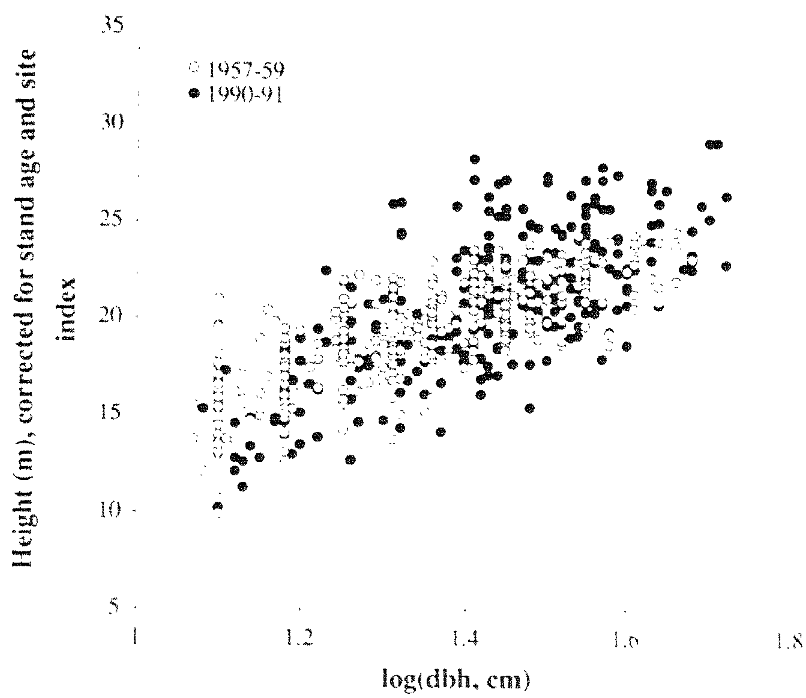


Figure 11.—Height-diameter relationship for sugar maple on two occasions 33 years apart. The relationship has been corrected for stand age and site index (Johnson and Strimbeck 1995).

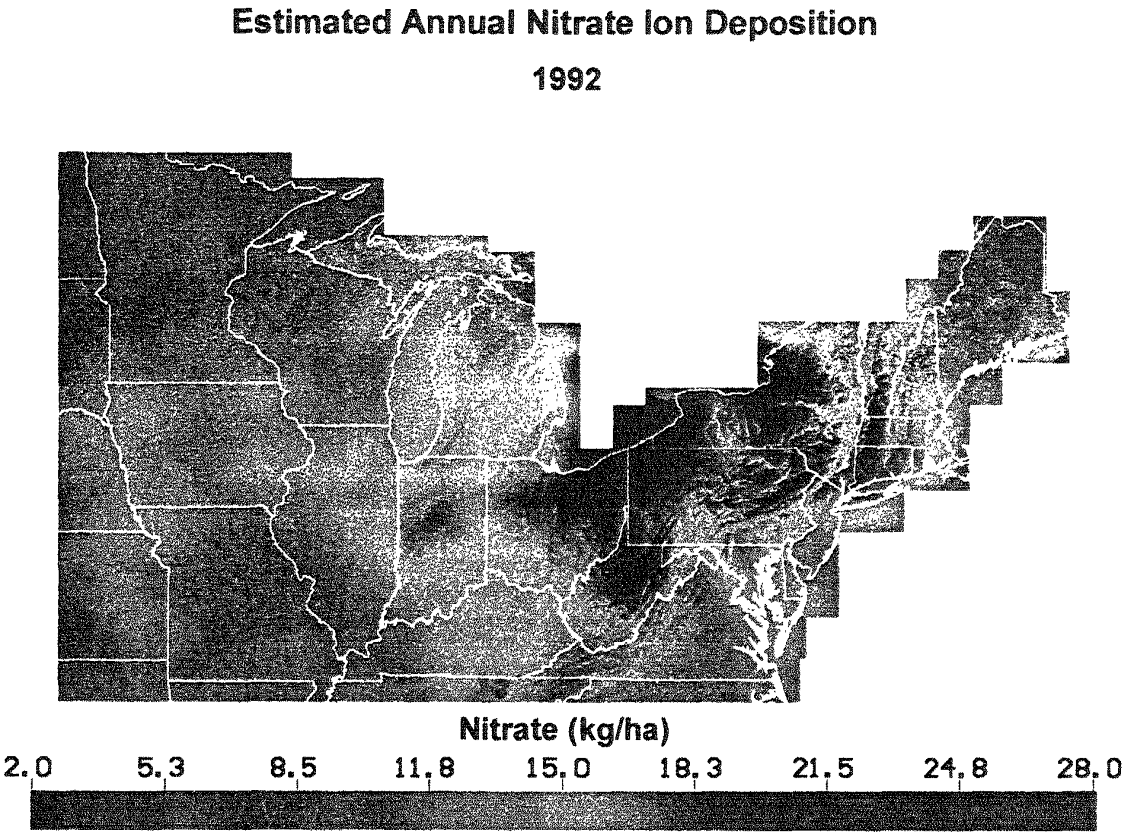


Figure 12.—Estimated annual nitrate ion deposition for the Northeastern and North Central U.S., 1992 (Lynch et al. 1995).

local scales in the Northeast and North Central States. Prominent regional features such as the Great Lakes or the Appalachian Mountains have important local effects that are missed in continental or global-scale models. We developed a microcomputer software program that interpolates historical climate records using geostatistical techniques, so that past trends can be estimated at any point or area. We can project climate trends at any location using a regional-scale model that nests within a global-scale climate model. We can accurately estimate the deposition of chemicals and the acidity of precipitation at geographic scales that resolve important topographic features, so that chemical inputs can be accurately matched with site and vegetation conditions.

Using these models, we estimated the deposition of N, an important nutrient, over the territory covered by the NGCP (Fig. 12). Nitrogen deposition can affect ecosystems in beneficial and harmful ways depending on the availability of existing N in the soil. High levels of N deposition eventually saturate some watersheds and may be exported via streams to contaminate freshwater supplies or disrupt marine ecosystems such as the Chesapeake Bay.

We are concerned about the uncertainty of model-based estimates and projections, and how much weight decisionmakers should give to such results. We completed a study of model validation methods and are beginning to incorporate error propagation techniques into some of our modeling studies. This will allow us to provide decisionmakers with an assessment of the level of uncertainty associated with projections of global change effects.

Atmospheric Interactions with Wildland Fires

Changes in the thermal structure of the atmosphere can potentially affect the frequency of weather systems conducive to fire. Several studies have begun to examine how large-scale atmospheric processes affect regional fire-weather systems (Heilman 1995).

Investigators identified two middle tropospheric circulation patterns that are correlated with the onset of severe wildland fires. These patterns produce abnormally low humidity and dryness at the earth's surface. Analogous surface pressure patterns also were identified. Some of these meteorological variables were integrated into an index for general use in predicting severe fire-weather episodes.

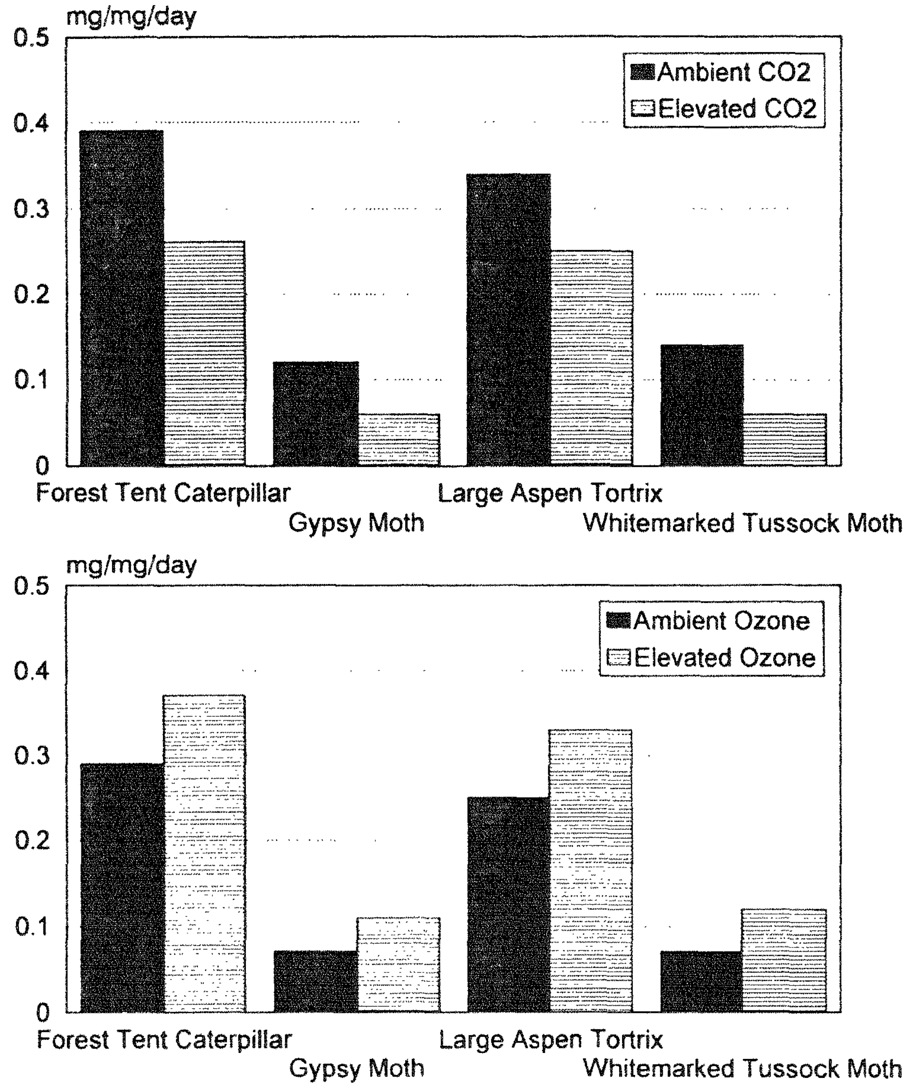


Figure 13.—The relative growth rate of several insects after feeding on foliage from plants exposed to elevated CO_2 (top) or O_3 (bottom) (Herms et al. 1995).

Multiple Stresses Affect Tree Resistance to Insect Attacks

Increasing CO_2 and chronic or episodic O_3 exposure change the chemical composition of foliage, which in turn impacts both the resistance of foliage to insect attack and the nutritional value of foliage for insect growth. Using plant material from open-top chamber experiments, researchers discovered that elevated CO_2 decreased insect growth, and elevated O_3 increased insect growth (Fig. 13). As with physiological responses, the magnitude of the effect on insect consumption of aspen foliage was dependent on the clone used in the experiment. Response also varied for different insect species and for different stages of insect development.

Environmentally induced variations in tree resistance to insects and other herbivores influence the distribution and abundance of insect pests, which in turn affect tree species composition and ecosystem processes such as nutrient cycling. Changes in tree resistance interact with weather changes, another important determinant of insect population dynamics. Using computer models, we are developing predictive tools to anticipate the likely geographic location and intensity of future insect outbreaks, so that managers will be prepared with appropriate control measures.

Human Activities and Natural Resource Interactions

Land Use and Management Intensity Affect C Dynamics

Attempts to quantify the role of Northern forests in the global C cycle, and to understand the effects of management

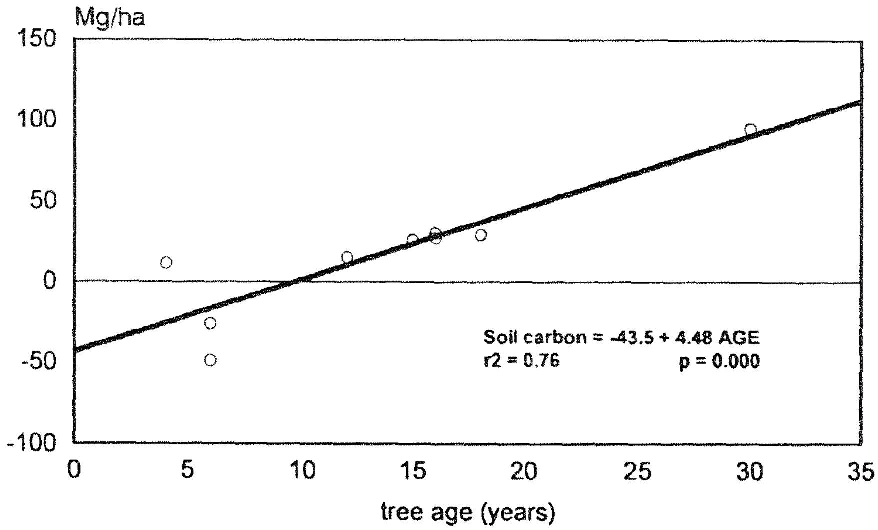


Figure 14.—Soil carbon accumulation with tree age for hybrid poplar after planting on land used for row crops in the North Central U.S. (Hansen 1993).

activities on C storage, have been hampered by a lack of quantitative information. The most statistically reliable information for large areas is derived from forest inventories designed to estimate timber volume and biomass. However, it is difficult to relate this information to specific management practices, and virtually impossible to make a definitive statement about how management practices would affect soil C except in a few specific situations. To help improve estimates for managers interested in tracking rates of C sequestration, we initiated a series of studies to quantify how C in forested landscapes changes over time and under different disturbance levels. By comparing sites with different disturbance histories, it is possible to determine how disturbance affects important ecosystem processes such as N and C cycling, biomass accumulation, species composition, and forest structure.

Hybrid-poplar plantations, common in the north-central United States, sequester significant quantities of C in biomass and soils. Establishing hybrid poplar plantations on former agricultural land increases C storage in the soil above the rate of adjacent agricultural crops by 1.63 Mg/ha/yr after the trees become established (Fig. 14). Red pine plantations in Minnesota, Wisconsin, and Michigan store more C than deciduous forests on similar sites, primarily in the litter on the forest floor (Rollinger and Strong 1995). Under various levels of harvesting, northern hardwood forests differ little in C storage except for expected differences among the components of aboveground biomass. Total ecosystem C under different harvesting intensities also did not differ under various treatments.

Such studies must be carried out in a wide variety of forest ecosystems under many different treatments to fully understand the alternative ways to manage forests to sequester more C. We are examining large soil data bases maintained by the Natural Resources Conservation Service for use in ecosystem process models. Our goal is to help managers understand the effects of disturbance, and to determine whether proposed activities will produce the desired results under changing environmental conditions.

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SOUTHERN GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

The mission of the Southern program is to conduct research and monitoring in the Southern region of the United States; to determine the interactive responses among forest ecosystems, atmospheric pollution, and climate change; and to use this knowledge to manage and protect the forest environment and resources. Initial research emphasized pine and pine-hardwood ecosystems. Other high-priority forest types are hardwoods, southern Appalachian spruce-fir, and forested wetlands.

The Southern program focuses on four of the environmental factors associated with physical and chemical climate: ozone, carbon dioxide, temperature, and moisture. Much work targets the interactions of multiple environmental stresses. A variety of research methods are used, such as controlled exposures of seedlings and mature tree branches to specific environmental stresses, experimental research in soil microcosms in the lab and field, correlational studies of stand and ecosystem functioning, and modeling studies. Models are used to integrate results, improve interpretation, and make predictions. Models are used to "scale up" from one hierarchical level to the next.

The Southern program includes research on the socioeconomic impacts of global change on forest resources of the South. Both timber and nonmarket economic resources are evaluated. Methods for assessing the socioeconomic impacts of global change are designed to provide information in a form especially useful for policymakers. Other socioeconomic research addresses questions of how forest management practices may be affected and how forest policies may change.

The Nation's timberland contains an estimated 858 billion cubic feet of timber, of which 92 percent is in growing-stock inventory (live, sound trees suited for roundwood products). Timber removals from growing stock inventory in the United States in 1991 totaled 16.3 billion cubic feet (Fig. 15). Nearly 55 percent of all timber removals came from southern forests. The South continues to increase its share of timber harvest—up from 45 percent in 1970. Timber harvests ranked among the top three crops in terms of value of production in all southern states. Forest industries employed one out of every nine workers, paid $1 out of every $10 in wages and salaries, and produced $1 out of every $11 of value added to the economy. Forest and forest industries are clearly of great importance to the economy and society of the South. It is also clear that they have been increasing in importance in recent decades.

Southern pines and other softwoods account for 38 percent of the timber volume in the South and 22 percent of the softwood volume in the Nation (Fig. 16). Predictions are that the average volume of softwood stands will decrease with proportionally more inventory in younger and faster growing stands, and there will be a transition from existing stands of mostly natural origin to stands with a higher proportion of managed acres. With the interest in hardwood forests in the region, these trends will likely apply to hardwood acres also.

The atmosphere's chemical environment is changing in the South. Ozone is considered the most phytotoxic air pollutant that can cause stress to trees. Ozone is a major concern especially in the summer months when stagnant air exacerbates the problem. Concentrations of O_3 in urban, suburban, and outlying areas often exceed National Air Quality Standards. Ozone occurs in concentrations sufficient to cause injury to foliage and disrupt physiological processes. The Clean Air Act does not provide a mechanism for reducing O_3 concentrations nor to slow its increase. With a 2 percent per year increase in tropospheric O_3 (Fishman 1991), the region will achieve a 50 percent increase in ambient O_3 concentration in 21 years (Teskey 1996).

Atmospheric CO_2 concentrations are rising at the rate of 1.4 ppm per year. Monitoring records and historic atmospheric CO_2 records obtained from ice cores show that the pre-industrial atmospheric CO_2 concentration in 1750 was 280 ppm and has increased in 1992 to 356 ppm (Mickler [In press]). Carbon dioxide concentrations in the atmosphere are expected to be twice pre-industrial concentrations by the middle of the next century. Carbon dioxide is a concern because of its direct and indirect effects on vegetation. Direct effects are the result of increased uptake and its effect on plant metabolism. Indirect effects include the climate altering impact of increased greenhouse gas concentration in the earth's atmosphere.

From 1960 to 1980, southeastern regional SO_2 emissions more than doubled from 2.0 teragrams per year to 4.4 teragrams per year. During the 5-year period from 1980 to 1985, SO_2 emissions increased to 4.8 teragrams per year. Sulphur dioxide emissions have not changed substantially from 1985 to 1992. Nitrous oxide emissions increased from 2.5 to 6.5 teragrams per year from 1960 to 1980. Since 1980, emission rates of NO_x have leveled off and may have decreased slightly (Allen and Gholz 1996). At ambient concentrations and rates of deposition, neither acid rain nor dry deposition of S and N has been shown to cause detrimental effects on southern pines. However, soil Ca availability is being significantly reduced by acidic deposition in high elevation spruce-fir forests, and this has long-term implications for the health of this forest ecosystem. Over the long term, some studies suggest that S, in solution, may leach nutrients from already depleted southern forest soils. At the same time, N, which is widely limiting to tree growth on many southern pine forested sites acts as a fertilizer.

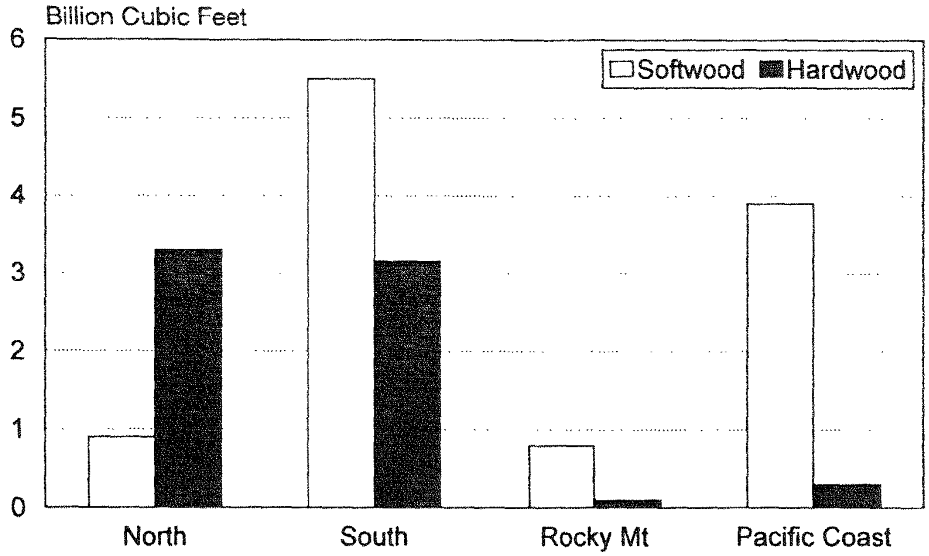

Figure 15.—Net annual removals of growing stock on timberland in the United States by region, 1992 (Powell et al. 1992).

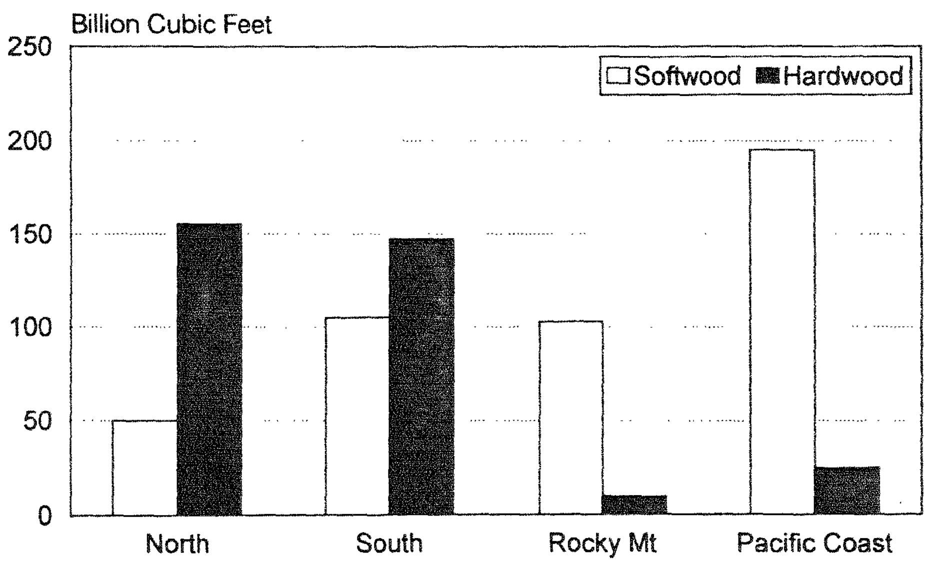

Figure 16.—Net volume of growing stock on timberland in the United States by region, 1992 (Powell et al. 1992).

Atmosphere/biosphere Gas and Energy Exchange

General Circulation Model Scenarios and Regional Climate Predictions for the Southern United States

Regionwide and within-region climate change projections were developed for the South by four General Circulation Models: the NASA Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the Oregon State University (OSU), and the United Kingdom Meteorological Office (UKMO).[1] Although some statements concerning possible global changes under double atmospheric CO_2 conditions can be made with varying levels of certainty, the regional expression of these changes remains highly uncertain. The regional results suggest agreement regarding warming in the South. The states of Louisiana, Mississippi, and Georgia could experience the greatest degree of change within the region. Although projected annual precipitation increases could result in a more favorable biological environment for the South, changes in the within-growing season distribution of precipitation make predictions of changes in biological productivity less certain. Uncertainty in the model parameterization of cloud formation and cloud radiation feedback makes statements regarding changes in humidity and solar radiation highly speculative. Critical findings for regionwide projections include: a mean regional temperature increase range from 3.6 to 6.7°C across the growing season, general model agreement suggesting an increase in growing season precipitation and decreased non-growing season rainfall, a slight increase in growing season solar radiation, and an increase in vapor pressure (Cooter [In press]).

Reconstruction of Historic Climatology and Ecosystem Disturbance from Tree Ring Chronologies

Tree-ring data can extend back in time for thousands of years allowing researchers to reconstruct certain environmental factors that have left an imprint in the tree-ring record. These factors can include annual precipitation or temperature for months or seasons to which a particular tree species is sensitive, and the timing and extent of natural phenomena such as volcanoes, earthquakes, El Nino-Southern Oscillations, fire, hurricanes, and atmospheric CO_2 concentrations. Baldcypress tree-ring data have shown that climate reconstruction for drought and hurricane events is possible. Small ring widths occur for drought years and for the immediate effects of a hurricane as a result of decreased productivity from drier soils and reductions in foliage area from high winds, respectively. These findings indicate that a reduction in baldcypress productivity and possible negative impacts on regeneration can be expected under climate scenarios for the South (Reams and Van Deusen [In press]). Tree-ring analysis of loblolly pine from plantations throughout the South indicates that loblolly pine is a sensitive indicator of ecosystem disturbance for drought and temperature. Loblolly pine along the western range in east Texas and southwest Arkansas revealed a very strong drought sensitivity, especially to June rainfall and temperature. In extreme northern plantations in eastern Maryland, the climate response was largely driven by January/February monthly maximum temperatures that average less than 10°C. This response indicates that loblolly pine could expand its northern range due to warming during the winter season, so long as this increase in winter temperature does not exceed 4 to 5°C (Cook et al. [In press]).

Ecosystem Dynamics

In natural and managed forest ecosystems, individual trees and entire stands are exposed to multiple changes in the chemical and physical environment. These changes include known plant stressors such as temperature, moisture, and nutrient stress that foresters have historically linked to limitations to forest productivity. But changes also include relatively recent stressors contributed by a rapidly changing chemical and physical environment on the regional and global scale. These new stressors include documented increases in CO_2 and O_3 concentrations, increases in deposition of S and N from the atmosphere, land use changes, and salinization of ground water in near-coastal ecosystems. To address the questions about the ecological effects of global change on forest sustainability and productivity, it is critical to begin to understand the interaction of stressors on forest ecosystems.

Tree Responses to Elevated CO_2 and Temperature

Regional climate scenarios predict increasing temperatures in the South. Extremes of high and low temperatures are already limiting factors of successful regeneration and productivity of southern forests. After 3 years of study, mature loblolly pine exposed to elevated temperatures and CO_2 showed an increase in net photosynthesis of 40 to 100 percent throughout the year and an increase in leaf area of 33 percent (Fig. 17). These increases are attributed to increasing concentrations of CO_2. Even though temperature is known to be an important factor in controlling the rate of physiological processes, elevating air temperature by +2°C throughout the year had little overall impact on C gain relative to the dramatic effect of elevated CO_2. These results indicate that increasing concentrations of CO_2 in the atmosphere will cause a large linear increase in the pine growth rates and stand productivity (Teskey [In press]).

Ozone and Water Stress Induced Growth Decline

Ozone episodes continue to occur widely across the South, including all the forested areas within the region. Air pollutants and impacts on forest health have drawn regional attention because of the reporting of growth reduction for some southern pines. More recently, O_3 was implicated as the causal agent for a 5 percent annual growth reduction in many important southern commercial pines. Water deficit is the most widely recognized factor that limits growth of forest trees in the South. Studies on pine seedlings exposed to a range of O_3 concentrations and levels of water deficit showed that water

[1]These GCM outputs did not include the effect of aerosols.

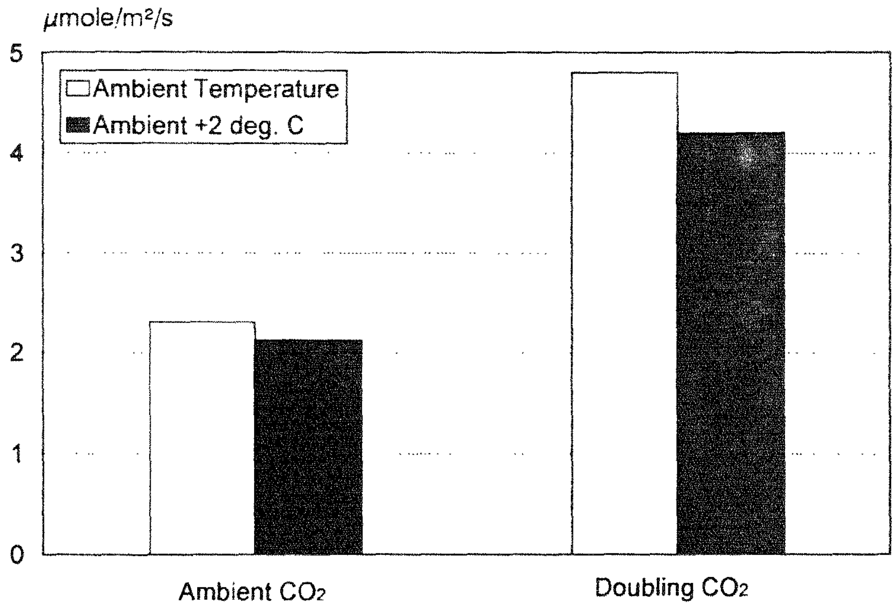

Figure 17.—Change in rate of net photosynthesis in loblolly pine in response to doubled CO_2 concentration and increased air temperature (Teskey [in press]).

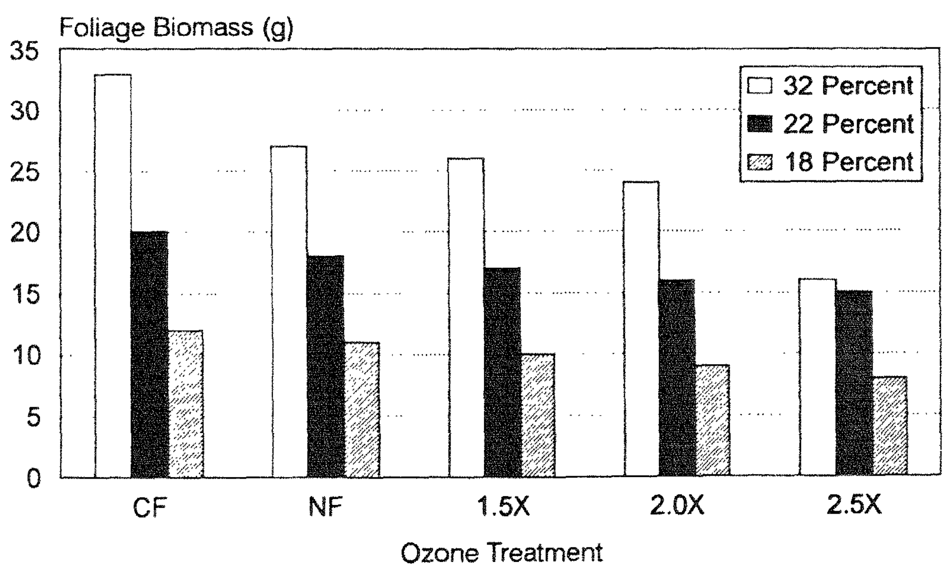

Figure 18.—Reduction in foliage biomass of shortleaf pine in response to increased concentration of O_3 and decreased soil water content (Flagler et al. [in press]).

deficit clearly limited growth and physiology. Of particular interest were the significant O_3 induced tree responses that occurred in the moderate and severe soil water deficit conditions (Fig. 18). Ozone uptake by trees continued at detrimental doses even under significant water limitations. These studies show that reductions in foliage biomass and tree growth as a result of O_3 exposure will continue under climate change scenarios for the South. The studies also illustrate that impacts of O_3 and water deficits obtained from previous crop studies cannot be generally applied to other vegetation types, such as forests (Flagler et al. [In press]).

Impacts of CO_2, Nutrient Inputs, and Water Inputs on the Condition of Southern Forests

Ongoing research in a loblolly pine forest is attempting to determine how changes in CO_2, nutrient inputs, and water inputs may be impacting forest productivity. Increases in CO_2

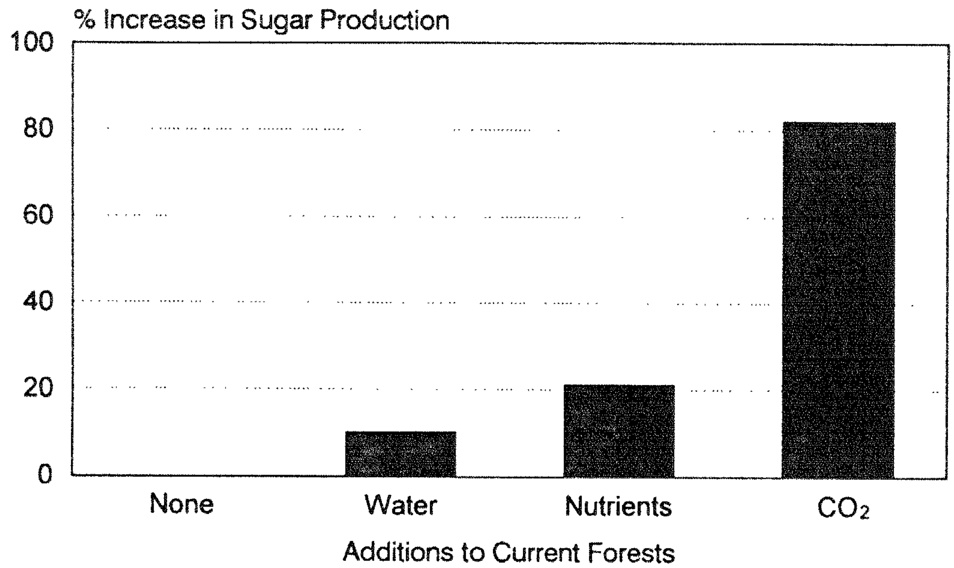

Figure 19.—Potential increases in forest productivity in response to increased soil water availability, nutrients, and atmospheric CO_2 (Dougherty et al. [in press]).

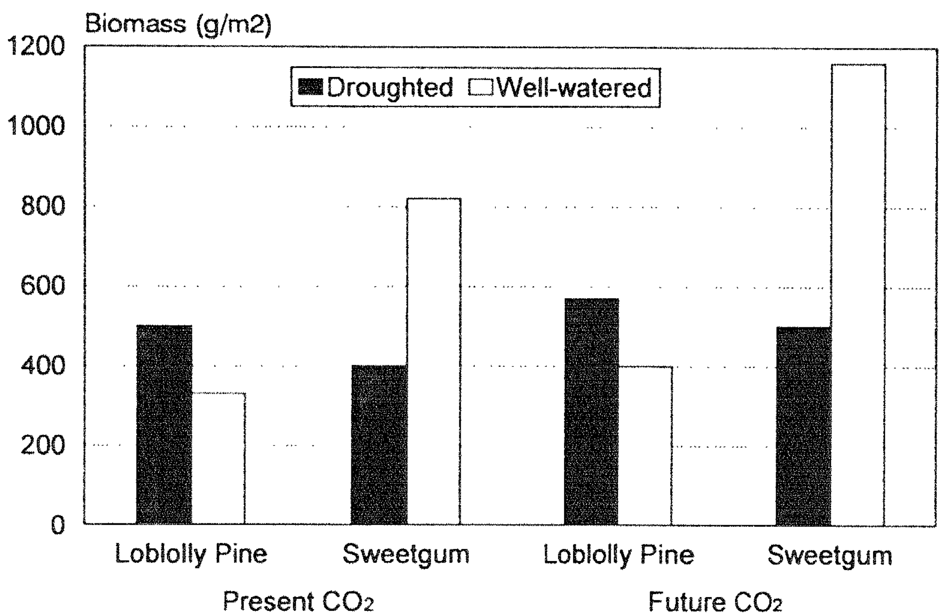

Figure 20.—Increases in total biomass of loblolly pine and sweetgum under different levels of soil moisture and increased atmospheric CO_2 (Groninger [in press]).

concentrations and nutrients increase pine productivity. The biggest increases in photosynthesis, as measured by sugar production potential, were due to a doubling of current concentrations of atmospheric CO_2. Maximum sugar production potential was increased by 82 percent compared to that in trees growing at current levels of CO_2 (Fig. 19). Improved nutrition, currently believed to be our best forest management strategy for increasing forest productivity, only increased maximum sugar production potential by 21 percent. Improving soil water availability increased maximum sugar production potential by 10 percent. These research findings show that the overall benefits from increasing CO_2, nutrients, and water indicate an additive potential for increasing forest productivity. The potential rates of increase may be reduced by projected increases in temperature regimes and decreases in rainfall. This research increases our basic understanding of the impacts of a changing environment on tree growth and physiology (Dougherty et al. [In press]).

Global Change Impacts on Reproductive Biology

Field studies have shown the importance of temperature, soil moisture, and light for the flowering and fruiting of forest trees. Little was known about the interaction of environmental factors with increases in global CO_2 concentrations and the effect on the reproductive biology of trees. Exposures of hardwood and pine trees to elevated levels of CO_2 and increased temperatures have demonstrated a significant impact on the time of pollen release and seed maturation. Pollen release occurred almost 2 weeks earlier and time of seed maturation was lengthened on treated trees. The research suggests that the number of seeds are reduced, but the size of the seeds increases in trees with elevated temperatures and CO_2. There was no impact on seed viability. These studies demonstrate that changes in reproductive biology should be considered when assessing the effects of global change on the natural migration of hardwood and pine species and in genetically improved plantations. Alteration in the time of year of flowering and fruiting of trees has the potential to alter the ranges of commercially important tree species and alter existing forested ecosystem biodiversity (Connor et al. [In press]).

Potential Effect of Climate Change on Tree Competition

Wood production in managed forests is hampered by competition from undesirable vegetation, but this key element of forest management has been largely ignored in studies of anthropogenic stress. Competition studies were conducted to mimic regeneration of pure seedling stands of loblolly pine and sweetgum and mixed stands of both species under different levels of soil moisture, N availability, and CO_2. Higher concentrations of CO_2 increased the total biomass of both species: 33 percent for sweetgum and 14 percent for loblolly pine (Fig. 20). In mixed stands, the balance of competition between these species as judged by biomass, was not altered by differing concentrations of CO_2. These findings differ from reports by other researchers measuring individual trees in pure stands. They concluded that sweetgum was a stronger competitor when grown with increasing concentrations of CO_2. Additional findings from these studies show that increasing concentrations of CO_2 cause large changes in below-ground biomass. In mixed stands, sweetgum had an increase of 96 percent and loblolly pine had an increase of 110 percent in fine root density in response to increasing CO_2 in the presence of adequate amount of soil moisture and N, but this result changed in seedlings grown in pure stands. These studies demonstrate that global change induced alterations in species competition across the range of southern pines must be considered when assessing future stand productivity and sustainability (Groninger et al. [In press]).

Potential Changes in the Vegetation Distribution in the South

An analysis of the potential impacts of CO_2-induced global warming on vegetation distribution was conducted to determine if the impacts on vegetation will be of sufficient magnitude, either positive or negative, to require shifts in forest management policies and practices. Vegetation distributions were simulated using the Mapped Atmosphere-Plant-Soil System (MAPSS). The model successfully predicted 503 million forested acres of the 562 million forested acres in the United States currently identified from field survey data and remote sensing forest maps (Fig. 21). We compared the MAPSS vegetation map under current climate and potential future forest distribution under global climate change scenarios. The area in southern pine and hardwood forests increases up to 42 percent in most future climate scenarios. These gains in forest area are

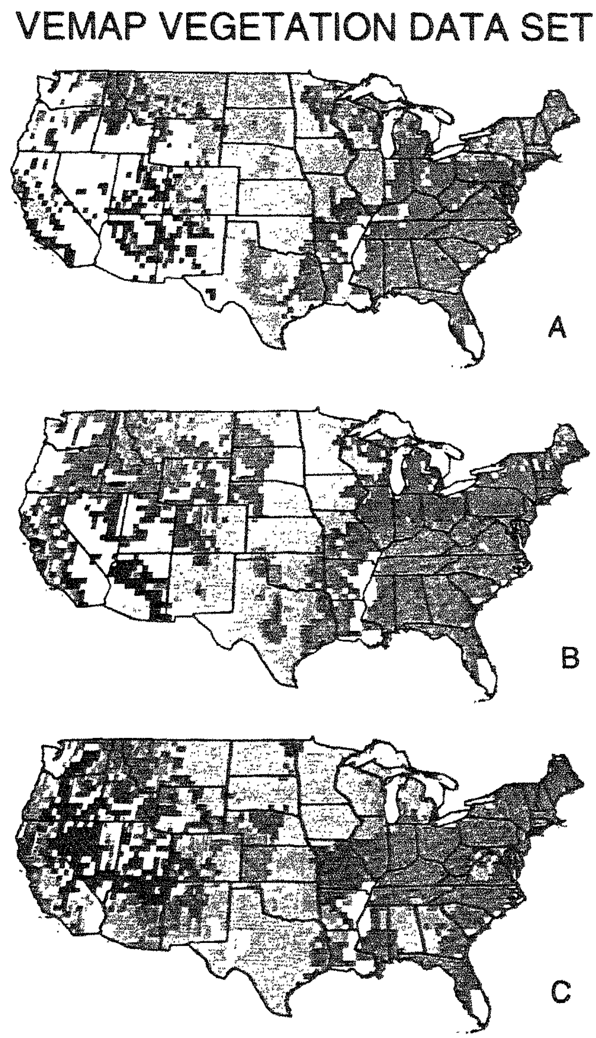

Figure 21.—Simulated vegetation distribution using the MAPSS model, (A) VEMAP vegetation data set, (B) potential future forest distribution showing expansion of southern pines, (C) potential future forest distribution showing increases in low density forest and moist tropical forest (Borchers and Nielson [in press]).

accompanied by associated large shifts in forest type from high-density forest to low-density woodlands. A comparison of the average forest density of each type in its current location with the average density of all trees for that type in its new location shows a reduction in average density of 15 percent across all forest types and a 51 percent reduction in southeastern mixed forests. Examination of foliar volume change indicates large volume losses (57 percent) in all southeast forest types. The results of the model indicate that in general there are northward and elevation shifts in all forest types and a trend to reduction in tree density and volume. Dry tropical forests with an open woodland structure and to a lesser extent moist tropical forests increase in the Gulf States. The MAPSS model and other biogeography and biogeochemistry models are being used to bracket the possible range of responses of forest ecosystems to environmental change (Borchers and Neilson [In press]).

Disturbance Ecology

Predicting Changes of Southern Pine Beetle Populations

From 1960 to 1990, southern pine beetles (SPB) caused $900 million in damage to forests in the South. Early detection of SPB outbreak areas is essential to controlling population increases, but tracking beetle damage is difficult and expensive. In the past, various models have been developed to predict SPB outbreak severity across the region, but these have had limited success. An improved regional scale forest process model has been developed to predict how forest growth and soil water use will affect SPB populations and assess how SPB populations are affected by present and future climatic variations. If across the southern United States, average monthly air temperature increases by less than 3°C and precipitation patterns and amounts remain relatively unchanged (± 5 percent), forest growth and water use will generally decrease moderately. This should cause a moderate decrease in SPB populations across the region. However, if the average monthly air temperature increases by more than 4°C and precipitation patterns and amounts remain relatively unchanged, then severe decreases in forest growth, geographic ranges, and water use, and increase in SPB populations can be expected (Fig. 22). In addition to assessing SPB population under future climate scenarios, the model can be used to predict changes in forest growth, water use, and SPB populations across the South under current climatic conditions (McNulty et al. [In press]).

Responses of Managed Loblolly Pine to Changes in Stand Environment

Forest health and productivity are a function of constant physiological interaction between the roots and crowns of trees. The availability of resources such as light, water, and nutrients regulates these internal physiological interactions. Shifts in temperature and precipitation that are predicted to occur with global climate change may strongly affect resource availability. Research is being conducted to define intrinsic relationships between whole-tree processes and climate that are critical for maintenance of southern pine forests. Intensive measurements of root growth, soil environmental variables, and crown physiology have shown that 58 percent of new loblolly pine root growth occurs in the period between May and June, and that new root growth is strongly tied to water availability (Fig. 23). For example, a spring drought lasting 22 days caused 59 percent and 36 percent reductions in soil water content and new root elongation, respectively. Low amounts of new root growth in late summer and fall may also be attributed to water deficit which occurs frequently in southern forests. Simultaneous crown physiological processes were not dramatically affected; however, negative effects of water deficit on crown physiology may remain latent until the following growing season. By conducting this research in four stand environments that were created using operational thinning and fertilization treatments, we are learning how these management tools can be used to manipulate resource availability, tree physiology, and stand productivity. Results indicate that silvicultural treatments strongly influence the environment and physiology of the lower crown. A positive relationship was observed between new root growth and levels of light, foliage production, and C fixation in the lower crown of individual stands. This suggests that management tools could be used to manipulate C fixation and portioning in forest stands to either offset the negative effects or capture the positive effects of global climate change on forest productivity (Sword et al. [In press]).

Climate Change Could Effect Biodiversity from Species to Landscape Levels

Climate has not been stable in the past with the greatest changes probably occurring during the last deglaciation, 12,500-11,000 years ago. However, in parts of the United States, great shifts in plant distribution and composition occurred during the past 120 years, mainly due to anthropogenic factors. Although global climate change projections for the South vary considerably, we can predict that the diversity of plants and animals is likely to be reduced as a direct result of global warming. The effects of global change will be most severe in the coastal habitats. A moderate rise in sea level would likely cause the destruction of already disturbed wetlands. This would result in the worst wildlife-related disaster caused by the greenhouse effect in the United States. Researchers suggest that climate change will cause a domino effect in southern forests, with each ecosystem losing space as it moves north and displaces species in other ecosystems. Many of the plant and animals that are associated with southern forests may become threatened or extinct because they are unable to move as rapidly as the tree species that provide their habitat. The salinization of ground and soil water resulting from a rise in sea level has and will continue to cause a reduction of pine forests in low-lying coastal ecosystems. Inland wetlands and forests, in contrast, will suffer from decreasing precipitation and increasing frequency of fire. Efforts to ameliorate climate change through conservation efforts will likely be overwhelmed by increasing numbers of threatened and endangered species. Many less conspicuous and economically important native species will probably not survive (Devall and Parresol [In press]).

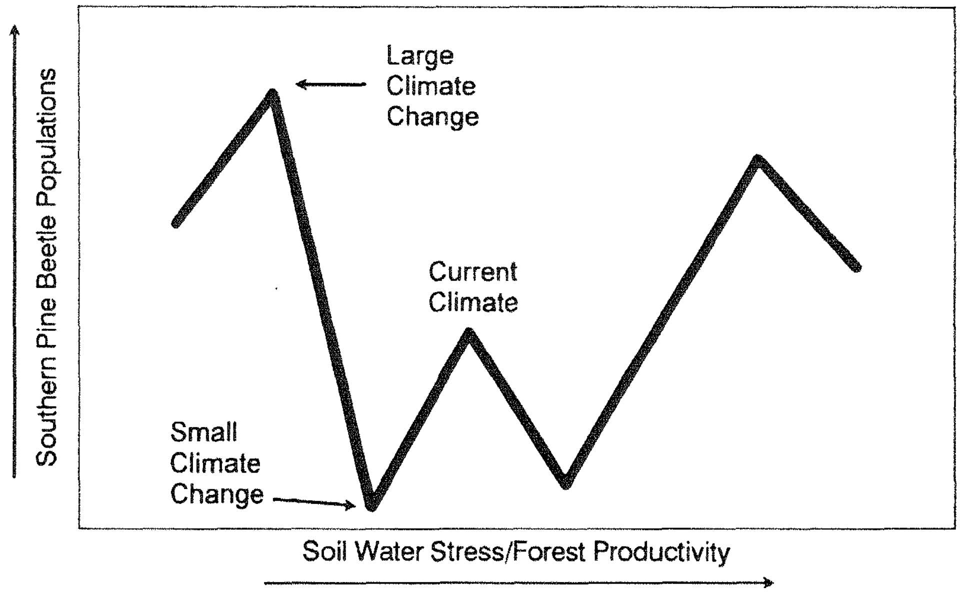

Figure 22.—Changes in southern pine beetle populations under altered forest growth and soil water availability in current and future climate change scenarios (McNulty et al. [in press]).

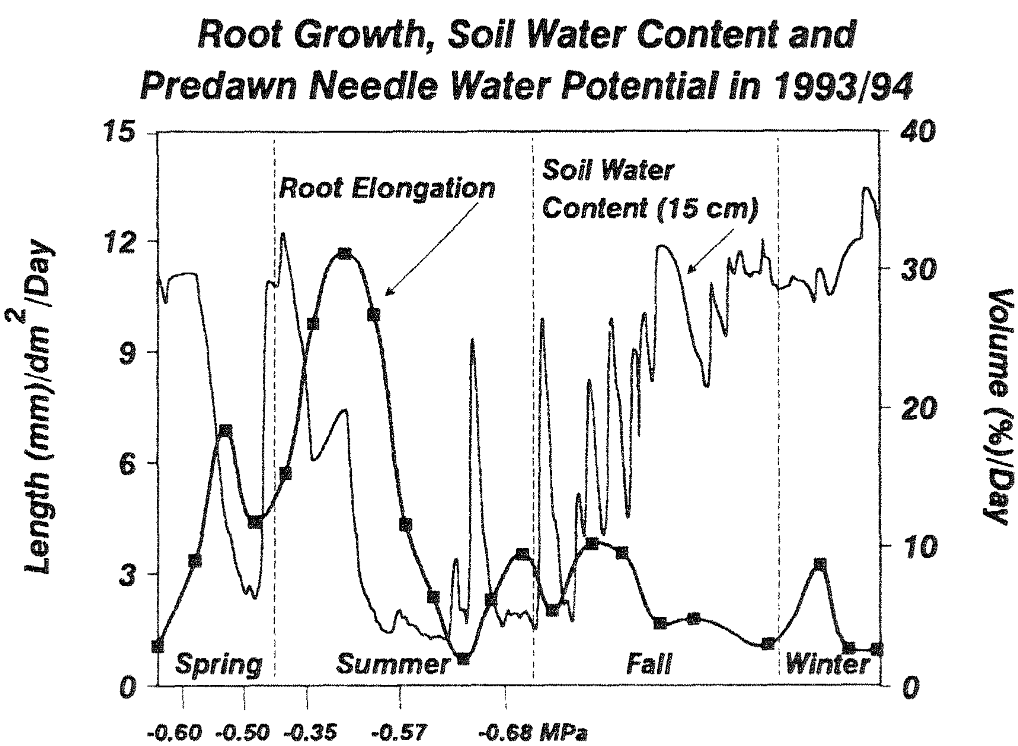

Figure 23.—Root growth, soil water content, and predawn needle water potential in a loblolly pine stand showing correlation of root growth and soil water availability (Sword et al. [in press]).

Atmospheric Circulation Patterns in the South Associated with Severe Wildfires Could Increase

Atmospheric conditions play a critical role in affecting the severity of wildfires and the probability of their occurrence in the South, as well as the rest of the country. Large-scale changes in the normal atmospheric circulation patterns as a result of global climate scenarios have the potential for increasing the frequency and intensity of wildfires across the South. Research on synoptic-scale circulation patterns in the middle troposphere has shown distinct weather patterns associated with the most severe wildfires (Fig. 24). The circulation patterns that are associated with severe wildfires in the South produce lower atmospheric temperature and moisture patterns that enhance the probability of fire occurrence if fuel conditions are adequate. Because severe wildfires are strongly linked to relatively short-term weather events that produce conditions favorable for their occurrence, any large-scale circulation changes in the atmosphere brought about by global climatic forcing factors have the potential to modify the normal weather events conducive to severe wildfires. If the occurrence of circulation patterns and weather events associated with wildfires increase as predicted by some climate change scenarios for the South, it is likely that the region would experience more severe wildfires (Heilman et al. [In press]).

Figure 24.—Large-scale circulation patterns associated with historically severe wildfires in the Southern United States (Heilman et al. [in press]).

Human Activities and Natural Resource Interactions

Evaluating the Impacts of Global Change Forest Policy Options on Forest Markets

Projections with the Forest and Agricultural Sector Optimization Model (FASOM) indicate that forest C can potentially be significantly increased in the South at the same time that timber production is increasing, without large increases in timber prices. Currently, forest industry controls approximately 20 percent of the total timberland and more than 60 percent of the pine plantations in the region. Non-industrial private forest lands offer a large and diverse private forest resource for increasing growth under global change policies and an array of robust market conditions. Long-term projections indicate the largest area-based changes will occur on private forest lands, and timber management intensification on these lands could act to mitigate timber-supply based impacts. A key projected land base change involves conversion of 6 million hectares of private hardwood land to pine plantations during the next decade. A small net gain in private timberland is projected in the region for the period between 1990 and 2039. Gains in timberland from agricultural cropland conversion are almost entirely offset by conversion of forest land to urban areas. Increased future competition for private forest land could lead to higher prices which may lead forest industry to intensify timber management on its fixed land base and increase the area in pine plantations. Attainment of C sequestration targets will require large areas of afforestation at a rate which exceeds past historical trends. Forest C projections are expected to increase the most in the South because of the region's young softwood stands. Overall, southern timber volumes are projected to increase by more than 70 percent and hardwood volumes will increase by less than 10 percent by 2039 (Alig et al., [In press]; Burton et al., [In press]).

Potential Economic Impact of Gradual and Abrupt Ecosystem Change

The uncertainty inherent in projecting forest response to climate change has limited attempts to evaluate the potential economic impact of ecosystem changes on forestry in the United States. Uncertainty is introduced into any economic assessment due to the long time horizon inherent in modeling climate change scenarios, which include regional projection of future temperature and precipitation regimes and interactions with atmospheric CO_2. Climatic change scenarios for the South were used to explore impacts on unmanaged forests and on the softwood timber supply. Forest distribution simulations indicated that forests in the extreme south and at the western margins would be replaced by prairie and savanna resulting in a 47 percent decline in forest land for the region. Loblolly pine was projected to replace shortleaf pine at higher elevations and the range of loblolly pine was extended to the north. The potential change in distribution of loblolly pine would have a substantial impact on future softwood supply. A 45 percent loss of suitable forest land would result in an 84.1 percent loss of softwood stumpage in the region. A 25 percent loss of land area for softwood forests causes a 45 percent reduction of stumpage. This scenario implies that every 5 percent area reduction results in more than a 9 percent decline in future softwood supply. A positive increase in net yield from increased atmospheric CO_2 would not offset more than 10 percent of the northern migration of southern forests. Thus, reducing the uncertainty in models estimating potential changes in vegetation distribution will reduce the uncertainty associated with economic impact assessments more than obtaining better estimates of effects of CO_2 enrichment on forest productivity (Gunter et al., [In press]).

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INTERIOR WEST GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

Studies at long-term research sites are yielding data about CO_2 and O_3 flux between the atmosphere and biosphere, either through direct measurement or by inference from chemical records in tree rings. Because climatic stability is rare in the Intermountain West, and there are many sites where vegetation is already under climate stress, scientists are looking for early signs of change at ecosystem boundaries. Paleoecological techniques are being used to reveal long-term patterns of climate change in tree rings and wood rat middens.

Tree-ring records and experiments in exposure chambers can yield valuable clues about how trees have responded, and are expected to respond, to changing levels of atmospheric CO_2. At the ecosystem scale, a variety of observational and modeling techniques have been used to study effects of climate and fire on mountain pine beetle populations and vegetation change in the mountains, and the interactions of trees and crops in the Great Plains.

Disturbance research has included the effects of fire, weather, and air pollution on mountain ecosystems. This includes study of the impacts on nutrient cycling, hydrology, and vegetation.

At landscape, regional, and national scales, models that integrate social and ecological systems, decision support tools, and historical analysis have all contributed to understanding of global change effects on ecosystems and human interactions. Much of this research is addressing problems that will be faced by land managers over the next few decades. Scientists have made notable contributions to integrated assessments at the national scale, addressing urgent policy issues dealing with climate change effects on forests.

The TERRA laboratory has experimented with decision process support tools designed to facilitate collaboration among scientists, managers, and resource stakeholders. They developed an active response geographic information system (GIS) to facilitate revisions of land management plans by the National Forest System.

Atmosphere/biosphere Gas and Energy Exchange

High-Resolution Climate Models Facilitate Analysis of Ecosystem Impacts

To help us understand global change impacts on forest and rangeland ecosystems, we use models based on what we know about biogeochemical processes, and then experiment with the models to project ecosystem responses under a variety of climate scenarios. Global climate models have shown that we can expect global warming, but they are not detailed enough to be accurate at a regional level, even with 50- x 50-km resolution models becoming available. We compared 50- and 10-km grid models for northern Idaho and western Montana. Preliminary results for the 50-km model show reasonable agreement with temperature, but precipitation is overpredicted and climatically important topographic features present in the 10-km model are lost (Fig. 25).

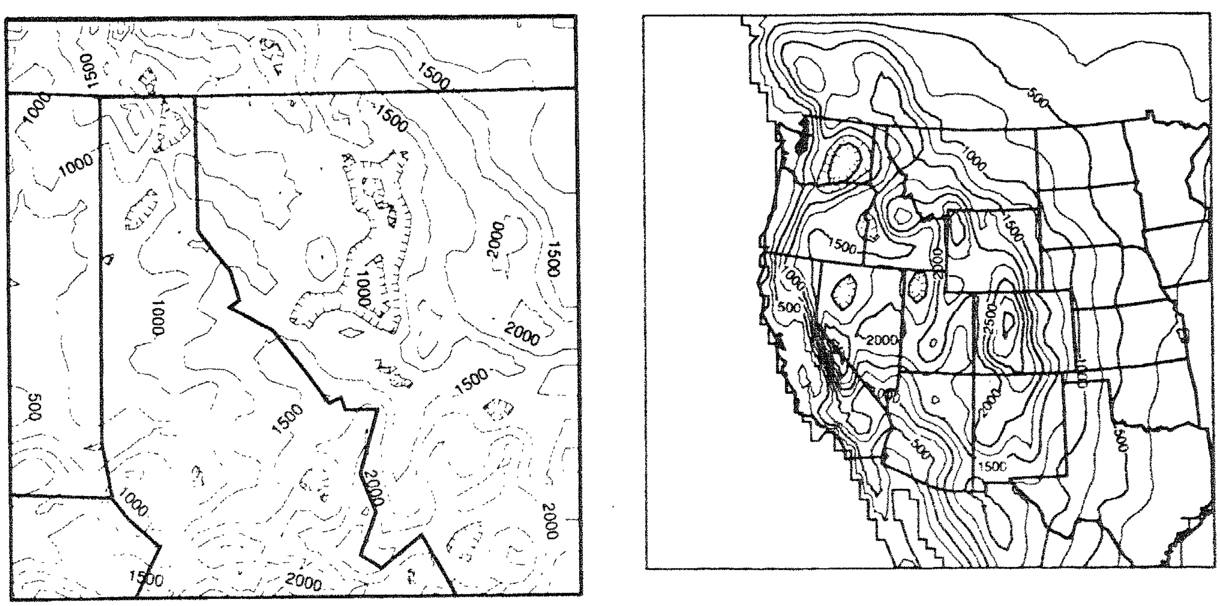

Figure 25.—A 10-km grid map (left) shows important features that are lost on a 50-km grid map (right) (Luce et al. 1995).

Ozone and CO_2 Flux in Subalpine Spruce-fir

Measurements of CO_2 concentrations near the forest/atmosphere boundary help us understand how forest ecosystems change the amount of atmospheric CO_2 as rates of photosynthesis and respiration change on daily and seasonal cycles. The Glacier Lakes Ecosystem Experiments Site in southeast Wyoming is one of the few remote subalpine sites in the United States where trace gases and environmental factors are measured. Measurements were taken at two heights on a tower, above and below tree canopy, to estimate the daily and yearly patterns of CO_2 and O_3 flux in a subalpine spruce-fir forest. Carbon dioxide flux responds dramatically to wind speed and temperature fluctuations, exhibiting strong daily and seasonal changes that follow weather patterns. Measurements of O_3 concentration help us identify the role of forests in the uptake and destruction of tropospheric O_3. This too changes on a daily and seasonal cycle, with some unexpected and unexplained interactions with winter snow cover (Zeller and Hehn 1996).

Carbon Cycling in Southwestern Ecosystems

The dynamics of the C cycle depend on the rate of processes that control storage in, and transfer between, the various reservoirs in the ecosystem (live biomass, coarse woody debris, litter, and soils). Preliminary findings indicate that litter quality and moisture, rather than temperature, are the major controlling variables in arid and semi-arid ecosystems ranging from desert shrubland to pinyon-juniper to ponderosa pine (Klopatek et al. 1995). Exploration of these ecosystem changes under various levels of management or natural disturbance will help us determine the effects of different levels of canopy change on the C cycle.

Ecosystem Dynamics

Conifers Respond to Increasing Atmospheric CO_2 and Changing Temperature

Over the past century atmospheric CO_2 has risen about 60 ppm. We tested whether this historical increase in atmospheric CO_2 has influenced the photosynthetic gas exchange of plants in field conditions, as suggested by experimental research. We analyzed the stable carbon isotope composition of tree rings laid down over the past 80 years to determine whether the proportional decrease in CO_2 concentration across the stomata had changed (Marshall and Monserud 1995). Species tested were western white pine, ponderosa pine, and Douglas-fir in northern Idaho. Results showed that the proportional decrease in CO_2 concentration became smaller and the inferred CO_2 concentration within the leaves increased during the 20th century in all three species. The shifts in gas exchange were just enough to maintain a constant CO_2 differential across the stomata, suggesting constant photosynthesis rates.

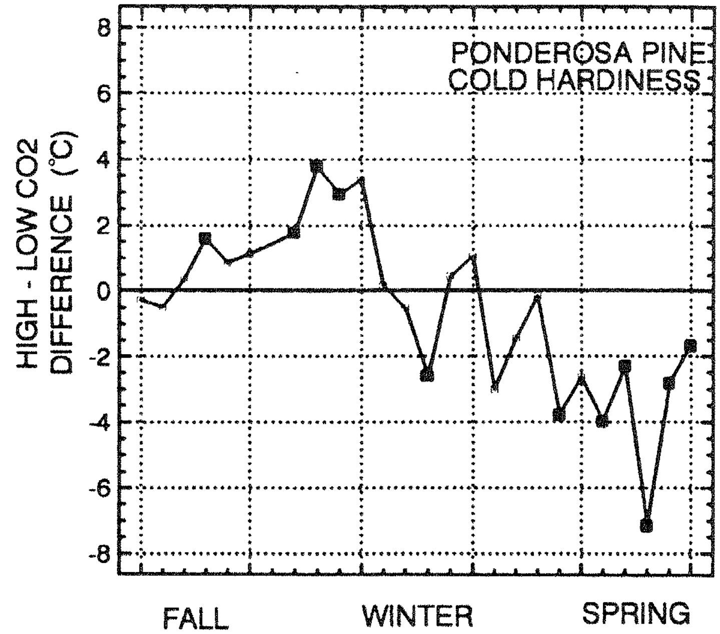

Figure 26.—With increased CO_2, ponderosa pine may be damaged by late spring frosts. A negative difference means that trees exposed to high CO_2 are not as hardy as trees exposed to low CO_2 (Tinus et al. 1995).

These results contrast with expectations that photosynthetic rates will increase at higher CO_2 concentrations.

We also examined the effect of elevated CO_2 on cold hardening and dehardening of three conifers in a growth chamber experiment. High CO_2 had little effect on cold hardiness of radiata pine, but increased autumn and spring hardiness of Douglas-fir. High CO_2 increased hardiness of ponderosa pine in autumn and decreased it in the spring (Fig. 26). In the future, ponderosa pine may become susceptible to late spring frosts.

Provenance studies have been used to characterize the temperature tolerance of western larch. Because genetic differences among populations are associated with temperature differentials of about 2.6°C, accommodating a climate change of 5.0°C would require wholesale redistribution of genotypes across the landscape (Rehfeldt 1995). Larch would move up in elevation about 800 m, and would disappear from its current lowest elevations.

Long-term Changes of Interior Western Forests

The earth and its ecosystems are constantly changing, and we must understand how current ecosystem conditions evolved from past events to predict future conditions or recognize when real change has occurred. Recorded history in the Middle Rio Grande Basin, New Mexico, for the past 455 years reveals major changes in the ecosystems during that time span (Scurlock 1995). Land uses such as grazing,

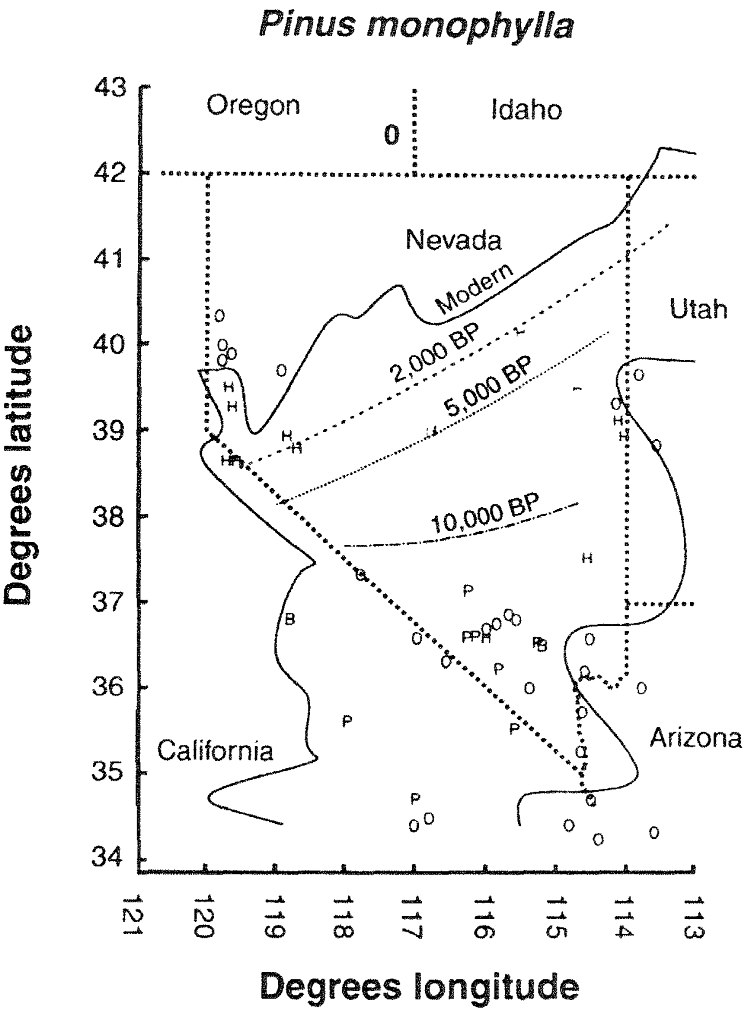

Figure 27.—Expansion of the range of singleleaf pinyon (*Pinus monophylla*) across the great basin during the Holocene. "P" denotes Pleistocene fossil occurences. "H" denotes Holocene fossil occurrences. "B" denotes both Pleistocene and Holocene fossil occurrences. "O" denotes fossil middens that did not contain pinyon. The bold line denotes the modern northern geographic limit of singleleaf pinyon (Tausch et al. 1995).

irrigation farming, logging, and building flood control structures, combined with climate fluctuations, have changed stream flow morphology, ground water levels, topsoils, biotic communities, and individual species. Human populations have been impacted throughout this history, and the rapidly rising population portends more change and major resource challenges.

Reaching further back into the past, we analyzed the contents of wood rat middens to infer climate and vegetation of central Nevada from 30,000 years ago to the present (Fig. 27). These studies depict ecosystems that were unique at each location and transient over time, clearly showing that communities and ecosystems are far less stable than we have assumed over the past few decades. Over the millennia, climate changes have influenced species adaptation, migration, or both. Current plant communities represent trajectories of change from the past, through the present, and into the future.

Impacts of Climate Change on High Elevation Forest Ecosystems

Vegetation growing at the boundary between biomes is already under stress, and even small changes in climate or land use may cause the biome boundary to shift. Tree-ring width chronologies of Engelmann spruce near treeline in Colorado indicate that the treeline may have surged upward about 30 to 40 m around 1250 AD, possibly in response to an increase in late spring temperatures (Fig. 28). No unusual growth increases were seen in recent years at treeline, suggesting a lack of response to slightly warmer conditions that might be associated with global climate change.

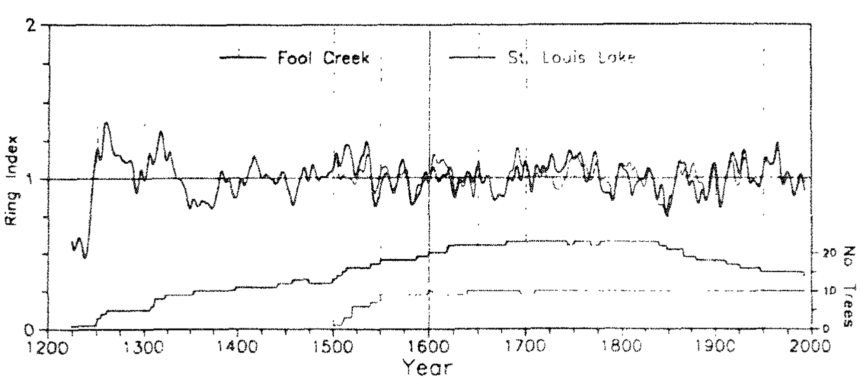

Figure 28.—Low-pass filters fit through Fool Creek and St. Louis Lake ring-width chronologies, and sample depth (number of trees per year) for each chronology. Low-pass filter was designed to emphasize decadal scale variability in the time series (Brown and Shepperd 1995).

Impacts of Climate Change on Great Plains Forest Ecosystems

Global climate models predict that summer soil moisture in the northern Great Plains would decline under CO_2-induced warming. Tree-ring data have been used to place such predicted declines in the context of natural climate variability. Analysis over a 100-year period has revealed a relationship of climate anomalies in the Great Plains with the well-known Southern Oscillation events in the Pacific Ocean (Sieg et al. 1995). Five seasons were identified with significant changes in mean temperature or precipitation that correlated with either the warm or cold phases of the Southern Oscillation. The ability to predict these phenomena several months in advance will help managers make better informed decisions. For example, research on the response of agricultural crops to shelterbelts suggests that yields of dryland maize are increased above unsheltered yields for all levels of climate change (Easterling et al. 1995).

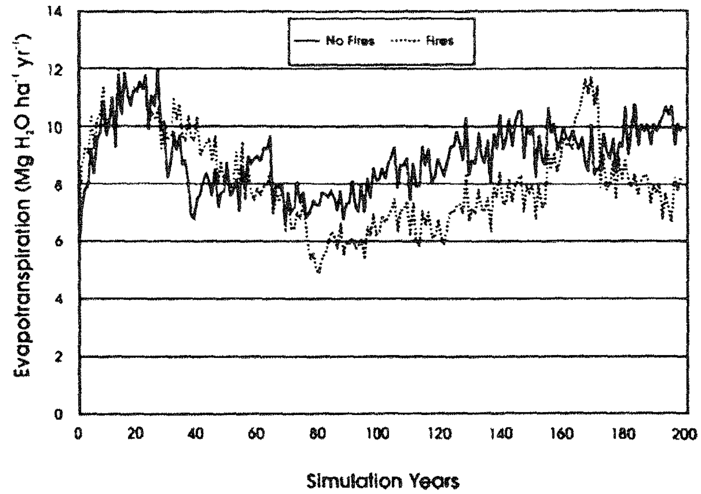

Figure 29.—Evapotranspiration rates simulated over 200 years in Glacier National Park with and without fire. Fire can greatly modify evapotranspiration over long time periods (Keane et al. 1995).

The overall landscape structure of the Great Plains is composed of large expanses of unforested land with scattered forest patches of various sizes and compositions. Trees make up about 3 percent of the land area, and although small relative to the entire landscape, play important ecological and economic roles. Understanding how potential climate change might affect these isolated forest patches requires an understanding of seed dispersal and varying water table, and linkages with climate. Scientists are developing a model called SEEDSCAPE, a derivative of the JABOWA family of models of patch dynamics (Guertin et al. 1995). When complete, the model will be applied to landscapes with forest patches to project likely responses to climate fluctuations.

Disturbance Ecology

Role of Wind and Atmospheric Deposition in High-Elevation Ecosystems

High-elevation ecosystems are particularly vulnerable to atmospheric deposition and climatic change. Research at the Glacier Lakes Ecosystem Experiments Site in southeast Wyoming addresses the effect of these changes on terrestrial and aquatic components of the ecosystems (Musselman 1994). Detailed maps of wind speed and direction, and snow depth show how these variables are strongly affected by topography (Woolridge et al. 1995). Snow depth is a good indicator of the amount of atmospheric deposition, and areas of deeper snow have higher amounts of chemicals contained in the snow. During snowmelt, there is a surge of chemicals into lakes that are normally free from detectable nitrate and phosphate levels during periods of greatest biological activity. Acidity increases slightly during snowmelt. How these chemical changes affect ecosystem processes is unknown but currently under study. High-elevation alpine and subalpine ecosystems have some unique problems associated with estimating the sensitivity of the vegetation to atmospheric deposition because of the high degree of plant diversity in a harsh environment.

Current laws designed to prevent significant deterioration of ecosystems have not established priorities for species or species groups; therefore, a strategy has been developed to rapidly estimate pollutant uptake ability by measuring stomatal conductance and leaf and crown characteristics in a single field season for many plant species (Williams et al. 1996). Examination of the mechanisms by which air pollutants affect plants has revealed that impact is more closely related to pollutant uptake than exposure (Shoettle 1995).

The components of plant sensitivity to atmospheric pollution are:

1. Dose - how much gets into the plant

   Exposure (concentration in the air)
   Plant uptake ability - a function of:
   - leaf conductance - uptake of gases (O_3, SO_2, NO_2)
   - leaf surface and crown structure - foliar absorption of wet deposition

2. Internal reactions - pollutant interactions in the cell

   There are no consistent correlations between biochemical characteristics of cells and their sensitivity to damage among species.

Role of Fire and Climate in the Northern Rocky Mountains

A mechanistic disturbance and succession model (FIRE-BGC) has been developed to investigate the role of fire and climate on long-term landscape dynamics in the northern Rocky Mountains. This model has been used to simulate vegetation change and evapotranspiration in the McDonald drainage in Glacier National Park, Montana, over 200 years with and without fire. Model results showed how the spatial distribution of evapotranspiration changed under the different scenarios (Fig. 29). When fully developed, FIRE-BGC will simulate changes in species composition and abundance as a consequence of multiple disturbances over long time periods.

Climate Change, Insects, and Ecosystem Impacts

Global warming is likely to increase the success of some insects, especially in areas where the trees are already stressed. In addition to an expected increase in tree stress, transport mechanisms across mountain ranges may change. Aggressive bark beetles (e.g., mountain pine beetle) may foreclose evolutionary options of sensitive species such as western pine beetle by negating the strategy of a long-lived tree species persisting until adverse conditions improve (Logan et al. 1995).

Human Activities and Natural Resource Interactions

Implications for Resource Managers

The following ideas were developed at a workshop of participating Global Change Program scientists in the Interior West region (Tinus 1995).

Considering the uncertainty of the magnitude and direction of change at the local level—the level at which managers must act—the prudent philosophy is to maintain resilient ecosystems that can adapt to change, whatever its direction. Some species that are rare now were abundant at one time in the past, and since we do not know which ones may become important in the future, we should maintain all that we can. Structural complexity of the ecosystem will help. Where there is a choice, we should favor species that have a broad range of adaptation within local ecotypes. We may need to be prepared to move species whose habitat may disappear, if the climate warms, as might happen on isolated mountain tops.

To know what is happening we need monitoring systems, but the extent and complexity of most ecosystems make it impossible to monitor everything. What needs to be monitored will vary by location, management goals, and changes identified by monitoring. However, several features will be common to many situations, including: (1) C fixation and accumulation, i.e., growth in relation to weather, (2) species composition, (3) the natural history of land use in time and space, and (4) the location of ecotones. The monitoring system needs to be intensive enough in time and space to detect changes and allow determination of their cause in relation to the range of past variation. The better the monitoring system, the sooner trends will be detected, the sooner management can take corrective action if needed, and the less likely that there will be an unstoppable ecological disaster. It is imperative to keep good long-term records, as this is the core database of any monitoring. The next step is to use the monitoring system as the control for adaptive management by evaluating the effects of management actions and noting departures from management intent. This would be the basis for revising plans for the next set of actions.

We must devise rapid-response managerial structures for ecosystem management. The Forest Service has been very successful at devising management structures for anticipating, preparing for, and responding to fires. The ecological disasters that might happen with climate change need similar structures.

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