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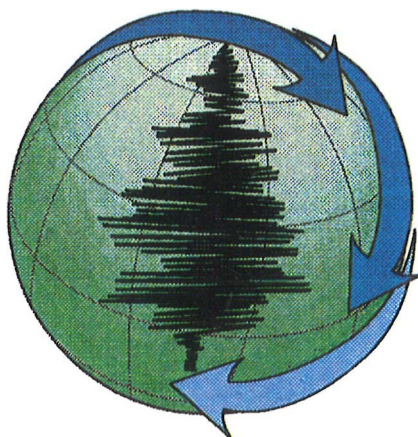
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USDA Forest Service Global Change Research Program Highlights: 1991-95



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

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INTRODUCTION: GLOBAL CHANGE RESEARCH IN THE USDA FOREST SERVICE

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 (CO₂), methane (CH₄), 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 (CO₂, CH₄, N₂O, H₂O) 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 CO₂ and CH₄. 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 CO₂, O₃, 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, O₃ 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 O₃ 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 O₃ 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 CO₂, 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 GCMs¹ 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 CO₂ on ecosystem productivity, and large reforestation programs may all have a measurable effect on the rate of carbon sequestration.

Effects of Warming on CH₄ Release from Minnesota Peatlands—Peatlands store huge amounts of C, more than 30 times that found in typical upland sites. Peatlands release CH₄, a greenhouse gas with high warming potential. Studies in Minnesota show that extended growing seasons and warmer soil temperatures would increase CH₄ 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 CO₂.

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 CO₂ 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 CO₂. 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 CO₂ and O₃ 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 O₃ levels, alone or in combination with elevated CO₂ levels. Experiments with yellow-poplar showed the expected response—increased CO₂ partially compensated for reduced growth caused by O₃ exposure. Experiments with O₃ sensitive aspen clones showed that increased CO₂ did not compensate for growth reduction caused by O₃ exposure; rather, the growth reduction was greater when the trees were exposed to both O₃ and CO₂. Experiments with white pine have been inconclusive. Knowledge of how trees may grow in the future environment allows managers to choose

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

appropriate species or genotypes to plant in areas of high exposure to O₃.

CO₂ Affects Growth of Loblolly Pine—After 3 years of exposure to elevated temperatures and CO₂, 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 CO₂ rather than warming. A temperature increase of 2°C had little effect compared to the growth stimulation effects of increasing CO₂. Other experiments have shown that increasing water, nutrients, and CO₂ 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 CO₂—During the past century, atmospheric CO₂ concentration has risen by about 60 ppm. Results from controlled experiments with immature trees suggest that this magnitude of increase in CO₂ 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 CO₂ 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 CO₂—Temperate and boreal woody plants must become hardy enough in the fall to withstand cold winter temperatures. Doubled CO₂ 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 CO₂ 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 CO₂ emissions. How these changes would interact with the physiological responses of plants to increased CO₂ and O₃ 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 CO₂. Higher concentrations of CO₂ 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 CO₂. 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 CO₂. 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 scenarios. 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 CO₂. 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 CO₂, 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 CO₂ 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 CO₂. 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 O₃ 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 CO₂-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 O₃ pollution, widespread in the South, reduces growth in some southern pines. Studies on pine seedlings exposed to a range of O₃ concentrations and levels of water deficit showed that water deficit was clearly the factor most limiting growth and physiology. However, there were significant O₃-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 O₃ 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 CO₂ and O₃ 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 O₃ generally increased insect growth, and that elevated CO₂ generally decreased insect growth. An increase in foliage volume expected under increased CO₂ may be partially offset by increased insect feeding, thus reducing the potential increase in tree growth. Likewise, a decrease in foliage volume from O₃ damage may not reduce plant growth as much if insects consume less foliage than trees without O₃ 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 CO₂ 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.

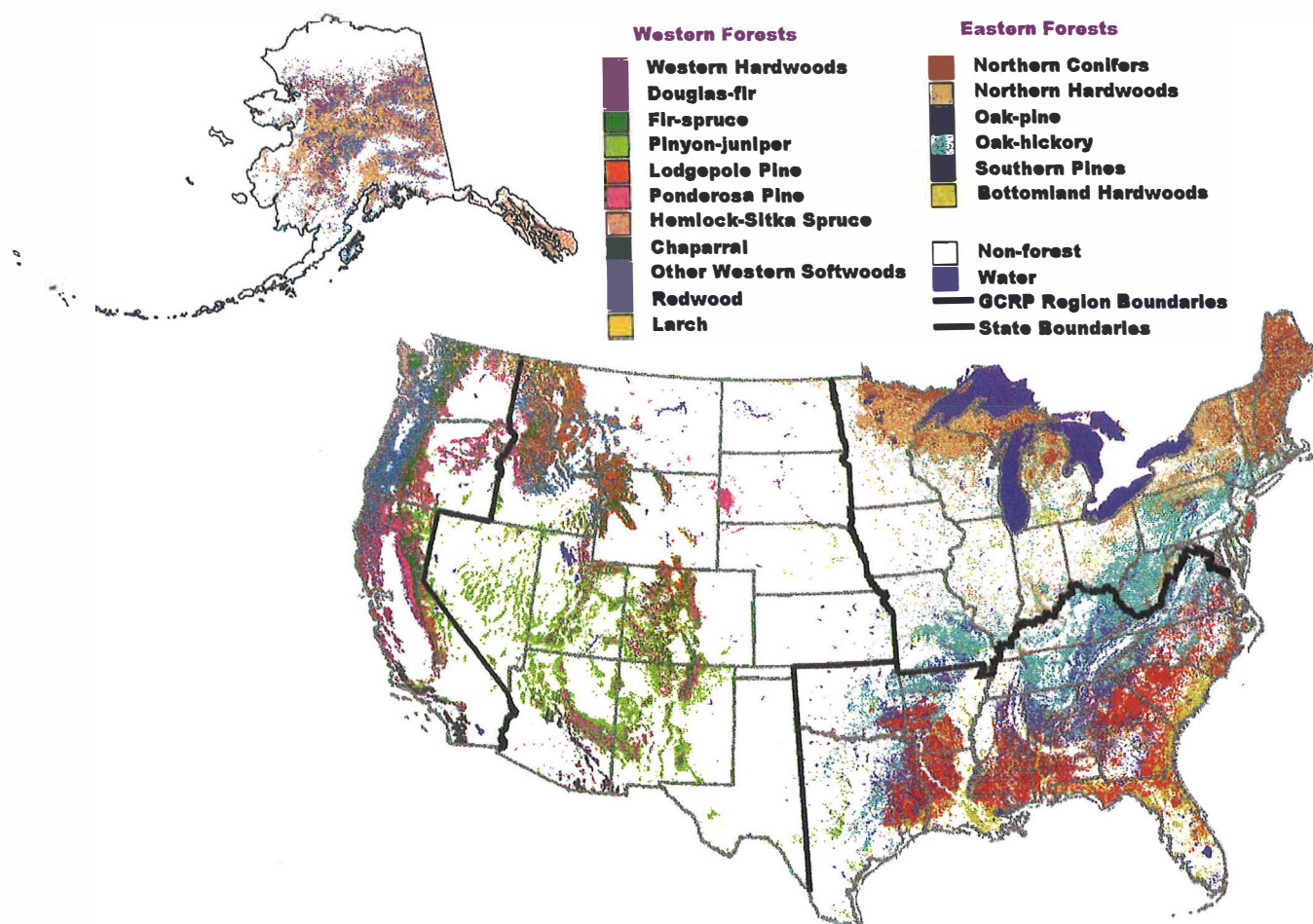


Figure 1.—Organization of the Forest Service Global Change Research Program, including major forest types by region.

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 (CO₂) and ozone (O₃), 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 CO₂ or methane (CH₄) 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 CH₄ release by 50 to 80 percent. Because CH₄ 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 CH₄ 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.

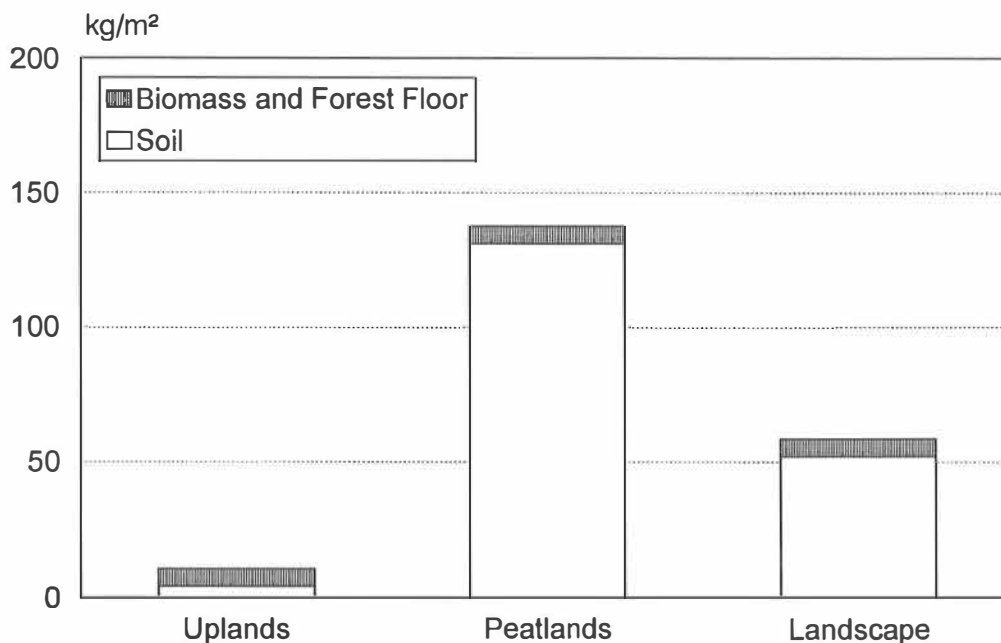


Figure 2.—Carbon storage in the landscape and broad land types of Cedar Creek, Minnesota (Bell et al. 1995).

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 CO₂ 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 O₃ levels, alone or in combination with elevated CO₂ 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 CO₂ does not compensate for the reduction. There has been a negative interaction between CO₂ and O₃ for aspen photosynthesis. By contrast, white pine and yellow-poplar were not adversely affected by experimental exposure to O₃, and their growth was stimulated by the simultaneous addition of CO₂. The responses change over time, suggesting that the trees may be adapting to elevated CO₂ and O₃.

Similar multi-factor experiments involving CO₂, water stress, and N deficiency also show complex plant responses. For

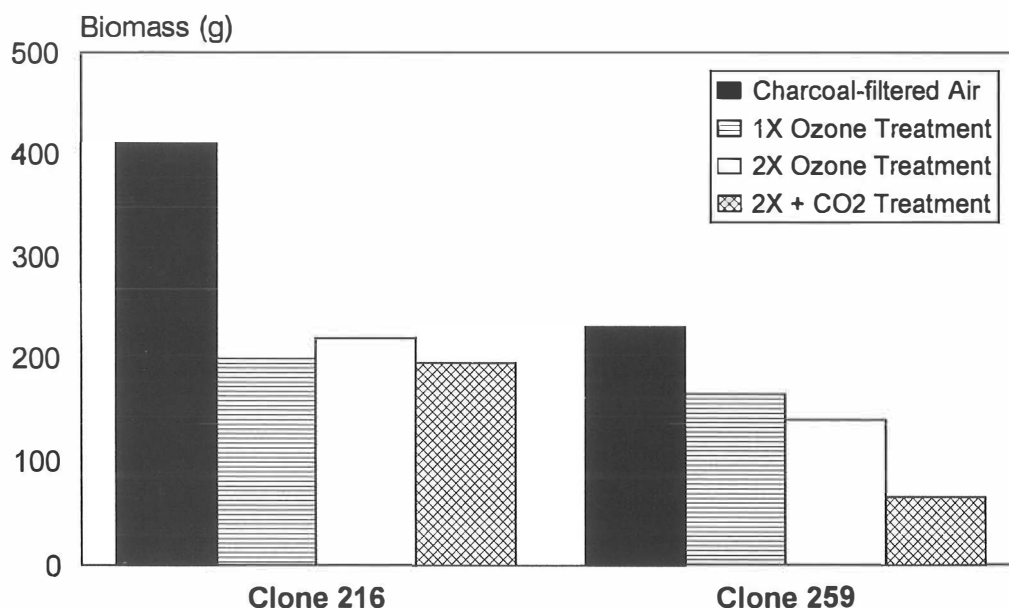


Figure 3.—Stem biomass of aspen clones exposed to various O₃ and/or CO₂ treatments for two years (Karnosky et al. 1995).

example, for northern red oak, increased CO₂ 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 O₃ 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 CO₂ 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,

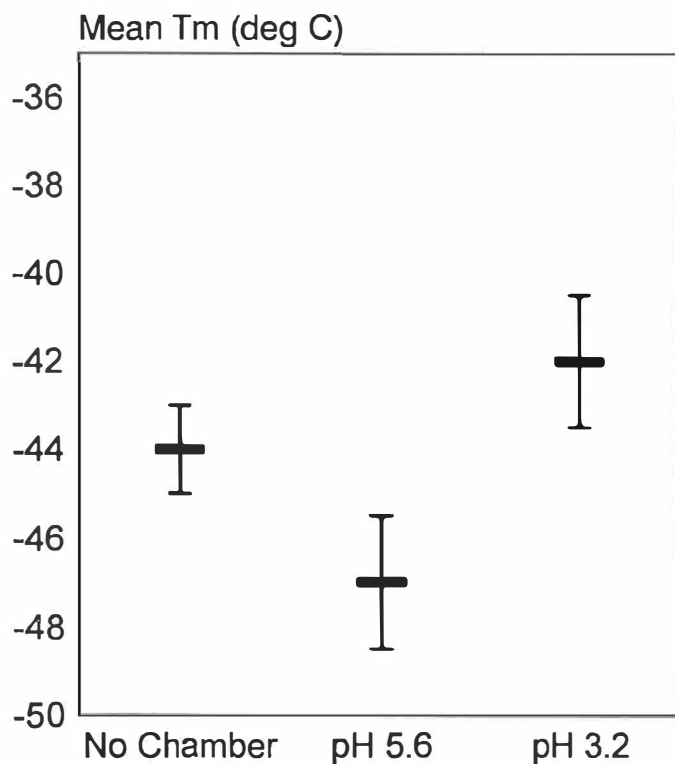
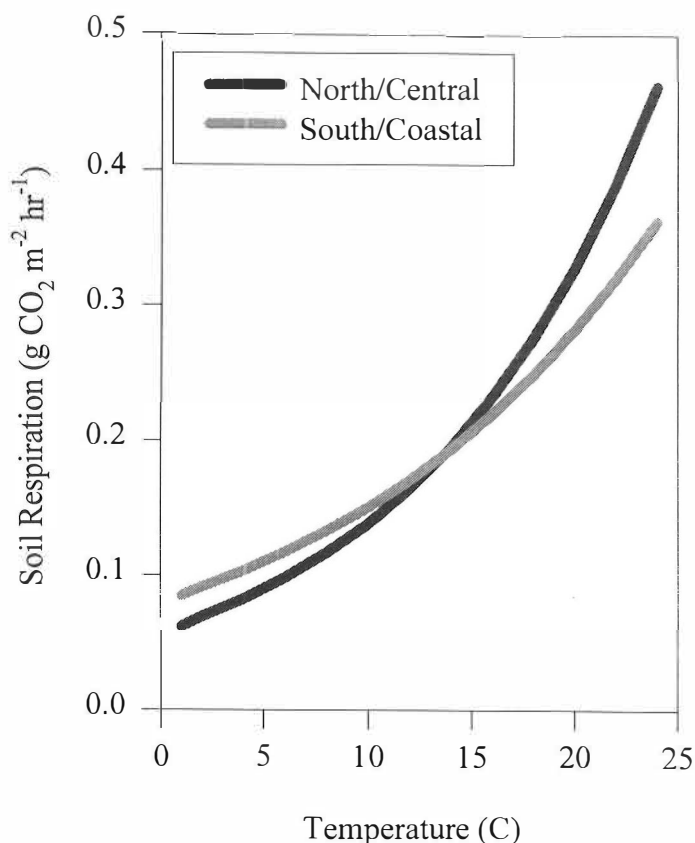


Figure 4.—Cold tolerance of red spruce by mist treatment. Mean Tm is an estimate of cold tolerance. There is approximately 5°C between pH 5.6 (above ambient) and pH 3.2 treatments (Strimbeck et al. 1995a).



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 CO₂ 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 CO₂ 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, $R = \exp(-2.84 + 0.0862 \cdot T)$. For South/Coastal Maine, $R = \exp(-2.52 + 0.0627 \cdot T)$ (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 CO₂ 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 CO₂ and O₃, 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 available 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

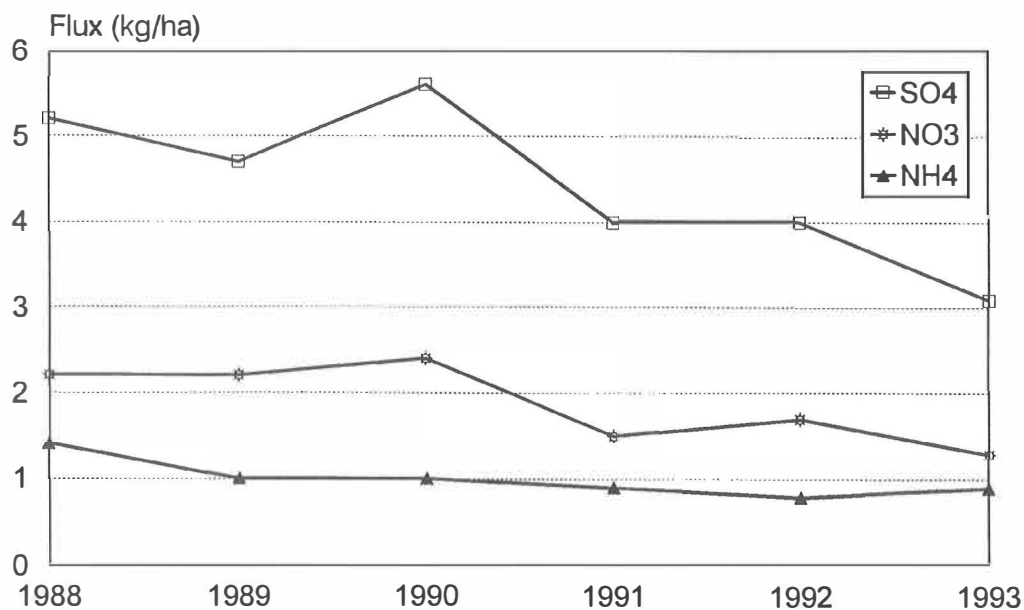


Figure 6.—Trends in atmospheric deposition of N and S in precipitation recorded at Howland, Maine over a 6-year period (McLaughlin et al. 1995).

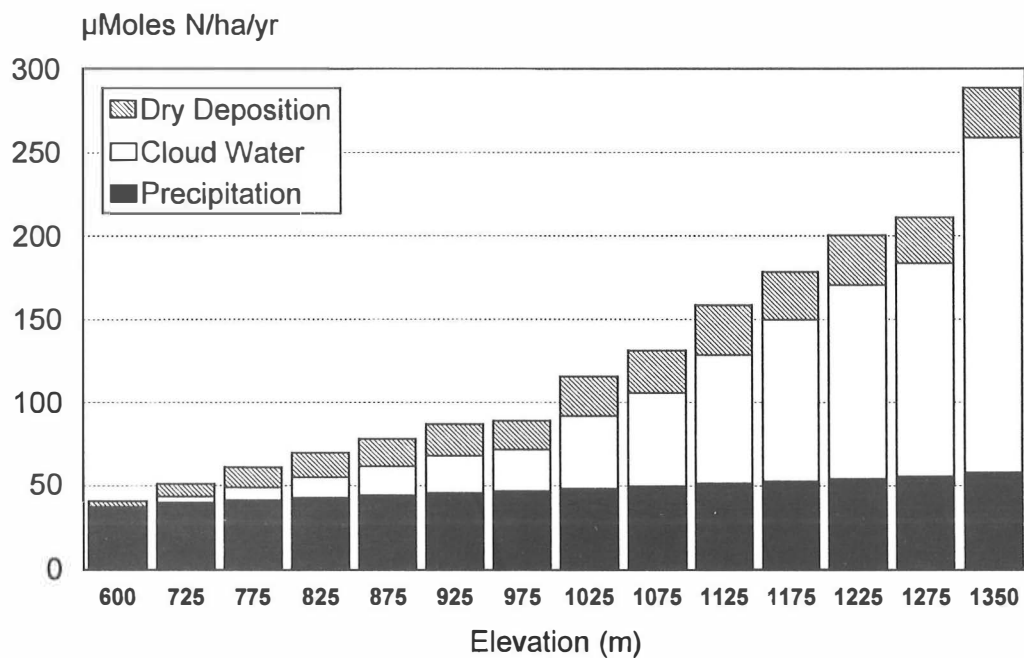


Figure 7.—Model estimates of the total annual deposition of N to the forest canopy on Whiteface Mountain, New York (Miller et al. 1993).

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 remeasurement 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 O₃ 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 O₃ was a reduction in photosynthesis. Using average O₃ exposures from 1987-92, we estimated that annual Net Primary Productivity (NPP) was reduced from 2 to 17 percent, with the greatest reductions in southern New York and New England where O₃ 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

Research Sites: Environmental Effects on Red Spruce Health

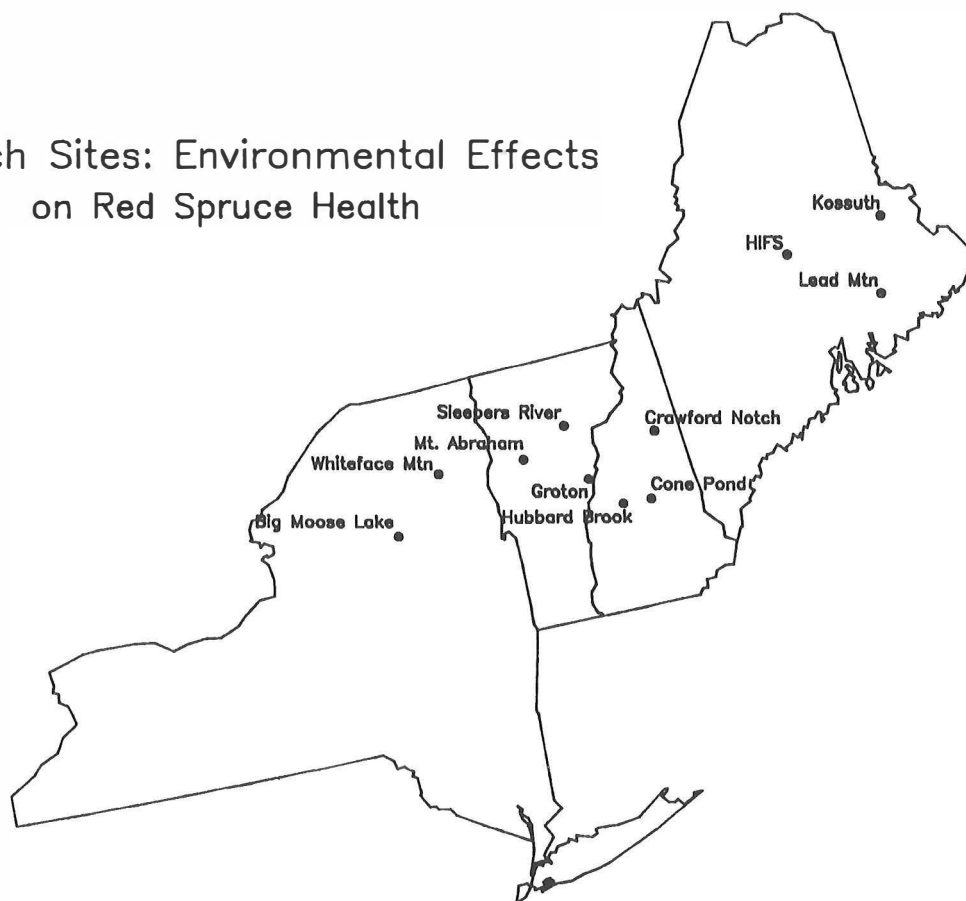


Figure 8.—Network of intensive research plots established to study the effects of environmental change on red spruce health (Lawrence et al. 1995a).

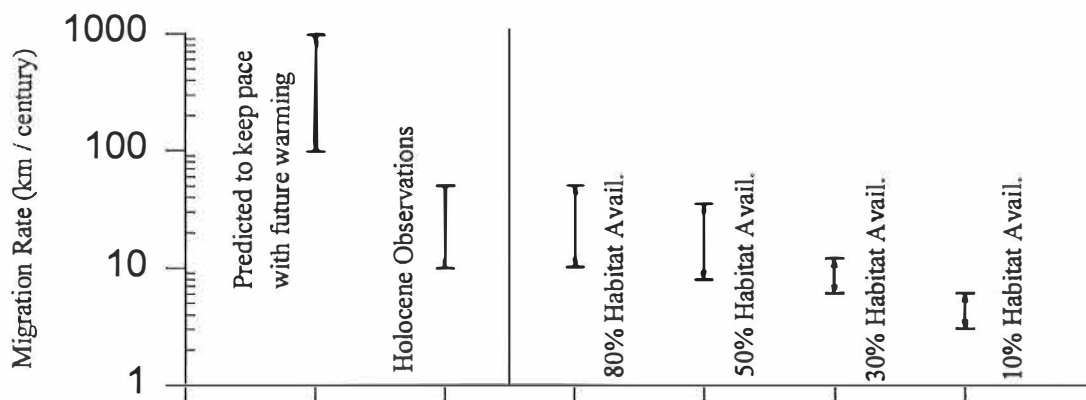


Figure 9.—A schematic diagram of variation in tree migration rates comparing: (1) rates that would be required to keep pace with climate change; (2) observations of Holocene migration rates; and (3) varying levels of habitat availability in a simulated landscape (Schwartz 1995).

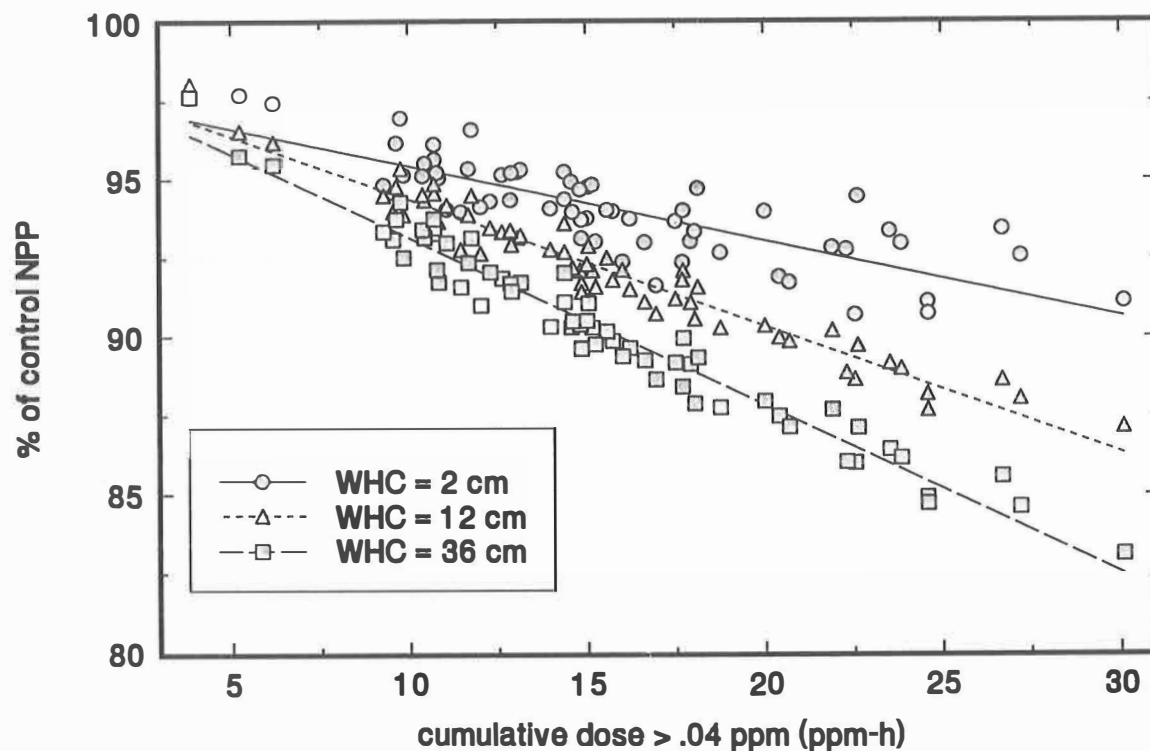


Figure 10.—Predicted change in annual NPP at 64 sites across New England and New York in response to O_3 levels from 1987-92. Predictions are shown for three levels of soil water holding capacity to show how the response changes from well-watered (WHC = 36) to drought-stressed (WHC = 2) conditions (Ollinger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

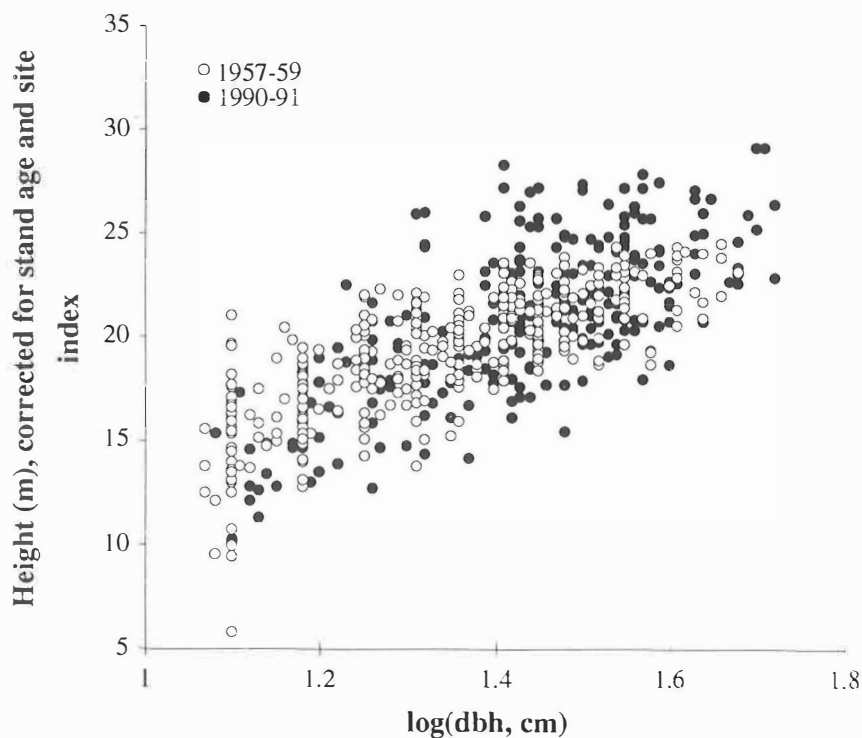


Figure 11.—Height-diameter relationship for sugar maple on two occasions 33 years apart. The relationship has been corrected for stand age and site index (Johnson and Strimbeck 1995).

Estimated Annual Nitrate Ion Deposition

1992

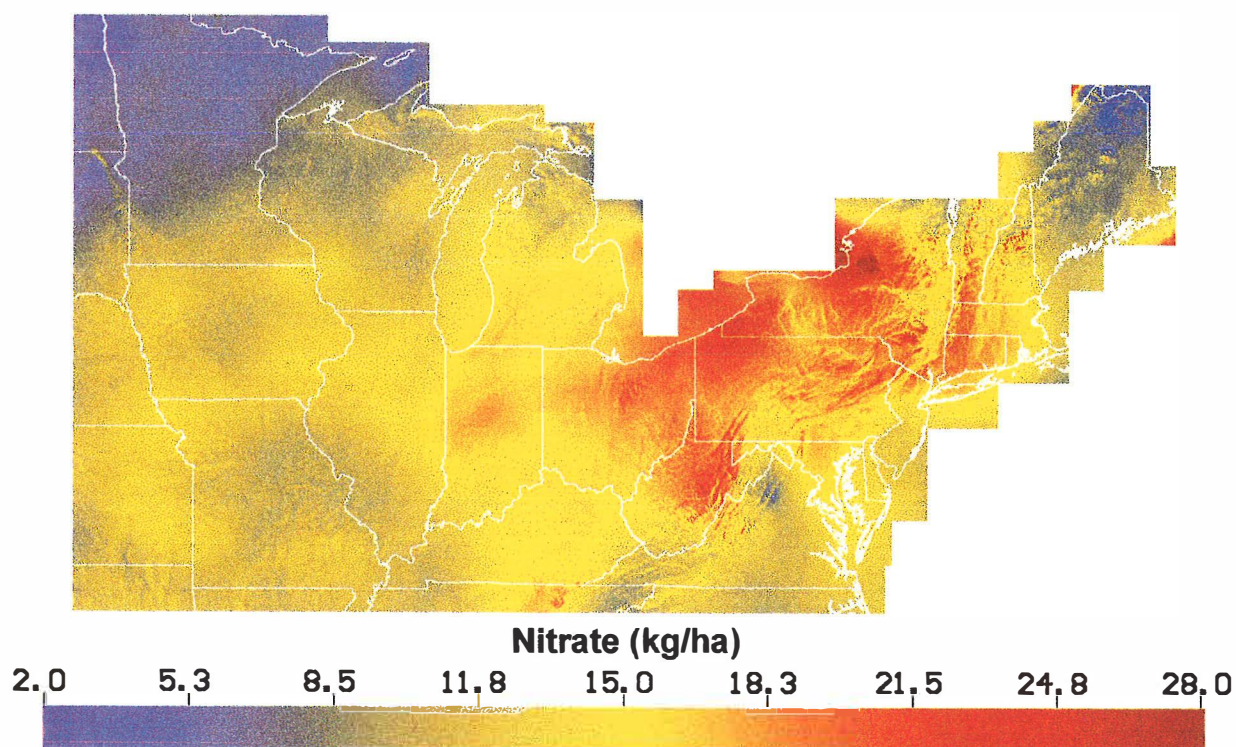


Figure 12.—Estimated annual nitrate ion deposition for the Northeastern and North Central U.S., 1992 (Lynch et al. 1995).

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.

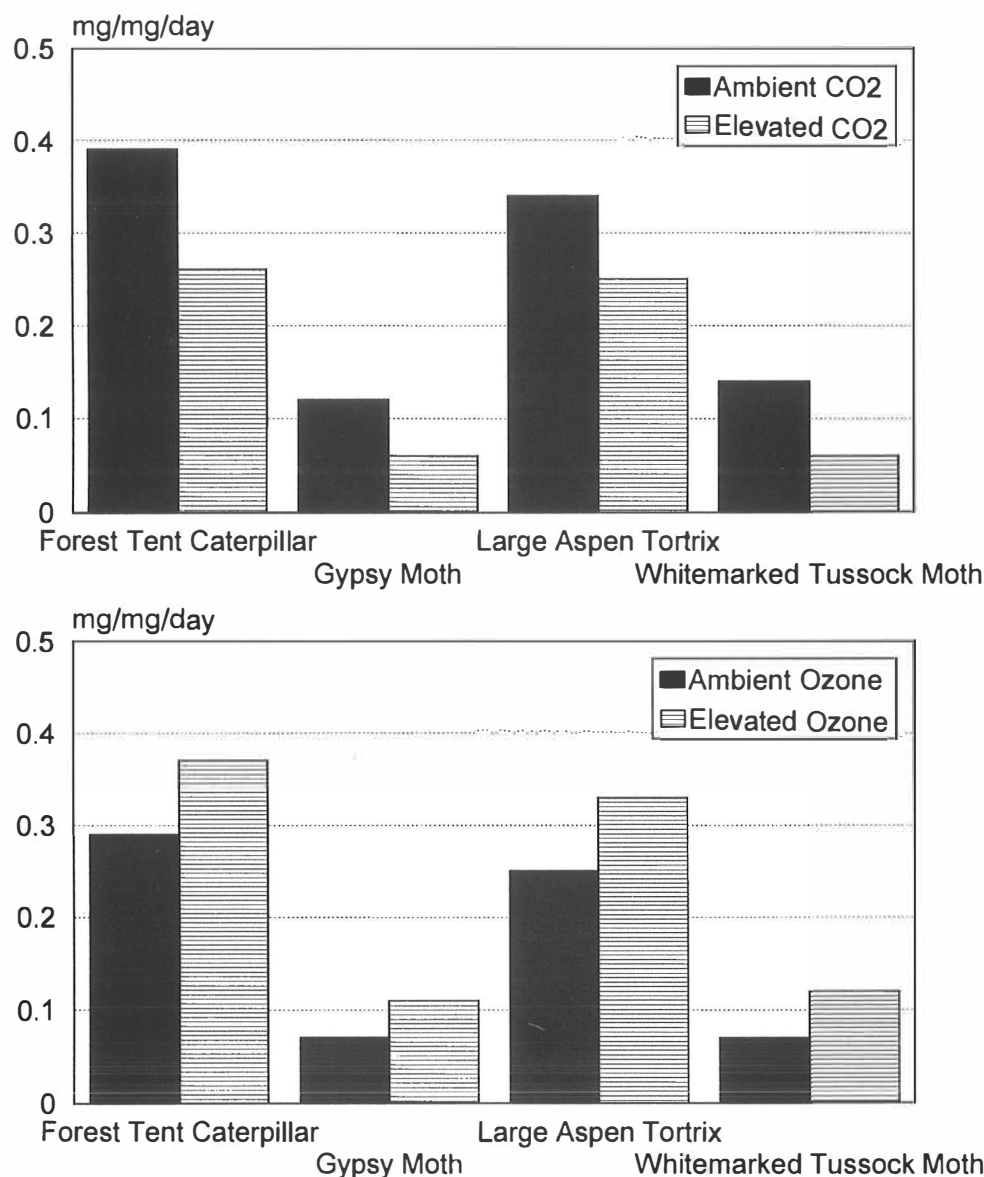


Figure 13.—The relative growth rate of several insects after feeding on foliage from plants exposed to elevated CO₂ (top) or O₃ (bottom) (Herms et al. 1995).

Multiple Stresses Affect Tree Resistance to Insect Attacks

Increasing CO₂ and chronic or episodic O₃ 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 CO₂ decreased insect growth, and elevated O₃ 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

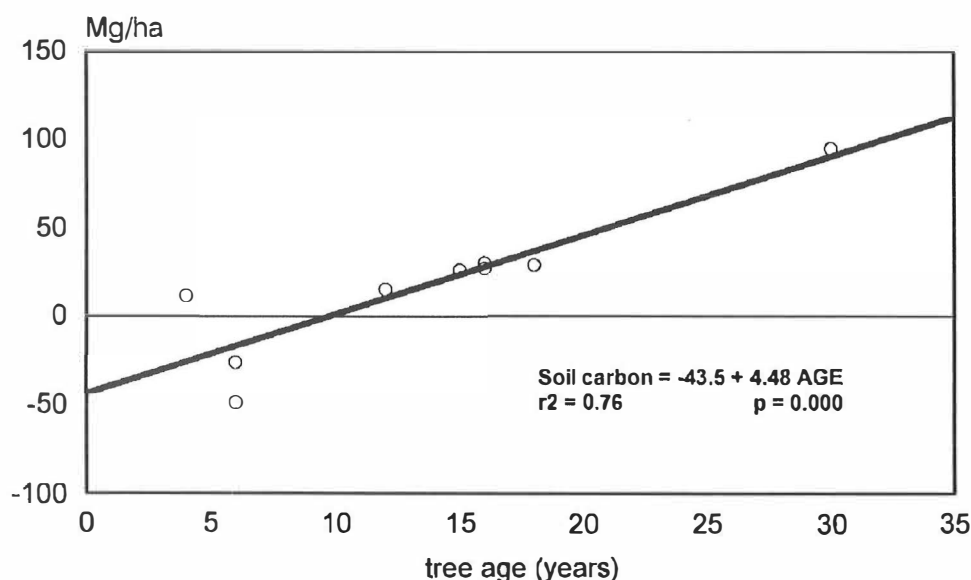


Figure 14.—Soil carbon accumulation with tree age for hybrid poplar after planting on land used for row crops in the North Central U.S. (Hansen 1993).

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.

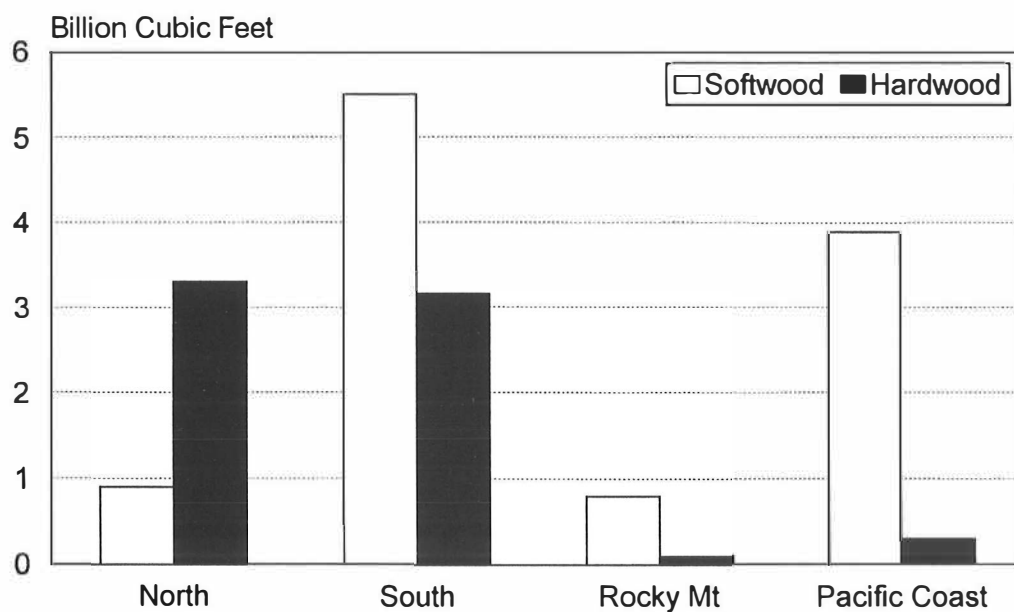


Figure 15.—Net annual removals of growing stock on timberland in the United States by region, 1992 (Powell et al. 1992).

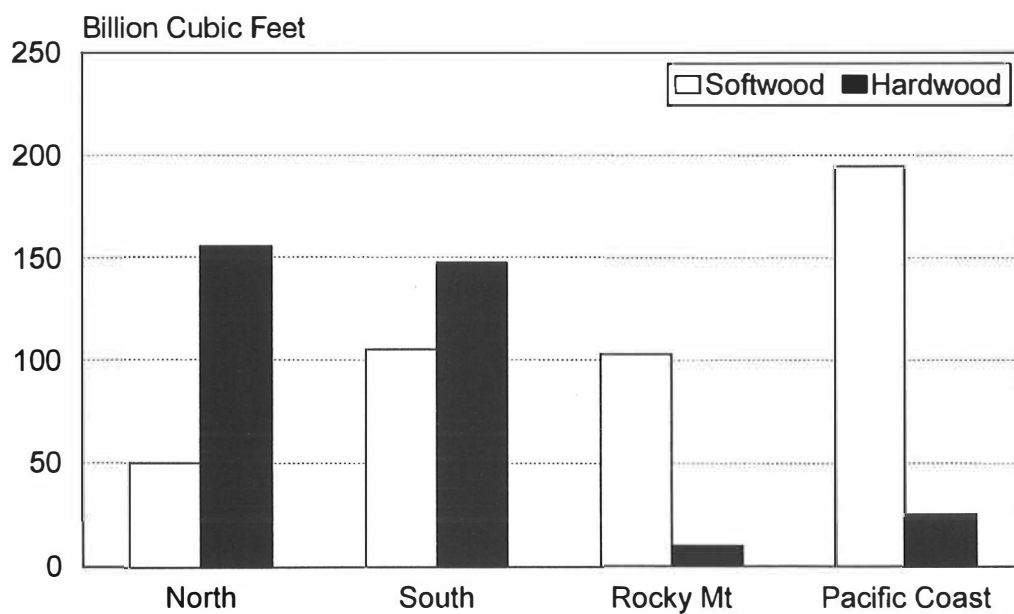


Figure 16.—Net volume of growing stock on timberland in the United States by region, 1992 (Powell et al. 1992).

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 CO₂ 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 Niño-Southern Oscillations, fire, hurricanes, and atmospheric CO₂ 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.

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

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 CO₂ and O₃ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂. These results indicate that increasing concentrations of CO₂ 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, O₃ 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 O₃ concentrations and levels of water deficit showed that water

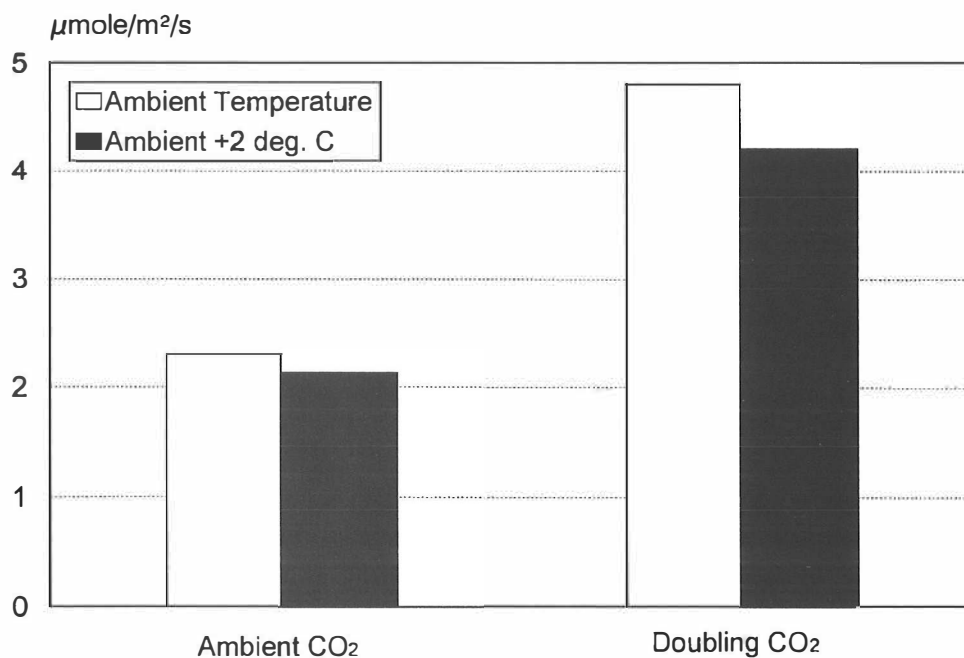


Figure 17.—Change in rate of net photosynthesis in loblolly pine in response to doubled CO₂ concentration and increased air temperature (Teskey [in press]).

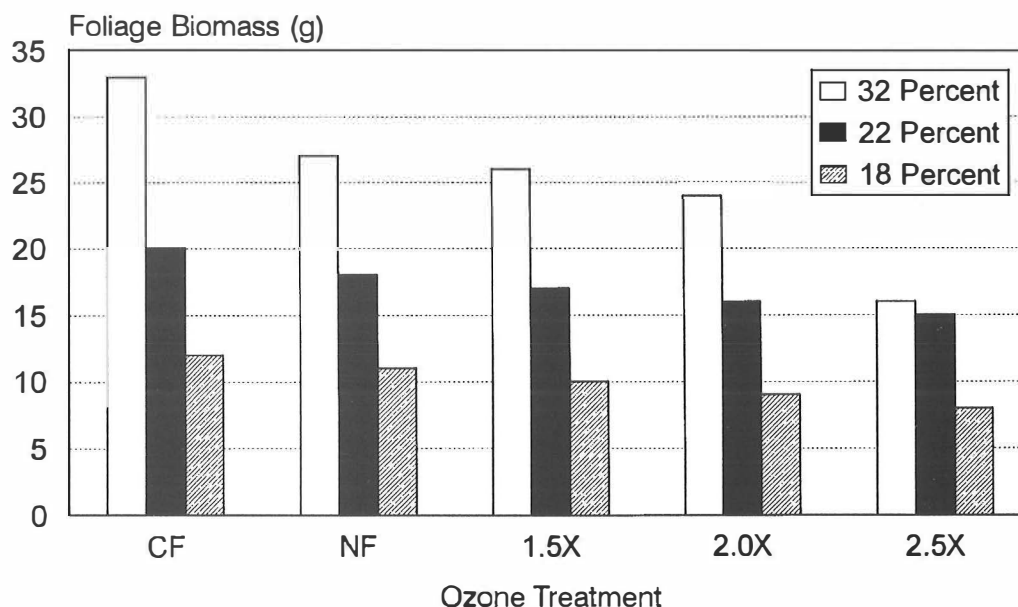


Figure 18.—Reduction in foliage biomass of shortleaf pine in response to increased concentration of O₃ and decreased soil water content (Flagler et al. [in press]).

deficit clearly limited growth and physiology. Of particular interest were the significant O₃ 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 O₃ exposure will continue under climate change scenarios for the South. The studies also illustrate that impacts of O₃ 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 CO₂, 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 CO₂, nutrient inputs, and water inputs may be impacting forest productivity. Increases in CO₂

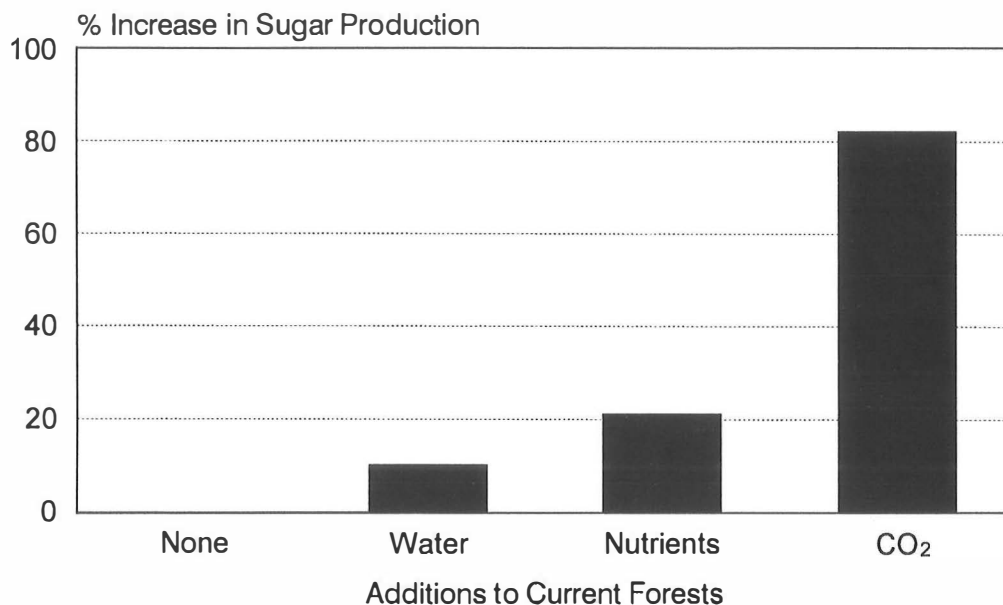


Figure 19.—Potential increases in forest productivity in response to increased soil water availability, nutrients, and atmospheric CO₂ (Dougherty et al. [in press]).

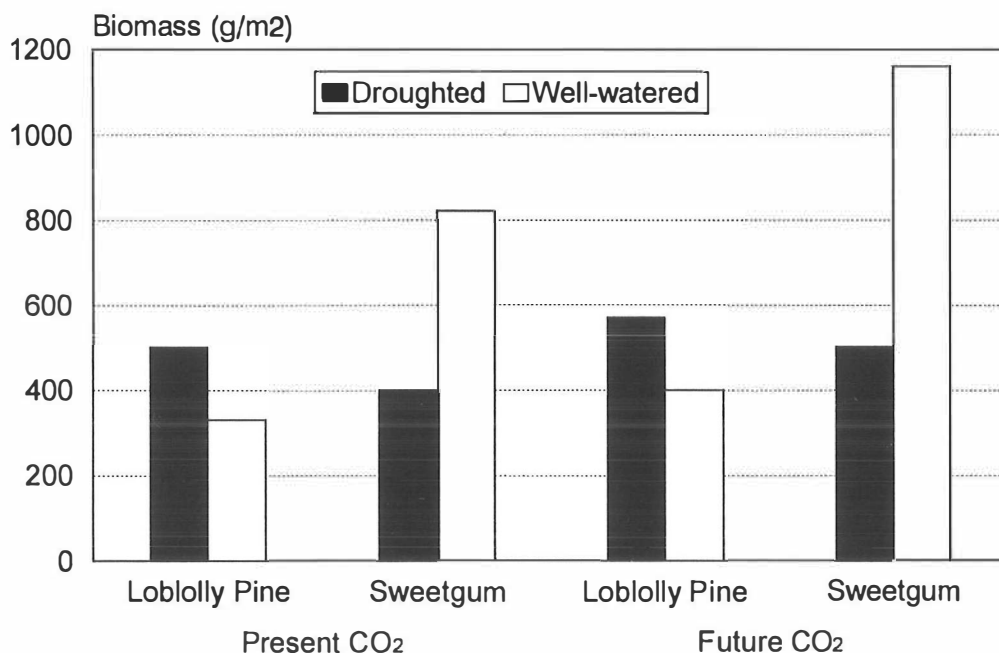


Figure 20.—Increases in total biomass of loblolly pine and sweetgum under different levels of soil moisture and increased atmospheric CO₂ (Groninger [in press]).

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 CO₂. Maximum sugar production potential was increased by 82 percent compared to that in trees growing at current levels of CO₂ (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 CO₂, 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 CO₂ concentrations and the effect on the reproductive biology of trees. Exposures of hardwood and pine trees to elevated levels of CO₂ 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 CO₂. 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 CO₂. Higher concentrations of CO₂ 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 CO₂. 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 CO₂. Additional findings from these studies show that increasing concentrations of CO₂ 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 CO₂ 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 CO₂-induced global warming on vegetation distribution was conducted to

VEMAP VEGETATION DATA SET

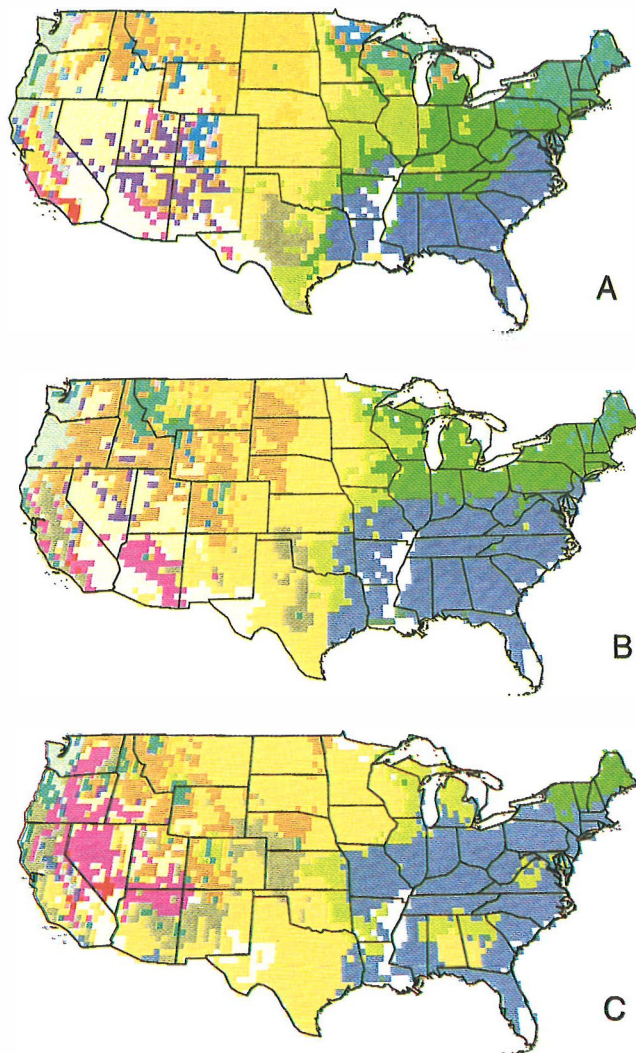


Figure 21.—Simulated vegetation distribution using the MAPSS model, (A) VEMAP vegetation data set, (B) potential future forest distribution showing expansion of southern pines, (C) potential future forest distribution showing increases in low density forest and moist tropical forest (Borchers and Nielson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

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

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]).

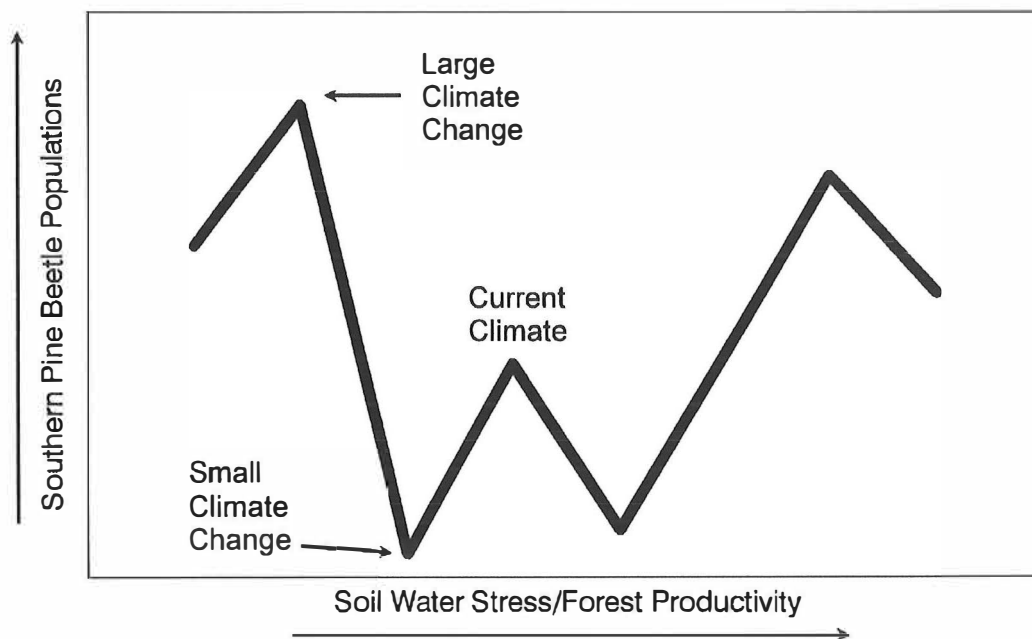


Figure 22.—Changes in southern pine beetle populations under altered forest growth and soil water availability in current and future climate change scenarios (McNulty et al. [in press]).

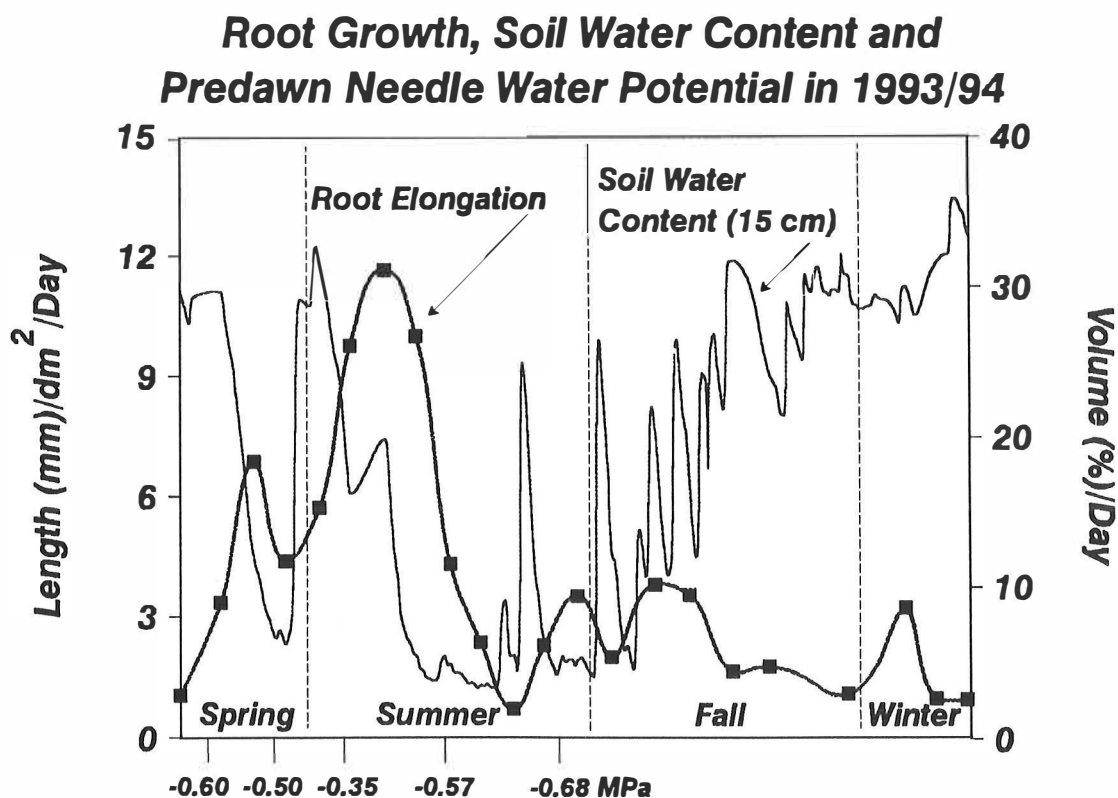


Figure 23.—Root growth, soil water content, and predawn needle water potential in a loblolly pine stand showing correlation of root growth and soil water availability (Sword et al. [in press]).

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]).

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

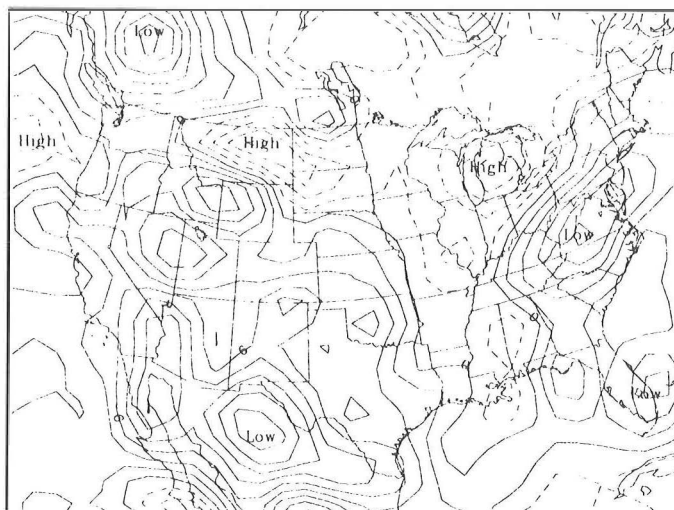


Figure 24.—Large-scale circulation patterns associated with historically severe wildfires in the Southern United States (Heilman et al. [in press]).

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 CO₂. 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 CO₂ 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 CO₂ 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 CO₂ and O₃ 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 CO₂. 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).

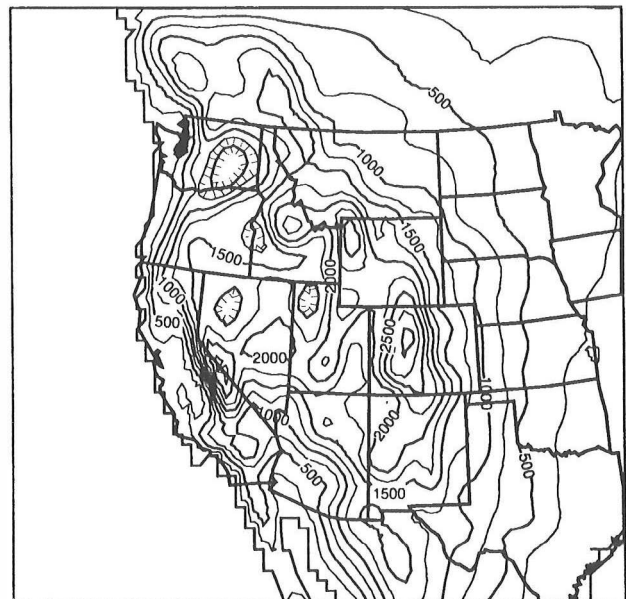
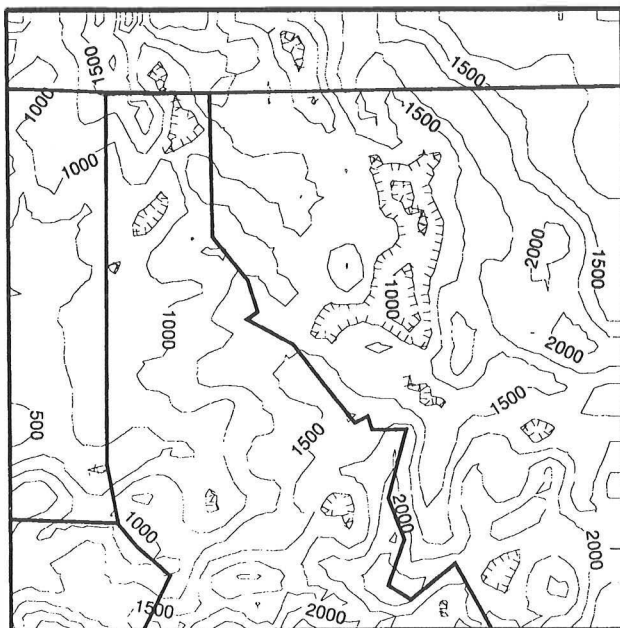


Figure 25.—A 10-km grid map (left) shows important features that are lost on a 50-km grid map (right) (Luce et al. 1995).

Ozone and CO₂ Flux in Subalpine Spruce-fir

Measurements of CO₂ concentrations near the forest/atmosphere boundary help us understand how forest ecosystems change the amount of atmospheric CO₂ 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 CO₂ and O₃ 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 O₃ concentration help us identify the role of forests in the uptake and destruction of tropospheric O₃. 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 CO₂ and Changing Temperature

Over the past century atmospheric CO₂ has risen about 60 ppm. We tested whether this historical increase in atmospheric CO₂ 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 CO₂ 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 CO₂ concentration became smaller and the inferred CO₂ 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 CO₂ differential across the stomata, suggesting constant photosynthesis rates.

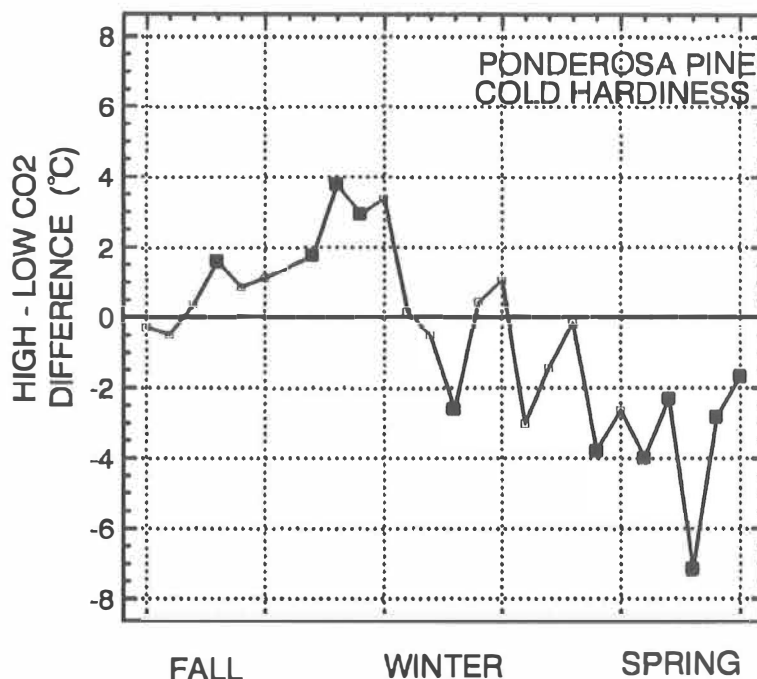


Figure 26.—With increased CO₂, ponderosa pine may be damaged by late spring frosts. A negative difference means that trees exposed to high CO₂ are not as hardy as trees exposed to low CO₂ (Tinus et al. 1995).

These results contrast with expectations that photosynthetic rates will increase at higher CO₂ concentrations.

We also examined the effect of elevated CO₂ on cold hardening and dehardening of three conifers in a growth chamber experiment. High CO₂ had little effect on cold hardiness of radiata pine, but increased autumn and spring hardiness of Douglas-fir. High CO₂ 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,

Pinus monophylla

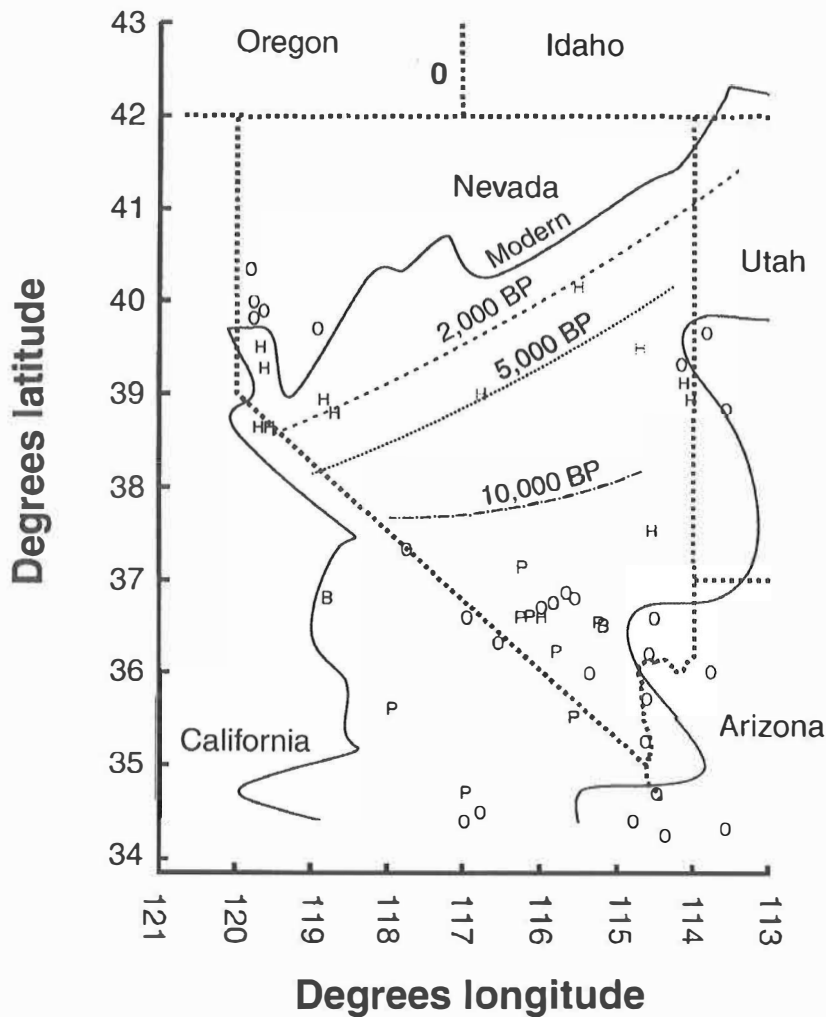


Figure 27.—Expansion of the range of singleleaf pinyon (*Pinus monophylla*) across the great basin during the Holocene. "P" denotes Pleistocene fossil occurrences. "H" denotes Holocene fossil occurrences. "B" denotes both Pleistocene and Holocene fossil occurrences. "O" denotes fossil middens that did 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.

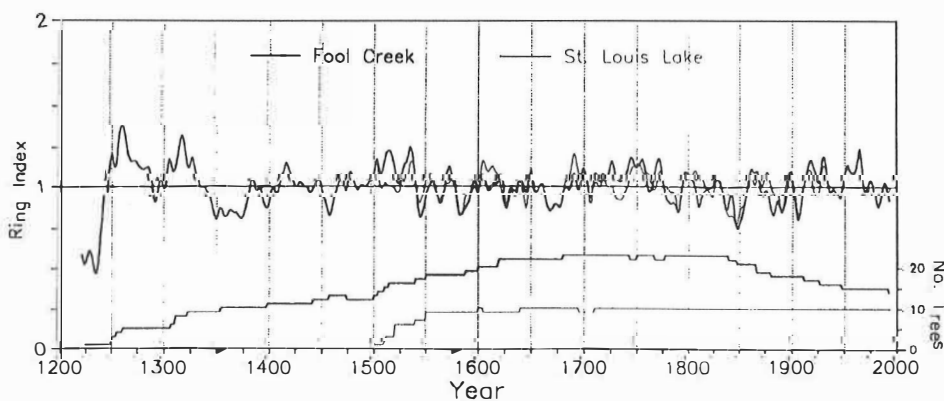


Figure 28.—Low-pass filters fit through Fool Creek and St. Louis Lake ring-width chronologies, and sample depth (number of trees per year) for each chronology. Low-pass filter was designed to emphasize decadal scale variability in the time series (Brown and Shepperd 1995).

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 CO₂-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).

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.

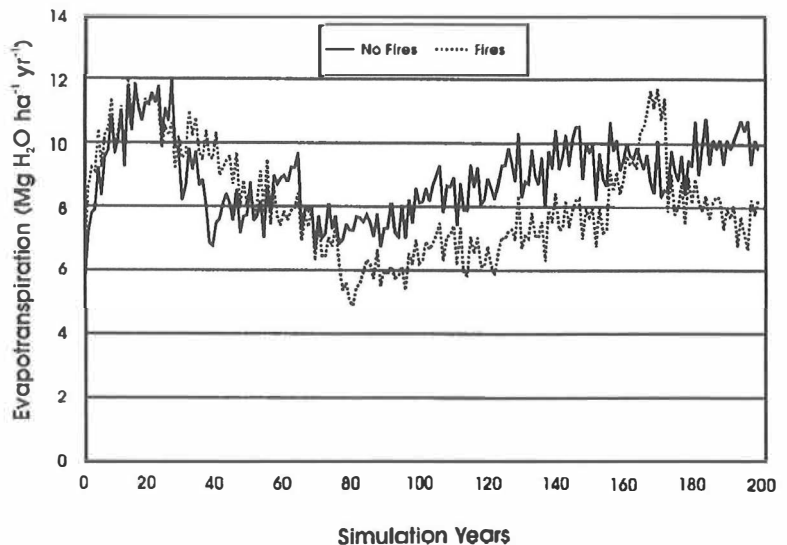


Figure 29.—Evapotranspiration rates simulated over 200 years in Glacier National Park with and without fire. Fire can greatly modify evapotranspiration over long time periods (Keane et al. 1995).

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 (O₃, SO₂, NO₂)
- 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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PACIFIC GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

The Pacific Global Change Research Program (PacGCRP) has identified four high-priority ecosystems for its research: the boreal forest, the moist temperate conifer, the Mediterranean (chaparral) and the dry temperate forest (ponderosa pine) types. PacGCRP research emphasizes better understanding and management of the interactions between climate change, air chemistry, and ecosystem processes and productivity in these ecosystems. The focus is on integrating process and small-scale response research with watershed and landscape-level studies. Long-term, sustained environmental monitoring will utilize a "Pacific mega-transect" of linked monitoring and research sites extending from Alaska to California and from coastal to alpine sites. Modeling will be integral to the program in guiding specific research tasks, predicting ecosystem responses to climate changes, and improving the predictive capability of General Circulation Models.

Atmosphere/biosphere Gas and Energy Exchange

General Circulation Models need to be Localized for the Pacific Region

General circulation models (GCMs) are the basis for climate change predictions, but they operate at the 300- to 500-km spatial scale using a limited number of climate features. Ecosystems and the policy decisions for managing ecosystems operate on much smaller scales, and vegetation management involves micro-climatic effects of particular importance to plants, animals, and belowground processes. To accurately drive models that predict climate impacts on wildlands, the additional parameters not previously considered in GCMs are necessary, such as humidity, surface winds, and lightning. This information is crucial when considering the effects of fire on future forests and wildlife habitat. Another critical aspect of climate scenarios is a measure of the uncertainty of the predictions, and expressing it in ways that are meaningful to policymakers.

A fire and environmental research applications team has been examining climate scenarios around the world to take into account these additional parameters. The team has developed special methods to (1) localize climate-change predictions, (2) model surface winds and humidity that control the rate of moisture and energy exchange between plants and the atmosphere (Fig. 30), and (3) link spatial and temporal lightning strike patterns with general circulation flow regimes for better understanding of fire ignition potential in a changing climate.

The Climate of Mexico City as a Future Model for Southern California

The climate of southern California is characterized by mild winters and summer drought. During the dry period, high

concentrations of tropospheric O₃ develop. In winter, the climate of the Mexico City area permits O₃ concentrations to be higher than they are in Southern California. Ozone in the Mexico City region might be higher in summer; however, tropical storms and associated cloudiness limit O₃ formation from precursor air pollutants even though pollutants and incident solar radiation remain high (Fig. 31). With global warming, southern California summer and winter temperatures are expected to increase. In effect the O₃ "season" may be extended earlier in the spring and later in the fall. Thus, studying the interaction of climate, O₃, and forests in Mexico and southern California may allow managers to predict the future damage to forests in a warming climate.

Climate, O₃ and tree injury data have been gathered in forest stands near Los Angeles and Mexico City (Miller et al. 1992). A persistent drought in southern California during the 1985-89 period limited stomatal uptake of O₃ and tree injury. The return of adequate moisture levels increased O₃ uptake and tree injury. The continuation of the mesic climate and high emission levels of pollutants in the Mexico City region contributed to a more constant level of tree injury.

Burning the Tropical Forests— How Much C is Added to the Atmosphere?

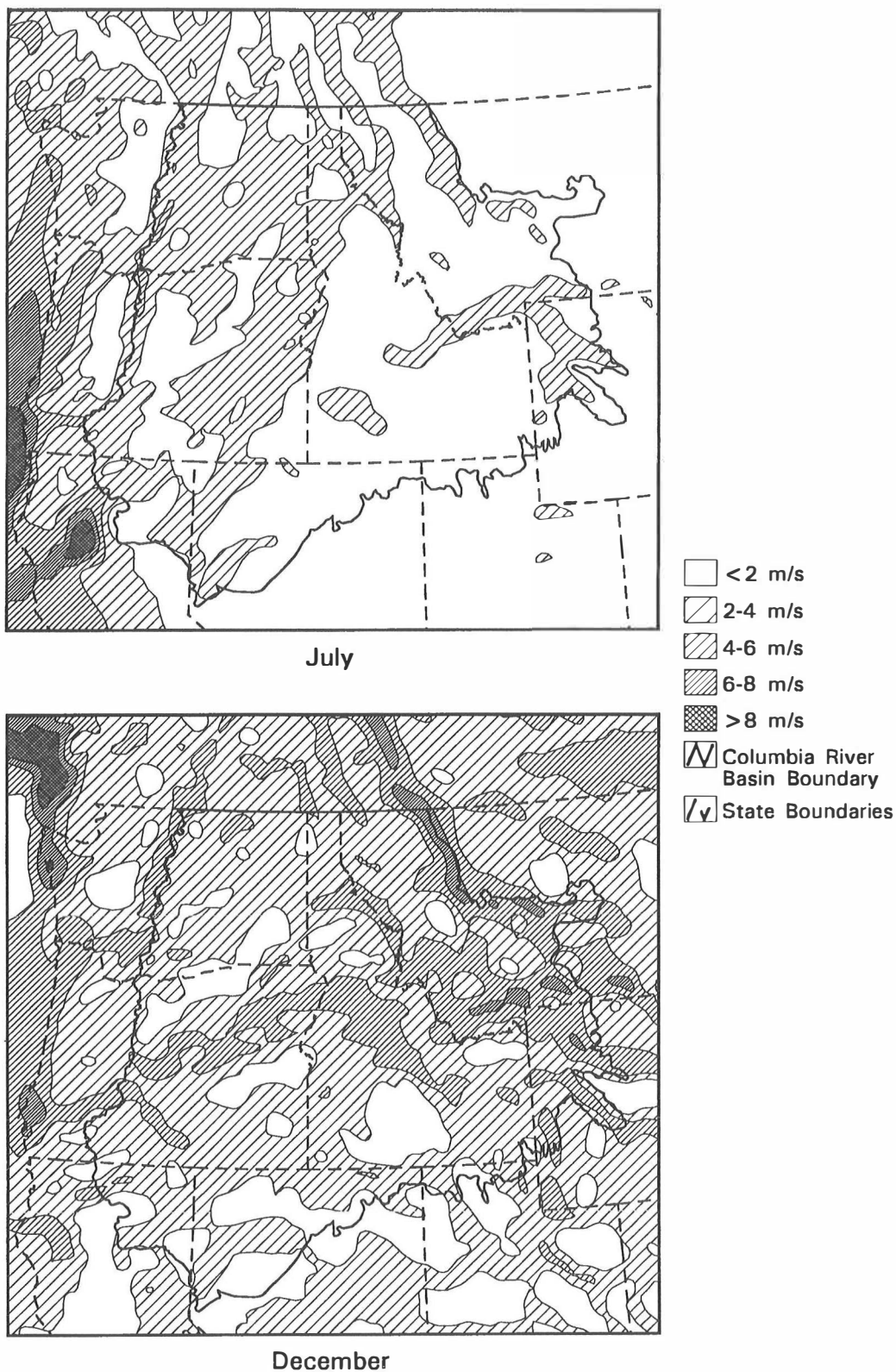
Wildland and agricultural fires may be contributing to climate change, varying in the extent and strength of their emissions. Best estimates show that biomass combustion is an important global source of atmospheric aerosols and trace gases that affect the earth's radiation balance.

We have participated in an international Working Group on Fire and Environmental Change in Tropical Ecosystems to assess the continental-scale impacts of fire and fire emissions on climate, human health, and ecosystems. The group has characterized fire emissions and developed statistical models of the emission rates of CH₄ and hydrocarbons. They have shown that the processes underlying combustion are the same in Brazilian savanna and forests as they are in the United States. Thus, the results are applicable to fire management on our forests and rangeland. Because of the high frequency of fires in Brazil, results were obtained at a fraction of the cost and time required to make the same measurements in the United States.

Ecosystem Dynamics

Increased Soil Temperature and Elevated Atmospheric CO₂ Affect C Balance in a Simple, "Model" Boreal Ecosystem

The boreal forest biome contains approximately 13 percent of all terrestrial organic C, and much of this is belowground. Conifers exposed to elevated atmospheric CO₂ allocate more C to roots which results in greater soil C as roots die. Changes in canopy structure in CO₂-enriched environments also have



Monthly Mean Surface Wind Speed

Figure 30.—Monthly mean surface wind speed for the Pacific Northwest region (Ferguson, personal communication).

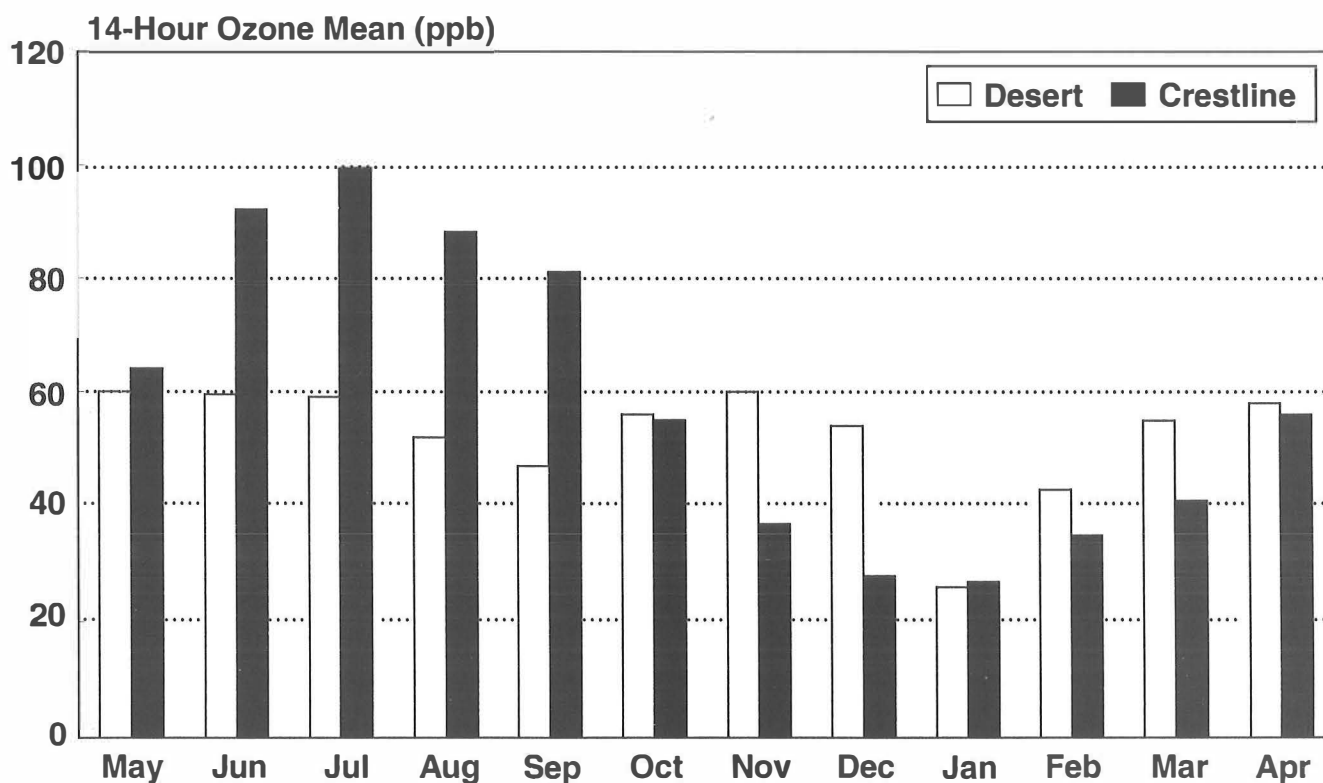


Figure 31.—Ozone levels are lower in summer at Mexico City because of cloudiness and rain, but during the dry winter O₃ can remain as high as summer values; the summer dry climate of Los Angeles and warmer temperatures contribute to high O₃ levels (Miller et al. 1992).

been found. In the boreal forest, presence or maintenance of permafrost is significantly affected by canopy cover, landscape albedo, and surface energy budgets. Increased soil temperature increases both root and microbial activity. Increased atmospheric CO₂ availability in the future will thus affect soil C balance in a complex web of interactions. Prediction of the changes in boreal forests due to increased atmospheric CO₂ and accompanying global warming will allow progressive management of an enormous soil C reservoir.

We are conducting an experiment on a model ecosystem by exposing plants to ambient CO₂, double ambient CO₂ levels, +4°C soil temperatures, and both elevated CO₂ and soil temperature. This experiment was designed to quantify C and nutrient allocation within the plant and soil at 1-year intervals over 3 years. Preliminary data indicate that white spruce seedlings grown in CO₂-rich air assimilated CO₂ more quickly in the first month, but that in the following months this rate slowed. In the second growing season, spruce in the CO₂-rich air had faster assimilation rates but acclimated within 2 weeks. At the end of the first year of exposure to CO₂-enrichment, seedlings increased in stem diameter (4 percent) and height (9 percent), and produced 35 percent more buds. Soil C was detectably enriched in the first year of exposure.

Permafrost of Alaska—C Sink or Source?

Global warming is expected to be observed first, and with devastating effects, at high latitudes. The boreal forest biome

is underlain by permafrost rich in C that was trapped over the last 8,000 years during a cooler period. Global warming threatens to melt the permafrost and release this stored C into the atmosphere. Increased C released into the atmosphere will further exacerbate global warming.

To improve our understanding of the functioning of permafrost zones, we are gathering data critical to a model that will predict the effect of permafrost loss on ecosystem water and C balance (Irons et al. 1992). Dissolved organic C constitutes 90 to 95 percent of the total stream-borne C (particulates constitute 5 to 10 percent), and total stream-transported C is high in the boreal forest relative to temperate environments. Dissolved organic C in stream water is proportional to the percentage of the watershed underlain by permafrost. Increased melting of permafrost due to global warming will directly release CO₂ to the atmosphere and increase C lost through runoff. The role of microbes in using stream-dissolved organic C is currently being investigated.

Excess N in Vegetated Watersheds—How Plants Respond

Northern temperate forests have long been considered to be N-limited. However, there is a growing concern that chronic N deposition near urban areas can lead to the contrasting condition of excess N, with undesirable effects on water quality. A N-saturated forest is one that no longer exhibits a positive growth response nor retains additional inputs of N.

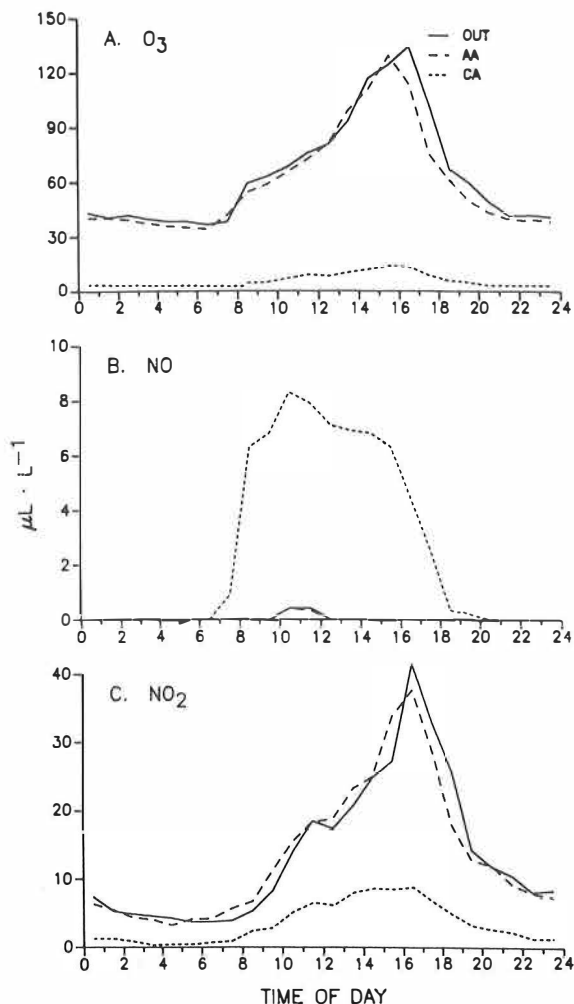


Figure 32.—Concentrations of air pollutants for different exposure regimes expressed as hourly means for 30 September 1987 through 11 October 1987 period (Bytnerowicz et al. 1990). "Out", outside chamberless plots; "AA", ambient air open-top chambers; "CA", clean air open top chambers.

Nitrogen-saturated forests have a persistent loss of N either as NO_3^- in solution into groundwater, or as NO_x release from the soil surface, further exacerbating global atmosphere concentration of this trace gas.

Nitrogen saturation in western forests can occur from natural sources such as N-fixation by red alder or by weathering from ammonia-rich rock. However, excess N deposition to ecosystems in the dry form (mainly NO_2 , NH_3 and particulate NO_3^- and NH_4^+), and NO_3^- and NH_4^+ in precipitation in the southern California air basin and the western slope of the southern Sierra Nevada ecosystems, are of concern. A team of scientists has been investigating atmospheric deposition in western forests by attempting to quantify the amount and rates of exogenous N deposition in the mixed-conifer zone of Central and Southern California (Fig. 32). Fires in N-saturated coniferous and chaparral ecosystems induce high pulses of NO_3^- in streamwater. We anticipate problems in the

next 20 to 50 years in Pacific forests near the Seattle-Tacoma area in Washington, and near Portland, Oregon.

Predicting Changes in the Distribution of Ecosystems

More than half of the world's major biomes will be converted to a different biome (e.g., temperate grassland to temperate deciduous woodland) in response to a doubling of CO_2 , according to the evaluation of climate change scenarios by leading biogeography simulation models. Anticipating where these changes will occur, and the rate of conversion (whether gradual succession or rapid deforestation as results from fire or other catastrophic disturbance) are key questions for policymakers. The volume, area, and location of forest types are of particular interest to both the forest products industry and conservation leaders. Predicting these changes will prove invaluable in managing the transition to new forest types.

A model of location, volume and area of forest types under the climate that might be produced under a doubling of CO_2 concentration has been developed by Neilson and others (1995). The Mapped Atmosphere-Plant-Soil System (MAPSS) is a biogeography model that calculates the potential natural vegetation that can be supported under a steady state climate (Fig. 33). The model also provides an essential link to other models that predict changes in regional forest products and economics. The MAPSS model is useful in scales from landscape to global.

Human Activities and Natural Resource Interactions

How Important is Climate Change?

The importance of climate change and its effects on ecosystems can only be defined in terms of the human values that are affected. Our tolerance for change, the rate of change society will accept, and the characteristics of ecosystems most important to protect are not well understood. Answers to these questions will guide future Forest Service research and development efforts to focus on the most important ecological changes.

We led a 3-day workshop entitled "Breaking the Mold: Global Change, Social Responsibility, and Natural Resource Policy" in May of 1994 that began to define the scope and purpose of the Forest Service Human Dimensions of Global Change Program (Geyer and Schindler 1994). It was organized jointly with Oregon State University, Consortium for Social Values and Natural Resources, and Battelle Pacific Northwest Laboratory. The workshop included national and international participation and was one of a series of regional and national workshops on the subject.

Problems and issues, research and management questions, and 29 recommendations were defined in each of four areas: governance, values and perceptions, local practices, and sustainability. For example, the Forest Service needs to work cooperatively with other agencies on a fully integrated global change agenda, focus on community-scale vulnerability to

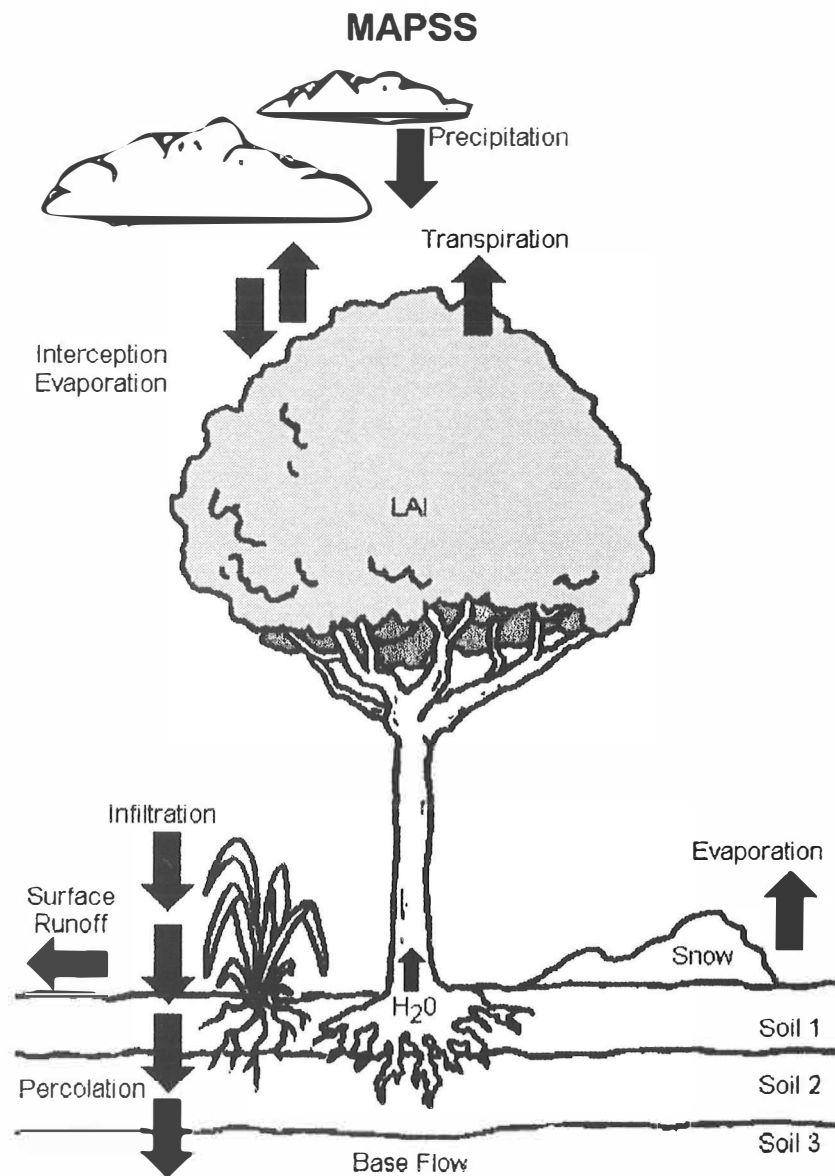


Figure 33.—Conceptual model of the water balance processes incorporated in MAPSS (Neilson 1995).

global changes, and link global change programs with ecosystem management planning and policy.

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FOREST PRODUCTS LABORATORY GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

The Forest Service's Forest Products Laboratory (FPL)—located in Madison, Wisconsin—conducts research aimed at enhancing the effective use of forest products and publishes its findings for government, industry, and the consumer. By developing techniques that increase the use and longevity of wood products, reducing negative environmental impacts associated with their production, improving energy conservation, and strengthening the forest products and construction industries, FPL contributes both to reducing the impact of global change and improving the economy. FPL's global change research program concentrates primarily on the Atmosphere/Biosphere Gas and Energy Exchange and Human Interactions elements of the national program.

Atmosphere/biosphere Gas and Energy Exchange

Fuel Alcohol from Wood

The goal of this research is to improve technology for producing alternative liquid fuels such as ethanol from renewable resources to replace fossil fuels and thereby reduce atmospheric CO₂ accumulation.

Xylose and arabinose are five-carbon sugars found in the hemicellulose of fast-growing hardwoods and other angiosperms. Xylose is the second-most abundant sugar found in terrestrial biomass, and its utilization is essential for the economic conversion of lignocellulose into ethanol. One way to more efficiently convert wood to ethanol is through fermentation, and we have applied for a patent on one transformation process to enhance use of xylose and arabinose fermentation as an adjunct to glucose fermentation. Only a few yeasts transform xylose and arabinose effectively. We are also continuing work on other yeast species. Mutant strains of some of our yeasts produce up to 55 percent more ethanol than the parent generation and exhibit higher fermentation rates (Amartey and Jeffries 1994).

Waste products such as grain hulls are potentially important to ethanol production. Grain hulls from corn wet milling are a major byproduct that has a limited market both here and abroad, but grain hulls consist largely of xylose and arabinose. These sugars can be recovered by acid hydrolysis, but their fermentation is very difficult. If we can solve the problem of xylose and arabinose fermentation, scientists in the grain processing industry estimate that the potential exists to produce almost 500 million gallons of ethanol annually from this byproduct. Scientists have identified *Pichia stipitis* and *Candida shehatae* as two of the best yeasts available for the fermentation of xylose (Amartey and Jeffries 1994). In a fed-batch fermentation, *C. shehatae* will produce up to 56 grams of ethanol per liter within 48

hours. This is one of the highest ethanol concentrations reported for xylose fermentation. Studies in other laboratories show that *P. stipitis* is an equally good fermenter, and is capable of producing even higher yields than *C. shehatae*.

Our research has shown that by selecting organisms for rapid growth on a number of slowly metabolized pentose sugars in the presence of respiratory inhibitors, we are able to increase ethanol production by 50 to 100 percent.

In addition to these traditional methods for strain improvement, our laboratory has developed a powerful genetic transformation system for *P. stipitis* (Jeffries et al. 1994). We have cloned one of the critical genes for nucleic acid biosynthesis, URA3, along with an autonomous replication sequence (ARS) that enables the URA3 gene to be maintained as an extrachromosomal element. We have also obtained a number of URA3 deficient recipient strains that can be transformed by the *P. stipitis* URA3 ARS-based vectors. By combining strain selection for improved fermentative mutants with genetic engineering to introduce and overexpress rate-limiting enzymes, we are able to increase ethanol production on these sugars (Fig. 34).

Reducing Volatile Organic Chemicals in Wood Finishes

To achieve the air standards required under the New Clean Air Act, widespread changes in the paint industry will be necessary. Many paint and stain manufacturers will have to change formulations to meet the required decreases in VOC content in wood finishes. These new formulations need to be evaluated.

We improved technology to permit decreased levels of volatile organic compounds (VOC's) in finishes for wood (Williams 1995). During the last 3 years, all studies initiated within our Wood Surface Chemistry and Preservation Research Work Unit have included VOC compliant finishes.

The studies have included but are not limited to the following:

- Cooperative study on low VOC finishes on decks constructed with western wood species.
- Effects of surface roughness on finish performance.
- Effects of back-priming on finish performance.
- Interaction of finishes, fasteners and substrate on a test house.
- Comparison of VOC compliant coatings with non-compliant coatings.
- Evaluation of moisture movement through coatings.

Forest Products Laboratory scientists participated in the Regulation-Negotiation Committee convened by EPA who is writing a regulation to control the emissions of VOC's from architectural and industrial finishes under provisions of the new Clean Air Act.

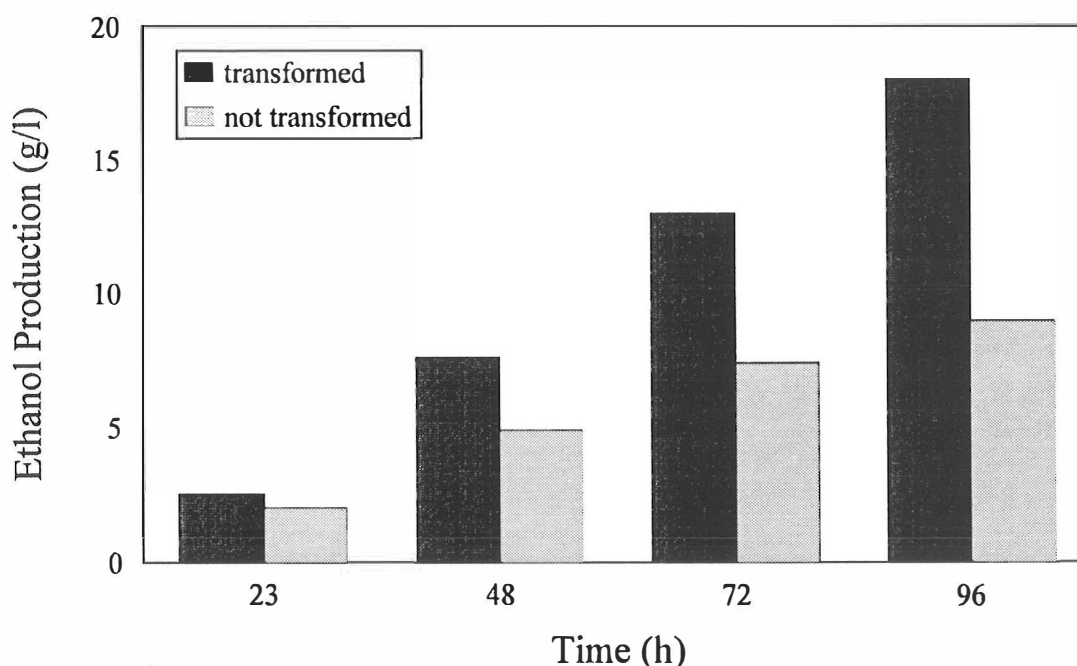


Figure 34.—Genetic transformation of yeast *Pichia stipitis* increases ethanol production from xylose (Amarthey 1994).

Recycled Material for Light-frame Construction

Research on the recovery of low-quality unsorted fiber from wastepaper and wood—major components of municipal solid waste—is another way of conserving resources, energy, and fossil fuel use.

An alternative use for recovered fibers is FPL Spaceboard, a value-added product (Gaumnitz 1994). Performance of Spaceboard panels for use in light-frame construction was evaluated. Tests of panels and materials in the wet- and dry-formed products resulted in a range of ratios from 2.0 to 3.5:1 (ratios of stiffness, tensile strength, and compression strength based on wet- vs dry-forming). Puncture load tests indicated the panels were capable of meeting industry-accepted performance standards for single-layer flooring. These test results will provide incentive for the structural panel industry to adopt molded fiber (Spaceboard) technology as a means for utilizing recycled paper fiber from mixed waste streams.

Fuelwood Issues: Increasing Recycling, Reducing Emissions, and Improving Efficiency

An engineering economic analysis on producing fuel from used pallets compared the capital and operating costs of four methods of pallet breakdown. The analysis included six sizes of facilities ranging from 900 to more than 100,000 tons per year¹. The study included an existing pallet repair facility and

a new breakdown-only facility. Capital and operating costs also were developed for burning this fuel at six different new wood-burning facilities and two retrofitted coal/wood-burning facilities.

Research on combustion of manufactured products such as particleboards and wood/plastic boards is funded by the Center for Clean Industrial and Treatment Technologies. The study measures the emissions of CO, aldehydes, organic C, polynuclear aromatic hydrocarbons, sodium, and potassium from a laboratory scale combustor (Baker 1991). The high and low molecular weight hydrocarbon emissions can be correlated with the emission of CO. These studies indicate minimum acceptable combustion conditions of various products.

We also developed a pressurized down-draft combustor for use with a gas turbine (Baker et al. 1991). Direct burning of wood in a turbine is among the most efficient ways to generate electricity.

Another study for the National Science Foundation analyzed the effect of reducing conditions on ash composition at various temperatures (Mahendra et al. 1992)

Human Activities and Natural Resource Interactions

The FPL has studied mitigation measures to combat adverse effects of global change. Studies focused on conserving energy, reducing volatile organic compound content in wood finishes, using biomass fuel as an alternative to fossil fuels, and sequestering C in wood products (Zerbe 1993).

¹MLSE & Associates. 1993. Report on engineering and economic analysis on processing used wood pallets, etc. to fuel. Final Report, FPL Contract No. 53-5680-3-440. Lockport, Illinois: M.L. Smith Environmental, Inc.

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GREENHOUSE GASES, CLIMATE, AND THE GLOBAL CARBON CYCLE

Richard A. Birdsey¹

GREENHOUSE GASES, AEROSOLS, AND CLIMATE CHANGE

Some gases in the atmosphere absorb heat radiated from the earth and cause a warming or greenhouse effect. Besides water vapor, the most radiatively-active gases are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and the chlorofluorocarbons (CFCs). Table 1 lists some important greenhouse gases, their global warming potential (relative to CO₂), and their relative effect on warming.

Table 1.—Greenhouse gases and relative contribution to global warming over 100 years.

Gas	Global warming potential (relative to CO ₂)	Relative contribution to "greenhouse effect" (%)	Rate of concentration change during 1980's (%/yr)
Carbon dioxide	1	61	+ 0.4
Methane	21	15	+ 0.8
Nitrous oxide	270	4	+ 0.25
CFCs	3500-7300	11	+ 4
Other gases	...	9	...

Sources: Houghton et al. 1990; 1995.

The atmospheric concentration of most of the greenhouse gases is rising. The Intergovernmental Panel on Climate Change (IPCC) projects increases in atmospheric concentrations of most of the greenhouse gases because of continuing increases in emissions (Houghton et al. 1996). Exceptions are CFCs and halocarbons, whose emissions are declining. Widespread concern about reductions in stratospheric ozone has led to international efforts to phase out their production.

Recent global assessments give more weight to the role of aerosols in climate. Aerosols tend to cool the climate because the small particles absorb and reflect radiation, and change cloud properties. Aerosols enter the atmosphere from volcanoes and from industrial emissions of sulfates. The combined effects of greenhouse gases and aerosols are integrated into projections of probable warming by the IPCC in the most recent global assessment (Houghton et al. 1996). Over the next 100 years, the average global temperature is expected to increase from 1°C to 3.5°C, a significant reduction below previous estimates that ranged from 1.5°C to 4.5°C (Houghton et al. 1995).

Changes in atmospheric gas concentrations and consequent climate changes could have a significant impact on forests. Solar radiation, temperature, precipitation, humidity, and

atmospheric CO₂ are among the most important factors affecting ecosystem processes. Because CO₂ has strong direct and indirect effects on forests, and because forest processes affect the global carbon cycle, the buildup of CO₂ is of great interest for forest policy and forest management. Forests of the globe, including forest soils, store approximately 987 Pg C², and on balance are emitting an estimated 0.9 Pg C/yr to the atmosphere (Brown et al. 1996). Although the evidence is incomplete, it is estimated that emissions from deforestation (about 1.65 Pg C/yr) are partially offset by additions to C storage in regrowing temperate forests.

Methane (CH₄) is another natural greenhouse gas whose concentration in the atmosphere is increasing (Houghton et al. 1995). Methane emissions from natural sources (including northern forested wetlands) comprise about 30 percent of all methane emissions. Methane emissions from wetlands

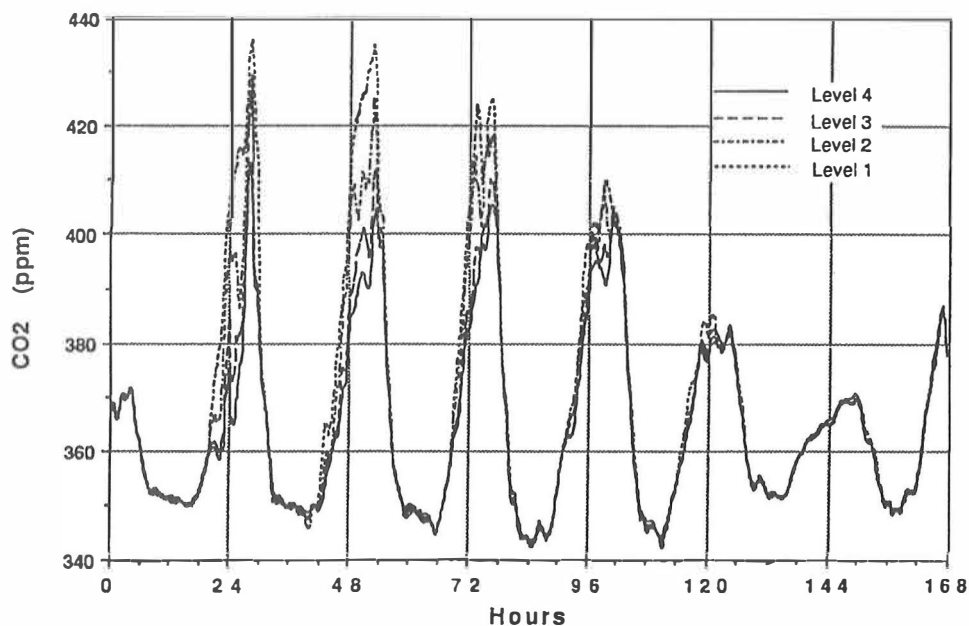
are very sensitive to changes in temperature or precipitation, indicating the potential for significant positive or negative feedbacks with the climate system.

THE GLOBAL CARBON CYCLE

The atmosphere, ocean, and land contain major reservoirs of C exchanged through regular cycles of varying length. On a daily basis during the growing season, land and ocean plants take up C through photosynthesis during the day, and release C through respiration both day and night. Daily and weather-related fluctuations are evident in measurements of atmospheric CO₂ taken at a tower in a forest canopy (Fig. 1). On a yearly cycle, the average global concentration of atmospheric CO₂ is lower in the North during the summer months because plants on the large land area of the Northern Hemisphere take up more C through photosynthesis than they respire, producing a net gain of C in biomass. Respiration in the North continues during the winter, while photosynthesis nearly stops, producing a net release of CO₂ from the land to the atmosphere. The yearly cycle is evident in measurements of atmospheric CO₂ from Mauna Loa, Hawaii (Fig. 2). Interannual variation is due to processes such as the well known El Nino/Southern Oscillation events (Francey et al. 1995), and may occasionally involve spectacular global events such as the recent eruption of Mt. Pinatubo.

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²One petagram (Pg) = 10¹⁵ grams = one gigaton (Gt) = one billion metric tons



HOWLAND, ME -- WEEK 26/1991

Figure 1.—A week of CO₂ profile data taken at four levels in and above the forest canopy at Howland, Maine. During this summer week the weather changed from sunny and moderately windy to cloudy with higher nighttime winds (Goltz 1993).

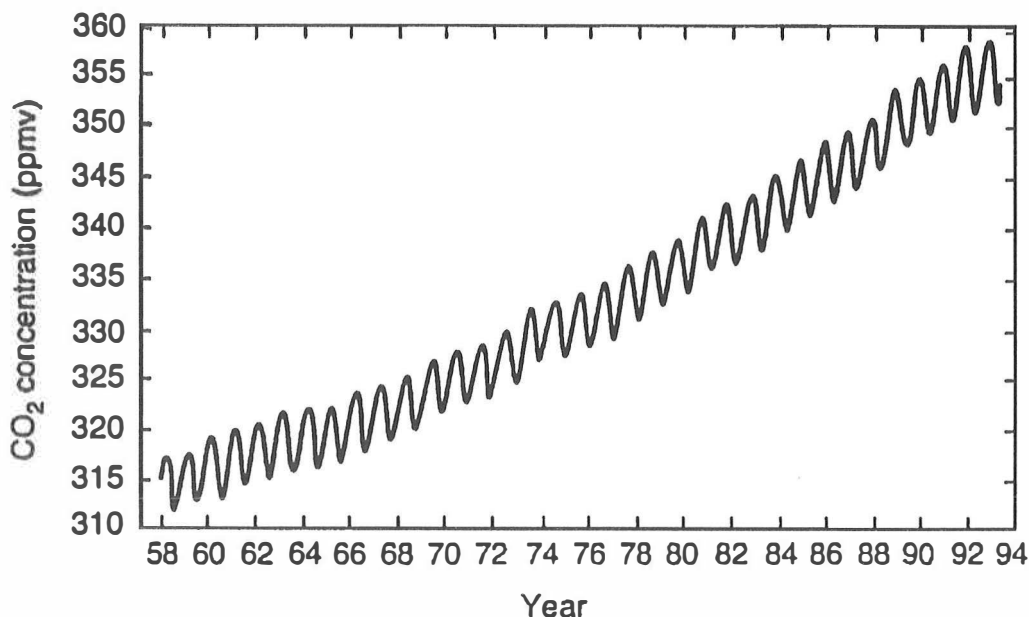


Figure 2.—CO₂ concentrations measured at Mauna Loa, Hawaii since 1958 showing trends and seasonal cycle (Houghton et al. 1995).

The atmospheric record shows that CO₂ has been increasing for the last 40 years, and when the contemporary record is supplemented by measurements of CO₂ in air bubbles trapped in ice cores, the combined record shows a continual increase for several hundred years (Fig. 3). Part of the increase is due to long-term natural cycles of radiation and temperature that influence other earth processes such as glaciation. According to the most recent Intergovernmental Panel on Climate Change consensus report (Houghton et al. 1996), human activity (primarily land use change and fossil fuel use) is causing some of the recent observed increase in

atmospheric CO₂. Projections based largely on expected economic activity and demographic changes show atmospheric CO₂ increasing at a rate that could double pre-industrial levels during the next 100 years.

Despite systematic measurements of atmospheric CO₂, and terrestrial and ocean reservoirs, the exact size of the various reservoirs and the fluxes between reservoirs are only partially known. Schimel (1995) summarized the current state of knowledge of the global C cycle, with particular reference to the role of terrestrial ecosystems (Fig. 4). Fluxes

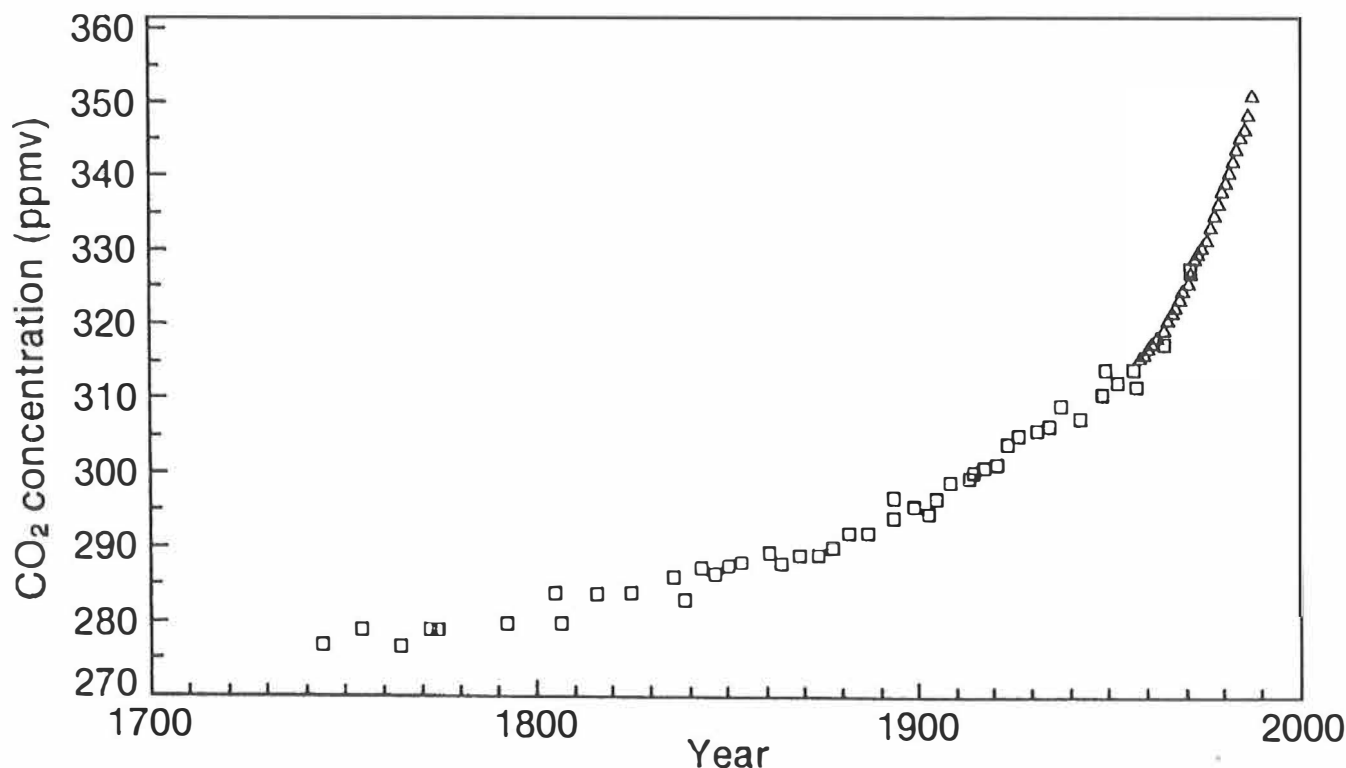


Figure 3.—Atmospheric CO₂ increase in the past 250 years, as measured from air trapped in ice (squares) and by direct atmospheric measurements (triangles) (Houghton et al. 1990).

among the four major reservoirs—fossil C, the atmosphere, the oceans, and the terrestrial biosphere—should be in balance, but our best estimates produce an imbalance or “missing sink” of approximately 1.4 Pg C/yr. Evidence from atmospheric measurements suggests that the missing sink is located in the Northern Hemisphere (Ciais et al. 1995). It is thought that inaccurate accounting for additions to C storage in regrowing forests, CO₂ fertilization of plant growth, and Nitrogen (N) deposition may all be contributing to the imbalance (Schimel 1995).

The evidence supporting the hypothesis that regrowing forests are a large C sink comes from three sources: periodic forest inventories, direct flux measurements above forest canopies, and measurements of the atmospheric concentrations of isotopes of C and oxygen.

Periodic inventories of timber volume in Europe and the U.S., when converted to estimates of C, show increasing C storage in forest ecosystems over the last 40 years (Birdsey 1993; Kauppi et al. 1992). These inventories are based on statistical sampling designs that provide representative data for large geographic areas. There is considerable uncertainty in estimating the non-timber components of ecosystem C (C in soils, litter, coarse woody debris, understory vegetation) that comprise the bulk of the total C (about 85 percent) in the ecosystem. Estimates from successive inventories can be compared to estimate average CO₂ flux over long periods.

Direct measurements of CO₂ flux at towers in the forest canopy are more precise over short periods and when

meteorological conditions are favorable. However, the few active measurement sites represent only limited areas of the landscape, and also have limited capability to specify the allocation of C to specific ecosystem components (e.g. Wofsy et al. 1993). A much larger network of sites is required to make statistical estimates for large regions of the globe.

Measurements of the concentrations of C isotopes at a global network of sites can quantify the net removal of CO₂ from the atmosphere by the oceans and terrestrial plants (Ciais et al. 1995). Analysis of this data shows strong evidence of a northern temperate C sink in 1992 and 1993.

CO₂ fertilization effects are thought to be significant because the many experiments conducted with individual plant species show typical increases in photosynthesis and growth of about 20 to 40 percent or more with doubling of CO₂ (Bazzaz et al. 1990). However, most studies have been short-term and involved immature plants in isolation from other ecosystem factors that may limit the plant response to increased CO₂. The effect of plant acclimation as well as the effects at the whole ecosystem level can only be inferred from incomplete evidence. It is thought that nutrient and water limitations reduce the magnitude of the CO₂ fertilization effect, but the interactions of C, N, and water are complex and can only be partially understood at the ecosystem level by using models. Only a few ecosystem-level experiments have been initiated and these studies tended to involve short-stature, non-tree vegetation. Direct observations of natural ecosystems cannot attribute responses to specific causes even if the measurement

The Global Carbon Budget (Pg)

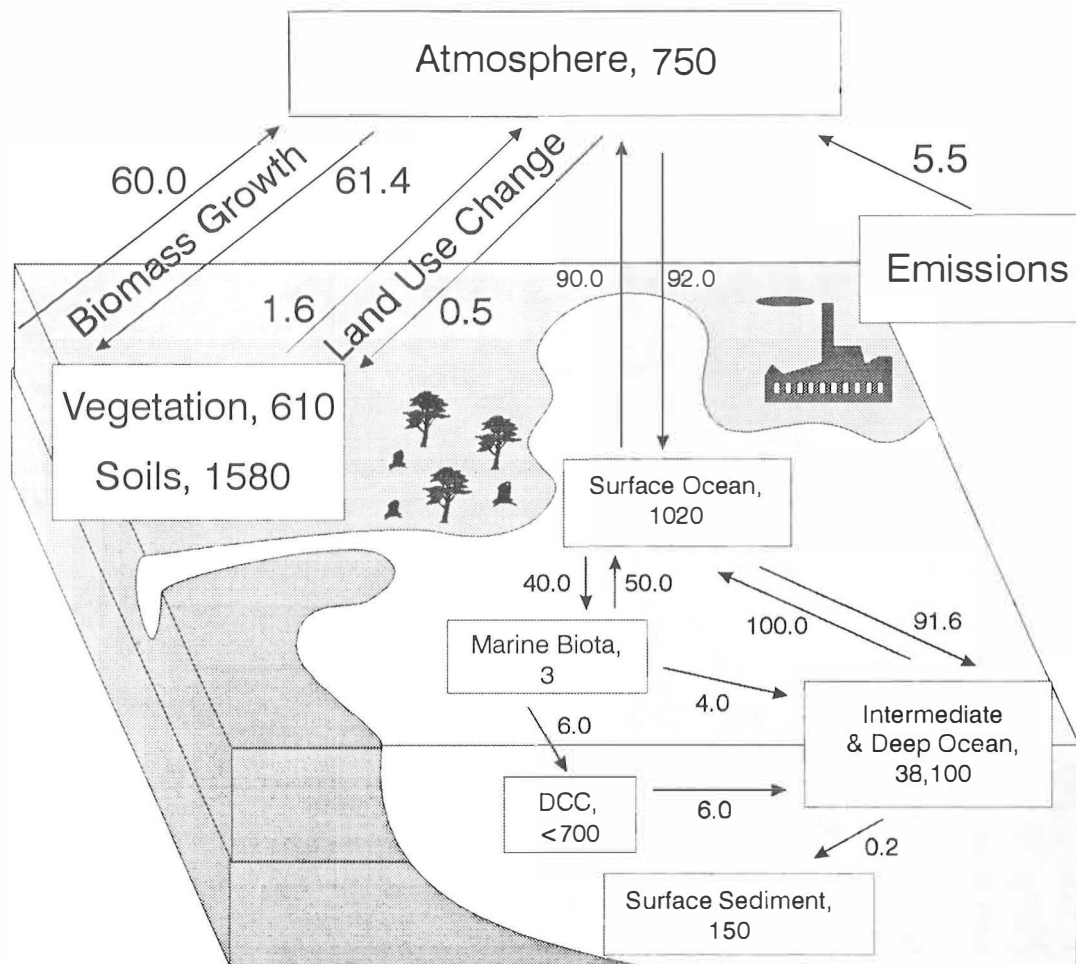


Figure 4.—The global carbon budget (Pg) (Schimel 1995).

difficulties could be overcome (e.g., measurement of root growth changes or changes in foliar biomass), because ecosystem responses integrate many different factors such as light, moisture, temperature, successional status, and nutrient availability, as well as a complex of atmospheric influences such as ozone and CO₂.

Nitrogen deposition is thought to increase C storage because most ecosystems respond positively to added N (Schindler and Bailey 1993). However, as with the C cycle, there are limited measurements available as well as a lack of understanding of some key processes that make the model estimates unreliable. There is also increasing evidence that some ecosystems can become saturated with N. Excess N may reduce growth and cause losses of N to water systems (Aber et al. 1989).

If northern forests are sequestering more C than expected, there remains a significant question about where that C is

located. Harrison and Broecker (1993) calculated that a 1.1 Pg C/yr increase in the inventory of C should be found in the following pools: 0.5 Pg C in the soil; 0.1 Pg C in litter, and 0.5 Pg C in vegetation. However there is great uncertainty in these estimates, and refinement would offer managers and policy makers better choices in their attempts to mitigate atmospheric increases in CO₂.

CONCLUSIONS

Reducing the uncertainty about feedbacks between the biosphere and the atmosphere is essential to improving our simulations of future atmospheric CO₂ and potential greenhouse warming. This knowledge also helps us understand and anticipate the effects on forest ecosystems so that managers may know how their actions could help mitigate the causes of warming, and how they could adapt to expected changes in the physical and chemical environment.

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CLIMATE SCENARIOS

Sue Ferguson¹

A climate scenario is a description of a possible condition. Usually scenarios are based on assumptions about the future and may be limited in scientific knowledge and certainty. Because there is no assigned probability of occurrence, scenarios are not forecasts. Most available climate scenarios are at relatively coarse spatial and temporal scales (several hundred kilometers and monthly to seasonal), which are above the resolution of typical hydro-ecological processes. Table 1 summarizes the climate inputs required by models supported in the Forest Service Global Change Research Program. Note that modeling hydro-ecological processes usually requires less than 100 km spatial scales and monthly or less temporal scales.

Assessing the impact of global change on ecosystem dynamics in the United States has required the specialized development of techniques to down-scale output from global and regional climate models. The following sections describe methods for generating baseline scenarios, from which the degree of possible future change can be determined, and possible future scenarios. Although methods to down-scale scenarios are becoming increasingly sophisticated, adequately representing climate variables that control disturbance (e.g., flood, fire, drought, insect infestation, blow-down, etc.) is difficult. Also, influences of complex topography and surface roughness (variable vegetation and water surfaces), which are common in wildland areas of North America, are poorly handled in many down-scaling methodologies. Some of the special methods that have been developed to incorporate climate scenarios into assessments of hydro-ecological responses are described.

BASELINE CLIMATE

To help understand the magnitude and rate of change in a possible future condition, baseline conditions usually are described from a database of historical information. If instrument data are used, empirical methods are required to spatially or temporally interpolate between observation sites and times, or to estimate climate variables that were not directly measured. Available global data sets range from 1/2° to 5° latitude-longitude resolution (e.g., Trenberth and Olson 1988a, 1988b; Shea 1986; Legates and Willmott 1990a and 1990b; Leemans and Cramer 1991; Hurrell and Campbell 1992; Warren and others 1986). Within the contiguous United States domain, the Historical Climatology Network (HCN) data provide high quality, long-period records (most greater than 70 years) of monthly mean, maximum, and minimum temperature, and monthly total precipitation. A subset of these stations have available daily data. Most HCN sites were established at early centers of population, preferentially located in river valleys or other low elevation sites. Observations are unevenly spaced (not in a grid-point format) about 1° latitude-longitude in the eastern United

States and about 2° latitude-longitude in the western United States (Hughes and others 1992). The HCN data are a subset of the National Weather Service Cooperative Observer network (NOAA 1988), which offers the highest spatial resolution of daily data throughout the nation. The highest temporal resolution historical data that are most easily available are in the National Solar Radiation Data Base (NSRDB) developed by the National Renewable Energy Laboratory (1992) with 30 years (1961-1990) of hourly data from National Weather Service primary stations. Observed and derived values of temperature, wind, radiation, snow depth, cloud cover, dew point, precipitation, and relative humidity are included. Climatological winds were derived by Elliot and others (1987) at 1.4° latitude by 1.3° longitude spatial resolution and seasonal temporal resolution. Various regional data sets provide added spatial and temporal resolution.

Several methods have been applied to the instrument and proxy data to generate long-term means of historical records. For example, Daly and others (1994) developed a Precipitation-elevation Regressions on Independent Slopes Model (PRISM) to distribute precipitation observations. PRISM is a statistical-analytical model that uses point data and a digital elevation model (DEM) to generate gridded estimates of monthly precipitation. It is well suited to regions with mountainous terrain, because it incorporates a conceptual framework that addresses the spatial scale and pattern of orographic precipitation. A database of long-term monthly mean precipitation has been generated at 5 minute (about 10 km) grid-cell resolution for the contiguous United States (Daly and others 1994).

To generate a climate database at 1/2° latitude-longitude spatial resolution for the contiguous United States, Kittel and others (1995, 1996) used PRISM-generated monthly precipitation data and applied an adiabatic adjustment to spatially interpolate monthly temperature observations (Marks 1990). A stochastic weather generator, WGEN (Richardson 1981; Richardson and Wright 1984), was used to generate daily mean data from these monthly statistics. Daily vapor pressure deficit and solar radiation was then estimated from WGEN temperature and precipitation by applying CLIMSUM (Running and others 1987; Glassy and Running 1994).

Regional daily scenarios include those in the Northwest and Southeast United States. Running and Thornton (1996) generated 2.5-km grid-cell scenarios for 3 characteristic years in the Columbia River Basin. A cool, wet year (1982), warm, dry year (1988), and a normal year (1989) were chosen to take advantage of more numerous mountain observation data that became available in the late 1970's. They used elevation-regression techniques to distribute daily data from over 400 stations within the region. Cooter and others (In press) used the Richman-Lamb 1° historical database (Richman and Lamb 1985; Richman and Montroy

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Table 1.—Climate input variables required for hydro-ecological models. Results of a 1994 survey of Forest Service Global Change Research Program modelers.

Model	Resolution		Climate Input Variables
	Temporal	Spatial	
TEM	monthly	n/a	temperature
			precipitation
			cloudiness
MAPSS	monthly	10km to 1 deg. lat/lon	temperature
			precipitation
			vapor pressure
			windspeed
BIOMASS	daily	1 km to 1 deg. lat/lon	temperature
			precipitation
			cloudiness
PnET	monthly	1 km	temperature
			precipitation
			solar radiation
			vapor pressure
MAESTRO	hourly	n/a	temperature
			precipitation
			relative humidity
			windspeed
MHMS	daily	.5 km2 to 75 km2	temperature
			precipitation
			solar radiation
Tree Regeneration	weekly or monthly	1 km	windspeed
			potential evapo-transpiration
Gap-phase	monthly	1 km	temperature
			precipitation

1986), of proxy data and known physical and statistical relationships, to form a 45-year (1949-1993) daily baseline scenario for the southeastern United States, which includes maximum and minimum temperature, precipitation, net radiation, and vapor pressure deficit.

Monthly time step scenarios are more common than daily. For example, Neilson (1993), Neilson and Marks (1994), and Monserud and others (1993) used various forms of the IIASA climate database (Leemans and Cramer 1991) for their global baseline scenarios at 1/2° latitude-longitude grid resolution. Ollinger and others (1993, 1995) used multiple-regression techniques to spatially distribute observations from 164 stations in the northeastern United States. A database of long-term (1951-1980) monthly mean precipitation, humidity, radiation, and minimum and maximum temperatures was generated at 30" (about 0.8 km) latitude-longitude spatial resolution.

Unfortunately, data sets built on monthly means do not easily represent extreme events that cause ecological disturbances

(e.g., flood, fire, drought, insect infestation, blow-down, etc.). Neilson (1995) compensated for this deficiency by assuming that summer precipitation occurs during similar atmospheric instability that causes lightning in the central United States. Therefore, he turned on and off a fire rule depending upon summer precipitation occurrence. The coarse resolution of wind climatology (Elliott and others 1987), however, prevents application to other ecological disturbances like blow-down, fire spread, and pollution trajectories.

CLIMATE CHANGE SCENARIOS

Output from general circulation models (GCMs) are the most commonly available climate change scenarios. These models have been used to test the atmosphere's sensitivity to increasing greenhouse gases. Quasi-steady state, or equilibrium, model runs typically have a dynamic atmosphere with simple approximations for hydrosphere, biosphere, and cryosphere. Currently available transient model runs couple dynamic atmosphere general circulation models (AGCMs) with dynamic ocean general circulation models (OGCMs).

These often are referred to as coupled (ocean-atmosphere) general circulation models (CGCMs). Recently, special emphasis has been directed toward improving dynamic sea-ice modeling (e.g., Lynch and others 1995; Wehner and others 1995) and dynamic vegetation modeling (e.g., Chase and others 1996; Neilson and Running 1996).

Equilibrium GCM experiments most commonly simulate the response of general circulation patterns to doubling the amount of current atmospheric concentrations of carbon dioxide ($2 \times \text{CO}_2$), or its greenhouse gas equivalent. There are baseline ($1 \times \text{CO}_2$) and $2 \times \text{CO}_2$ scenarios available from each model. USDA Forest Service researchers commonly use model output data that have been generated by modeling groups at: Oregon State University (OSU, Schlesinger and Zhao 1989), Geophysical Fluid Dynamics Laboratory (GFDL, Gordon and Stern 1982), United Kingdom Meteorological Office (UKMO, Slingo 1985), Goddard Institute for Space Sciences (GISS, Hansen and others 1983), and Canadian Climate Center (GCMII, Boer and others 1992; McFarlane and others 1992). Model output from the Max Planck Institute (MPI) also is available (ECHAM, Rockner and others 1992). The International Society of Biometeorology recently established a study group to evaluate scenarios of possible global warming and made available several climate scenarios from MPI's ECHAM GCM, including one high resolution (about 100 km by 100 km) $2 \times \text{CO}_2$ scenario (Auliciems and von Storch 1994).

Because of the global scale of these GCMs, grid resolutions are from 4° latitude by 5° longitude to 8° latitude by 10° longitude. The temporal resolution of most available output data are monthly to seasonal. The models reasonably simulate large-scale flow patterns that are controlled by continentality, or the contrast between land and sea (IPCC 1990, 1992). Down-scaling techniques are required to determine local and regional climate responses to increasing greenhouse gases from global model output (Giorgi and Mearns 1991).

Mesoscale or regional climate models can be nested within GCMs to obtain higher spatial resolutions and evaluate regional responses to changes in global circulation. Currently, output from only one nested model is available for the contiguous United States. It was developed by Giorgi and others (1993a, 1993b, 1994) at the National Center for Atmospheric Research (NCAR). The model, RegCM, nests the NCAR and Pennsylvania State University mesoscale model, MM4 (Anthes and others 1987), with the NCAR Community Climate Model, CCM (Thompson and Pollard 1995a and 1995b). The spatial resolution of RegCM output is 60 km x 60 km. Two continuous 3.5-year-long climate simulations over the continental United States are available, one for present-day conditions and one for conditions under double CO_2 concentration (Giorgi and others 1994). Output from RegCM shows reasonable representation of topographically controlled climate in the Pacific Northwest (Giorgi and others 1993a; Giorgi and others 1994). For this reason it was used to help generate a climate change scenario for the Columbia River Basin Assessment and Eastside Ecosystem Management Project (Ferguson, in press).

McCorcle and others (1993) used the Mesoscale Atmospheric Simulation System, MASS (Zack and Caplan 1987; Cram and others 1991) with GFDL's $1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ output to demonstrate the importance of mesoscale climate features in the eastern United States. In particular, mesoscale soil-moisture and lake-land variations significantly affected temperatures, cloud cover, and precipitation in the midwestern United States. Work now is underway to develop MASS-GFDL generated data at 25-km x 25-km spatial resolution in the eastern United States for characteristic climate years (e.g., 1988 Great Plains drought and 1993 Midwest flooding)².

Equilibrium model runs have limited application for assessing disturbance because the models do not adequately simulate daily through decadal patterns of variability (Mearns and Rosenzweig 1994; Campell and others 1995). Also, extreme values typically are not reported. The physical models do calculate instability, humidity, incoming radiation, and winds, however, that are missing from most observation data. Therefore, if appropriate output formats can be acquired, they may provide useful tools for generating some types of climate disturbance scenarios.

Time-series scenarios can be generated by using output from CGCMs or by selecting a function (e.g., linear or exponential) of change from current to $2 \times \text{CO}_2$ using equilibrium GCM output. Model output from transient (time series) CGCMs are becoming more available. Descriptions and comparisons of output from the NCAR (Washington and Meehl 1989), MPI (Cubasch and others 1992), GFDL (Stouffer and others 1989), and UKMO (Cullen 1993) coupled ocean-atmosphere runs also are available (IPCC 1992; World Climate Research Programme 1992; Kattenberg and others, in press). Most commonly, simulations of the dynamic response of oceans and atmospheres assume 1% per year increases in CO_2 concentration, or its greenhouse gas equivalent. Available output includes monthly values for periods averaging around baseline (current) and the time of $2 \times \text{CO}_2$ (about 70 years from baseline).

The spatial resolution of the atmospheric component in CGCMs is similar to GCMs (from 4° latitude by 5° longitude to 8° latitude by 10° longitude). A high resolution (60km by 60km), 10-year (1979-1988) baseline simulation of monthly mean and daily time-series values from RegCM is available (Giorgi and others 1993a) for the contiguous United States. Bowles and others (1994) are working to extend this baseline scenario to 15 years for the western States.

LINKAGE

Available process-modeled climate scenarios exist at large spatial scales, short time periods, or small domains. Therefore, empirically generated scenarios most commonly are used to represent current (baseline) climate for hydro-ecological applications. The baseline climate scenarios are

²Personal communication. 1996. Warren Heilman, North Central Forest Experiment Station, 1407 South Harrison Road, Room 220, East Lansing, MI 48823.

then linked to process-modeled change scenarios. One way of creating this linkage is to apply the change calculated between model control runs and model 2 x CO₂ runs onto the empirical baseline scenarios (Neilson 1993; Monserud and others 1993; Kittel and others in press; Cooter 1996; Cooter and others, in press; Running and Thornton 1996). This method preserves spatial variability that is inherent in the baseline scenarios.

Most often equilibrium change scenarios are applied to a baseline of long-period means (20 to 50 years). Output from several GCMs are used in order to illustrate a range of possible change. Running and Thornton (1996) applied a "best guess" regional change scenario (Ferguson 1997) to a "normal" year (1989) baseline for the Columbia River Basin; a limited, but effective way of illustrating spatial variability in daily climate patterns.

Scenarios based on surprise alternatives or historical analogues are scarce. The "MINK" study used a "dustbowl" scenario for the central United States based upon 1930-1939 observations of temperature and precipitation (Crosson and Rosenberg 1993). Some researchers select an unusual year of observation data and then hold that year's weather constant for 10 to 20 years to simulate surprise scenarios.

Linking empirical and process-modeled scenarios with time series is more difficult but still desirable to preserve the spatial and temporal variability best represented by observations. Efforts to model the transient response of vegetation to climate change have been hampered by the lack of high temporal resolution climate scenarios (Mearns and Rosenzweig 1994). Recent efforts have begun to generate long-period, high temporal resolution, transient scenarios for the contiguous United States at 1/2° spatial resolution by VEMAP and for the state of Oregon at 2.5' resolution (Ferguson and others, in preparation)³. The effect of changes in climate variability at daily to decadal scales is an important uncertainty. Therefore, the scenarios generated by these projects will be of great value for future global change assessments.

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MULTIPLE STRESS STUDIES ON FOREST TREE SPECIES

John Hom¹

Plants are subjected to environmental factors that reduce their potential for growth, including limitations of water, light, and nutrients. Plants, especially long-lived trees, must endure simultaneous and sequential environmental stresses to survive and maximize productivity. Forest ecosystems currently face a new suite of stresses in the chemical and physical environment that are increasing at unprecedented rates: ozone, atmospheric deposition, and elevated carbon dioxide. These anthropogenic stresses impose new conflicting demands on plant resources as they modify natural environments, and result in conditions that the plant has not adapted to and may exceed its genetic ability for compensation.

Adaptation to stress is an integrated, whole plant process. Biochemical and physical adjustments, occurring over different time scales, compensate for environmental changes. However, most physiological studies on plant stress usually focus on a single process over a short period of time. The results are extrapolated to predict losses in long-term yield. This approach can be equivocal as it does not consider interactive effects with other stresses or long term adaptation to stress.

Our program emphasizes physiological research on the effects of multiple, interactive stresses of major air pollutants, greenhouse gases, and environmental stresses, individually and in combination, on the growth and carbon allocation of important timber tree species.

CO₂, WATER, AND NUTRIENTS

Elevated CO₂ has been shown to increase photosynthesis and growth in plants, increase water use and transpirational efficiency, and decrease dark respiration. Thus, elevated CO₂ is normally not considered a stressor. However, some plants under high CO₂ may initially increase their photosynthetic rate but readjust to ambient conditions after a short acclimation period. Limited nutrient resources may reduce net photosynthesis under elevated CO₂.

Forest productivity in the South is limited by water stress and soil nutrient status. Field studies on the effects of elevated CO₂ with water and nitrogen fertilization showed that net photosynthesis for loblolly pine increased 32 to 91 percent compared with ambient controls in branch chamber studies (Fig. 1). Fertilization produced a 20 to 24 percent increase in net photosynthesis in elevated and ambient CO₂ treatments, while irrigation increased net photosynthesis 5 percent in both CO₂ treatments (Dougherty and Allen 1994; Murthy et al. 1995; Allen et al. 1995). Elevated CO₂ may increase the growth potential of these southern pine forests on sites not limited by nutrients and water.

Elevated CO₂ was found to compensate for water stress in red oak in environmental chamber studies (Tomlinson and Anderson, 1995). Water stress decreased biomass, leaf area, leaf number, height, and stem diameter, while elevated CO₂ increased these growth parameters. Water stress also reduced chlorophyll content and increased the nitrogen concentration in seedlings. With elevated CO₂, photosynthetic rates and chlorophyll content appears to plateau between 530 and 700 ppm. The combined effects of elevated CO₂ and water stress showed that CO₂ may offset the effects of water stress on growth and biomass production.

CO₂ AND TEMPERATURE

The Southern region is predicted to increase in temperature under global change scenarios. Temperature stress is a limiting factor in the productivity and regeneration of southern forests. A study of the effects of CO₂ and elevated temperature on carbon fixation of mature field-grown loblolly pine (Teskey 1995; Liu and Teskey 1995) indicated that long-term exposure to elevated CO₂ in branch chamber increased net photosynthesis 40 to 100 percent, increased leaf area 33 percent, and decreased dark respiration 10 percent when compared with foliage exposed to ambient CO₂. There was no downward acclimation in photosynthesis in the long term response to elevated CO₂. Increasing the air temperature by +2 °C had a slightly negative effect on photosynthesis, which is minor compared with the large CO₂ effect.

The direct effects of elevated CO₂ may change the cold hardiness of some economically important tree species and consequently change tree productivity and distribution. Seedlings of three conifers were cold-hardened in growth rooms under ambient levels of CO₂ (350 ppm) or 2X ambient levels (700 ppm). High CO₂ had little effect on cold hardiness of radiata pine, but increased the fall and spring hardiness of Douglas-fir. High CO₂ increased hardiness of ponderosa pine in autumn and decreased it in the spring. This preliminary study suggests that Douglas-fir is well adapted at its present upper elevational limit and may increase its distribution to higher elevations with elevated CO₂ and a warmer climate (Tinus et al. 1995).

OZONE AND WATER STRESS

Ozone is a potent phytotoxin that causes significant growth reduction and damage to sensitive tree species. Ozone accelerates foliar senescence, decreases leaf area and growth, and generally lowers the photosynthetic capacity and carbon accumulation through damage to the photosynthetic machinery. Generally, plants with higher rates of photosynthesis are more susceptible to ozone damage (Reich 1987), as ozone damage is cumulative. Water stress and low stomatal conductance will decrease plant growth and the interaction of water stress and ozone may decrease ozone injury by reducing the cumulative uptake of ozone through the stomates.

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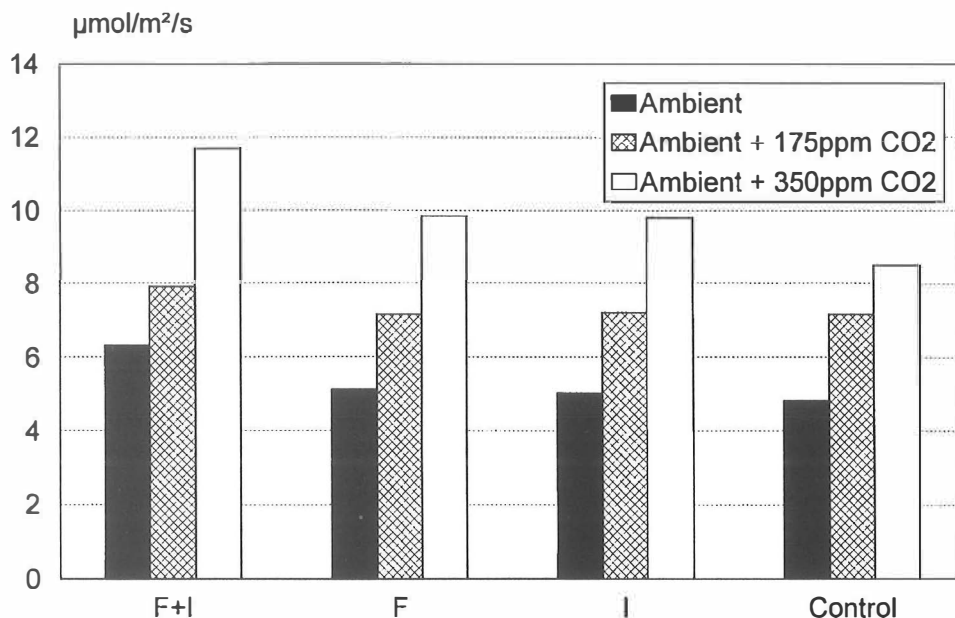


Figure 1.—Maximum photosynthetic rates of loblolly pine under elevated CO₂, irrigation (I), and fertilization (F), Dougherty and Allen, 1994.

Peak ozone concentrations as well as water stress occurs during the summer months in southern California. A long, persistent drought during 1985 to 1989 reduced the uptake of ozone and limited tree injury. A return to adequate precipitation increased plant gas exchange, resulting in greater ozone uptake and tree injury (Miller et al. 1994).

Water stress is recognized as the most limiting factor to growth in southern forests. However, significant ozone damage occurred in shortleaf pine in open-top exposure chambers (Flagler et al. 1993) even at severe water deficit conditions, resulting in accelerated senescence of foliage and decreased biomass, chlorophyll and nitrogen content, photosynthesis and stomatal conductance. Ozone has been implicated as the causal agent for a 5 percent reduction in the annual growth of southern commercial pines (Teskey 1995b). This annual, compounding loss in productivity is expected to increase under scenarios of increased drought and regional ozone exposure. The interaction of ozone and drought stresses under existing ambient conditions may cause greater growth reduction than either stress alone (McLaughlin and Downing, 1995a). This analysis is currently being debated (see Reams, et. al., 1995, McLaughlin and Downing, 1995b).

CO₂ AND OZONE

Elevated levels of atmospheric carbon dioxide are generally thought to ameliorate the detrimental effects of ozone. The higher concentration gradient of CO₂ from leaf interior to exterior would decrease stomatal aperture, yet maintain equivalent photosynthetic rates while limiting ozone uptake into the leaf interior. Increased carbon assimilation and reserves would support additional carbon requirements to repair ozone damage to membranes and biochemical constituents in the leaf.

Long term exposure of yellow-poplar to ozone and elevated carbon dioxide showed compensatory growth (Rebbeck 1993, 1994, 1995; Fig. 2) when the plants were exposed to two times ambient levels of O₃ and 700 ppm CO₂ (2X+CO₂). However, eastern white pine initially showed no response or a small decrease in stem height with increasing O₃, with the largest growth reductions in trees grown at 2X+CO₂. White pine photosynthetic rates for 2X+CO₂ increased substantially in the second year of treatment, but greater whole tree growth was not observed. The interaction of ozone and CO₂ in pines showed less compensatory response to elevated CO₂ than yellow-poplar, demonstrating that it is difficult to generalize or predict a species response to ozone, alone and in combination with elevated CO₂.

Clones of trembling aspen, grown in open-top chambers, responded very differently to elevated ozone, alone or in combination with CO₂ after two years of exposure (Kull et al. 1996; Coleman et al. 1995, 1996). Physiological and biomass measures for ozone-sensitive clones of trembling aspen showed a significant negative response to O₃. The negative impact of O₃ was not compensated by the simultaneous addition of 150 ppm CO₂ above ambient levels, resulting in significant negative interaction of O₃ and CO₂ on photosynthesis, biomass, stomatal conductance, chlorophyll content, leaf abscission, and leaf area (Fig. 3). These experiments show that different plant species and even clonal varieties within a species may respond differently to greenhouse gases individually and in combination. These are exceptions to the generalization that elevated CO₂ will compensate for ozone stress, emphasizing the importance of multiple stress studies on different species. For some clonal species such as aspen, land managers may wish to select for resistant stock.

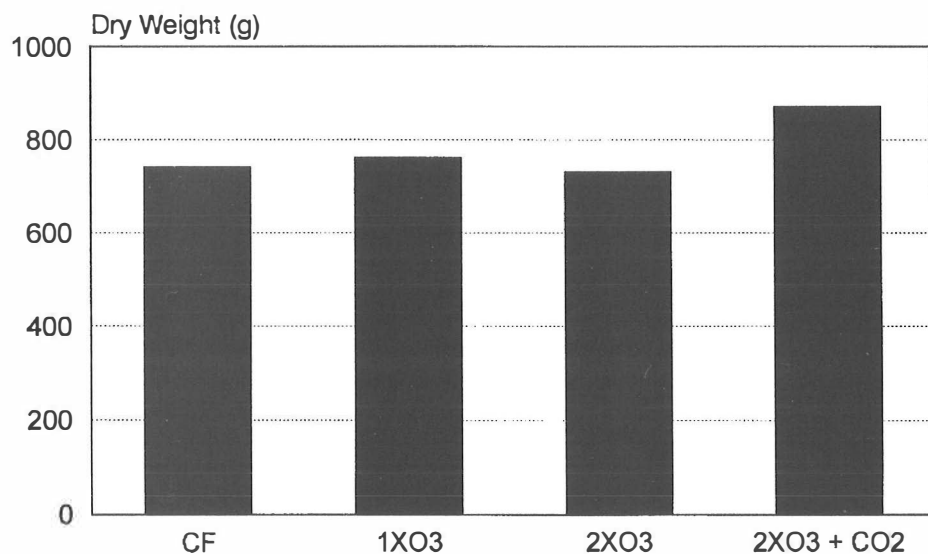


Figure 2.—Total biomass of yellow-poplar grown under charcoal filtered (CF), ozone and elevated CO₂ treatments (from Rebbeck, 1995).

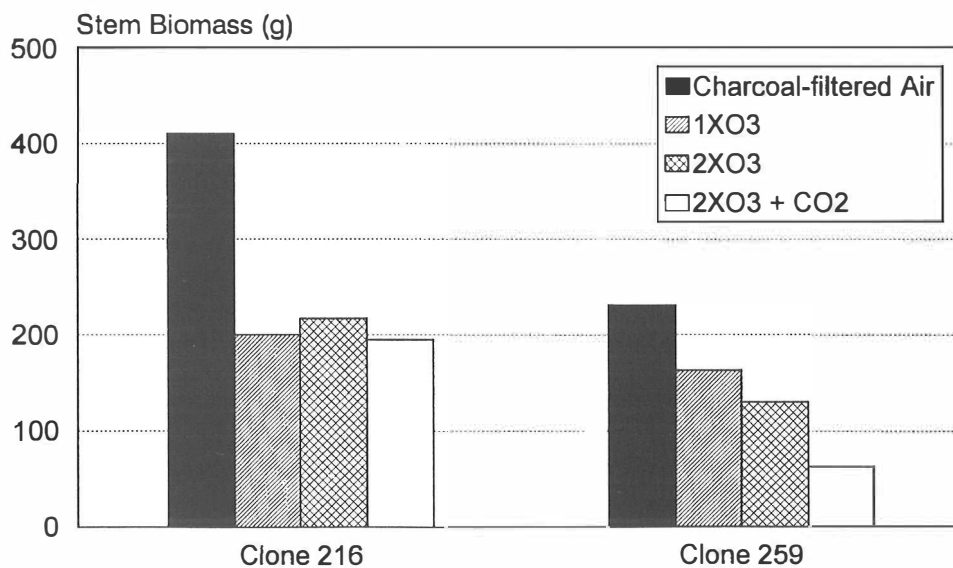
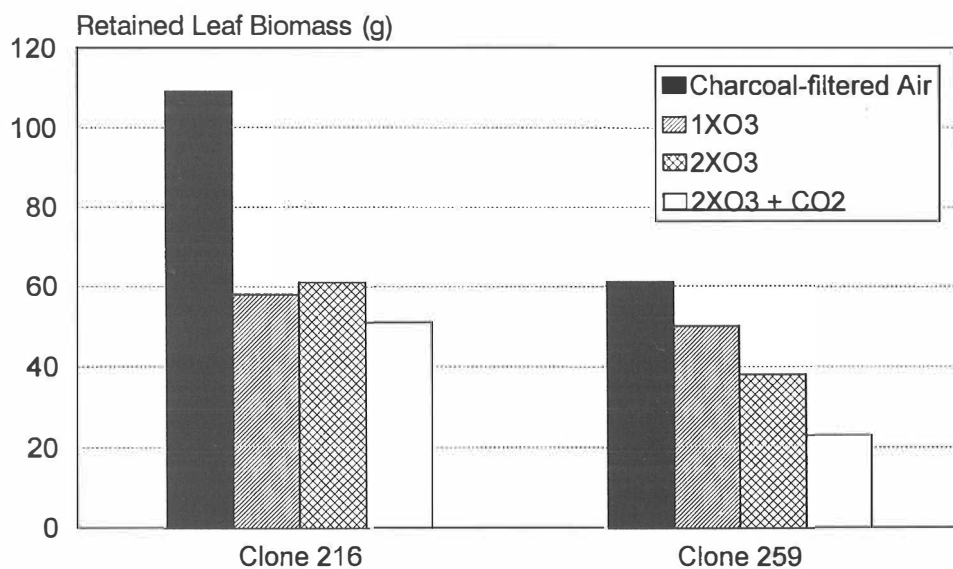


Figure 3.—Response of ozone tolerant (216) and ozone sensitive (259) aspen clones to elevated CO₂ and ozone treatments, (D. Karnosky, personal communications).

CLIMATIC AND POLLUTION GRADIENT STUDIES

Controlled experiments utilize step increases in treatment dosage above ambient levels (2XCO_2 , 2XO_3) to emphasize the treatment effect while controlling confounding factors. However, this does not address how environmental stresses influence ecosystem processes, nor does it address realistic rates of increase for climatic factors and greenhouse gases (i.e., 0.4 percent per annum for CO_2). Studies along climate and pollution gradients address ecosystem processes but encounter difficulties with year to year climate variability and confounding factors such as geographic differences in climate, soils and plant compositions along the gradient.

Despite spatial and temporal variation, there is evidence that pollutant deposition has altered soil and vegetation processes in gradient studies. The Michigan Gradient was established to examine the effects of climate and atmospheric deposition on forest productivity and ecosystem processes. Leaching of calcium (Ca) and magnesium (Mg) from foliage and soil solution at sites receiving high levels of acidic deposition was a consequence of the pollution deposition. Higher foliar biomass in the southern sites may be a consequence of higher temperature and longer growing season, but is also consistent with the effects of chronic nitrogen (N) deposition in this region.

The San Bernardino Mountains in Southern California represent a west-to-east air pollution gradient for high-to-low ozone and nitrogen deposition from anthropogenic emissions (Riggan et al. 1985; Fenn and Bytnerowicz, 1993). The use of fossil fuels releases nitrogen pollutants, typically nitric oxide (NO). In the presence of photooxidants, ozone, and with sufficiently warm temperatures, the NO is rapidly oxidized to NO_2 and subsequently to nitric acid (HNO_3) vapor by gas phase reactions. Daily peak concentrations of nitric acid and ozone occur at the same time in the mountains of the South Coast Air Basin. Exposed plants may be predisposed to phytotoxic effects of other pollutants. However, forests may benefit from the fertilizer effect of nitrogen deposition to compensate for ozone damage with higher foliar N concentrations and carbon assimilation rates (Pell et al. 1994).

PRIMARY AND SECONDARY STRESSES

The timing and intensity of multiple stresses may determine how a tree responds to environmental change. An initial stress such as acidic deposition predisposes red spruce to freezing damage. Several studies have shown that acid mist, common in high elevation red spruce, lowers the cold tolerance of red spruce foliage by 3 to 5 °C, predisposing it to winter injury (Strimbeck et al. 1995).

The sequence of environmental stress, along with phenological stage of the plant, may allocate limited carbon resources to leaves, roots, plant secondary compounds, or antioxidants and lower the plant's resistance to secondary

stresses. Hypothetically, a plant that may be tolerant to ozone may shift its carbon and nitrogen resources to antioxidants instead of secondary compounds, and therefore may be susceptible to insect vectors.

PRIMARY AND SECONDARY EFFECTS

Environmental stress directly affects plant productivity and survival, and secondarily affects ecosystem processes, which in turn affect forest health and productivity. For example, elevated CO_2 can increase the photosynthetic rate at a lower nitrogen content, increasing the photosynthetic efficiency per unit nitrogen, and reducing the respirational requirements to maintain photosynthetic enzymes. However, the lower nitrogen content will eventually change the quality of the leaf and litter. This feedback would increase C:N ratios in the soil, lower decomposition rates, and affect nutrient cycling. A greater proportion of carbon may be required for new roots to acquire limited nutrients, changing plant productivity.

A change in leaf quality was seen with insect herbivory studies on plants grown under CO_2 and ozone (Herms et al. 1995). Growth rates of insects decreased when fed leaf tissue grown under elevated CO_2 , whereas ozone-fumigated foliage increased insect growth rate over ambient controls.

FUTURE RESEARCH

Without multiple stress studies, we cannot develop a comprehensive understanding of how plants respond to interactive stress. 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. The challenge is to design integrated studies, at larger scales, to address multiple stress interaction on forest ecosystem processes, such as the Free Air Carbon Dioxide Enrichment (FACE) studies at Duke University, and the large ecosystem-scale exposure facility under construction at the USDA Forest Service Laboratory at Rhinelander, WI. Stand-level process models parameterized for important forest species should be developed in parallel with field experimentation to integrate across scales. Managers and policy analysts need to know these outcomes and should carefully evaluate broad conclusions based on numerous small-scale experiments, many of which involve immature trees in short term studies.

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POTENTIAL CHANGES IN THE VEGETATION DISTRIBUTION IN THE UNITED STATES

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INTRODUCTION/APPROACH

The potential impacts on U.S. vegetation of CO₂-induced global warming were analyzed for sufficient effects, either positive or negative, that might require dramatic shifts in forest management policies. The Mapped Atmosphere-Plant-Soil System (MAPSS) was used to simulate vegetation distributions, and the results were compared with other ecological models to explore uncertainties.

The point of departure for the analysis was the Resources Planning Act (RPA) Assessment *Forest Resources of the United States, 1992* (Powell et al. 1993). Tables in the 1992 RPA assessment present the area of each forest type as determined from forest survey data. The data selected for this analysis are for all forests in the conterminous U.S., including forest reserves. The 1992 survey also includes a forest type map produced as a remote sensing product. The map has a spatial resolution of 1 km and, when incorporated in a Geographic Information System (GIS), allows an independent estimate of forest area by type. The GRASS GIS was used for these analyses (USA-CERL 1993).

Potential future forest distribution under global change was determined in two separate projects, a USFS-sponsored project and a consortium-sponsored project (USFS, NASA, NSF, EPRI). The MAPSS project is an ecosystem distribution simulation project with a spatial resolution of 10 km over the conterminous U.S. and 0.5° latitude-longitude over the globe (Neilson and Marks, 1994; Neilson 1995). The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) is an IGBP core project (VEMAP members 1995) to compare three global biogeography models (MAPSS, DOLY (Woodward and Smith 1994) and BIOME2 (Haxeltine and Prentice in press)) and three global biogeochemistry models: TEM (McGuire et al. 1995; Raich et al. 1991), CENTURY (Parton et al. 1988), and BIOME-BGC (Running and Hunt 1994) under current and 2xCO₂ climates. The advantage of the MAPSS project is the relatively high spatial resolution (10 km) and the greater number of climate scenarios, but the project is limited to the use of only one biogeography model. The advantage of the VEMAP project is the use of several different ecological models, but the project is limited by the coarse spatial resolution of 0.5° and fewer scenarios.

The MAPSS model (Neilson 1997, this volume), a process-based biogeography model, was implemented over the conterminous U.S. at a spatial resolution of 10 km. The model has been calibrated to current climate and the simulations compared to the RPA forest area data (Powell et al. 1993). Since MAPSS only simulates potential natural vegetation distribution, there is no facility for directly

incorporating land use. Therefore, the 1992 remote sensing image of forest distribution and forest type (Powell et al. 1993) was used to develop a mask of the non-forest area. This mask was used in the GIS to limit analysis of the MAPSS output to those areas that are currently forested, as represented in the satellite image. The MAPSS model was then operated under several 2xCO₂ climate scenarios produced by different General Circulation Models (GCM). The present-day, non-forest, mask was also used for all potential future forest distributions, imposing the unrealistic assumption that areas currently non-forested will remain non-forested, primarily due to agriculture.

Scenarios of double CO₂ climatic change were derived from six GCM 2xCO₂ equilibrium simulations. Climate scenarios were supplied by the Data Support Section within the Scientific Computing Division of the National Center for Atmospheric Research (NCAR). Model outputs for current and 2xCO₂ climates were obtained from the following models: GISS (Goddard Institute of Space Studies, Hansen et al. 1988); UKMO (United Kingdom Meteorological Office, Mitchell and Warrilow 1987); GFDL (Geophysical Fluid Dynamics Laboratory, Wetherald and Manabe 1988); and OSU (Oregon State University, Schlesinger and Zhao 1989). The GFDL-R15 (ca. 4° x 5° grid), R15 Q-flux and R30 (ca. 2° x 2.5° grid) versions were used. The Q-flux version of the GFDL model (GFDL-Q) includes a prescribed ocean-atmosphere coupling (Manabe et al. 1991). The coarse grid from each model was interpolated using a 4 point, inverse distance squared algorithm to a 10 km albers grid in a raster-based Geographic Information System (USA-CERL 1993). The scenarios were applied as recommended and calculated by the NCAR Data Support Section. Scenarios were constructed by applying ratios ((2xCO₂)/(1xCO₂)) of all climate variables (except temperature) back to a baseline long-term average monthly climate dataset (NOAA-EPA 1993). Ratios were used to avoid negative numbers, but were not allowed to exceed 5, to prevent unrealistic changes in areas with normally low rainfall. Temperature scenarios were calculated as a difference ((2xCO₂) - (1xCO₂)) and applied to the baseline dataset. The VEMAP project was limited to the UKMO, GFDL-R30 and OSU scenarios.

It is expected that elevated CO₂ concentration will produce global warming. However, elevated CO₂ concentration may also produce direct physiological effects on plants that could offset some of the negative effects of global warming on vegetation. The MAPSS model is capable of simulating the physiological effects of elevated CO₂ concentration by reducing the maximum stomatal conductance to confer an increased water use efficiency (WUE) (Eamus 1991). Since the "CO₂ effect" is not well understood and may not operate in complex ecosystems to the extent that it does in growth chambers (Eamus and Jarvis 1989), companion simulations with and without the WUE effect were completed.

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The MAPSS vegetation classification is based on physiognomic properties, such as leaf form (broadleaf or needleleaf), leaf phenology (evergreen or deciduous) and stand structure (closed forest or open woodland/savanna). Vegetation types were both geographically and logically translated into the forest type categories used in the RPA

assessment (Powell et al. 1993). This required aggregation of some of the RPA forest types to be compatible with MAPSS types. Table 1 presents the classification strategy. Twenty of the 22 RPA forest types were aggregated into 9 groups. Pinyon-juniper and chaparral types were not calibrated in the MAPSS output.

Table 1.—Cross Classification between RPA forest types and MAPSS vegetation classes.

	MAPSS Assessment Classes	RPA Forest Type Groups	MAPSS Original Classes
Eastern Forests	1 NE Mixed Conifers and hardwoods	1 White-red-jack pine 2 Spruce-fir 10 Aspen-birch	Forest Mixed Cool
	2 NE Mixed Woodland (Boreal Woodland)		Tree Savanna Mixed Cool (Evergreen Needleleaf)
	3 Maple-beech-birch	9 Maple-beech-birch	Forest Hardwood Cool
	4 Oak-Hickory Forest	6 Oak-hickory 8 Elm-ash-cottonwood	Forest Temperate Deciduous
	5 SE Mixed Pines and Hardwoods	3 Longleaf-slash pine 4 Loblolly-shortleaf pine 5 Oak-pine 7 Oak-gum-cypress	Forest Mixed Warm Deciduous to Evergreen, Broadleaf to Needleleaf)
Western Forests	6 Western Fir-Spruce	17 Fir-spruce 22 Aspen-birch	Taiga/Tundra
	7 Douglas Fir	11 Douglas-fir 16 Larch	Forest Evergreen Needle
	8 Coastal Spruce-Hemlock Redwood	12 Hemlock-Sitka spruce 18 Redwood	Forest Mixed Warm (Evergreen Needle)
	9 Western Pines	13 Ponderosa pine 14 Western white pine 15 Lodgepole pine	Tree Savanna Evergreen Needle
	10 Western hardwoods	21 Western hardwoods	Tree Savanna Mixed Warm (Evergreen Needle)
Tropical	11 Moist Tropical Forest		Forest Evergreen Broadleaf Tropical
	12 Dry Tropical Forest		Forest Seasonal Tropical Evergreen to Deciduous
Arid Woodlands	13 Oak-Hickory Woodland		Savanna Temperate Deciduous
	14 SE Mixed Woodland		Savanna Mixed Warm (DEB)
		19 Chaparral	Not Calibrated
		20 Pinyon-juniper	Not Calibrated

FOREST DISTRIBUTION

Current Climate

The comparison between the MAPSS output under current climate, and the RPA forest area statistics from both survey data and the remote sensing forest map, is presented in Figures 1-3. Of the 562 million acres shown on the RPA forest map, (excluding pinyon-juniper and chaparral), MAPSS captures 503 million acres as forest (Figure 1). MAPSS-simulated non-forested areas tend to occur in the more arid interior regions and on high mountain tops where the model overestimates the area of alpine tundra and ice.

RPA forest classes do not recognize a distinction between closed forest and open woodland or savanna types containing the same species; whereas, the MAPSS model does make the distinction. For the comparison statistics in Figure 2, the MAPSS woodland/savanna classes have been aggregated with the closed forest classes in order to be consistent with the RPA data. That is, MAPSS types 13 and 14 (Table 1) have been aggregated with types 4 and 5, respectively. However, the two woodland types (13 and 14) are displayed separately in all maps. Geographic designations are misleading, but are retained to reflect the RPA nomenclature with the SE Mixed Forest type representing all warm mixed forests, and the NE Mixed Forest type representing cool mixed forests. These types occur in some MAPSS simulations in the western U.S. as minor elements.

The satellite data indicate too much western pine (Ponderosa, Lodgepole and Western White, Figs. 1-4) in comparison to the ground survey; although, it may in part be due to classification issues. The western pines are often successional to other conifers, such as Douglas-fir, true firs and spruce. It may be that some of these stands were classified differently, based on the successional data. Also, the MAPSS model clearly underestimated the distribution of pines over the Colorado Plateau and in the Sierra Mountains.

Western hardwoods are simulated by MAPSS as a warm, needleleaf woodland/savanna, which occurs as a nearly closed forest in the Willamette Valley and other western locales. Conifer forest is the natural climatic climax associated with the western oak woodlands in the absence of fire (Franklin and Dyrness 1973), a process not included in these simulations. The western hardwoods are underestimated by both MAPSS and the satellite data, likely, in part, due to the complex successional status and the small spatial scale of variation among the different successional states. Also, the western hardwoods class, as defined in the RPA data is not a pure class. The survey data for western hardwoods include Alder, Oaks and Aspen-Birch. The Alder-Oak combination in the western hardwoods cannot be specifically simulated by MAPSS, since the two genera occur at opposite ends of the moisture spectrum in succession toward conifer forests, primarily Douglas fir with respect to oaks and Douglas fir-hemlock or hemlock-cedar-spruce with respect to alder

(Franklin and Dyrness 1973). Aspen-Birch is associated, in part, with succession to spruce-fir (Long 1995; Bartos et al. 1983). Also, the RPA databases are inconsistent, with Aspen-Birch being aggregated with western hardwoods in the survey statistics; while, the satellite map separates Aspen-Birch as a distinct type, which is also separate from eastern Aspen-Birch. Most of the simulated western hardwoods class in the Willamette Valley, Oregon is excluded by the non-forest mask and is not included in the analysis (Fig. 3).

The average simulated Leaf Area Index (LAI) is a relationship of the surface area of the leaves to the surface area of the ground (m^2/m^2). The LAI of the two woodland types ranges from about 2.5 to 3.0 (all-sided) while that of the two forest types ranges from 6.6 to 7.4. Thus, foliar density in the closed forests is about 2.5 times greater than in the woodlands. If the two types are aggregated in the analysis of global warming impacts, then large changes in the areas of woodland relative to forest are not well represented. The aggregated results may indicate that total forest area changes very little; while, in fact total forest biomass could change considerably. Changes in LAI are used as an index of change in forest density or basal area. Although the relationship is not strictly linear, foliage volume will be used as a rough index of biomass or timber volume. The foliar volume is calculated as the density (in units of LAI) times the area. Percent change in foliar volume is calculated as foliar volume of the future scenario minus the volume of the control simulation, divided by the volume of the control simulation.

2xCO₂ Climate

Three criteria of change are examined; changes in forest area, changes in foliar density (LAI), and changes in foliar volume (LAI x Area). Foliar density is used as a coarse index of basal (stem) area per unit land area; while foliar volume will be used as a coarse index of biomass or timber volume over the entire forest area. Since the relationship between LAI and basal area or biomass is not strictly linear, these indices are only intended as coarse metrics of direction and general magnitude of change. These analyses are comparisons of the steady-state statistical properties of the forests under current and "future" climate conditions and do not consider the relocation of the forests to new sites via dieback, regeneration, dispersal, establishment and growth.

Potential changes in the area and volume of forests are presented in Figures 4-5. Maps of these future scenarios are shown in Figures 6-8. The area changes are presented in two forms: 1) the two eastern forest woodland types (Table 1, types 13 and 14) aggregated with their respective forest types (4, 5) and 2) woodlands tabulated separately. Each bar-graph figure (4,5) contains four panels, with and without aggregation of woodlands and with and without a WUE effect. Since woodlands and tropical types are of little importance today, but increase dramatically under some of the climate scenarios, the percent changes in these types dominate the overall changes. The maps (Figs. 6-8) are

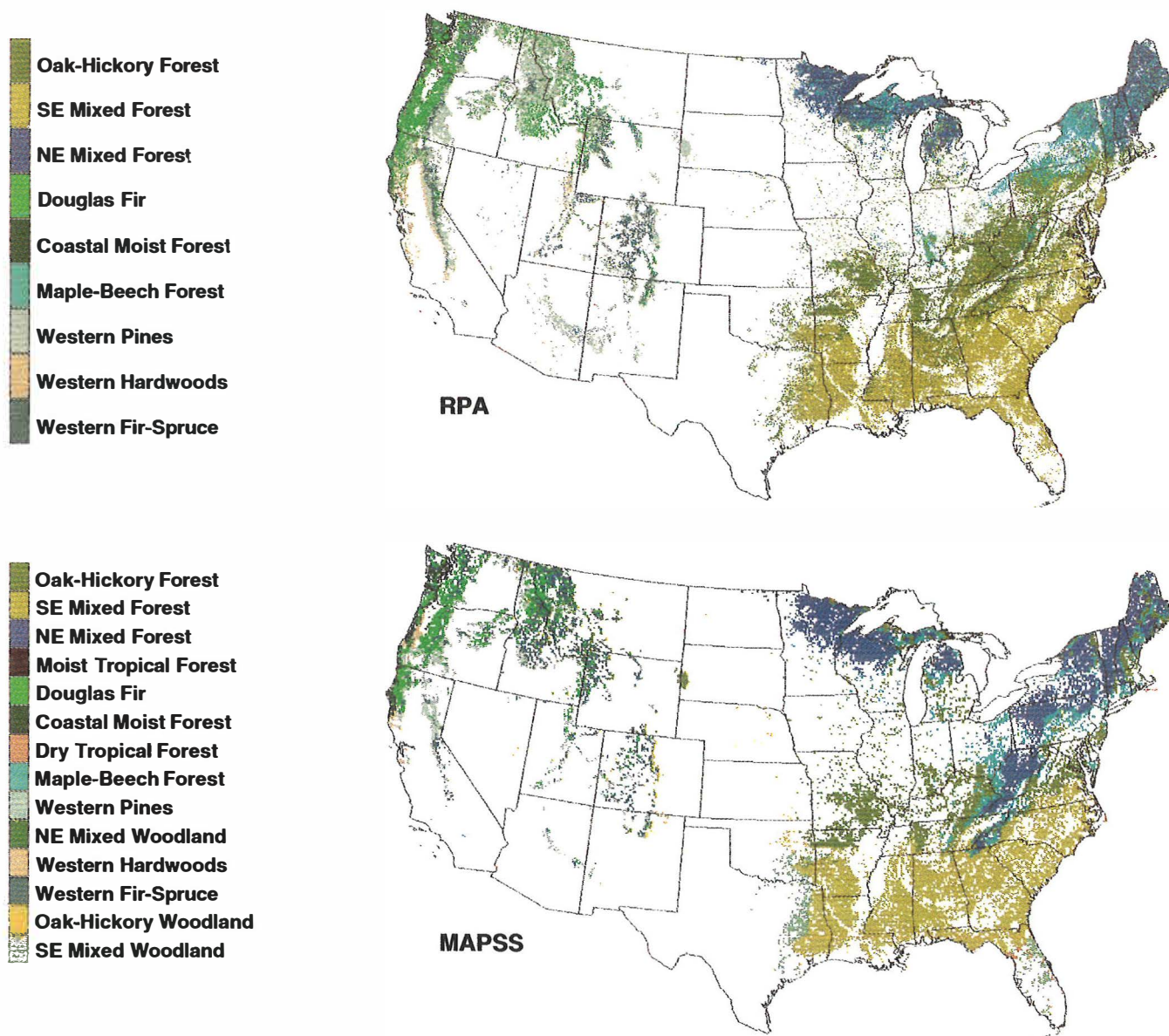


Figure 1.—Maps of United States forests based on (a) RPA satellite analysis (1-km resolution) and (b) MAPSS simulation (10-km resolution).

presented with woodlands disaggregated from forest classes.

Eastern Forests. In general there are northward and elevational shifts in all forest types, whether there are increases or decreases in total area and volume. The cold forest types (types 1-3) tend to show large decreases (average area loss over 6 scenarios, no WUE effect, 32 percent-100 percent). Since most of these forest types are constrained by temperature, there is a great deal of consistency in their loss among the different climate scenarios. However, increased water use efficiency confers a benefit to the cool hardwood forests in the NE, showing increases under GISS (48 percent)

and OSU (6 percent) scenarios, but at the expense of oak-hickory forests (Figs. 4-8). Even so, the average across all six scenarios, with a WUE effect, indicates losses ranging from 37 percent to 100 percent. Without a WUE effect the average losses of the cold forest types across the six scenarios ranges from 74 percent to 91 percent.

If the eastern woodlands (Table 1, types 13 and 14) are aggregated with true closed forest, then, in the absence of a WUE effect, oak-hickory forests (type 4) change little (7 percent loss) or expand (up to 50 percent) in area under all scenarios (average 29 percent increase across 6 scenarios). Increased WUE (with aggregated woodlands) results in a

Forest Area - Baseline Estimates

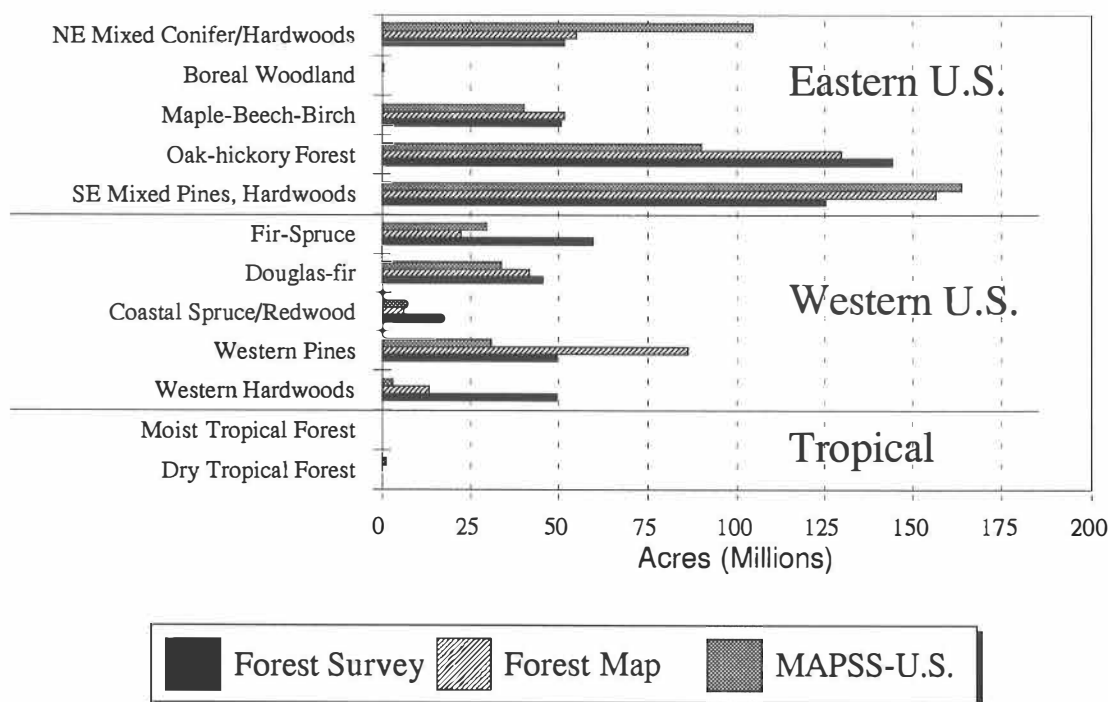


Figure 2.—Comparison of forest area as estimated from 3 separate approaches: ground survey, satellite analysis, and MAPSS simulation.

more modest increase in area (average 7 percent across 6 scenarios) due to encroachment by the southeastern pines and hardwoods and to a less detrimental effect on cool hardwoods (Fig. 4-8, types 1 and 3). The cooler and wetter scenarios with a WUE effect tend to favor beech-maple in the NE (type 3) while allowing the SE mixed forests to move north due to warming. The combination then produces the most severe losses of oak-hickory forest area through displacement, e.g. a 47 percent loss under the GISS scenario.

The SE pines and hardwoods increase in area (up to 42 percent) in all scenarios, with (average 30 percent) or without (average 25 percent) a WUE effect, except the non-WUE UKMO scenario which shows a minor decrease (7 percent) in area. However, these modest losses to large gains in area in these two forest types (4, 5) with woodlands aggregated obscure the large shifts in forest type from high density forest, to low density woodland (Fig. 4-8).

If woodlands are tabulated separately, then the oak-hickory (Table 1, type 4) and the SE mixed forests (type 5) demonstrate significant losses under most scenarios without a WUE effect, averaging losses of 31 percent (oak-hickory, range -82 percent to +29 percent) and 53 percent (SE forests, range -97 percent to 0 percent), respectively. Oak-hickory increases in area under GISS (21 percent) and OSU (29 percent) scenarios as it displaces northern cool forests (types 1-3). As before, with increased WUE, the gains in oak-hickory

are reversed by shifting dominance toward the beech-maple in the north; while being displaced by SE forests from the south, averaging losses of 6 percent (range -47 percent to +24 percent). With a WUE effect, the SE forests average a 9 percent gain in area, even with woodlands tabulated separately (range -53 percent to +37 percent), although they may no longer be centered in the southeast.

Comparing the average foliar density (LAI), as an index of basal area, of each type in its current location with the average foliar density for that type in its new location, in most scenarios there is a reduction in the average density of all U.S. forests of 15 percent (woodlands aggregated) or 11 percent (woodlands separate, no WUE effect, based on the mean across all forest types of the mean LAI change of each forest type). The numbers are slightly reduced with a WUE effect. Most of the density change occurs in the eastern forests with average losses of 35 percent and 51 percent for oak-hickory and SE mixed forests, respectively, without a WUE effect, or 10 percent and 17 percent, respectively with a WUE effect (woodlands aggregated). These numbers are considerably reduced if woodlands are considered separately, but still indicate density losses.

Examination of the foliar volume change plots (Fig. 5), as an index of change in total wood volume, indicates large volume losses in all eastern forest types, especially when woodlands are aggregated. Area-weighted foliar volume losses over the conterminous U.S. averaged over the six scenarios are 57

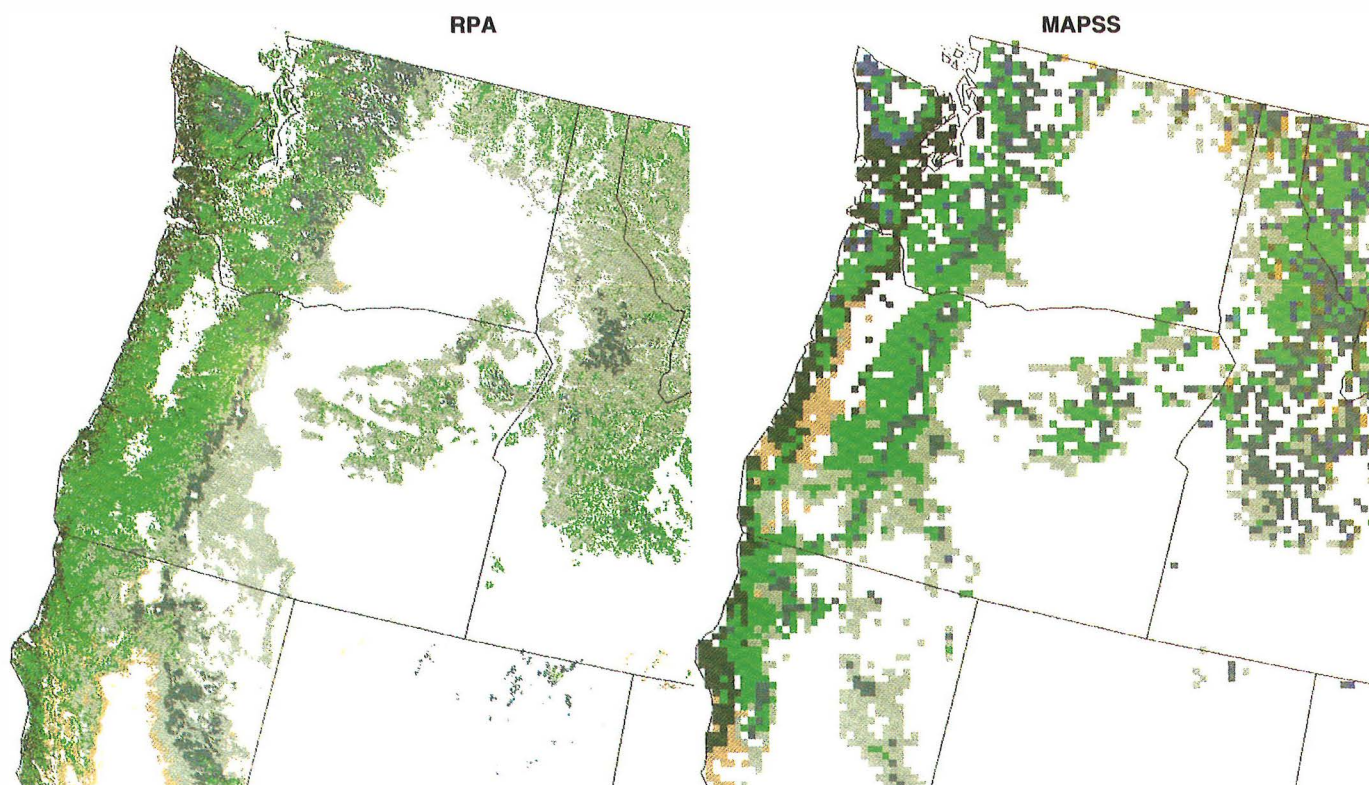


Figure 3.—Maps of forest distribution as estimated by (a) RPA satellite analysis (1-km resolution), and (b) MAPSS simulation (10-km resolution), Pacific Northwest Region.

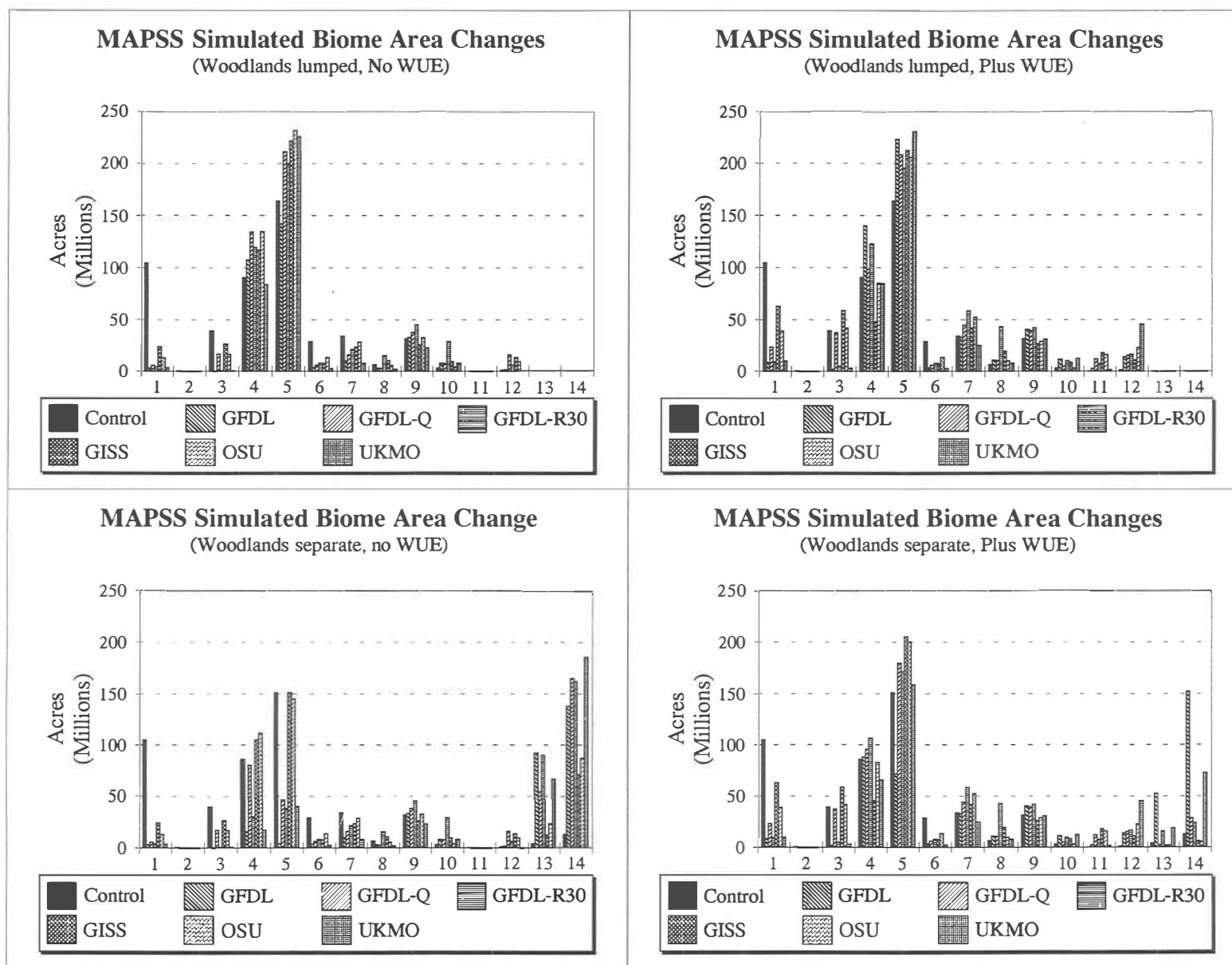
percent without a WUE effect or 26 percent with a WUE effect. The GISS scenario with a WUE effect is the only scenario that shows an overall increase in foliar volume across all the forests.

In a few simulations there is a very small increase in the foliar volumes of oak-hickory and SE mixed forests (GISS and OSU scenarios), due to a shift into more northern lands and only when a direct CO₂ effect (WUE) is incorporated. These increases in foliar volume under a WUE effect occur whether woodlands are considered separately or not. There is a large effect of increased water use efficiency on both forest types (4, 5), offsetting the large losses that occur without a WUE effect, and producing a mix of scenarios with both increased and decreased volume, usually accompanied by an increase in the area of the type. Dry tropical forests (type 12) and to a lesser extent moist tropical forest (type 11) increase in the Gulf states area, but the dry tropical forests are not very dense, being similar to open woodlands.

Western Forests. Fir-spruce forests (type 6) in the western U.S. decrease in area and foliar volume in all scenarios (average 76 percent loss, range -91 percent to -53 percent), largely a result of being pushed off the top of the mountains (Figs. 6-8). Douglas-fir (type 7) shows quite mixed results, depending on the presence or absence of a WUE effect. In the absence of a WUE effect the Douglas-fir forests decrease in all scenarios in area (average loss 47 percent, range -76 percent to -15 percent) and total volume (average

loss 52 percent, range -83 percent to -19 percent). The volume losses incorporate an average 13 percent loss in foliar density (LAI), an index of basal area. In the presence of a WUE effect there are increases in area in all scenarios except UKMO and GFDL (average gain 26 percent, range -26 percent to +73 percent). Foliar volume changes with a WUE effect are similarly mixed with average gains of 18 percent (range -40 percent to +63 percent). The increased volume of Douglas-fir under a WUE effect occurs primarily through increases in area, since the foliar density (LAI), i.e., basal area, actually decreases (average -8 percent, range -19 percent to +6 percent) with the only increased density occurring under GISS and OSU scenarios. Range contractions of Douglas-fir and related types occur in the southern Cascades and Coast Ranges. Expansions bring Douglas-fir into the higher elevations of the Cascades, Sierras, Blue Mountains and northern and central Rocky Mountains (Figs. 6-8). Other range expansions extend into the Pine zone under increased WUE.

Coastal spruce-hemlock and redwood forests (type 8) show mixed responses without a WUE effect with large increases in area under the GFDL-R30 and GISS scenarios (up to 133 percent), but large losses under the other scenarios (to -71 percent under UKMO). The differences arise from large differences among the scenarios in regional precipitation changes. However, with a WUE effect the coastal humid forests increase significantly in area and total foliar volume in all scenarios (average 158 percent, range 21 percent to 550

Figure 4.—Estimates of change in forest area by type under 2xCO₂ climate.

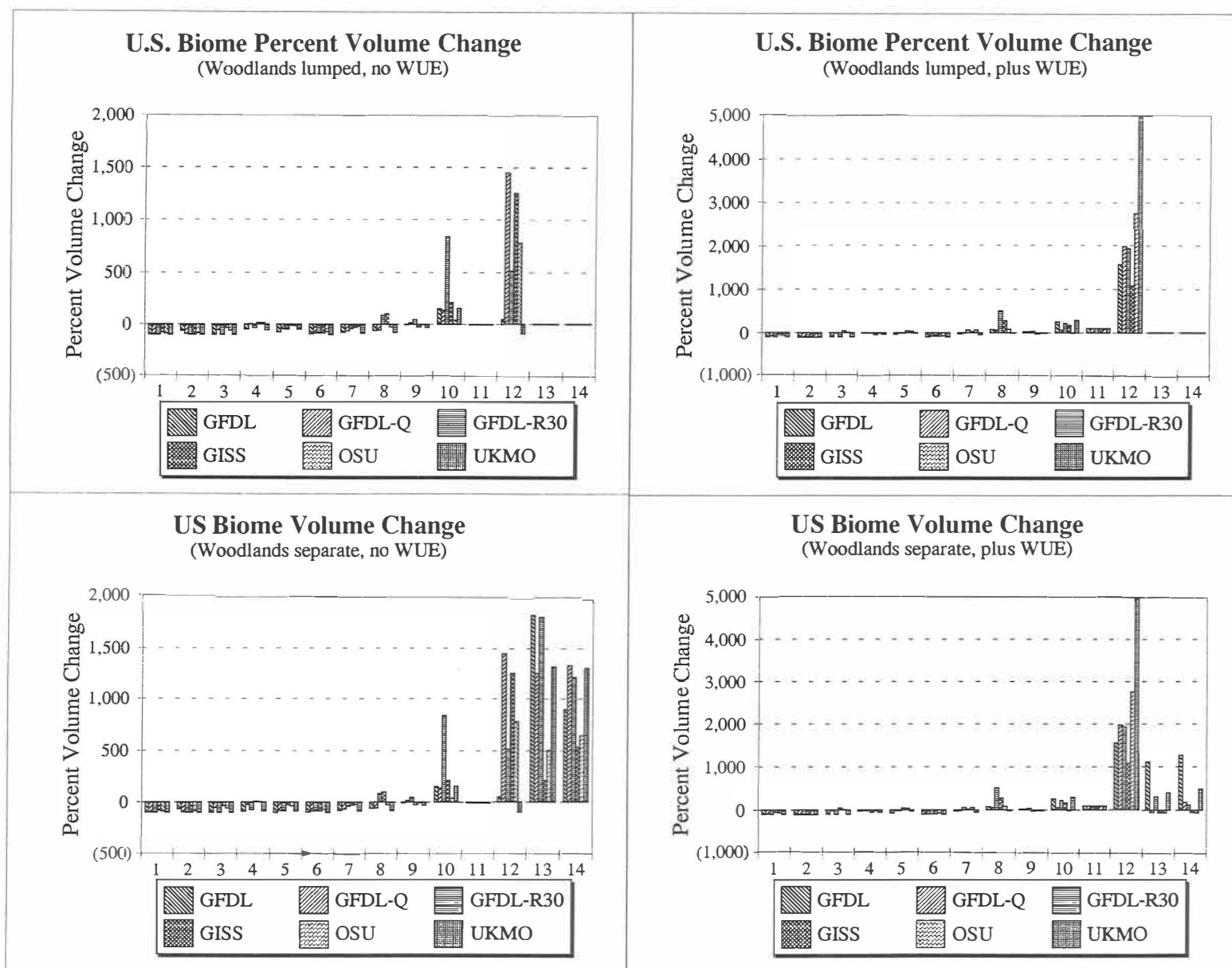


Figure 5.—Estimates of percent change in forest volume by type under 2xCO₂ climate (note different scales).

percent), although they are displaced northward in some scenarios. The foliar volume changes are of a similar magnitude, but also incorporate some increases or decreases in average foliar density (LAI). Range contractions occur in the central and southern Coast Range forests of Oregon; while, extreme range contractions extend declines into the coastal Redwood zones of California (Fig. 6-8). Range expansions bring the mesic coastal forests into the east side of the Coast Range and into the Willamette Valley and the lower reaches of the west slope of the Cascades.

Western pines (ponderosa, lodgepole and western white, type 9) show variable responses with some increases and decreases in area under all scenarios and water use efficiencies (average +6 percent, range -26 percent to +44 percent, non-WUE, average +11 percent, range -15 percent to +34 percent, with a WUE effect). Foliar density changes are slight within this type. The increases are larger and the decreases smaller with increased water use efficiency under the various scenarios. The pines tend to disappear from their southern and lower elevational limits being replaced by more xeric, non-forest vegetation. The most consistent losses across all the scenarios occur in the Southern Rockies and Colorado Plateau, especially the Mogollon Rim. Under situations where Douglas-fir contracts from the Cascade Range and other locales, they are generally displaced by the pines (Fig. 6-8).

Western hardwoods (type 10) show increases in area under all scenarios and water use efficiencies (average non-WUE increase 274 percent, range 42 percent to 870 percent). The increases under increased WUE are smaller than the non-WUE simulations (average 125 percent, range 0 percent to 320 percent). The smaller expansion of western hardwoods with a WUE effect occurs because of the retention of closed forests in potential expansion zones. The large percentage changes occur, of course, because of the relatively small amount of the forests in the control simulation. Western oaks, in particular, increase in area and volume as they replace the lower elevation Douglas-fir and mesic spruce-hemlock-redwood forests. These forests would be converted to a western hardwood type as they open up due to temperature-induced drought and as fire becomes more prevalent.

MODEL COMPARISONS

Under VEMAP, three biogeography models (MAPSS, DOLY, and BIOME2) were compared under current and altered climate, as were three biogeochemistry models (TEM, CENTURY, and BIOME-BGC). The 2xCO₂ climate scenarios were derived from the UKMO, GFDL-R30 and OSU simulations. These results are summarized (VEMAP members 1995).

The six models were parameterized to simulate 21 different vegetation types, aggregated from Küchler (Küchler 1964). No attempt was made to mask out current land use from the analyses. Under control climate all three biogeography models exhibit nearly identical statistical skill in simulating the aggregated Küchler map. However, each model exhibited its own unique signature. Likewise, the three

biogeochemistry models exhibited nearly equal skill in simulating the net primary productivity and carbon pools of the different vegetation types. All models in both groups exhibited very different levels of sensitivity to global warming, even given their similarity under current climates.

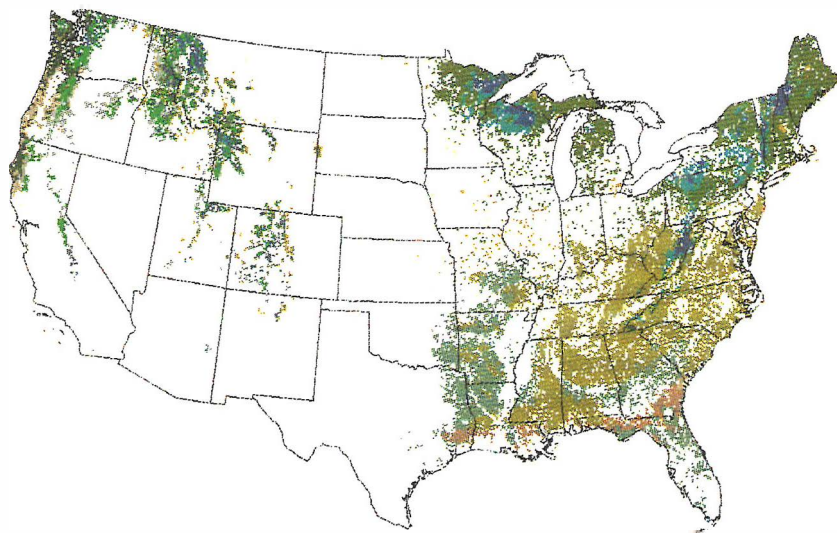
Of the three biogeography models, MAPSS was found to be the most sensitive with respect to temperature induced drought stress effects on forests, while BIOME2 was the least sensitive. DOLY was intermediate. The MAPSS results at the 0.5° resolution used in VEMAP are quite similar to those described above, although the western U.S. forests are not well resolved at the coarse resolution and results are more questionable. BIOME2 in contrast to MAPSS shows substantial increases in forest area under most scenarios and with or without a CO₂ effect. MAPSS also has the most sensitive CO₂ response of the three models, BIOME2 the least and DOLY is intermediate. Thus, simulations incorporating the direct effects of CO₂ were more similar among the three models than were those without the CO₂ effects. The range of simulations presented above for MAPSS encompasses most of the range of forest responses encompassed by all three models, except that BIOME2 would extend the range of forest expansions a bit.

One of the primary reasons for the differences among the three biogeography models appears to be in the assumptions made with respect to mass and energy coupling of the canopy to the atmosphere. MAPSS assumes strong coupling such that transpired water is easily mixed, through turbulence, to the atmosphere and carried away from the region, thus producing little negative feedback on the demand for moisture from the vegetation. BIOME2 is configured such that transpiration produces a strong negative feedback on further moisture demand. Strong negative feedback occurs if transpiration from the canopy is not well mixed through turbulence to the general atmosphere. DOLY is intermediate in these processes.

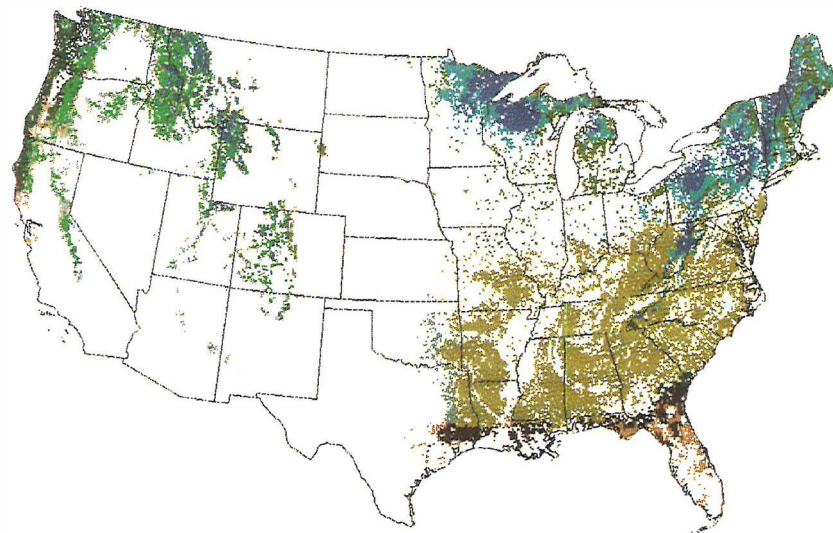
At the opposite end of the vegetation gradient, semi-arid land (southwestern deserts), DOLY was the most sensitive, showing substantial increases in desertification under most scenarios. MAPSS and BIOME2 were similar and produced rather mild increases in desertification. It is not yet clear why DOLY is more sensitive to desertification potential than MAPSS and BIOME2, but again may involve canopy-atmosphere coupling with respect to water balance.

The biogeochemistry models produced a similar range of disparity among the 2xCO₂ simulations. TEM was the most conservative, producing significant increases in forest productivity both with and without a CO₂ effect under most 2xCO₂ scenarios. BIOME-BGC was the most sensitive to temperature induced water stress and produced results similar to MAPSS. CENTURY was intermediate. TEM and BIOME2 are relatively consistent in terms of combined biogeochemistry and biogeography results, both showing relatively small decreases in productivity and forest area, and potentially much gain from global warming. BIOME-BGC and MAPSS are, likewise, consistent with each other, both indicating significant water-balance sensitivity of U.S. forests to global warming.

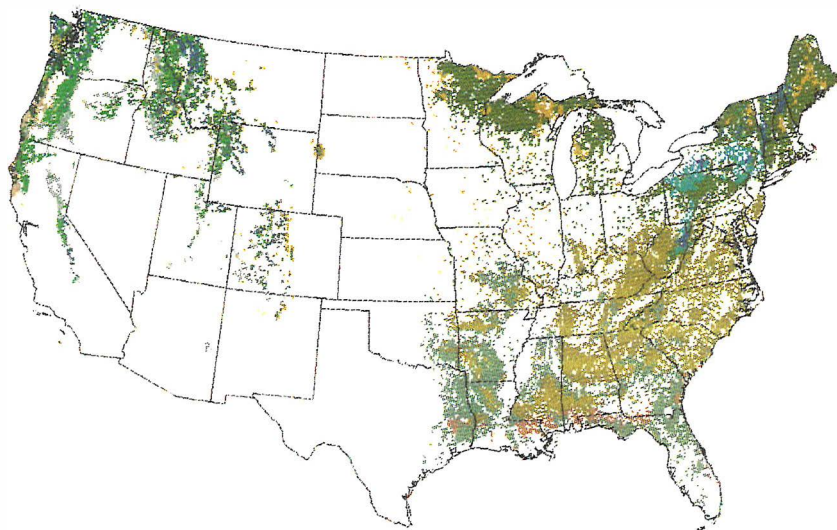
MAPSS GISS



MAPSS GISS + WUE



MAPSS OSU



MAPSS OSU + WUE

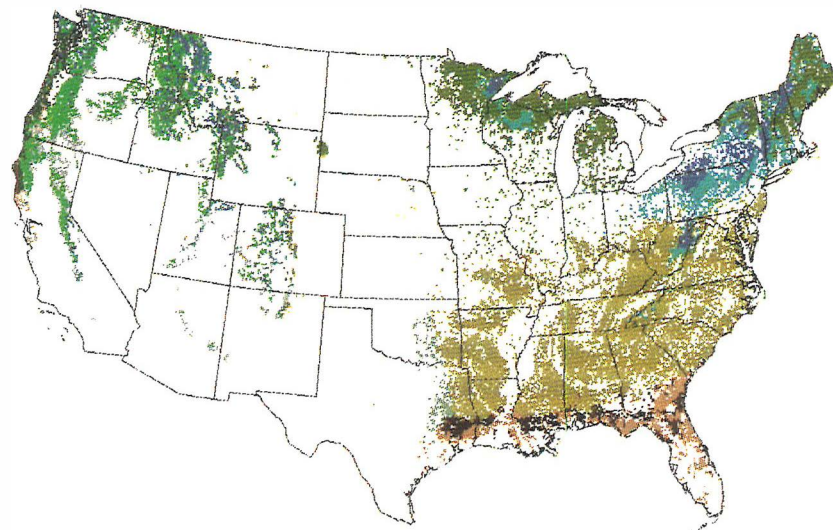


Figure 6.—Maps of potential future forest distribution under 2xCO₂ climate, with and without a CO₂-altered water use efficiency effect (WUE), GISS and OSU scenarios.

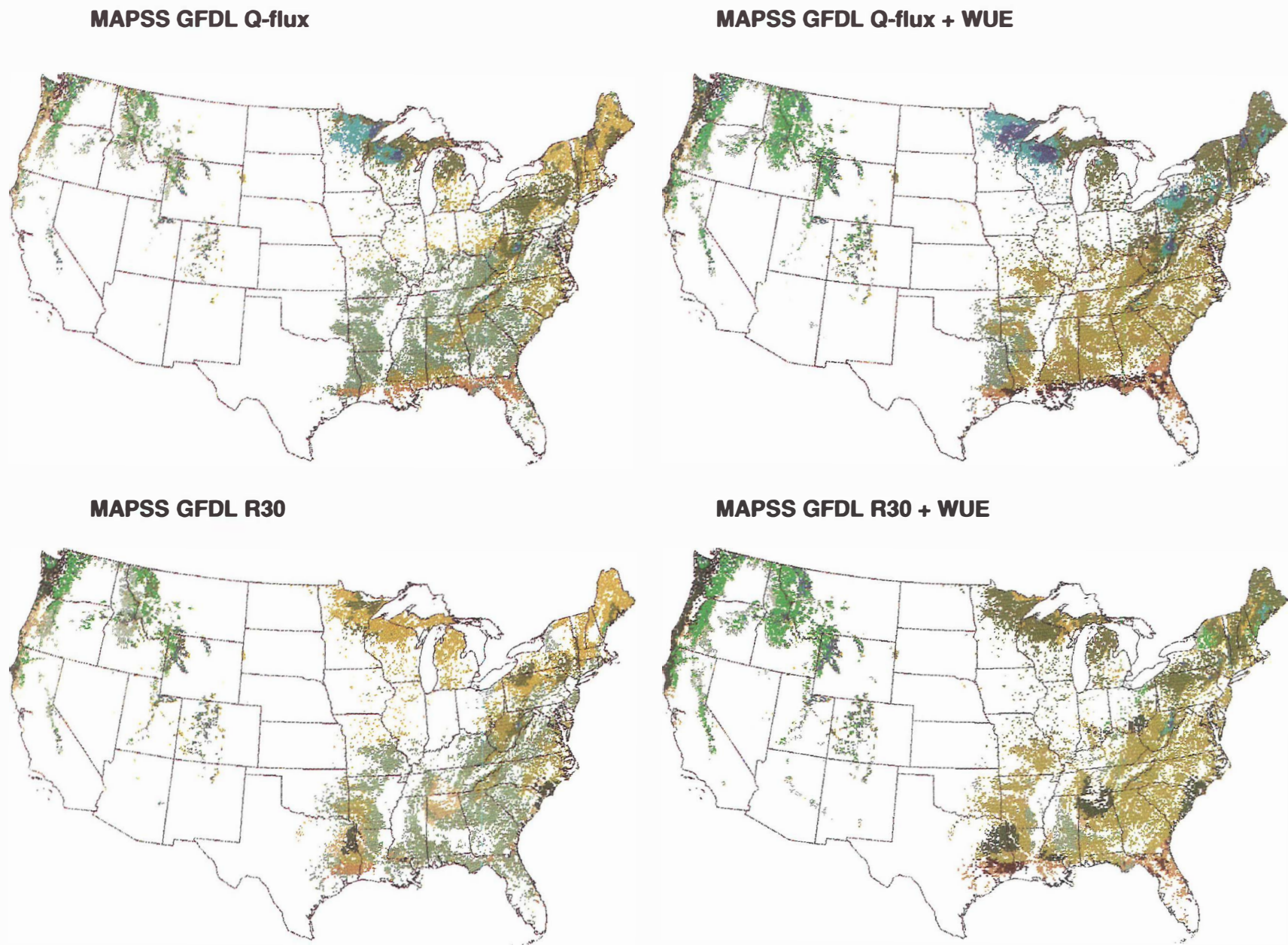
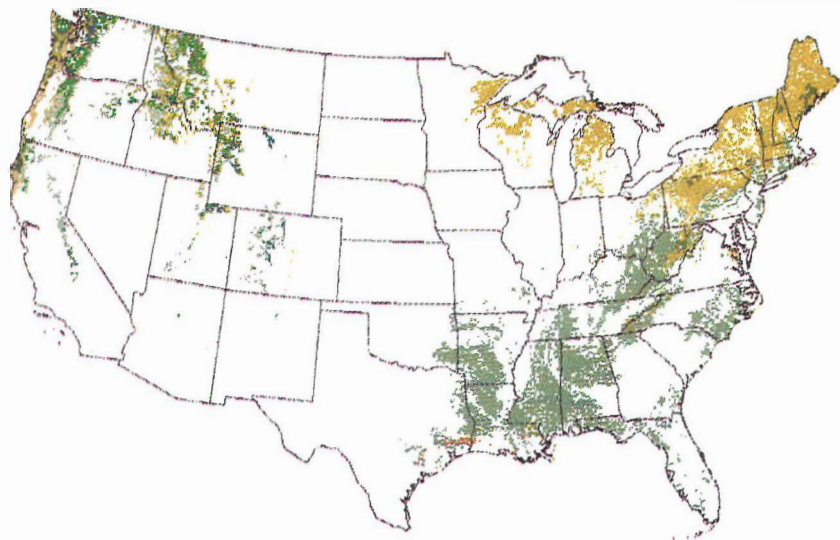
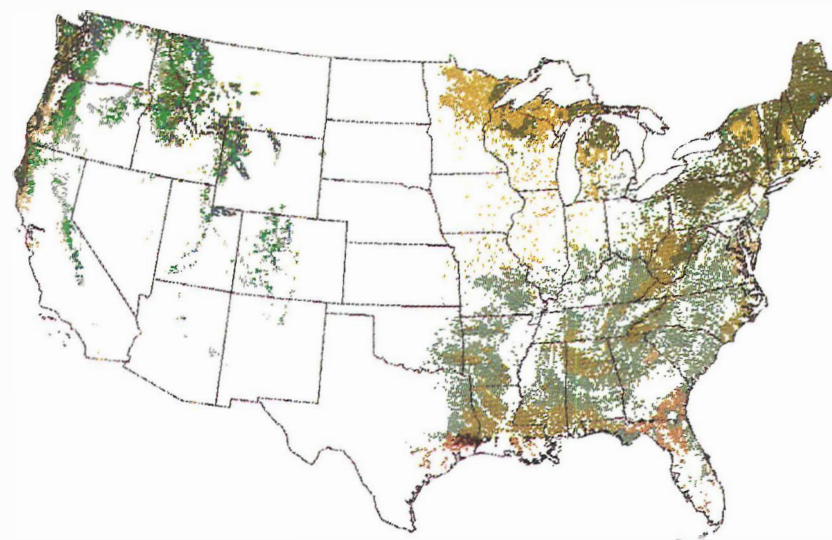


Figure 7.—Maps of potential future forest distribution under $2\times\text{CO}_2$ climate, with and without a CO_2 -altered water use efficiency effect (WUE), GFDL-Q and GFDL-R30 scenarios.

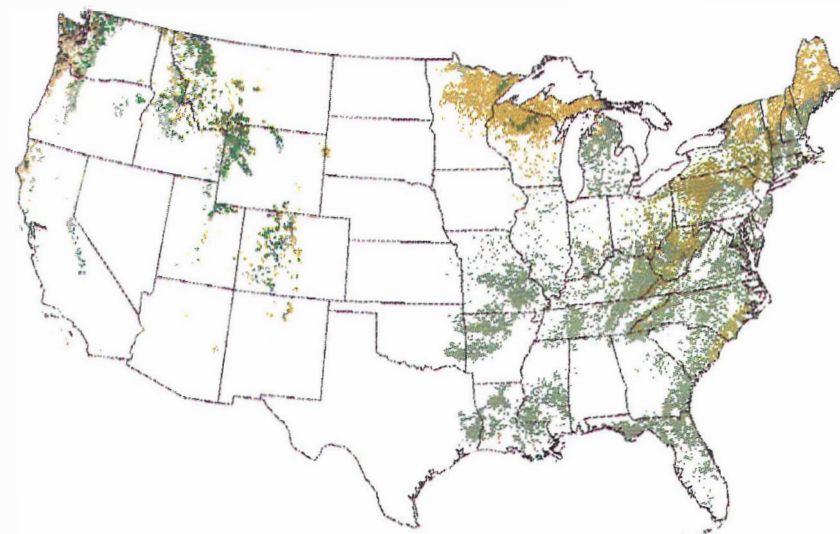
MAPSS GFDL R15



MAPSS GFDL R15 + WUE



MAPSS UKMO



MAPSS UKMO + WUE

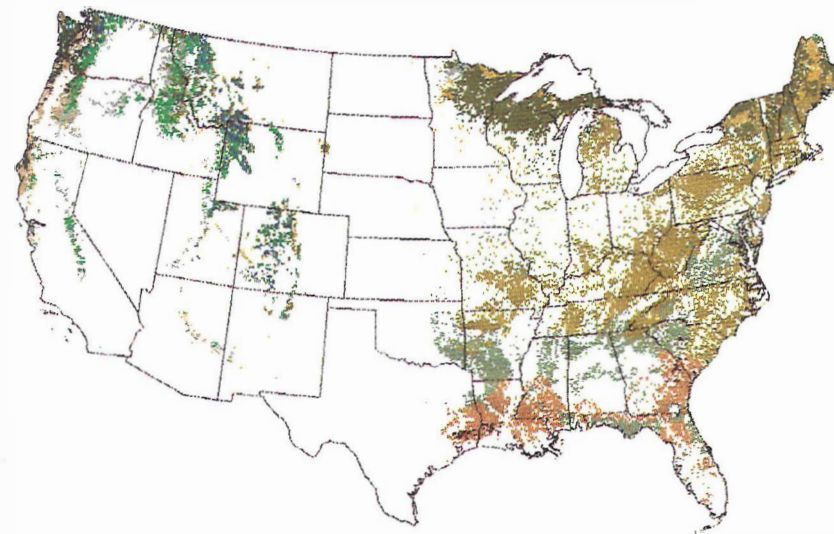


Figure 8.—Maps of potential future forest distribution under 2xCO₂ climate, with and without a CO₂-altered water use efficiency effect (WUE), GFDL-R15 and UKMO scenarios.

CONCLUSIONS

There is no clear agreement among the different scenarios and vegetation models with respect to the potential responses of U.S. forests to global warming. However, given the variety of ecological and atmospheric models the possible range of future forest responses has likely been bracketed by these results. One thing seems certain; change is likely. Also, there are several relatively consistent patterns.

Forests that are constrained to cool climates, such as northeastern hardwoods and high altitude forests, will likely be lost or reduced significantly in size. High latitude forests, however, would shift north. Soil characteristics at high altitudes and latitudes may restrict expansion of forests into those regions.

Forests that occur in warm regions are potentially sensitive to increased drought stress. Notable among these are the southeastern mixed pines and hardwoods and the western Douglas-fir regions. The southern Coast and Cascade Ranges are particularly sensitive in this regard. These closed forests could be replaced by woodlands or savannas, possibly with similar species composition. In the West the forest classification acknowledges differences between closed forests and open woodlands and savannas. To some extent this occurs because there is a species replacement. For example, when Douglas-fir forests occur in drier climates, they tend to exist with a fire regime that promotes the establishment of pines or oaks. However, in the Eastern U.S. the companion woodlands to the closed oak-hickory and SE mixed forests are not explicitly recognized in the classification. This presents difficulties in defining or interpreting the potential impacts of global warming.

The three most important uncertainties contributing to the wide range of these results are: differences among the GCM scenarios, the direct effects of elevated CO₂, and the mechanisms and degree of coupling between the canopy and the atmosphere. The uncertainties with GCM scenarios are covered elsewhere.

Most of the increase in forest volume and area under these global change scenarios occurs when the direct effects of elevated CO₂ are explicitly simulated. However, there are numerous uncertainties with these results. None of the six models in the VEMAP exercise incorporated CO₂ effects in the same way. Some imparted an increased productivity, others an increased water use efficiency and others included both effects. It is not yet clear how to incorporate these physiological effects. Even more uncertain, is how CO₂ effects will be manifest under complex ecosystem constraints, as distinct from growth chamber studies. For example, the CO₂ sensitivity in the MAPSS model may be too high and that in the BIOME2 model may be too low.

The problem of atmospheric coupling has several components. The quantitative aspects of canopy roughness are not well understood yet are the dominant controls on turbulent mixing processes between the canopy and the

atmosphere. The relative importance of stomatal control on stand water balance can only be understood in the larger context of the importance of turbulence in the canopy. Above the canopy the boundary layer gradually mixes with the upper atmospheric layers. How well this canopy boundary layer mixes with upper layers is also not well understood, nor well measured; although new syntheses of existing data are clarifying this coupling somewhat and indicate a relatively large degree of coupling between forest canopies and the atmosphere (Hollinger et al. 1994; Schulze et al. 1994). These canopy-atmosphere coupling processes may not be well simulated until vegetation models and GCMs are dynamically coupled to fully express all energy, mass and momentum feedbacks in a fully closed Earth System Model.

Other issues not dealt with in this assessment include: dynamic land-use simulation, dispersal and succession. As forests are forced to move around, some areas will experience dieback, possibly catastrophic with severe drought death, infestation and fire (King and Neilson 1992; Neilson and King 1992; Overpeck et al. 1990; Smith and Shugart 1993; Neilson et al. 1994; Neilson 1993a; Neilson 1993b; Franklin et al. 1991). Establishment in new locations may be difficult due to dispersal and soil constraints. Even if dispersal constraints produce lags in the colonization of an area by new species, there will usually be other species already present that will be able to live in those regions. For example, if the eastern hardwoods are not able to colonize northern boreal forest regions very rapidly, the boreal species may still survive but at a different density, if their reproduction is not constrained to certain cooling requirements.

The fixed land-use map used for the MAPSS analysis is a severe and unrealistic constraint, particularly in those scenarios that portend significant expansion of forests. A deterministic land use model is required that will allow conversions of forest to agriculture and vice versa as a function of the population density, supply and demand economics, and cultural status. Such models are only now being constructed.

The potentially catastrophic conclusions presented here are consistent with other studies of the potential impacts of global warming on U.S. forests (Franklin et al. 1991; Winjum and Neilson 1990). The potential changes are of sufficient magnitude, either positive or negative, that dramatic shifts in forest management policies may be required. These results present a broad spectrum of possible futures, and should act as a catalyst to the formation of alternative policy options.

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THE FOREST CARBON BUDGET OF THE UNITED STATES

Richard A. Birdsey and Linda S. Heath¹

SUMMARY

An ongoing synthesis of basic forest statistics and development of carbon (C) accounting models have highlighted the past and prospective role of U.S. forests in the global C cycle. We have shown that increases in biomass and organic matter on U.S. forest lands over the last 40 years have added 281 Tg/yr⁽²⁾ of stored C, enough to offset 25 percent of U.S. emissions for the period. When added to estimates of C increases in other northern temperate forests, there is sufficient C to account for a significant portion of the "missing" C in evaluations of the global C cycle. Projections show additional increases of approximately 177 Tg/yr through 2040. Increasing amounts of C in harvested wood, the effects of increasing atmospheric CO₂ on ecosystem productivity, and large reforestation programs all substantially effect the rate of C sequestration.

Results from the U.S. Carbon Budget Model (FORCARB) have helped quantify the effects of alternative policies for offsetting greenhouse gas emissions through forestry actions under the President's Climate Change Action Plan. Basic information about C 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. Estimates of C accumulation by region for different forest types are used by individuals and companies who plant trees and then report the results of these voluntary actions to the Department of Energy as an offset of CO₂ emissions. Planting trees to offset CO₂ emissions is becoming popular among companies that generate electrical power by burning fossil fuel.

FORCARB is one component of a national integrated model of global change effects on forests. This integrated modeling system allows us to simulate the effects of environmental changes on productivity, natural forest succession, harvesting, natural disturbance, timber production, and carbon storage. The integrated model includes socioeconomic models used to conduct national assessments required by the Resources Planning Act (RPA). The socioeconomic models provide estimates and projections of human activities such as land use change and timber harvest that have major impacts on the status of forest vegetation. The integrated modeling system has been used in the 1993 RPA Assessment update. Current efforts focus on improving projections of potential forest vegetation distribution, forest ecosystem composition, forest growth, and the national C budget.

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²One teragram (Tg) = 10¹² grams = one million metric tons

APPLICATIONS OF THE U.S. CARBON BUDGET MODEL

Initial Estimates for the U.S.

Although estimates of C in U.S. and global forests have been made for decades, the initiation of the U.S. Global Change Program in the late 1980's focused scientific attention on the accelerating buildup of CO₂ in the atmosphere. The Program generated global interest in exploring options for reducing emissions and increasing terrestrial C sinks. Tans et al. (1990) attempted to account for all of the C exchange between the atmosphere, the oceans, and the terrestrial biosphere, and restarted a worldwide effort to find the "missing" C, suspected to reside somewhere in the Northern Hemisphere.

We began our efforts to estimate carbon in 1989 using the most current compilation of national inventory statistics (Waddell et al. 1989) and biomass statistics (Cost et al. 1990). Initial baseline estimates were reported in 1990 at the IUFRO World Congress (Birdsey 1990a). It was estimated that U.S. forests contained 52.5 Pg C, 4 percent of all the C stored in the world's forests. About 32 percent was estimated to be in live vegetation, 9 percent in dead organic material, and 59 percent in the soil. Detailed estimates of C storage and accumulation for states, forest types, and several land classifications were published in 1992 (Birdsey 1992a). At that time the rate of C accumulation in U.S. forests (trees only) was estimated to be 106 Tg/year, equivalent to about 9 percent of annual U.S. emissions of CO₂. Periodic refinements to these initial estimates using updated methodology and newer inventory statistics have not changed the baseline estimates significantly. A similar methodology produced equivalent estimates for C in major forest ecosystem components except for coarse woody debris which differed significantly (Turner et al. 1995).

Offsetting CO₂ Emissions by Tree Planting and Forest Management

Concurrent with developing the national baseline, we attempted to quantify the impacts of U.S. forest management policies on the C cycle (Birdsey 1990b, 1992b). Using estimates of C storage by age class for different forest types and conditions, we estimated that converting 22 million acres of marginal cropland and pasture in the South to forest would increase C accumulation by about 32 Tg/year, enough to offset about 3 percent of U.S. emissions of CO₂. Other forest management practices such as increasing the density of trees on poorly stocked forest land did not appear to produce much gain in the rate of C accumulation compared with simply leaving the land alone to regenerate and grow. At the same time, Moulton and Richards (1990) estimated the costs of reforestation and forest management for various levels of investment. They concluded that a maximum program level of \$20 billion could offset about 56 percent of U.S. emissions.

The cost/ton of C would be about \$10 for a 5 percent offset and about \$18 for a 30 percent offset.

A more thorough analysis included estimates for broad management practices by major region and forest type in the U.S. (Birdsey 1992c). Recommended management strategies to maximize C accumulation included: (1) increasing the area of forest land by planting trees or allowing natural regeneration, (2) converting poorly stocked forest land by clearing and regenerating only if current productivity is well below average, (3) applying intermediate stand treatments (thinning or timber stand improvement) only if the current stand is overstocked to the point of stagnation, (4) managing for longer rotation lengths.

A Carbon Budget Model for Trend Estimates and Projections

We became interested in developing a U.S. Carbon Budget Model (FORCARB) for making projections and investigating alternative policy scenarios. We chose to link FORCARB with the timber supply models used for RPA assessments. This enabled us to include the effects of C management on the supply and demand for timber products, which could affect harvested volume and the amount of C stored on the land at any time. The data for the C model was an aggregation of all of the data prepared for previous analyses, combined with additional data about timber growth and yield. The new model produced estimates of C in forest ecosystem components plus harvested wood products. The first application showed continued increases in carbon storage on private timberlands through 2020, with decreases thereafter as increasing timber removals outpaced growth (Plantinga and Birdsey 1993). Additions of C to forest product and landfill pools offset the projected decline on private timberland.

A subsequent analysis expanded the model to include public timberland (Birdsey et al. 1993). Expected gains in biomass on public lands due to reductions in mandated harvest levels were projected to offset the declines on private timberland. This study also included a retrospective look at changes in timber volume on U.S. timberland since 1952, and converted those estimates to carbon. Carbon storage in U.S. forests has increased by 38 percent since 1952, or 8.8 Pg, enough to account for 21 percent of the hypothesized carbon sink in northern temperate regions over that period (Birdsey et al. 1993).

Exploring Alternative Management and Modeling Options

We noted many uncertainties in the development of the initial estimates and projections. There were several international meetings to refine estimates for forests in major regions of the globe (tropical, temperate, boreal) in an attempt to better quantify the sources and sinks for C. There was a continual need for analysis of management options for the Presidential Initiative to reduce greenhouse gas emissions to 1990 levels, coordinated by the U.S. Department of Agriculture, the Environmental Protection Agency, and the Department of Energy (Clinton and Gore 1993).

We extended projections to 2070 and simulated the effect of a drastic “no harvest” scenario (Heath and Birdsey 1993a). Under baseline conditions, U.S. timberlands would be a net source of C by 2070, but would sequester an average of 328 TgC/year if all harvesting were stopped. In another study of management policy options, we showed that increased recycling would be as effective as a modest tree planting program of about 10 million acres, and that the disposition and storage of C after harvest is an important factor for determining effectiveness of strategies (Heath and Birdsey 1993b).

Because of the importance of the disposition of harvested C in evaluating alternatives, we did a special study to estimate the magnitude of this component of the total C pool (Heath et al. 1995). We showed that of the 10.7 PgC harvested in the U.S. since 1900, 35 percent remained in products and landfills, 35 percent was burned for energy, and 30 percent was emitted to the atmosphere without producing energy for consumption. The current average net flux of C into products and landfills is about 37 TgC/yr, with 50 TgC/yr burned for energy or emitted.

Estimates for the 1993 RPA Assessment Update

We have aggregated the previous work into a revision of the national C budget (Birdsey and Heath 1995). We updated estimates of C allocation among tree and ecosystem components and among regions of the U.S. (Figures 1, 2). We confirmed earlier estimates that U.S. forests have been a significant C sink since 1952, and that additional C will be sequestered through 2040 but at a slower rate (Figure 3). Between 1952 and 1992, C stored on forest land in the conterminous U.S. increased by 11.3 PgC, an average of 281 TgC for each year, enough to have offset about one quarter of U.S. emissions of CO₂ for the period. Most of the historical increase in C storage has been on private timberland. Base projections through 2040 show an additional increase in storage of 8.5 PgC, and average accumulation of 177 TgC/yr.

Most of the projected increase in C storage is expected on public forest land. The expected effects of increased atmospheric CO₂ on forest productivity, and alternative forest management strategies, could each result in additional C storage through 2040. The baseline estimates from Birdsey and Heath (1995) are used in preparing the forestry baseline for the President’s “Climate Change Action Plan” (Clinton and Gore 1993).

Reporting and Information for Landowners

We have synthesized and expanded the estimates of C storage over time for the major forest types in the conterminous United States (Birdsey 1996). The estimates include the C stored in live trees, understory vegetation, litter and other organic matter on the forest floor, coarse woody debris, soil, and timber removed from the forest. The estimates cover 120 years beginning with the regeneration of clearcut timberland, cropland, or pasture. Birdsey (1996) includes C yield tables designed to represent the most common forest types and conditions in nine regions of the conterminous United States. Carbon yield tables are reported for natural

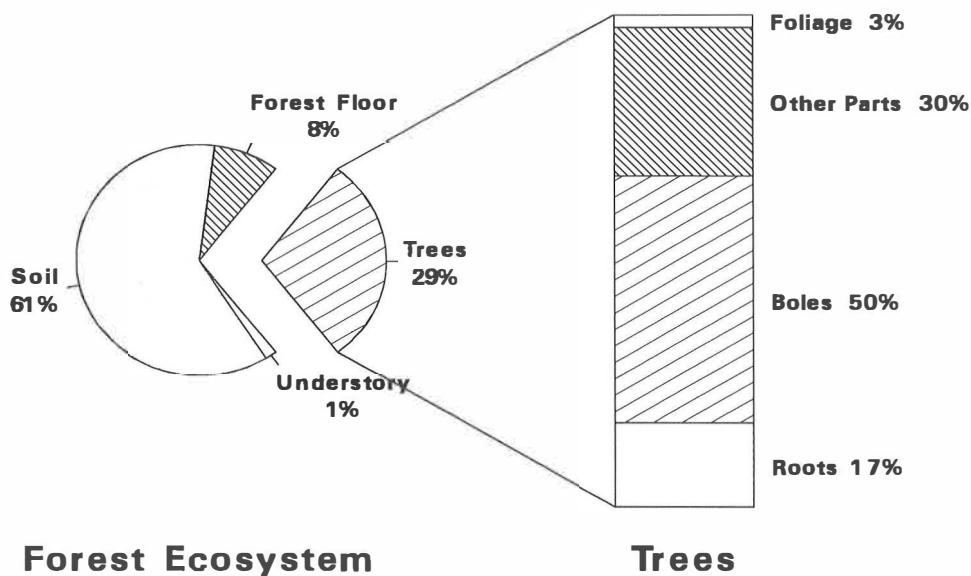


Figure 1.—Allocation of carbon in forest ecosystems and in trees, U.S. forests, 1992. Total storage in the U.S. is 54.6 Pg.

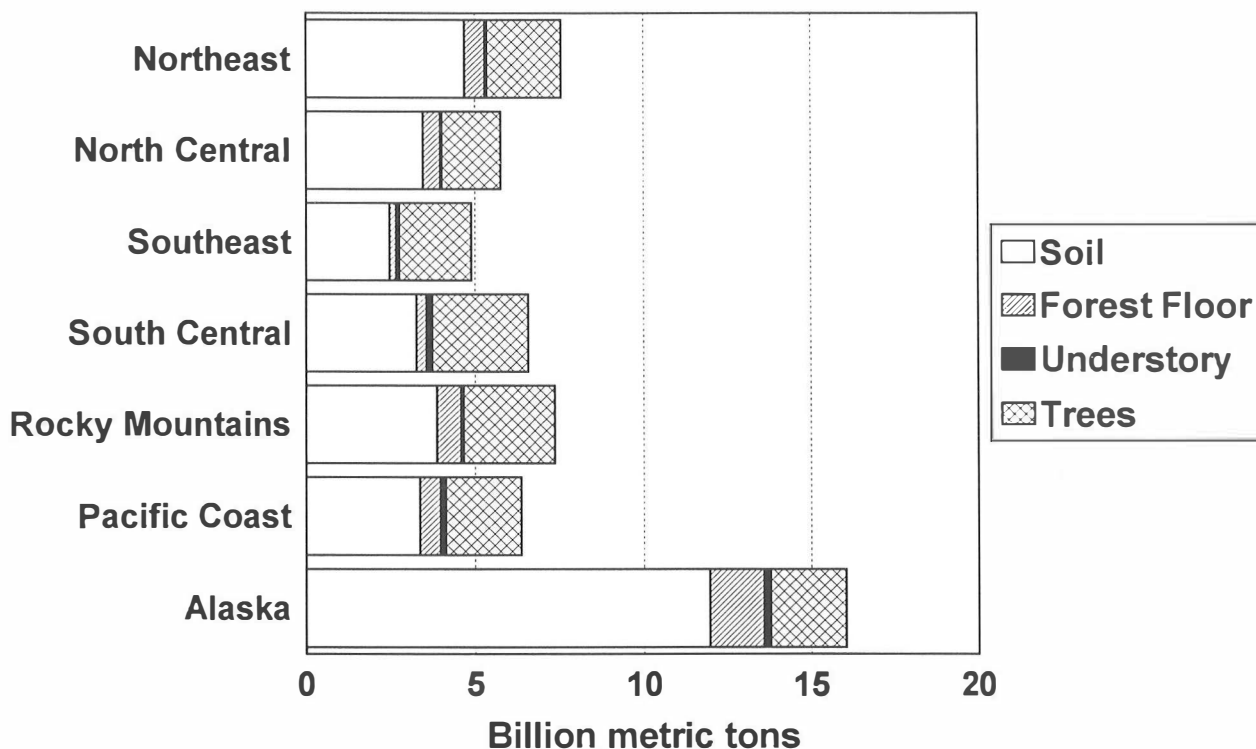


Figure 2.—Total carbon storage by region and ecosystem component, U.S. Forests, 1992.

forest types and plantation species that are harvested and regenerated, and for pasture or cropland that is planted with trees or allowed to revert naturally to forest. Different site productivity classes and management intensities are included for some regions. All of the estimates represent expected regional averages for different vegetation classes (e.g. by forest type and past land use), actual yields on specific tracts of land will be more or less than the regional averages.

Carbon yield tables can be used to analyze the effects of specific actions outside the context of economic or policy

models. The tables provide the basis for estimates of C storage in forests that would result from reforesting marginal crop and pasture land and increasing timber growth on timberland. The impacts of two of the action items in the President's plan for reducing greenhouse emissions were estimated with C yield tables: reducing the depletion of nonindustrial private forests and accelerating tree planting in nonindustrial private forests (Clinton and Gore 1993). On the individual scale, guidelines for voluntary offsets proposed by the Department of Energy have adopted carbon yield tables (U.S. Department of Energy 1994).

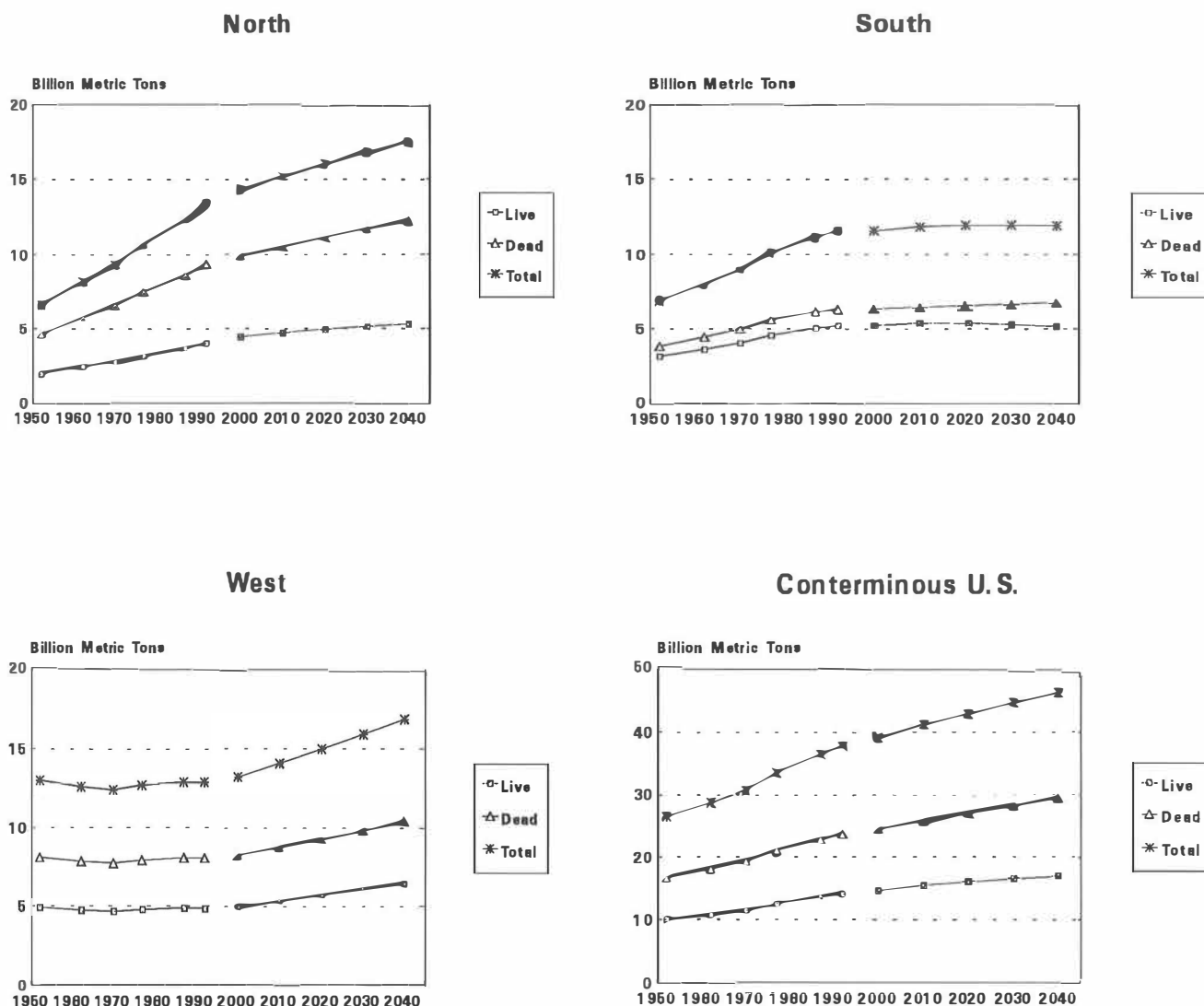


Figure 3.—Carbon storage in live (tree and understory) and dead (soil and forest floor) organic matter, conterminous U.S. forests, 1952-2040.

FUTURE ANALYSES

In looking ahead to the 1998 RPA Assessment, we are beginning a complete overhaul of the FORCARB model to reduce uncertainties in estimates of components of the C budget, expand the analysis capabilities for additional scenarios, improve the linkages with other models, and update the modeling techniques for public lands. A separate modeling effort will cover Alaska, which accounts for more than 1/4 of all C in U.S. forests and is a key component of the northern boreal forests of the world.

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HUMAN ACTIVITIES AND NATURAL RESOURCE INTERACTIONS: AN OVERVIEW OF THE *HUMANI* PROGRAM ELEMENT OF THE FOREST SERVICE'S GLOBAL CHANGE RESEARCH PROGRAM

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Since the 1970's, social scientists have been using the term 'global change' to refer to changes in international social, political, and economic systems, particularly in the context of concerns about international insecurity and decreases in the quality of life (Price 1989). In many ways, this anthropocentric use of global change anticipated the concept of sustainable development, first brought to international attention by the World Commission on Environment and Development in 1987 and subsequently adopted as a policy objective by governments and other institutions around the world.

The *HUMANI* element of the Forest Service Global Change Research Program (FSGCRP) is concerned with the interactions between human activities and global change, i.e., how these activities may both cause, and be affected by, global change. Three broad problem areas for research have been identified:

- (a) Assessment of ecosystem change impacts: Identification and assessment of the effects of forest ecosystem responses to climate change on communities and society;
- (b) 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;
- (c) Implications for forest management: Research on the integration of risks associated with potential climate change into rural and urban forest management decision processes.

This paper presents a brief overview of the context for *HUMANI* research, ongoing and planned *HUMANI* activities, and some suggestions for possible future *HUMANI* research directions.

THE HUMAN DIMENSION RESEARCH CONTEXT FOR *HUMANI* ACTIVITIES

A variety of organizations both in the United States and abroad are involved in conducting research on human dimensions of global change (HDGC). These groups provide a reservoir of knowledge relevant to *HUMANI* program activities. An awareness of the linkages among this web of knowledge and experience will be an important ingredient in the effectiveness of subsequent *HUMANI* research efforts. In the most general terms, the HD research context for *HUMANI* activities includes:

- Other elements of the FSGCRP
- The mission and programs of the U.S. Forest Service
- Global change research efforts within the United States
- International research on HDGC: International organizations and individual countries.

Research in *HUMANI* problem areas needs to complement and enrich that conducted within the other FSGCRP program elements, both via communication and the exchange of knowledge. This may frequently involve using models that include human, as well as geophysical and biophysical systems. The vast majority of the 191 million acres of forests and grasslands managed by the U.S. Forest Service are simultaneously natural and human settings; and understanding how human-ecosystem *interactions* shape present and future conditions of these settings is a task for natural and social scientists working together on different dimensions of the same phenomenon. In this regard, the National Forest System represents a wealth of empirical possibilities for accomplishing this task as part of the agency's mission (USDA Forest Service 1995).

This also points to the importance of the broader context of Forest Service priorities, programs, and capabilities. At the highest policy level, HDGC research themes are evident within the four priority research and management actions defined by the Chief in his "Course for the Future" speech during the 1994 Forest Service Leadership meeting in Houston, Texas. One major theme is to increase understanding of the human dimension of ecosystem management. This also was emphasized in the Forest Service's "Strategy for the 90's for Forest Service Research" and in the National Research Council's 1990 report "Forestry Research: A Mandate for Change." There are also important linkages between the FSGCRP and assessments conducted under the Resource Planning Act (RPA), with respect to which the Forest Service has played and will continue to play a major role. Specific areas of mutual interest relating to HDGC include:

- Estimation of expected changes in resource productivity and species composition
- Analysis of the economic impacts of global change and the effects of policies on atmospheric chemistry through linkage of global change models and RPA assessment models
- Identification and evaluation of policy options for mitigating or adapting to global change.

The US Global Change Research Program (USGCRP) was established in 1989 to combine and coordinate the research and policy development activities on global change of various federal departments and agencies. It is organized under the auspices of the Subcommittee on Global Change

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Research of the National Science and Technology Council's Committee on Environment and Natural Resources Research. The broad context and scope of the USGCRP is described in "Our Changing Planet", an annual report prepared by the Office of the USGCRP. The Office's research programs in the social, economic, and policy sciences are organized around the following themes: 1) International population trends and the human condition; 2) Patterns of trade and global economic activity; and 3) Adaptation and mitigation, including environmental resource use and management. The USGCRP is currently expanding its efforts with respect to two elements involving HDGC themes:

- Analyzing the impacts and consequences of global change on environment and society
- Developing tools for assessing national and international policies and options for responding to global change.³

Finally, there is also a growing body of HDGC research occurring as part of programs conducted at the national level within a number of countries, or under the auspices of a variety of international organizations. While it is not possible to summarize these efforts here, an overview of the organizations and countries involved—the latter including nine European countries plus Canada and the United States—as well as their HD-related foci of research, may be found in Price and Lewis (1995). All of the above suggests that those engaged in HUMANI research have a wealth of resources from which to draw, including the communicative links with those thinking about and working on various aspects of human-nature interactions and linkages of the latter to global environmental change.

ONGOING AND PLANNED HUMANI ACTIVITIES AND ACCOMPLISHMENTS

In the 1992 FSGCRP Plan Update, a number of broad objectives were identified for the HUMANI element for the period of 1992-1996. These included:

- Linkage of econometric forest sector models with carbon budget models, to allow analysis of changes in commodity and non-commodity resource outputs and values, and evaluation of alternative policies for mitigating or adapting to global change;
- Development of an integrated model, linking an econometric model of potential land use changes resulting from climate change scenarios with a forest sector model, to evaluate land use and vegetation interactions;
- Identification of communities and social groups at risk from changing urban and rural forest conditions, based on sociological case studies of analogous situations;
- Identification of historical (and archaeological) relationships between climate change, ecosystem conditions, and society;

³More details on the variety of agencies and organizations participating in the USGCRP and their HD-related research may be found in Price and Lewis (1995).

- Identification of changes in resource outputs and values likely to result from changes in forest health and productivity, as a basis for policy and management planning;
- Identification and evaluation of national and international forestry strategies for mitigating and adapting to global change.

During this period, HUMANI activities in the Southern Region have focused on the socioeconomic impacts of global change on forests, especially potential impacts in the southern pine timber market, with research in the following areas:

- Comparison of models of the economic impacts of potential climate change scenarios on southern commercial forest inventories;
- Examination of the effects of global change on aesthetic forest resources in the southern Appalachians;
- Exploration of the utility of existing biological data and impact information for economic modeling;
- Exploration of the suitability of existing economic criteria for assessing global change damage to forests;
- Examination of the economics of cost-share tree planting for sequestering carbon emissions.

In the Northern Region, attention has centered on understanding the effects of historical and current land use and management intensity on regional carbon dynamics, and this has included the modeling of carbon dynamics in contrasting environments along an urban/rural gradient. Among the activities of the TERRA Laboratory is included a HUMANI-related project designed to:

- Develop an initial understanding of the social forces affecting landowners' land use decisions in northeastern Colorado;
- Determine the relative significance of enterprise, socio-cultural, and political-economic factors needed for an economic model linked to an ecological model.

In the Interior West Region, activities during 1992-1996 have been concerned with assessing the impacts of humans on ecosystems and landscapes and evaluating management options from ecological, economic and social perspectives to enhance the sustainability of human populations and ecosystems. Current HUMANI research foci include:

- Assessing the impacts of ecosystem management policies and practices on economic stability and development
- Improving understanding of the environmental history of the Rio Grande Basin, the historic and contemporary human role in basin ecosystems, the nature and extent of anthropogenic disturbances to the basin, and the sustainability of cultural diversity
- Synthesizing literature on suburban and rural land use change in a wildland setting to produce a scheme for classifying human development near forests based on density and type of development.

The Pacific Region has to date sponsored a workshop focused on defining parameters of the human dimension (see following section) and provided support for several integrative reports on the status of HDGC research in the Forest Service and elsewhere (Price and Lewis 1995).

On an overall basis, future goals (from 1997 onwards) in the HUMANI element have been anticipated to include:

- Improvement of integrated forest sector and carbon budget models, to incorporate the effects of climate change on local economies and evaluate the cumulative effects of local management decisions on gas exchanges with the atmosphere;
- Projections of the likely effects on forest ecosystems of expected changes in land use;
- Research and analysis of public perceptions of, and responses to, global change.

These objectives were identified in 1992. Subsequently, it has been recognized that it may be desirable to define other research priorities for the HUMANI program element.

MAPPING THE TERRITORY: RECENT FOREST SERVICE WORKSHOPS ON HDGC

Both the scope and the relatively recent origin of the FSGCRP—along with the equally recent emergence of attention to the human dimensions of natural resource management in ways that explicitly link natural and social processes at varying scales—have required a great deal of effort by those involved at “getting a handle on what we are dealing with,” both conceptually and in terms of practical implications for policy and management. In response to this, the Pacific, Northern, and Interior West regions each sponsored a workshop in 1994-1995 to review progress and map out future program directions. The Pacific and Northern region workshops focused exclusively on the HUMANI program element, while the Interior West workshop involved all four program elements, with two topics devoted to HUMANI components. This section presents a brief overview of conclusions and recommendations emanating from each of these workshops.

The objective of the Pacific Region Workshop (Geyer and Shindler 1994) was “to explore the link between human activities, ecosystems, and global change and lay the groundwork for a meaningful program of cooperative interdisciplinary research”. The participants agreed that four principles should guide the definition of future HUMANI activities:

- Questions addressed should be relevant to the USDA Forest Service.
- Research should be integrated with other FSGCRP program elements.
- Research should emphasize linkages between national policy decisions, regional ecosystem management, and local level stewardship.

- Research strategies and management implementation should incorporate opportunities for social learning.

Recommendations for future HUMANI activities were divided into four thematic areas. These may be found in Table 1, along with research and management topics identified as important research concerns.

A first set of topics centered on institutional and organizational structures and processes that would be efficient and flexible in defining and addressing problems and opportunities related to human and environmental dimensions of global change. The need for understanding the nature and interrelationships of human perceptions, values, and behaviors related to global change formed a second broad topic of concern. A key aspect of this concerned how perceptual and objective aspects of risk and uncertainty regarding the nature and scope of the phenomena contribute to shaping human actions. The importance of assessing not only the nature and intensity of values, but also perceived tradeoffs among them, was also stressed; as were mechanisms for effectively conveying information conducive to responsible public judgements on the part of stakeholders and the broader populace. Key behavioral manifestations of values and perceptions, as reflected both in household consumption patterns and in relation to broader social and biophysical carrying capacities, were other key topics of concern.

A third key theme focused on local communities and the role of agency-public interactions in enhancing understanding of the significance of global change processes for both short and long term community growth and stability. This will require recognizing the limits to sustainability of ecological and human systems, including societal thresholds for assessing tradeoffs. Such a shared understanding can only be achieved via communication networks in which public decision makers, resource users, agency administrators and managers, and the broader public are active participants. A fourth set of topics was concerned with operationalizing the concept of sustainability with respect to both ecological and human systems. Reliable estimates of biophysical and social carrying capacities, economic and social costs of achieving levels of sustainability, impacts of changes in land use, and the ability to learn from past land use practices and resource consumption patterns were all identified as important priorities.

The objective of the Northern Region workshop (Emery and Paananen 1995) was “to identify critical social science issues where human needs, expectations, and values meet forest ecosystems and natural resource policy”. The participants at this workshop developed six broad categories of research foci. These were recast and prioritized at a subsequent meeting. Participants at the latter meeting stressed the need for baseline social science data that integrates information on social, physical, and biological systems. Their suggestions for research at a variety of social scales involving both rural and urban forests may be found in Table 2.

Table 1.—Themes & related topics for HUMANI research identified at the Pacific Region workshop (May 1994).

-
- 1) *Governance: Policy processes and institutional behavior*
 - Institutional structures: Role in contributing to undesirable change and acting as barriers to program goals
 - Organizational structures: Incorporating common focus for GC research
 - Criteria and protocols to guide decisions for allocating scarce resources
 - Organizational adaptive capacity: Flexible mechanisms for responding to surprise events or unexpected outcomes
 - 2) *Values and perceptions: Human behavior and public understanding*
 - Public's current understanding of GC, including factors influencing risks and uncertainties
 - Social science information: Values and desires as distinct from tradeoff assessments
 - Social acceptability vs. biophysical system capabilities: Perception and reality
 - Information for responsible public choices: Nature and mechanisms for conveyance
 - Green practices and household economics: Impact on consumption patterns
 - 3) *Local practices: Effects on communities and agency-public relationships*
 - GC impacts most significant for growth/atrophy of communities in short and long run
 - Criteria for defining local limits of biophysical and social sustainability
 - Public thresholds relevant to assessing resource tradeoffs
 - Value and potential application of community case studies for assessing GC and agency response
 - Local communication networks, including key decision makers, for access, use and control of resources
 - Social, political, and organizational mechanisms to enhance agency-public interaction
 - 4) *Sustainability: Ecosystem management (EM) and scales*
 - Degrees of sustainability for natural and social systems: Economic, social & environmental costs
 - Social vs. biophysical carrying capacities: Definition and assessment; Locations and circumstances where we are at or beyond carrying capacities
 - Historic human consumption and land use patterns: Learning potential for future options
 - Land use scenarios: Effects on ecosystem management
 - Ecosystem Management: Local and national sustainability, and relevance on a global scale
-

Source: Geyer and Shindler (1994) Slightly modified from original phrasing

Table 2.—Prioritized topics for HUMANI research resulting from the Northern Region workshop (1995).

-
- A. *Behaviors and demography*
 - How do trends in human uses of forests affect the ecosystem/s?
 - How do demographic trends affect forest use?
 - What are the impacts of human actions on forested ecosystems?
 - B. *Social impacts of forest ecosystem management and policy*
 - What are the intended and unintended consequences of management and policy?
 - What are the differential effects of forest management actions and environmental changes across social groups and time?
 - How can risk assessment techniques be used to evaluate social impacts of changes in forested ecosystems?
 - C. *Technology*
 - How do various technologies affect the ways people use forests?
 - How will changes in forested ecosystems affect technologies?
 - D. *Human response thresholds to environmental changes*
 - What triggers human responses to changes in forested ecosystems?
 - How do people respond to changes in forested ecosystems?
 - E. *Stakes and stakeholders*
 - What methods can be used to identify stakeholders and communities of interest at various scales?
 - Who are the relevant stakeholders and communities of interest at various scales?
 - What methodologies can be used to identify and evaluate tradeoffs among benefits and costs of management and policy options for various stakeholders?
 - What are the tradeoffs among benefits and costs of management and policy options for various stakeholders?
 - F. *Values and social constructions*
 - What are the sources of environmental values?
 - What are the interactions between environmental values and changes in forested ecosystems?
 - How do social constructions of the relationships between nature and humans affect options for responding to change in forested ecosystems and landscapes?
 - What are the relationships among values, beliefs, perceptions, and behaviors?
-

Source: Emery and Paananen (1995)

Critical research foci included the interrelationship between human behaviors and the status of forested and other ecosystems, including the range of influences that may trigger changes in such actions and behaviors. The significance of demographic manifestations of these behaviors for ecosystem stability was also explicitly recognized. Another key concern involved social impacts of resource policy and management decisions, especially in terms of how both intended and unintended consequences are experienced by different individuals and groups. The importance of incorporating measures of risk in assessing social impacts was also stressed, as was the relationship between changing technologies and forest uses. Another high priority was the need for identifying stakeholders and communities of interest at varying social scales, as well as assessing tradeoffs among benefits and costs of management and policy options as both perceived and actually experienced by different stakeholders. The nature of environmental values and their relationship to ecosystem change was also emphasized, as was their interplay with other key psychological attributes and behaviors in forming social constructions of human-ecosystem interactions. The impacts of such constructions need to be considered as they are expressed in changing patterns of forest uses and their concurrent effects on ecosystem health.

In April 1995, the Interior West region sponsored a GC workshop for the purpose of reviewing accomplishments over the past five years, outlining the implications of research results for natural resource management, and identifying future research needs. The workshop encompassed all four elements of the Interior West GCRP and resulted in a document containing twenty-eight papers, two of which dealt explicitly with HUMANI-related subjects (Tinus 1995). These focused on:

- Historic interrelationships of humans and the ecosystems of the Middle Rio Grande Basin
- Collaborative decision process support tools from global change research.

An ongoing study of the environmental history of the Middle Rio Grande Basin in New Mexico examined the historic period from 1540 A.D. to the present (Scurlock 1995). Four spatial and temporal models sequentially encompassing the entire historic period were described, in which climatic data is integrated with extant and new historical and archaeological data to model long term ecological trends in terms of: a) historic stream hydrology-morphology; and b) river-floodplain biological/ecological components. Testing and revision of the model is expected to provide a context for improved bioremediation, evaluation of sustainability of land use practices, and development of appropriate management programs. Scientists are also reviewing recent advances in geographic information systems (GIS) that will enhance collaborative decision capabilities for land and resource management (Fox and Faber 1995). An application of collaborative GIS techniques in the Arapaho-Roosevelt National Forest is described, and potentials for further enhancement of this management tool are discussed.

DIRECTIONS FOR FUTURE RESEARCH IN THE *HUMANI* ELEMENT

The variety of ongoing GCRP activities, the wide array of themes suggested in regional workshops, and the range of projects being conducted by other organizations in the United States and elsewhere, provide a basis for future research within the HUMANI element of the FSGCRP. From the perspective of HUMANI researchers, this also includes how we identify topics of actual or potential importance to understanding GC processes; how we acquire and organize knowledge and information about these processes; and how we communicate and share this knowledge with fellow researchers, resource managers, and others in different socio-geographic settings and contexts. Table 3 contains the broad subject areas that were identified as important research concerns by participants in the workshops described earlier; these served as headings within which more specific topics were situated.

One way of conferring a degree of order to the topics depicted in Table 3 is by relating them to one or more **levels of HD analysis**. When we consider the movements and characteristics of people "on or across the land," as do those topics in Table 3 related to demographics and population dynamics, this *biophysical* level may be re-characterized as the social-geographic level of analysis. A person, however, is not simply a biophysical body, but someone to whom the natural and human worlds are significant in various ways. A number of topics in Table 3—i.e., those concerned with perceptions, values, attitudes, as well as individual behaviors either contributing or responding to GC processes—are focused at the level of the *person*. Persons, moreover, interact and form relations with one another; and characteristics of these *relations* bring us to the level of the group or *society*. A variety of topics in Table 3 address this level—e.g., understanding patterns of social relations (social structures); assessing social impacts on relations among individuals and groups; understanding institutions as relational patterns in which actors occupy particular roles that shape behavioral expectations; and the whole class of interactions and relations specifically concerned with policy and management activities related to human-nature interactions and their global manifestations. Finally, when beliefs, values, modes of perception, etc., come to be *shared* within a group or society and passed on from generation to generation, we are concerned with the level of *culture*. A society's cultural fabric gives meaning to its members' interactions with nature (the ecosystem) over time (this is the basis of the historical 'cultural landscape' research perspective), including the technologies they develop and employ in interacting with the natural world.

By relating the list of topics in Table 3 to levels of analysis for the human dimension—i.e., biophysical–personal–societal–cultural—we may begin to view the human dimension of global change systematically in terms of actors, relations, and processes that are manifest at different levels of social scale, including the biophysical level through which human actions and behaviors are directly linked to global environmental change. This requires not only recognizing

Table 3.—Broad areas for future HDGC research as identified in regional workshops.

A. Monterey workshop (Pacific FSGCRP region): May 1994	
- Governance: Policy processes and institutional behavior	
- Values and perceptions: Human behavior and public understanding	
- Local practices: Effects on communities and agency/public relationships	
- Sustainability: Ecosystem management and scales	
B. Harvard workshop (left) and Pittsburgh meeting (right) (Northern FSGCRP region): February-March 1995	
- Policy and management	- Behaviors and demography:
- Perceptions and behaviors	- Social impacts of forest ecosystem management and policy
- Valuation	- Technology
- Environment-Culture-Technology systems	- Human response thresholds to environmental changes
- Population trends and resource use	- Stakes and stakeholders
- Social structures and institutions	- Values and social constructions
C. Interior West GC Workshop (April 1995 -- Fort Collins, CO): Human dimensions papers	
- Historic interrelationships of humans and ecosystems of the Middle Rio Grande Basin	
- Collaborative decision support tools from global change research	

these HD levels, but also understanding how they are dynamically interrelated. How do actions of individuals (*persons*) contribute to social relations and processes (*society*) which, expressed within a fabric of shared symbolic meanings (*culture*), play out in interactions (i.e., as behaviors) with the natural environment at different *social-geographic* scales? And, of course, how, on a global scale, are the impacts of these HD processes manifest in terms of global environmental change? In this light, incorporating levels of analysis for the human dimension may help replace the 'laundry list' perspective conveyed in Table 3 with a systematic basis for identifying and organizing the wide variety of HD topics to correspond more closely to empirical HD processes at various scales, including their impacts on the global human and natural environment.

Another consideration for future research concerns the distinction between **conceptual clarification vs. empirical application**, and its relevance to substantive HDGC topics. Ultimately, of course, HDGC research must help us understand what is going on 'on the ground,' and this empirical focus is explicit in many topics in Table 3—e.g., local practices, social impacts, behaviors, population trends, etc. But all such topics have a conceptual side as well, and for a number of potential HD research foci the need for conceptual clarification—that is, research on what we mean by the concept and how it is manifest empirically—is paramount. The fact that many key terms in social science are expressed in everyday language means that virtually everyone—researchers, managers, the public, etc.—is likely to have an intuitive 'feel' for what these concepts mean; but this is not sufficient for rigorous HD research. There is a real need for conceptual clarification in a number of areas. In Table 3, for example, the meaning and empirical manifestations of such terms as social structure, institution, social construction, sustainability, values vs. valuation (the two are by no means synonymous), and even that of culture itself, need to be systematically explicated for use by HD researchers and for conveyance to interested and general publics. For even the most sophisticated empirical research,

if based on inadequately specified concepts, will likely have a short half-life in terms of its practical relevance.

With respect to **substantive content** of future HDGC research, a number of common themes emerged from the GC workshops. One pertains to the interrelationship between, on the one hand, perceptions, beliefs, values, and attitudes regarding environmental and global change issues and, on the other, the behaviors of individuals, groups, and organizations that ultimately affect these issues. Such research could focus on this interrelationship for a variety of relevant groups and/or populations—e.g., the general public, stakeholders, business community, natural resource agency personnel, political representatives, and so on—and examine the degree of correspondence or divergence among them. The perception and expression of risk and uncertainty and its relationship to GC issues across all levels of HD analysis—i.e., persons, groups/organizations, and as expressed in the cultural fabric of society itself—was another topic given considerable emphasis. This also entails understanding how risk and uncertainty are incorporated within management strategies and policy development, and the kinds of institutional and organizational structures that would be most flexible in this regard. Identifying 'stakes and stakeholders' at different levels of social scale—i.e., individuals, groups (industries, users, etc.), communities, nations, etc.—in terms of potential impacts of GC processes was viewed as a priority concern at all workshops. The integration of ecological and social modeling techniques will likely be important here, and the latter will in turn require a better understanding of how benefits and costs may be identified and assessed, what critical thresholds are perceived by various stakeholders, and the likelihood of different kinds of behavioral responses when such thresholds are viewed as being approached or breached. The role of technological change and its interaction with global environmental processes was another theme accorded substantial attention, and it will likely be important to integrate this within the above kinds of modeling efforts.

Finally, much can be learned via **communication and knowledge exchange** with researchers working on HDGC topics as part of national and international programs, including other organizations participating in the USGCRP. Recalling the Monterey workshop recommendation that questions addressed as part of HUMANI research efforts should be relevant to the Forest Service mission, the topics for HD research depicted in Table 3 are by and large congruent with much ongoing Forest Service research on the human dimension of ecosystem management (see Price and Lewis 1995). In this light, much will likely be gained by enhanced interaction with those working in this area as well. In a practical vein, given current budget scenarios and the vulnerability of GC research being perceived as 'more peripheral' than other more 'central' agency activities, perhaps the most immediate opportunity is for increased interaction among HUMANI researchers with one another and with those focusing on the other elements of the FSGCRP. Regarding the former possibility, for example, it does not appear that results generated at the 1994 workshop were discussed or utilized as inputs to subsequent 1995 workshops sponsored by other regions. With respect to integrating HUMANI research with that of other FSGCRP elements, perhaps the most effective ways to achieve this would be in the project definition stage, where an interdisciplinary approach involving both natural and social scientists could be adopted as part of regional and/or other geographically specific projects. In summary, linking HUMANI research efforts with others working at all levels of the research context will likely become an even more important part in the complex task of understanding the human dimensions of global change.

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PROGRESS TOWARD AN INTEGRATED MODEL OF THE EFFECTS OF GLOBAL CHANGE ON UNITED STATES FORESTS

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PAST RPA ASSESSMENTS OF CLIMATE CHANGE EFFECTS

Strategic planning at the national level in the Forest Service was institutionalized with the passage of the Forest and Rangeland Renewable Resource Planning Act of 1974 (RPA), P.L. 93-378, 88 Stat. 475 as amended. This Act directed the Secretary of Agriculture to prepare a decadal Assessment that would include "an analysis of present and anticipated uses, demand for, and supply of the renewable resources of forest, range, and other associated lands with consideration of the international resource situation, and an emphasis of pertinent supply, demand and price relationship trends" (Sec. 3. (a)). Past assessments have focused on the demand and supply of timber, wildlife, range forage, water, minerals, and recreation. The 1990 Farm Bill added the additional stipulation that climate change impacts on productivity and species shifts be included as a part of the Forest Service RPA analyses. Prior to this point in time, these strategic planning analyses had not considered the potential impacts of climate change on the future uses, demand for, and supply of renewable resources (Fosberg et al. 1992).

The need to address issues related to climate change became evident in 1988 and was included in that decadal RPA assessment. The initial work consisted of a review of the current scientific understanding of the potential effects of climate change on forests (Joyce et al. 1990). Between that initial effort and the RPA assessment update in 1993, research led to the development and integration of several additional model components into the set of models used to analyze timber supply and demand (Joyce 1995). The update focused on how prospective climate change could affect the forest sector by changing estimates of productivity. The analysis included effects on the supply and demand for timber, and on the national carbon budget.

The structure of the modeling system used in the 1993 RPA update is shown in figure 1. The forest sector model (TAMM) interacts with the timber supply model (ATLAS) to approach an equilibrium between supply and demand for forest products. Within this structure are a fuelwood model (NAWEM), a pulp and paper model (NAPAP), timber growth and yield models (embedded in ATLAS), models that predict timberland area and forest type changes, and a link to

global climate models (GCMs) through a model of ecosystem productivity (TEM). A variant of ATLAS, ATLASC, produces ATLAS outputs that feed a link to FORCARB, a carbon accounting model for all components of the forest ecosystem. Estimates of carbon in forest products can be made by a link between FORCARB and HARVCARB.

This modelling framework was used to address the effects of 4 different scenarios of climate change on forest productivity, market responses, and carbon storage (Joyce 1995). 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 many other economic factors besides supply of timber. 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. This integrated analysis demonstrated the need to link climate, ecological, and economic responses in any assessment of climate change effects.

The analysis for the 1993 RPA assessment update revealed a number of areas where models or model linkages could be improved. Research is in progress to update many of the models, to develop the linkages to improve the flow of information between models, and to add several more components (figure 2). Some of the specific improvements underway include:

1. Develop a data base to help manage and organize the inventory data, and reconcile the inputs from several models. Inventory data will be tracked in more detail than before, to facilitate outputs at different scales.
2. Replace HARVCARB with a new model for carbon in wood products, WOODCARB.
3. Include a model of changes in vegetation distribution for global change scenarios (MAPSS).
4. Explicitly model fire and pest disturbances; improve regeneration modelling.
5. Link TEM and FORCARB to include soil carbon change in carbon accounting.

We expect to use the cluster of models depicted in figure 2 to analyze the scenarios of global change selected for the 1998 RPA Assessment.

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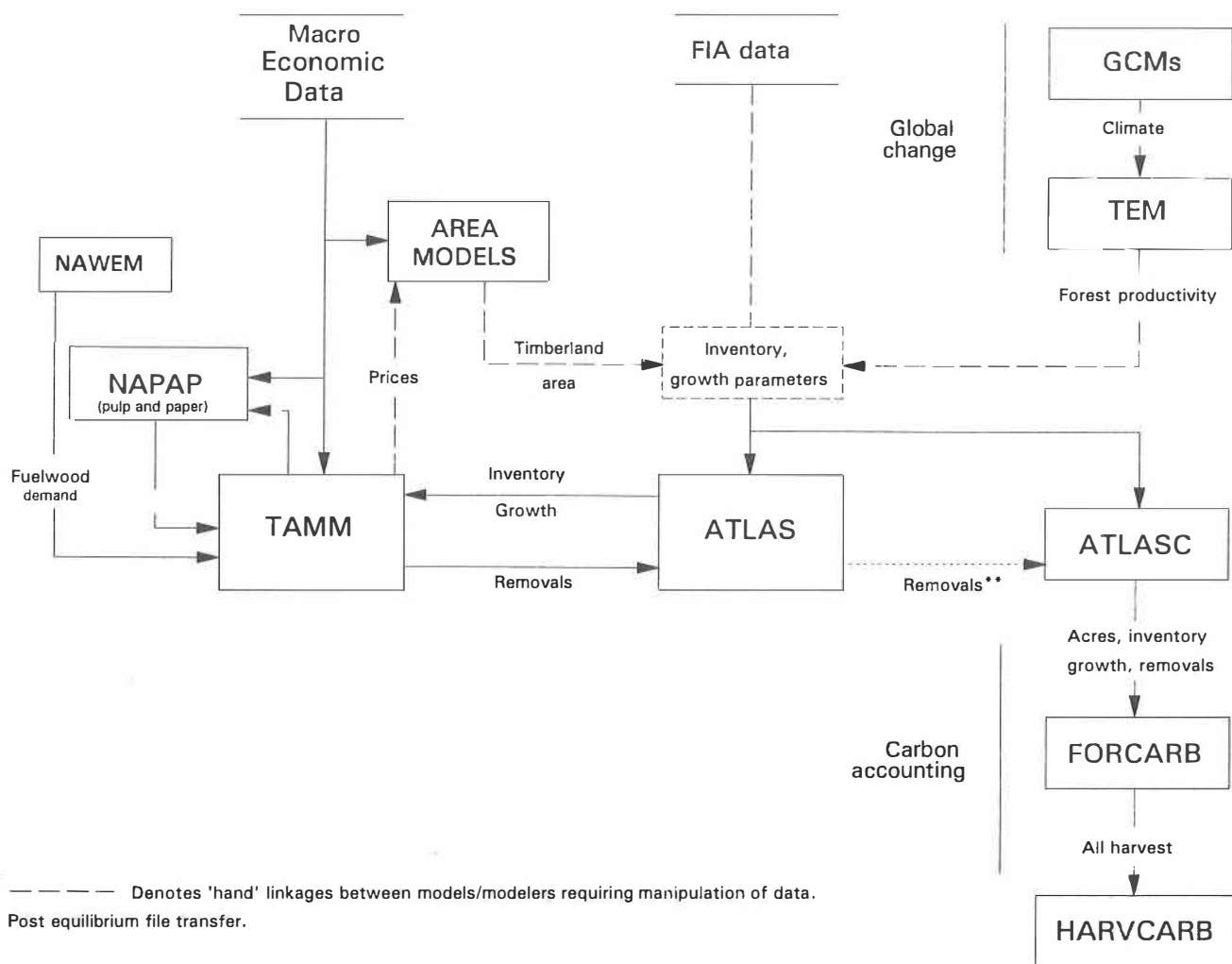


Figure 1.—Modeling system as used in the 1993 RPA Assessment Update.

THE 1998 GLOBAL CHANGE ASSESSMENT

Implementation of the U.S. Global Change Research Program including participation by the Forest Service has resulted in new policy questions, new experimental research results, and new or improved modelling tools for analysis and synthesis. The 1998 Global Change Assessment will address a broader array of policy issues than were addressed in the 1993 RPA update. The following list of policy questions has been guiding our research activities and we expect to address these issues in the 1998 RPA Assessment:

Effects of Global Change on Ecological Processes

What are the likely effects of increasing atmospheric CO₂, N deposition, and prospective climate change on ecosystem productivity (measured by changes in net primary productivity)?

To what geographic extent will potential ecosystem types change or move across the U.S. (composition and boundary changes)?

Effects of Changes in Ecological Processes on Forest Values

What changes in forest and rangeland productivity will occur (measured by changes in volume, growth, and biomass)?

What changes in water availability will occur (measured by changes in runoff)?

What are expected impacts on biodiversity, and wildlife habitat for selected species (measured by various indices)?

Effects of Changes in Forest Values on the Forest Sector

What are potential impacts on the forest sector under climate change (measured by employment, timber prices)?

When forest policy questions for the RPA Assessment (such as reduced NFS harvest) are examined with and without climate change, do the forest sector impacts differ greatly in magnitude or kind?

How will expected changes in disturbance regimes for fire and insects affect mortality and timber harvest?

study to determine which projected climate data bases for the U.S. are available for use in the time frame for the 1998 Assessment. Our goal is to have at least 2 climate scenarios that bracket the expected variability in climate, plus a baseline/contemporary climate scenario. Climate scenarios, including the effects of increasing atmospheric CO₂ on plants, will be tested primarily by the MAPSS and TEM models.

Ecological Scenarios

Ecological scenarios include impacts of disturbance (fire, insects) and N deposition on forests. Changes in disturbance regimes are an expected outcome of rapid climate change. A transition period to a new climate equilibrium would likely be characterized by high rates of tree mortality and declines in forest health. High levels of N deposition are chronic in some areas of the U.S., particularly in the East. The effects of N deposition on productivity can be strong, and can interact with the effects of other stresses. Because transient versions of MAPSS and TEM are not yet available, disturbance effects will be evaluated using ATLAS, AREA change models, and FORCARB. N deposition will be part of the analysis provided by TEM.

Mitigation Scenarios

Various combinations of mitigation activities will be analyzed to develop policy options for offsetting greenhouse gas emissions. Tree planting, increased recycling, and changes in forest management practices may be combined to help avoid more costly emission reduction programs. Combinations to achieve various offset levels will be explored using AREA change models, ATLAS, NAPAP, FORCARB, and WOODCARB.

Integrated Scenarios

The second stage of the analysis will be to use the complete integrated model to analyze various combinations of climate, ecological, and mitigation scenarios. A complete or partial factorial design will be used, depending on the number of levels of each category selected during the first stage of the analysis.

The final set of scenarios could look something like:

Baseline economic future using RPA assumptions, baseline climate and ecology, no mitigation policy

Worst case climate and ecological scenarios, no mitigation policy

Best case climate and ecological scenario, no mitigation policy

Average case climate and ecological scenario, no mitigation policy

Worst case climate and ecological scenarios, with mitigation policy

Best case climate and ecological scenarios, with mitigation policy

Average case climate and ecological scenarios, with mitigation policy

The “best”, “average”, and “worst” case climate and ecological scenarios would be identified during the first part of the analysis. During that time we would also be analyzing the behavior of all the integrated model components under the conditions imposed by the different scenarios. A few anticipated modelling issues include accounting for the international impacts of climate change (in particular Canada), how to allocate harvest subregionally, estimating soil carbon changes, and how to handle public lands, non-commercial forests, and Alaska.

Ongoing work on the individual modelling efforts is described in the following sections. Evaluation is underway to determine which models and model combinations are most appropriate for addressing the different policy issues, to compare how the different models treat similar ecological processes, to begin to understand the uncertainty with making long-term projections of climate change effects on forests, and to develop the different proposed scenarios more precisely. One example of this activity is the recently completed Vegetation Mapping and Analysis Project (VEMAP 1995).

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PRODUCTIVITY OF AMERICA'S FORESTS AND CLIMATE CHANGE

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INTRODUCTION

The Forest and Rangeland Renewable Resources Planning Act (RPA) requires the Forest Service to conduct periodic assessments of the condition of and future supply and demand of natural resources. As amended in 1990, the potential effects of climate change on these resources must be addressed in the national assessment. As a part of the RPA planning for the 1993 update, the decision was made to bring climate change into the timber planning analyses (Joyce and Haynes 1992). While the timber policy model (Timber Assessment and Market Model (TAMM)), and Aggregate Timberland Assessment Model (ATLAS)) integrates the behavior of regional prices of timber and wood products, the consumption of wood products, and production (timber yields); the impact of environmental factors such as climate on forest productivity is not specifically described (Adams and Haynes 1980, Fosberg et al. 1992, Mills and Kincaid 1992). This assessment of climate change required an ecological model that could integrate climatic factors and ecosystem productivity. The Terrestrial Ecosystem Model (TEM) is a process-based model developed by scientists at The Ecosystem Center, Woods Hole, MA (Raich et al. 1991, McGuire et al. 1992, 1993, Melillo et al. 1993). TEM uses spatially referenced data on climate, soils and potential vegetation to estimate net primary productivity (NPP) as affected by carbon and nitrogen cycling and environmental factors (McGuire et al. 1993).

To support the analysis of climate change effects on forest productivity, a series of studies was initiated in 1988 to: 1) examine the interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America; 2) compare the climate change impacts predicted by a process-based model and a regression-based model; and 3) implement a framework to link general circulation model output, the ecological model, the timber policy model, and a carbon accounting model at the national scale. These studies are now complete (Joyce 1995, Joyce et al. 1995). Additional research examined the modeling assumptions involved in processes related to soil carbon accumulation at different soil depths and has made improvements in TEM to include soil texture effects. Ongoing research is focused on assumptions within the 1993 RPA Update with respect to the role of species in ecosystem function.

INTERACTIONS BETWEEN CARBON AND NITROGEN DYNAMICS IN ESTIMATING NET PRIMARY PRODUCTIVITY

In this first study, TEM was used to examine the interactions between carbon (C) and nitrogen (N) dynamics in estimating

net primary productivity (McGuire et al. 1992). The model was modified so that carbon uptake would respond to gains or losses in site fertility. Data from intensively studied field locations were used to estimate vegetation-specific parameters for each of the 17 grassland, shrubland, and forested ecosystems examined in this study. TEM was extrapolated to the North American continental scale using spatially referenced data on climate, soils, and potential, undisturbed, natural vegetation.

TEM estimates the continental annual NPP to be 7.032×10^{15} g C yr⁻¹ (McGuire et al. 1992). Estimates for forest NPP ranged from 230 gC m⁻²yr⁻¹ for boreal forests to 1113 gC m⁻²yr⁻¹ for tropical evergreen forests. At the continental scale, TEM estimated a 32.5 percent increase in NPP if N were not limiting. Nitrogen limits productivity as a function of N-C coupling and temperature, thus the N limitation predicted by TEM is weakest in the tropical forests and increases along a northerly transect through the temperate and boreal forests. The linkage between C and N dynamics improved the spatial resolution in estimating NPP across the continent (McGuire et al. 1992).

A factorial experiment evaluated the interactions between C and N dynamics in the response of NPP to a use of 2°C in temperature. In TEM, C cycling can be uncoupled from the N cycle by setting the feedbacks of N availability to 1. Thus, the experiment was a 2X2 factorial of N-C coupling (uncoupled, coupled) and temperature (+0°C, +2°C). To minimize ecosystem differences, we focused on the temperate mixed forest of North America. When only C cycling is considered, NPP decreases because of higher plant respiration under a 2°C increase. When both C and N cycles are considered, NPP increases because the warming increased N availability and this offset higher costs of plant respiration. These diametrical differences in NPP responses to climate change suggested that process-based models need to consider linkages between the C and N cycles (McGuire et al. 1992). Additional research is needed to establish the nature of the linkages between the N cycle, elevated CO₂ and NPP (McGuire et al. 1995b).

COMPARISON OF A PROCESS-BASED MODEL AND A REGRESSION-BASED MODEL

While several ecological models were being applied to climate change questions in 1988, no cross-model comparisons of the predicted impacts had been made. In this second study, regression- and process-based approaches for predicting productivity responses to global change were compared (McGuire et al. 1993). A regression-based model, the Osnabruck Model (OBM), and a process-based model, the Terrestrial Ecosystem Model (TEM), were applied to the historical range of temperate forests in North America in a factorial experiment with three levels of temperature (+0°C,

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+2°C, and +5°C) and two levels of carbon dioxide (CO₂) (350 ppmv and 700 ppmv).

For contemporary climate (+0°C, 350 ppmv), the two models estimated similar NPP for temperate forest at the continental scale (McGuire et al. 1993). Regionally, the NPP estimates from the two models varied. While model estimates of NPP were within 20 percent of each other for deciduous and mixed forest types in the Ohio Valley, the estimates of OBM were lower than those of TEM both north and south of this area. In the mountainous regions of western North America, the differences were great and may reflect the complex topography.

Although the contemporary climate responses were similar at the continental scale, the model responses to altered climates differed at both the continental scale and at the regional scale. The elevated temperature response was similar in northern areas of moist temperate forest only. For elevated CO₂, the responses differed qualitatively in all regions between the models. With no change in temperature and an elevated CO₂ level of 700 ppmv, OBM predicted median increases in NPP of 12.5 percent whereas TEM predicted median increases of only 2.5 percent. For increases in both CO₂ and temperature, the models differed qualitatively in their response. In OBM, NPP increased only in those grid cells that were temperature-limited under contemporary climate. In TEM, NPP responded to both elevated temperature and CO₂ (McGuire et al. 1993).

These NPP differences under altered climates occurred because environmental factors and elemental availability limited NPP differently within these models. In OBM, NPP was a function of the one most limiting factor: precipitation or temperature, and the response to elevated CO₂ was independent of these limiting factors. In TEM, an increase in temperature can alter the decomposition of soil organic matter, releasing inorganic N into the soil and enhancing N availability, or may reduce soil moisture thereby reducing N availability and NPP.

Regression-based models have contributed greatly to our understanding of the global carbon cycle. However, regression-based models may not be adequate to examine ecosystem behavior under climatic conditions not now experienced by ecosystems. For example, increases in temperature may result in seasonal similarities in the temperate and tropic zones, but seasonal intercepted solar radiation may differ. Thus, it may not be feasible to extrapolate the current combinations of environmental variables and NPP responses to the future altered climates. Further, the process-based approach allows experimentation of important feedbacks and constraints on NPP responses.

THE IMPACT OF CLIMATE CHANGE ON FOREST PRODUCTIVITY, FOREST SECTOR AND CARBON STORAGE

The consequences of elevated carbon dioxide and climate change on forested ecosystems and the feedbacks on harvest patterns and vegetation change from the forest

sector had not been addressed together. The geographical extent of the RPA Update analysis was national with the timber policy models resolved only to timber supply and demand regions within the United States. Assessing the potential impacts of climate change on forest productivity required a spatially explicit examination of net primary productivity. A framework was implemented to link climate change scenarios, an ecosystem model, a forest sector model, and a carbon accounting model (Fig. 1, Joyce et al. 1995, Joyce 1995). Contemporary climate data and four climate change scenarios were used as input for the Terrestrial Ecosystem Model (TEM) to estimate net primary productivity (NPP) for forests in the United States (Melillo et al. 1993). Input climate and vegetation data for TEM were gridded at the 0.5° latitude x 0.5° longitude scale (Raich et al. 1991). We were interested in the forested ecosystems only: boreal forest, temperate coniferous forest, temperate deciduous forest, temperate mixed forest, temperate broadleaved evergreen forest, tropical deciduous forest, tropical evergreen forest.

The impacts of climate change on productivity as estimated by TEM are shown in Figure 2. Differences between the NPP responses from the contemporary climate and each of four altered climates were summarized in an average (mean) response, a maximum and a minimum response to climate change for each timber management type within the timber supply/demand regions. These changes in productivity were used to modify timber growth within the Aggregate Timberland Assessment Model (ATLAS). Lacking specific information about the transient climate and the corresponding ecological response, the adjustment to projected timber growth was a linear function of the total change in NPP from climate over the 1990 to 2065 period. Changes in timber inventories reflecting market responses were then translated into changes in the amount of carbon stored on private timberlands using a national forest carbon model (FORCARB). FORCARB accounts for carbon in biomass, soil, and the litter layer including coarse woody debris.

While the contemporary climate offered an ecological baseline in which climate was assumed not to change from historic patterns, economic considerations required a socioeconomic baseline for the 50-year projection period. For the economic baseline, the projected future from the 1993 Forest Service RPA Assessment Update was used. Assumptions included basic determinants of timber demands such as growth in population, economic activity and income, technological and institutional changes, energy costs, capital availability, and public and private investments in forest management, utilization, and research (USDA Forest Service 1989).

The largest changes in ecosystem productivity were not followed by similarly large changes in the forest sector (Joyce et al. 1995, Joyce 1995). Increases in NPP in the northern timber regions and slight or no responses in the southern regions were followed by larger harvest increases in the South relative to harvest in the northern regions. The cost of producing timber in the South was more competitive than the northern regions even with a greater increase in

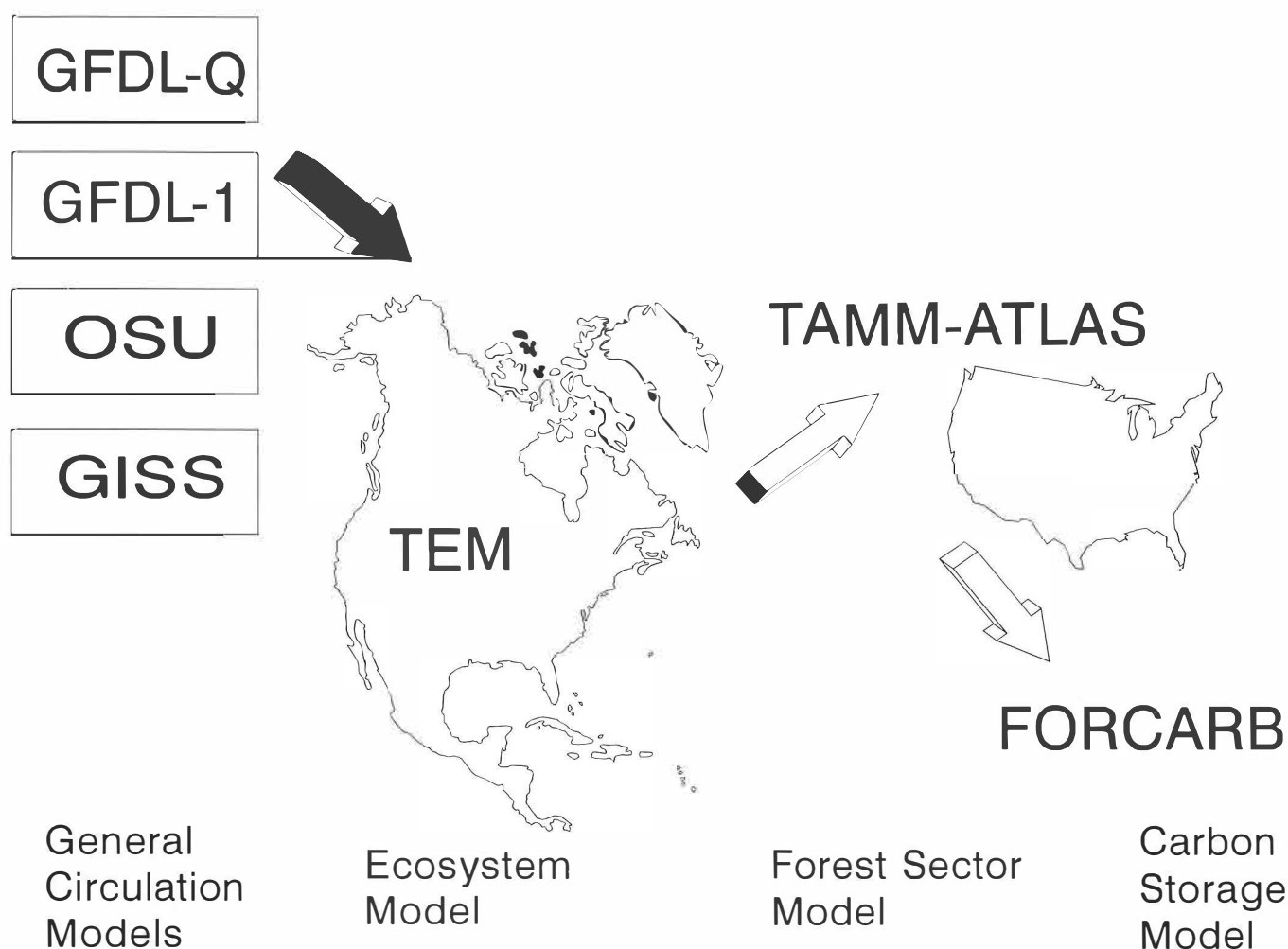


Figure 1.—Schema for analysis of climate change impacts on the forest sector: the Terrestrial Ecosystem Model (TEM), the Aggregate Timberland Assessment Model (ATLAS), the Timber Assessment Market Model (TAMM), and the Forest Carbon Model (FORCARB). The general circulation models are: GFDL-1 and GFDL-Q, Geophysical Fluid Dynamics Lab, GISS, Goddard Institute for Space Studies, and OSU, Oregon State University.

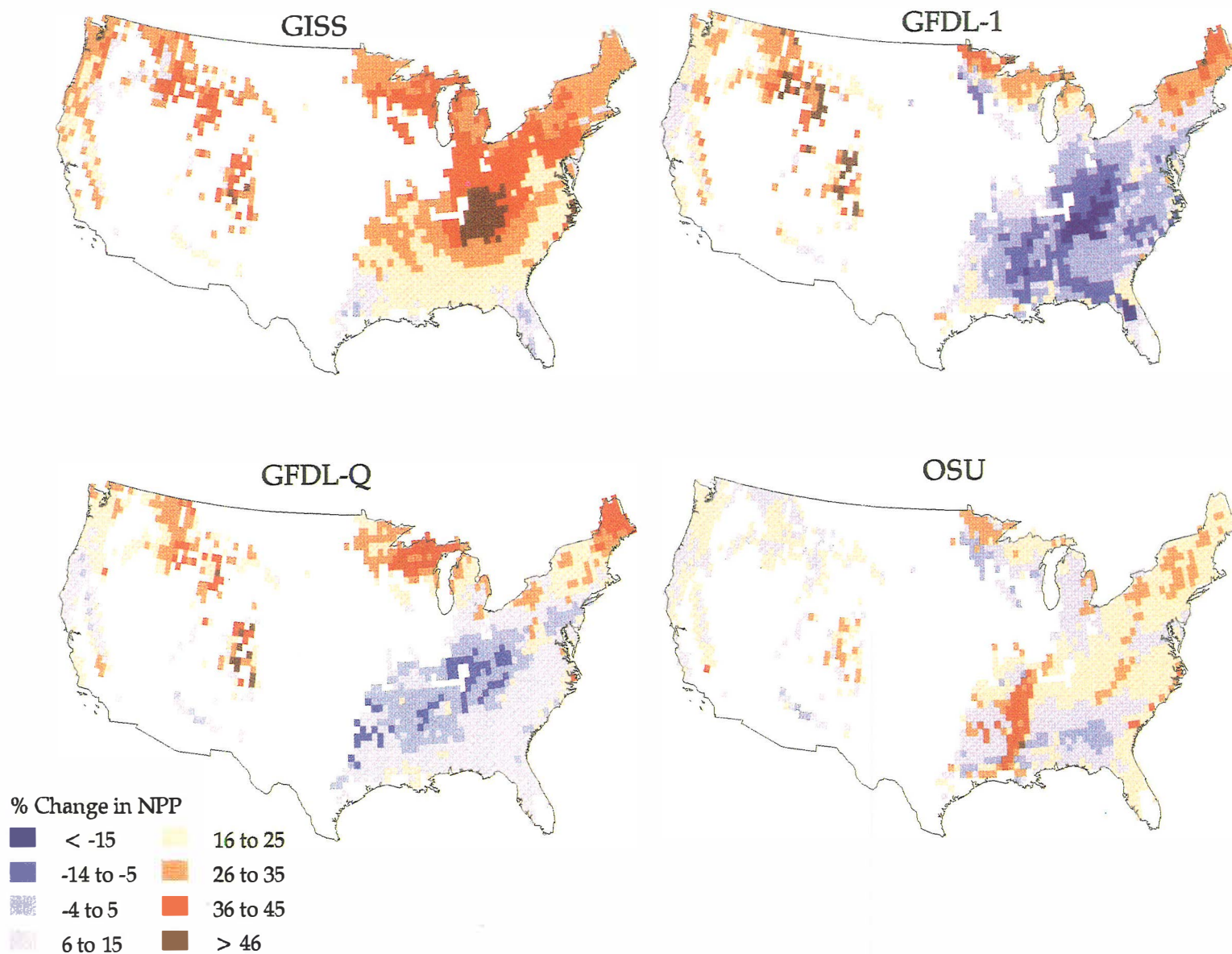
productivity in the northern regions. Harvest shifts also occurred between ownerships and between product types (softwood and hardwood). Long-term changes in carbon storage indicated that these private timberlands will be a source of carbon dioxide for all but the most optimistic climate change scenario.

ONGOING ECOLOGICAL RESEARCH WITH TEM

Scientists at The Ecosystem Center have been further modifying the structure of TEM to increasingly capture the nature of ecosystem productivity and the carbon exchange between the biosphere and the atmosphere. Modifications funded by Forest Service Global Change research focused on the soil dynamics in TEM. An analysis of processes influencing reactive soil organic carbon across climatic gradients was made. The sensitivity of soil organic carbon to a 1°C warming was examined using an empirical and a

process-based analysis (McGuire et al. 1995a). Inclusion of mean annual volumetric soil moisture in the empirical model explained an additional 19.6 percent of the variance of soil organic carbon, suggesting that soil moisture should be included in carbon models. A new version of TEM (TEM4) has been modified to allow soil texture differences to affect NPP and nutrient cycling processes.

This version (TEM4) has been ported to the research facility in Fort Collins, CO. The model results from the Sun workstation in Woods Hole, MA were compared to results from the IBM RISC/6000 in Fort Collins to assure platform compatibility and accuracy of results. Data sets from the western United States were run on each machine and compared using Idrisi overlay images and the TEM statistical utility analdatm. The Idrisi overlay showed that all cells were identical. Model development occurs on stand-alone PCs with the modifications ported over to the workstation for production runs. ARC-Info is used for display purposes.



Linda Joyce: June 1996

Figure 2.—Percent differences in net primary productivity from the baseline run (contemporary climate) and the four general circulation model scenarios. The general circulation models are: GFDL-1 and GFDL-Q, Geophysical Fluid Dynamics Lab, GISS, Goddard Institute for Space Studies, and OSU, Oregon State University.

On-going research is focused on the role of plant species in ecosystem function. The fundamental question of whether changes in plant species composition and diversity will significantly affect ecosystem function is critical in bridging ecological analyses of global change and economic impact analyses of global change. While ecological research has shown situations where species are and are not important (Davis 1988), forests are managed on the basis of species, and economic impacts are determined as a function of species. In the 1993 RPA Update, we used a biogeochemical model to estimate ecosystem productivity as a function of climate and other environmental factors. As typical of these types of models, the prediction is for the ecosystem average without delineation of individual species production.

Two different modeling approaches have been used to examine climate change responses in ecosystems: the ecosystem process modeling approach used in the 1993 Update and the population/community modeling approach of the JABOWA-FORET-ZELIG family of models (Shugart 1984, Pastor and Post 1986, Urban et al. 1993). Both approaches have their strengths and weaknesses. Population/community models describe the species dynamics of birth, growth, and death enabling an examination of the species shifts, but without consideration of ecosystem processes such as nutrient cycling. The ecosystem-process models simulate fixation, allocation, and decomposition of carbon, cycling of nitrogen and other elements and hence can be used to look at productivity and biomass changes, but ignore individual species responses. On-going research will examine the influence that species can have on ecosystem function, particularly the estimation of NPP, under the current climate and under altered climate regimes. Yeakley et al. (1994) identified the significance of multi-annual periodicities in temperature and precipitation on biomass estimations in both types of ecological models. Biomass estimations without these periodicities tended to be lower for forested ecosystems than when these climate periodicities were included. Similar considerations need to be made for the inclusion of species-specific ecological responses. If consideration of species influences is critical in the estimation of ecosystem productivity, these considerations will need to be incorporated into the other models within the framework used in the 1993 Update. Species are not currently identified in either the timber policy model or the carbon accounting model.

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GLOBAL CHANGE MODELS—LINKING THE TIMBER SECTOR TO CLIMATE

John R. Mills¹ and Richard W. Haynes¹

National and regional timber supply and demand analysis has taken place intermittently for more than 100 years (see Appendix C, Haynes 1990). With the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974, as amended by the National Forest Management Act of 1976, the Secretary of Agriculture is required to make regular assessments and propose national policy to address natural resource issues. In these assessments, the Forest Service appraises the Nation's current natural resource base from a perspective that is both historical and forward looking. The resource base includes outdoor recreation, wilderness, wildlife, fish, forest-range grazing, minerals, water, and timber. The Forest Service 1993 RPA Timber Assessment Update (Haynes et al. 1995) describes the current status of timber resources and includes a supply and demand analysis to help identify opportunities for private or public investment. Emerging trends are identified that may warrant modification of resource policy or programs. Due to increased concern over a changing global climate, the Update included an analysis of the potential impact of climate change on timber markets. This paper reviews the forest sector models and sections by Joyce et al. and Joyce discuss the broader global change modeling system; the RPA results and a full discussion are reported in Joyce (1995).

The Timber Assessment incorporates a suite of models to represent the forest sector.² In brief, these are the Timber Assessment Market Model (TAMM, Adams and Haynes 1980), the Aggregate Timberland Assessment System (ATLAS, Mills and Kincaid 1992), the North American Pulp And Paper model (NAPAP, Ince 1994), and several land use models developed by Alig et al. (1985, 1990, 1992).³ The models consider a broad spectrum of factors, including: raw material costs and availability; imports and exports; land use changes; growth rates and resource management; demographics; and trends in housing, recycling, manufacturing efficiencies, and products markets. The system is flexible and broad enough to allow for a comprehensive set of scenario projections. Recent scenarios incorporated into the RPA analysis include increased rates of wastepaper recycling, both higher and lower rates of timber growth, reduced National Forest harvest, changes in the levels of exports and imports, the effects of tree planting programs, expanded regulation of private timberlands, alternative assumptions regarding economic growth (gross national product) and housing starts.

Climate was linked to the forest sector via the Terrestrial Ecosystem Model (TEM, McGuire et al. 1992). An altered climate was created by running general circulation models (GCMs) with ambient levels of atmospheric carbon dioxide doubled ($2\times\text{CO}_2$). It was assumed $2\times\text{CO}_2$ would be reached in 75 years.

The projected equilibrium solution depicts the entire U.S., however, because of data and model limitations, the climate induced changes in productivity were projected for private timberland only.⁴ Though public lands,⁵ reserved areas, sparsely stocked or arid lands, and urban areas were excluded, private timberlands are significant in a market sense because they represent 73 percent of the 490 million acres of timberland in the conterminous U.S. For 1991 it was estimated that 82 percent of the harvest came from the private ownership (Powell et al. 1993). The public share of harvest enters into the solution as an input provided directly to TAMM.

The Timber Assessment Market Model-TAMM

TAMM provides an integrated structure for examining regional prices, consumption, and production in both stumpage and product markets. To a far greater extent than was possible in the past, TAMM focuses on the effects of alternative forest policies and programs and the dependence of projections on input assumptions. Since its inception in the late 1970's, this system of models has been extended and revised to improve the realism of its projections and the utility of its output to resource analysts and policy makers. The general structure of the modeling system is shown in the modeling progress paper presented here by Joyce et al. TAMM and surrounding models consider fuelwood, a pulp and paper, timber growth and yield, and timberland area and forest type changes. Recent additions to the system have been made to address carbon sequestration and storage issues (see section by Heath and Birdsey).

The results of TAMM represent a spatial equilibrium in the markets modeled for each year of the projection period. The basic market solution algorithm cannot readily be used to find intertemporal production or consumption strategies that are in some sense optimal. The production, consumption,

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²A forest sector model, in general, combines activities related to the use of wood: forest growth and harvest; the manufacture of pulp, paper, and solid wood products; and international trade and intermediate and final consumption of these products (Kallio et al. 1986).

³A figure illustrating these linkages is presented in the section authored by Joyce, Birdsey, Mills, and Heath.

⁴Areas qualifying as timberland have the capability of producing in excess of 20 cubic feet per acre per year in natural stands and some may be inaccessible and/or inoperable. Further, these projections include only live trees of commercial species meeting specified standards of quality or vigor. When associated with volume, these net growing stock inventories include only trees 5.0-inches dbh and larger. Cull trees are excluded.

⁵Public timberland is not explicitly modeled in TAMM/ATLAS, harvest on public lands is derived from formal land planning efforts (vs. markets), and detailed resource data is not yet available for National Forest land in the West.

and price projections are only estimates of outcomes of contemporaneous interactions in freely competitive markets.

Briefly, product demand, such as softwood lumber, is obtained by multiplying the ratio of product use per unit of activity (such as the number of housing starts) times the number of units and summing these results over all the various end uses for the product. Hardwood lumber is treated on the demand side in about the same end use detail as softwood lumber but consumption and production are set equal and price is determined as a function of softwood lumber prices. Hardwood sawtimber stumpage prices are a function of hardwood lumber prices. The economic activity measures (e.g., population growth, forecasts of GNP, and housing starts) are exogenous and are generally taken from long-term macro forecasts such as those prepared by Wharton Econometrics.⁶

Each product supply function includes operating capacity as an independent variable. Increases or decreases in this ready ability to produce are a function of anticipated changes in relative regional profitability or rate of return. The basic economic representation of timber supply at any point in time is a function of the private timber inventory levels, stumpage prices, and the amount of public harvest available. Finally, the timber demand functions are derived from product market demand and supply functions. The pulp fiber requirements are determined by NAPAP's interaction with TAMM and ATLAS. Trade and fuelwood projections are also input variables. The trade projections reflect a future where the U.S. remains a net importer of softwood forest resources.

Pulp and Paper

TAMM produces projections for the solid wood industries while NAPAP produces projections for the pulp and paper industry. NAPAP uses linear programming to solve for market equilibrium in spatially specific markets (see Ince 1994). NAPAP shows how recovered paper and pulpwood markets are expected to respond to shifting demand and changing technology, and in turn how technology is expected to evolve in response to market conditions. The model includes regional supply functions for pulpwood and recovered paper (recycling), and a detailed representation of production capacity and supply for all principal grades of market pulp, paper, and paperboard, in five North American production regions. The model also includes demand functions for all end products, with separate demand functions for U.S. domestic demand, Canadian domestic demand, and demand from various trading regions for export from the U.S. and Canada.

Timber Supply Model

The inventory resource model, ATLAS, was developed to project timber inventories at subregional, regional, and

national scales⁷. The system was first linked to TAMM for use in the 1989 RPA Timber Assessment (Haynes 1990). ATLAS simulates growth, harvest, shifts in timber management, forest type changes, and via information from TEM, changes in forest productivity. Projections represent approximately 339 million acres of private timberland in the conterminous U.S.

For purposes of the RPA, the conterminous U.S. was divided into 9 timber supply regions. Initial forest statistics and many of the forest growth parameters were derived from sample-plot data collected by the various USDA Forest Service Forest Inventory and Analysis Units (FIA). Timberland area is adjusted each period for gains and losses as projected by area models developed by Alig (1985), and Alig et al. (1990). Within each region, private timberland was stratified by 2 ownerships, up to 10 forest types, and up to 18 age classes. The South and the Pacific Northwest Douglas-fir subregion were further stratified by 3 site productivity classes and 5 management intensity classes. Five-year age classes represented the South and 10-year age classes represented all other regions.

Timber volume is projected as net growing stock. Changes in net growing stock are represented by various model activities, including: subtractions from thinning and harvest, subtractions and additions from area losses and gains, additions from investments in forest management, and additions from regeneration and growth. The growth and yield parameters were derived from various sources including FIA plot data, previous studies, and other resource models.⁸

To interface with the products market in TAMM, forest types in ATLAS are grouped by fiber type, namely hardwoods and softwoods. This is because hardwoods and softwoods have different characteristics and potential uses in products. To satisfy consumer demand, TAMM requests a mix of fiber that meets the needs of product manufacturer's at lowest cost. As prices shift in response to changes in the availability of timber, the system will allow for both a shift in the fiber mix and a shift in harvest to regions or owners where the supply exists and prices are lower.

Several key assumptions underlie the projections. These include: (1) timberland data can be stratified by descriptive variables and then aggregated to the regional scale (multi-state) without significant loss of growth and yield information; (2) as age classes represent broad mixes of actual conditions, the even-age characterization of ATLAS gives way to a multi-age model in which age classes might resemble growth classes; (3) harvest to supply industrial needs in TAMM can be converted via a set of factors into a net removal of hardwood or softwood growing stock from the ATLAS inventories; and (4) timber management intensification practices would actually increase growth and lower the age at which trees become merchantable.

TEM Linkage

Spatially referenced climate outputs of both baseline (continued current climate) and 2XCO₂ projections were input to TEM. Using data on climate, soils, and vegetation,

⁶See the 1989 RPA Timber Assessment for further details (Haynes 1990).

⁷The ATLAS system evolved from earlier work by Beuter, Johnson, and Scheurman (1976) and Tedder, LaMont, and Kincaid (1987).

TEM produced projections of net primary productivity (NPP) for vegetation assumed in equilibrium with climate for both the baseline and 2XCO₂ projections. The percent change in NPP that occurred between the baseline and 2XCO₂ projection was calculated across 7 forest ecosystems (aggregations of Kuchler types, 1964) that were matched to the RPA forest types in ATLAS. The key linkage assumption was that of a one-to-one relationship between a percent change in NPP and a percent change in the ATLAS calculation of net growing stock growth. There was no specific information available regarding the transition to an equilibrium condition (transient response), so to simplify the analysis a linear rate of change was applied beginning in 1990.

Limitations

This study was a significant first attempt to link the U.S. forest sector to GCM generated climates. Several limitations exist, however, and these are chiefly associated with linking very large and very different models. Differences exist in both the scales at which these models are calibrated and their characterizations of the resource. Regions contain a broad range of habitats and species that were aggregated into forest types and then loosely matched to Kuchler (1964) types. The NPP driven changes in growth did not recognize potential differences based on individual species, site, age, or forest management regimes as represented in ATLAS. Changes in climate, forest productivity, and growth will likely not be linear with respect to time. The lack of a feedback loop among the productivity and process models ignores a myriad of variability in the biogeographical relationships associated with atmospheric CO₂ fluctuations, temperature changes, rainfall patterns, nutrient cycling, and thresholds in growth or site carrying capacity related to the ability of ecosystems to adapt to change.

Future Research

Model refinements, stronger linkages, and broader coverage will increase our ability to examine the market and social effects associated with projected climates. There are several areas where research has been proposed.

- 1) Include all forest lands in projections: public timberlands, other forest not including timberlands, reserved lands, and Alaska. This will also help account for carbon storage.
- 2) Finalize a connection between the Mapped Atmosphere-Plant-Soil System (MAPSS; Neilson 1995) and ATLAS so as to include both climate driven changes in forest productivity the potential redistribution of forest types.
- 3) Link MAPSS to the area models to provide ATLAS with forest area change information that is of greater detail and of broader coverage than is available now.
- 4) Develop a new system to allocate and account for harvest at a finer resolution and include species composition (forest type) changes that may occur as a result of the harvesting.

5) Develop a natural (non-catastrophic) mortality component to account for additional available harvest volume.

6) Explicitly accounting for the catastrophic 'natural' disturbances, fire and pests, preferably related to climate change effects.

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A MODEL FOR ESTIMATING THE U.S. FOREST CARBON BUDGET

Linda S. Heath and Richard A. Birdsey¹

The carbon budget of forest ecosystems of the United States is estimated using a core model, FORCARB, and several subroutines that calculate additional information, including carbon in wood products. FORCARB is tightly linked with the linked model system consisting of TAMM (Adams and Haynes 1980), NAPAP (Ince 1994) and ATLAS (Mills and Kincaid 1992). Through this linkage, FORCARB projects changes in carbon storage in forests and wood products as a function of management of the private timberlands of the United States. Timberland is forest land that is capable of producing industrial wood (currently defined as producing 20 cubic feet per acre per year in natural stands), and that is available for harvest. Approximately 60 percent of the forest land in the conterminous U. S. (Powell and others 1993) is considered timberland. Separate analyses were performed for carbon on publically owned timberland, and any other forest land not meeting the criteria for timberland. The methods are discussed in the following section. Additional details of the assumptions, estimation methods, and models can be found in Birdsey and Heath (1995) and Plantinga and Birdsey (1993).

COMPONENTS OF FOREST CARBON STORAGE

All models partition carbon storage in the forest into four separate components: trees, soil, forest floor, and understory vegetation. The definitions of these components are broad enough to include all sources of organic C in the forest ecosystem. The tree portion includes all aboveground and belowground portions of all live and dead trees, including the merchantable stem, limbs, tops, and cull sections, stump, foliage, bark and rootbark, and coarse tree roots (greater than 2 mm). The soil component includes all organic C in mineral horizons to a depth of 1 m, excluding coarse tree roots. The forest floor includes all dead organic matter above the mineral soil horizons except standing dead trees: litter, humus, and other woody debris. Understory vegetation includes all live vegetation other than live trees.

FORCARB FOR PRIVATE TIMBERLANDS

For private timberlands, profiles of average C storage by age or volume of forest stands were composed for each ecosystem component for forest classes defined by region, forest type, and land use history. Thus, equations were developed to estimate C storage in the forest floor, soil, and understory vegetation for each forest class. These equations were then applied to projections of growing stock inventory and increment, harvested area and volumes, and timberland area obtained from ATLAS. Tree carbon was estimated for aboveground and belowground tree components by multiplying growing stock volume by conversion factors

derived from the national biomass inventory (Cost and others 1990) and estimates of wood density by region and forest type. Climate change effects on forest productivity forecast by the TEM model (McGuire and others 1992) were reflected in FORCARB through growth and inventory changes projected by ATLAS linked to TEM. Climate change effects on other ecosystem components (forest floor, soil, and understory vegetation) are not calculated at this time due to the uncertainty in response of soils.

OTHER FOREST LANDS

For public lands, changes in forest inventories are estimated using an inventory model not linked to the system of TAMM, NAPAP, and ATLAS models. Planned harvest levels, treated exogenously in the economic models, were assumed to be realized on lands not reserved from timber harvest. Changes in forest inventories were then converted to C estimates using conversion factors listed in Birdsey (1992). For lands reserved from timber harvest, a model was developed using average age-class distributions, stand profiles, and total area in reserved status.

CARBON IN WOOD PRODUCTS

The C pools of wood from projected harvests on both private and public lands were estimated with a model based on the work of Row and Phelps (1991). Carbon from forest harvests before 1980 were estimated using a similar method in Heath and others (1996). There are four disposition categories: products, landfills, energy, and emissions. Products are goods manufactured or processed from wood, including lumber and plywood for housing and furniture, and paper for packaging and newsprint. Landfills store C as discarded products that eventually decompose, releasing C as emissions. Emissions also include C from wood burned without generation of usable energy, and from decomposing wood. Energy is a separate category from emissions because wood used for energy may be a substitute for fossil fuels.

RESEARCH UNDERWAY

Future work with FORCARB includes: model development and linkages, parameter estimation, accounting system, and model application to all forest lands of the United States. Currently, the model is being updated and restructured to partition forest ecosystems into different pools. Figure 1 illustrates the pools planned for the updated model.

We are updating estimates of carbon quantities in each of the pools, and changes in carbon storage and flux due to forest succession, forest management, and natural disturbance. Previous analyses and reviews of methodology have uncovered sources of uncertainty in estimating conversion factors and other parameters. Updating these estimates is an ongoing process. We have initiated several research studies to improve estimates of carbon in coarse

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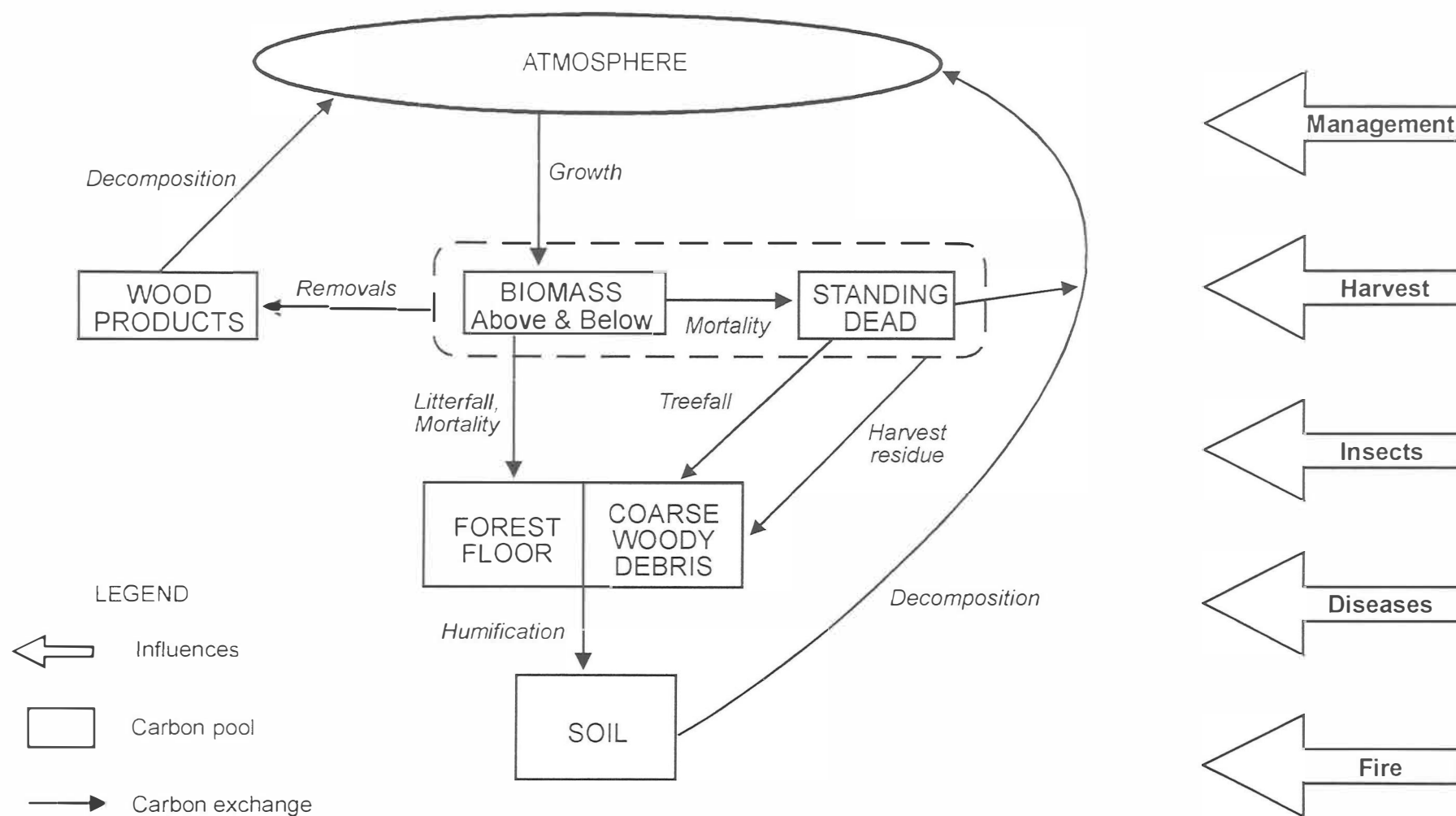


Figure 1.—Conceptual model of the net carbon budget of United States forest ecosystems.

woody debris, soil, and harvested wood, as impacted by various management activities, land use changes, and natural disturbances.

The model framework will be expanded to include public timberlands, and other forest land will be included to the extent that information is available. A separate carbon budget model is being developed to cover lands in Alaska.

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CARBON CYCLING THROUGH WOOD AND PAPER PRODUCTS

Ken Skog¹

After wood is harvested and leaves forests, much of it is held in products and landfills for a long period of time. Eventually almost all of the C in wood and paper products is released to the atmosphere as CO₂ or methane (CH₄) by burning or decay.

Research at the Forest Products Laboratory has prepared historical estimates and long range projections of the net annual accumulation of C in wood and paper products, in landfills, and in emissions of CO₂ and CH₄ from burning and decay.

Two models track the disposition of C in all roundwood harvested from the continental United States; plus imports of logs, wood products and paper products; minus exports of logs, wood products and paper products. A spreadsheet model makes historical estimates from 1909 through 1986. Projections are made from 1987 through 2040 by the WOODCARB model.

Historical data on wood harvest and end use from 1909 through 1986 are from U.S. Forest Service surveys and estimates. Historical wood use is tracked through 1986 to end uses and dumps or landfills (Nicholson, 1995).

The WOODCARB model tracks C from roundwood removal, through production of primary products and generation of residue (and its use for products or fuel) through end uses (e.g., housing or newsprint) to burning or landfills (dumps prior to the 1970's) and decay and release from landfills as CO₂ or CH₄. The model tracks C in all timber removed from U.S. land plus C in net imports of logs, and wood and paper products.

WOODCARB tracks both historical and projected removals and net imports of C. Projections are made by the NAPAP and TAMM/ATLAS forest sector models. The North American Pulp and Paper Model (NAPAP) simulates operation of markets and projects consumption of pulpwood; use and change of processing technology; and consumption of pulp and paper. It projects consumption of hardwood and softwood pulpwood, 4 categories of recycled paper, and production and trade of 13 categories of pulp and paper. TAMM and the ATLAS timber inventory projection model simulate the operation of solidwood markets and project consumption of timber, production of lumber and panel products, end use of lumber and panels in construction, manufacturing, shipping, and other end uses. TAMM also tracks imports and exports of logs, lumber and panels. The ATLAS model uses NAPAP and TAMM calculations of timber removals to project U.S. forest inventory.

Historical information, and projections from NAPAP and TAMM/ATLAS are processed by the WOODCARB model to estimate the following amounts through 2040:

- 1) net C sequestered in products in use each year,

- 2) net C sequestered in landfills/dumps each year,
- 3) carbon released by burning and energy production each year,
- 4) carbon released by decay or burning without energy each year.

A key element of the research for the C cycling model was estimating the extent and rate of decay of wood and paper in dumps and landfills. Prior to 1972 most materials were placed in dumps where a proportion was burned, and the contents were more exposed to oxygen so decayed more completely.

Legislation required that dumps be phased out by 1986. Since then, all materials are placed in landfills. Materials in landfills are periodically sealed so no additional oxygen can be added. For dumps we estimate that 65 percent of waste was burned either intentionally or unintentionally through spontaneous fires. We assume the remaining waste decayed evenly over a 96 year period with a greater proportion of C being released as CO₂ rather as opposed to CH₄ to due a greater mix of oxygen with the materials.

The pattern of decay of wood and paper is markedly different for landfills. A relatively short time after material is placed in landfill, a cover of material is placed over it and oxygen is sealed out. While oxygen is available, brown rot fungus can act to decay lignin to a limited degree, but the oxygen is used up rapidly. After the oxygen is gone only anaerobic bacteria are present. Anaerobic bacteria can break down exposed cellulose and hemicellulose, but not lignin. To the extent that cellulose or hemicellulose are enclosed in lignin, anaerobic bacteria cannot reach them. This means there is very little decay of solid wood. Newsprint with a lignin content of 20-27 percent is also very resistant. Other papers with less lignin can decay somewhat more. But in general, much less than half of C in wood or paper is ever converted to CO₂ or CH₄ (Micales and Skog, forthcoming).

In 1990, U.S. roundwood harvest, plus imports, minus exports held about 145 Tg of C. Using the USFS 1993 RPA Timber Assessment base case projections, this increases to 209 Tg by 2040. Preliminary results indicate net sequestration of 60 Tg of C in products and landfills in 1990. This increases to about 70 Tg by 2040 (Skog and Nicholson, in preparation).

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THE MAPSS MODEL

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MAPSS (Mapped Atmosphere-Plant-Soil System) is a global biogeography model that simulates the potential natural vegetation that can be supported at any upland site in the world under a long-term steady-state climate. MAPSS operates on the fundamental principle that ecosystems will tend to maximize the leaf area that can be supported at a site by available soil moisture or energy (Woodward 1987, Neilson et al. 1989, Neilson 1993a, Neilson 1995).

CONCEPTUAL FRAMEWORK

The conceptual framework for this approach is that vegetation distributions are, in general, constrained by either the availability of water in relation to transpirational demands or the availability of energy for growth (Neilson and Wullstein 1983, Neilson et al. 1989, Stephenson 1990, Woodward 1987). In temperate latitudes water is the primary constraint, while at high latitudes energy is the primary constraint (exceptions occur, of course, particularly in some areas that may be nutrient limited). The energy constraints on vegetation type and leaf area index (LAI) are currently modeled in MAPSS using a growing degree day algorithm as a surrogate for net radiation (e.g. Botkin et al. 1972, Shugart 1984).

The model calculates the leaf area index of both woody and grass life forms (trees or shrubs, but not both) in competition for both light and water, while maintaining a site water balance consistent with observed runoff (Neilson 1995). Water in the surface layer is apportioned to the two life forms in relation to their relative LAIs and stomatal conductances, i.e., canopy conductance, while woody vegetation alone has access to deeper soil water.

Biomes are not explicitly simulated in MAPSS. Rather, the model simulates the distribution of vegetation lifeforms (tree, shrub, grass), the dominant leaf form (broadleaf, needleleaf), leaf phenology (evergreen, deciduous), thermal tolerances, and vegetation density (LAI). These characteristics are then combined into a vegetation classification consistent with the biome level (Neilson 1995).

MODEL WORKINGS

The principal features of the MAPSS model include algorithms for:

- 1) formation and melt of snow,
- 2) interception and evaporation of rainfall,
- 3) infiltration and percolation of rainfall and snowmelt through three soil layers,
- 4) runoff,
- 5) transpiration based on LAI and stomatal conductance,

- 6) biophysical 'rules' for leaf form and phenology,
- 7) iterative calculation of LAI, and
- 8) assembly rules for vegetation classification.

Infiltration, and saturated and unsaturated percolation, are represented by an analog of Darcy's Law specifically calibrated to a monthly time step. Water holding capacities at saturation, field potential, and wilting point are calculated from soil texture, as are soil water retention curves (Saxton et al. 1986). Transpiration is driven by potential evapotranspiration (PET) as calculated by an aerodynamic turbulent transfer model based upon Brutsaert's (1982) ABL model (Marks and Dozier 1992, Marks 1990), with actual transpiration being constrained by soil water, leaf area, and stomatal conductance. Stomatal conductance is modulated as a function of PET (a surrogate for vapor pressure deficit) and soil water content (Denmead and Shaw 1962). Canopy conductance (i.e., actual transpiration) is an exponential function of LAI, modulated by stomatal conductance.

Elevated CO₂ can affect vegetation responses to climate change through changes in carbon fixation and water-use-efficiency (WUE, carbon atoms fixed per water molecule transpired). The WUE effect is often noted as a reduction in stomatal conductance (Eamus 1991). Since MAPSS simulates carbon indirectly (through LAI), a WUE effect can be imparted directly as a change in stomatal conductance, which results in increased LAI (carbon stocks) and usually a small decrease in transpiration per unit land area.

MAPSS has been implemented at a 10 km resolution over the continental U.S. and at a 0.5° resolution globally (Neilson 1995, Neilson 1993a, Neilson and Marks 1994). The model has been partially validated within the U.S. and globally with respect to simulated vegetation distribution, LAI, and runoff (Neilson 1993a, Neilson 1995, Neilson and Marks 1994). MAPSS has also been implemented at the watershed scale (MAPSS-W, 200 m resolution) via a partial hybridization with a distributed catchment hydrology model (Daly 1994, Wigmosta 1994).

THE FUTURE

One fundamental objective of MAPSS is to build the linkages between biogeography and biogeochemistry models using the MAPSS biogeography model and three biogeochemistry models, in order to allow transient dynamics. Additional development is proposed for process-based succession, disturbance (primarily fire) and lifeform-based competition. Also, spatial and temporal scaling issues, largely ignored under steady-state simulations, will become of paramount importance for transient simulations over large areas. Other critical issues are land-use simulation and dispersal.

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The goals are:

1. Re-engineer MAPSS for fully transient operation, allowing time-dependent simulation of actual vegetation dynamics, carbon balance, and succession under altered climate, land-use and disturbance regimes.
2. Develop an interface for analysis of alternative land management strategies.
3. Further advance the theoretical biophysics and observations with regard to canopy-atmosphere coupling to insure appropriate process simulation within the MAPSS model and its sensitivity to a rapidly changing climate. Build the theory and technology to link the MAPSS model to a GCM while accounting for the disparate temporal and spatial scales normally required for simulating atmospheric and vegetation processes.
4. Develop scaling technology to reduce uncertainties in shifting from high resolution, landscape simulations to low resolution, regional and continental-scale simulations. Coupling MAPSS to more process-based hydrologic models at fine and coarse scales will be required, as will the development of process-based disturbance (primarily fire and wind) simulation at fine and coarse scales.
5. Link the MAPSS model with economic, supply and demand models of land-use change such as TAMM/ATLAS.
6. Assist in the development of regional, continental and global transient climate datasets, of both observed and potential future climates.

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INSECT HERBIVORE DISTURBANCE MODELS

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Insect herbivory is an important component of forest dynamics that is not addressed in current forest assessment modeling. Outbreaks of moth and sawfly defoliators and bark beetles may cause extensive changes in forests, resulting in impacts on growth, changes in species composition, and tree mortality. The goal of this work is to develop models for examining the spatial and temporal effects of insect herbivory on forest dynamics at the national level.

A general prediction for change in the range and spatial pattern of insect outbreaks under greenhouse warming is the movement toward higher latitudes and higher elevations. The modeling of such geographical change entails three basic processes: production of maps of insect outbreak distributions, as assessed by visible impacts, and of environmental variables, such as temperature, precipitation, and the presence of a susceptible forest type; development of a model to predict the occurrence of outbreaks as dependent on values of the environmental variables; and extrapolation of spatial changes in the occurrence of outbreaks by applying the model under potential environmental change scenarios. Previous investigations of the effects of climate change on spatial distributions of forest insects have been of relatively narrow scope, focusing on two insect defoliators in just two U.S. states.

Our studies used maps of historical defoliation, climatic variables, and susceptible forest type in a geographic information system. Potential changes in the spatial distribution of outbreaks were investigated for the western spruce budworm, *Choristoneura occidentalis*, in Oregon and the gypsy moth, *Lymantria dispar*, in Pennsylvania (Williams and Liebhold 1995a,b,c). Maps of defoliation frequency were assembled from historical aerial survey data. Weather maps for monthly temperature and precipitation were developed by interpolation of long-term weather station data. Statistical relationships (that is, discriminant functions) were estimated between defoliation and the environmental variables. These relationships were used to extrapolate potential changes in areas defoliated under several scenarios of climate change after the changes had taken place and an equilibrium was reached in the forest and defoliator distributions. Given the slow growth and migration rates of trees, the time frame of the scenarios was on the order of several centuries. Although susceptible forest types were incorporated in the model, their distributions were not changed in developing the scenarios. With an increase in temperature (+2°C), the projected defoliated area decreased relative to ambient conditions for the budworm and increased slightly for the gypsy moth. With increases in temperature (+2°C) and precipitation (+0.5 mm

per day), the defoliated area increased for both species. Conversely, the defoliated area decreased for both species when temperature increased (+2°C) and precipitation decreased (-0.5 mm per day). Scenarios from two general circulation models (GCM) of climate change also were investigated. The results for the two species and models contrasted sharply, predicting complete or nearly complete defoliation for one GCM and no defoliation for the other. Spatial changes in defoliation patterns were interpreted in terms of simultaneous shifts in the ranges of both defoliator populations and susceptible forest types.

The number of insect species and the geographical scope are appreciably wider in the work in progress. Species under investigation include the gypsy moth, spruce budworm, western spruce budworm, southern pine beetle, and mountain pine beetle. Considered together, they produce some of the most widespread and devastating disturbances in U.S. forests. The spatial and temporal dynamics of these species are being investigated across their historical ranges of distribution in the conterminous United States. Figures 1 and 2 show the distribution for the two spruce budworm species. For each grid cell, the frequency maps show the proportion of years with detectable defoliation (that is, greater than 30 percent) as observed in aerial surveys from 1954 to 1980 for the spruce budworm (Fig. 1) and 1977 to 1992 for the western spruce budworm (Fig. 2). For the analyses used to generate climate change scenarios (discussed earlier), the maps are simplified to a binomial scheme with grid cells in one of two possible states: those that were defoliated at least once and those never defoliated.

Correlating the effects of observed outbreak impacts, such as defoliation, with changes in tree growth and mortality rates is essential to developing a disturbance model for linkage with models of forest dynamics. Accordingly, relationships between outbreak frequency and tree mortality and growth reduction are being estimated using published literature and available data. These relationships predict the probability of mortality or the proportion of growth lost as a function of historical outbreak frequency. They will be superimposed on the frequency maps to project areas experiencing varying levels of mortality or growth change that can be used as the basis for other scenarios of climate change.

In addition to spatial modeling, we have used time series analysis and modeling to investigate relationships between insect population dynamics and weather. A theoretical study by Williams and Liebhold (1995d) explored the effects of changing weather and general predation on the detection of delayed density dependence, a major factor in the regulation of animal populations. Changing temporal patterns and variability of weather are anticipated as the climate changes, and such changes may have significant impacts on our interpretation of the factors that influence population dynamics. A second study that investigated the effects of weather on regional outbreaks of gypsy moth in New

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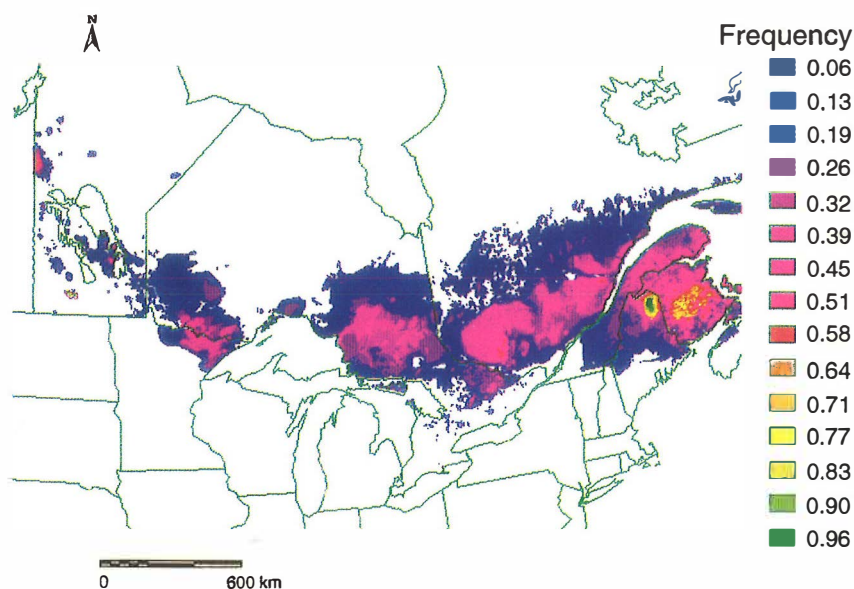


Figure 1.—Frequency of aerially detectable defoliation by spruce budworm in Eastern North America, 1954-80.

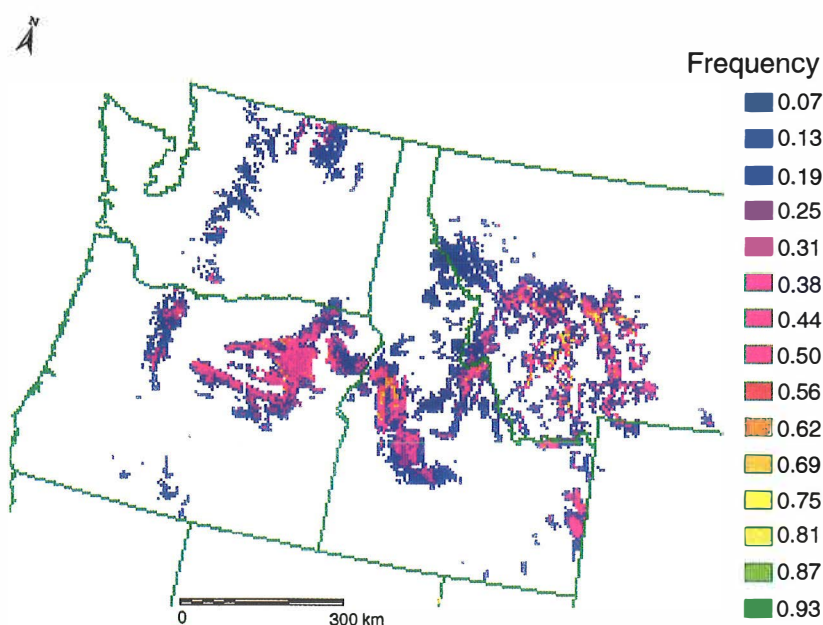


Figure 2.—Frequency of aerially detectable defoliation by western spruce budworm in Washington, Oregon, Idaho, and Montana, 1977-92.

England (Williams and Liebhold 1995e) explored the role of common weather over the region in synchronizing local populations to produce the areawide outbreaks generally observed for gypsy moth.

In continuing investigations, time series models of outbreaks by the five insect species are being developed. Models of outbreaks that include the effects of time lags are fitted using standard techniques from time series analysis. Developed for individual species at the state and regional levels, such models will predict pest impact annually based on observed impacts in previous years. We also are using geostatistics and spatial time series analysis to investigate the spatial development and synchrony of outbreaks over time.

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MODELS OF REGENERATION, TREE GROWTH, AND CURRENT AND POTENTIAL RANGES OF TREE AND MAMMAL SPECIES IN THE EASTERN U.S.

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We are developing a multi-phase set of models that simulate tree and mammal migration in response to global change. The phases involve:

1. Tree regeneration processes
2. Tree growth and development
3. Potential tree migration rates across a fragmented landscape
4. Current and potential distributions of tree species
5. Current and potential distributions of selected animal species
6. Predicted distribution of tree and selected animal species under global change

TREE REGENERATION PROCESSES

An environmentally responsive, mechanistic regeneration simulator should simulate important ecological relationships and disturbance effects. Development of such a regeneration simulator is complex because of the many attributes that characterize reproductive strategies and the importance of forest history and disturbance in determining the composition of the next forest. We are constructing a model of tree regeneration based on the requirements of different tree species and the potential pathways by which available species might regenerate. This rule-based Mechanistic Origination Model (MOM) combined with a gap-phase model that includes disturbance processes (Phase 2) will be used to predict the migration of tree species for the central hardwood region of the United States, and we will progressively apply the same techniques to other regions (eg., northern hardwoods).

We synthesized information from the forest biology and ecological literature to determine a set of tree-regeneration attributes that would be applicable to a wide range of forest types. These attributes are important in the colonization or revegetation of forests during the gap phase of forest development. Twenty attributes representing flowering, seed production, seed dispersal, seed dormancy, germination, and survival were used to create a matrix of categorical data suitable for classification analysis. We evaluated these attributes for 62 tree species in the central hardwood region of the eastern deciduous forest of North America. We used classification analysis to delineate guilds of species with similar regeneration attributes over a wide range of categories. The guilds represent niches in the central hardwood forests; species within the guilds have similar

regeneration attributes such as dispersal mechanisms, time of flowering, and requirements for germination.

We expected that species within guilds would exhibit similar regeneration behavior and that a guild would have a common pathway through the regeneration process. However, this was not the case. Although species within guilds do have similar regeneration attributes, the regeneration behavior or pathway of a species at a given place and time depends on forest history and type of disturbance that incites a regeneration event. For example, a species may respond differently to overstory removal than to a ground fire. The common element here is not the nature of the species but the characteristics of the disturbance. Stated another way, common pathways by which regeneration occur depend on the disturbance (its effect and scale) and the conditions at the time of disturbance. The pathway by which regeneration and recruitment occur depends on both species attributes and the nature of the disturbance.

The needs of the model were defined by our understanding that common pathways driven by disturbance determine regeneration outcomes. First, we are defining the potential pathways. Then, for each pathway, we are determining the attribute thresholds for species that could follow that pathway. Examples of attribute thresholds include the amount of light at the forest floor and soil and moisture requirements. Finally, to model regeneration, we also must model disturbances since these alter site attributes. In Phase 2, plot status information that MOM requires (eg., quantity of light on the forest floor, seedbed condition, number and species of seed producing trees and number and species of sprouting-capable trees) will be calculated at least each year and after each disturbance event.

TREE GROWTH AND DEVELOPMENT

Phase 1 and Phase 2 are highly interactive, and Phase 2 simulates the growth and development of trees. Several models were evaluated on the basis of whether they were parameterized for the entire United States, their sensitivity to climate change and the ability to predict annual diameter growth and mortality of each tree. The gap model ZELIG was chosen, which relies heavily on monthly climatic conditions and may be easily modified for site specificity. ZELIG has been streamlined by eliminating many of the diagnostic print and screen displays, which will allow the program to update the many thousands of Forest Inventory Analysis (FIA) plots efficiently in Phase 6. We are replacing the REGEN subroutine of ZELIG with MOM to create MOM/Z (Figure 1). For MOM to work in this context, disturbance routines are being added to ZELIG to provide simulations of the many conditions that can stimulate regeneration. Parameters controlling the probable frequencies and intensities of these disturbances are easily modified to simulate different

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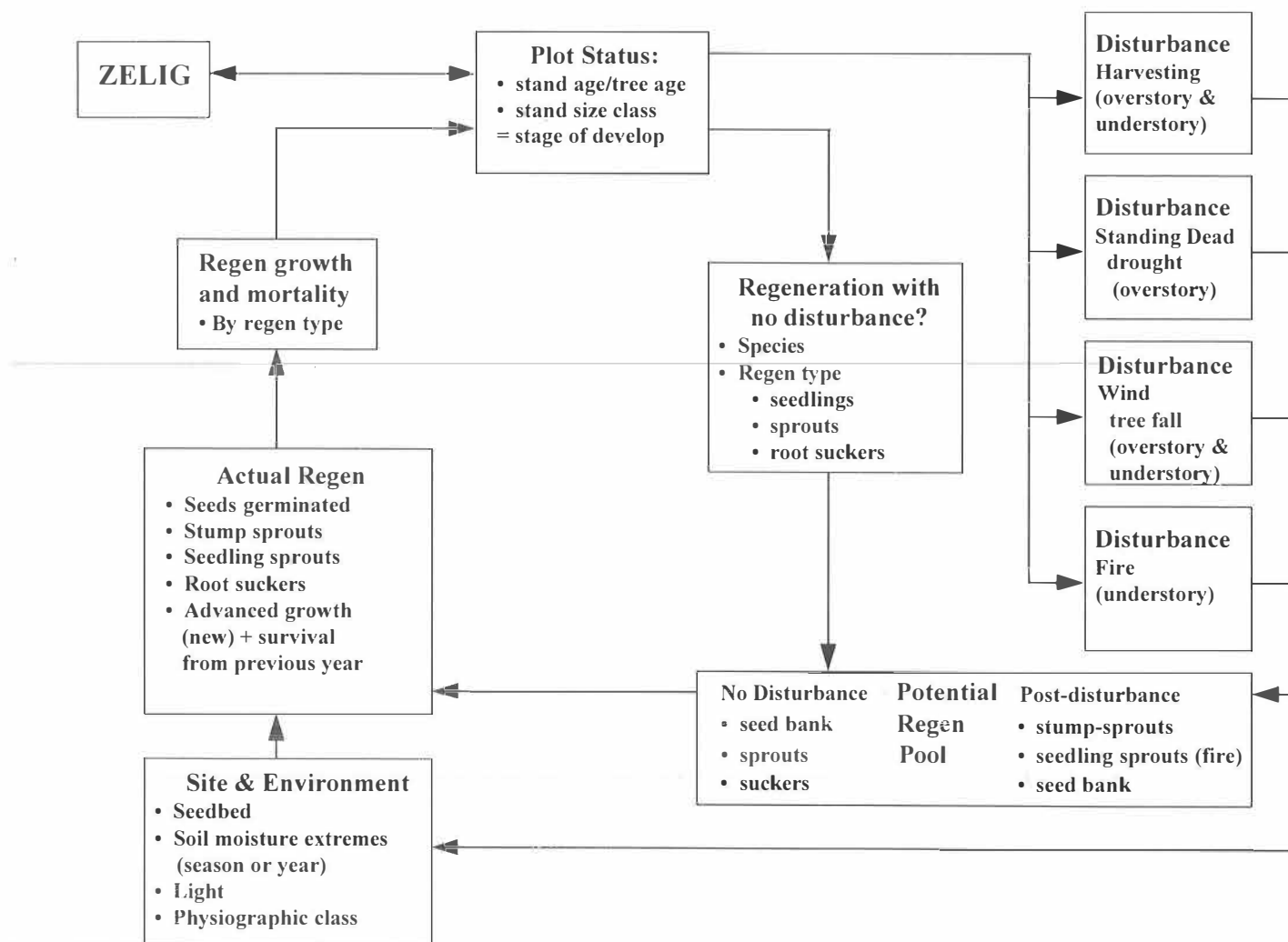


Figure 1.—Flow diagram of the Mechanistic Origination Model (MOM) to be used with the ZELIG gap-phase model modified to simulate disturbance events. ZELIG will provide plot status information that MOM requires (eg., quantity of light on the forest floor, seedbed condition, seed producing trees, sprouting-capable trees) at least each year and also after each disturbance event.

management strategies. We are in the process of adding harvesting, fire, and windthrow disturbance algorithms to the model which are regionally specific. This will facilitate the replacement of ZELIG's recruitment algorithm with the MOM regeneration algorithms. The use of MOM will avoid the unrealistic assumption of gap models that all species are able to regenerate on each site.

POTENTIAL TREE MIGRATION RATES ACROSS A FRAGMENTED LANDSCAPE

In Phase 3, or MYGREAT, we determine maximum tree migration rates in response to a changed climate. Examinations of the relationship between current plant distributions and climate suggest that a northward distributional shift of 400-800 km will be required for many species. Holocene reconstructions of past tree migrations provide a model for how fast trees may be able to respond to

climatic change. These historical studies suggest that trees will not respond at rates of more than 50 km per century, or about an order of magnitude slower than may be required to keep pace with future warming. The historical model, however, may not represent an accurate prediction of future response, because the data generally record trees moving across a mostly forested landscape. The current landscape is much more fragmented, with environmental barriers and a matrix of low quality habitat reducing potential migration rates. We use a simulation model to predict the ability of trees to migrate in response to climatic change under various conditions of habitat availability. The model uses Holocene tree migration rates to approximate maximum migration rates in a forested landscape. Habitat availability and local population size are varied systematically under two dispersal and colonization models. The underlying dispersal models varied in the likelihood of long-distance dispersal. The results of the first model indicate that migration rates could decline

Quercus falcata falcata (S. Red Oak)

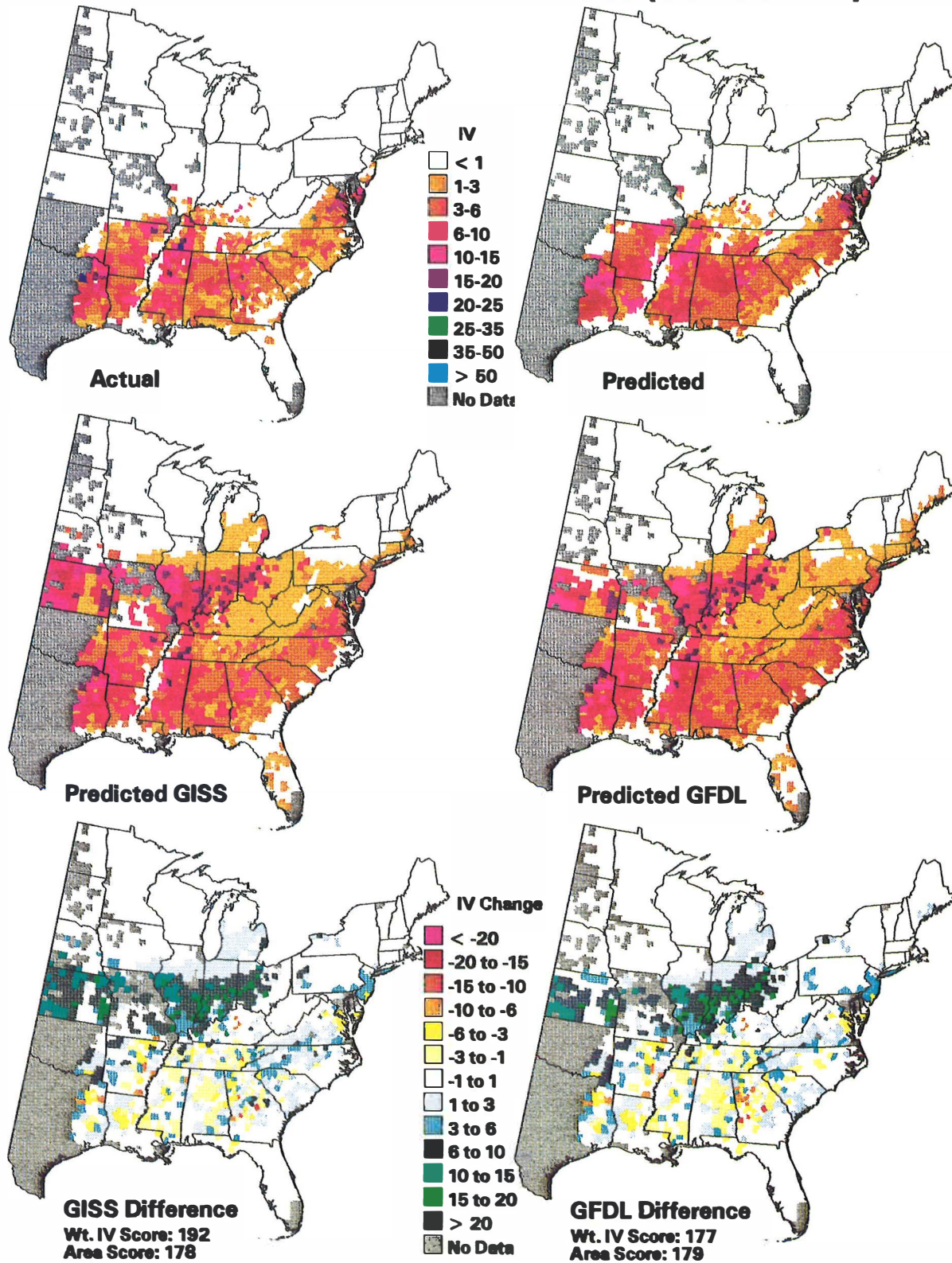


Figure 2.—Example model outputs for *Quercus falcata* var. *falcata* (southern red oak), including: a) actual county importance values as calculated from FIA data; b) predicted current importance values from the RTA model; c) predicted potential future importance values after climate change according to the GISS GCM; d) predicted potential future importance values after climate change according to the GFDL GCM; e) and f) difference maps showing potential change in importance values for the GISS and GFDL maps, respectively.

by an order of magnitude where habitat availability is reduced from 80% to 20% of the landscape. The second model, using an inverse power function, carried a higher probability of long-distance dispersal events. The results from this model predict relatively small declines in migration rates when habitat availability is reduced to 50% of the landscape, but mean migration rates for lesser forest areas are similar to those of the first model. Initial results predict maximum migration rates of 1-10 km per century when habitat availability is less than 30%.

We now are refining the model to run on a real landscape, the state of Ohio, with a cell resolution of 1 km by 1 km. We have computed the percent forest cover by cell with classified Landsat TM data (overall forest cover = 30%), and used this as an indicator of habitat availability for the model. For comparison, we ran the same model with the Ohio landscape as it existed prior to European colonization (overall forest cover > 95%). The model has been run for four species that have their northern limits in Ohio: yellow buckeye, southern red oak, Virginia pine, and persimmon. The fragmented nature of today's forest significantly slows the migration potential, according to the model outputs. The next phase is to revise the model to run at the scale of the Eastern United States.

CURRENT AND POTENTIAL DISTRIBUTIONS OF TREE SPECIES

An envelope analysis of current tree species ranges with environmental variables was needed to establish bounds on the migration and regeneration potentials mentioned above. In Phase 4, the DISTRIB component, we relate current tree distributions to associated environmental variables, and then change the climate to model the potential future tree distributions. Two main assumptions are made for this model: (1) the tree will get there if conditions are suitable, i.e., there are no barriers to migration, and (2) the current distribution defines the range of conditions possible for the species to grow. We have collected, summarized, and analyzed data for climate, soils, land use (including the spatial configuration among land use types), socio-economic factors, and species assemblages for over 2,100 counties east of the 100th meridian. FIA data for over 100,000 forested plots in the East provided the tree species range and importance values information for 103 species of trees. Regression tree analysis (RTA) is being used to devise prediction rules from current species-environment relationships, which are then used to replicate the current distribution as well as predict the future potential distributions under two scenarios of climate change with 2xCO₂ (Figure 2). Validation measures prove the utility of the RTA modeling approach for mapping current tree importance values across large areas, leading to increased

confidence in the future predictions. Although these future predictions do not address the fate of species migrating through fragmented landscapes, they do give an idea of the basic envelope to which the species may be adapted should no restrictions to migration apply. Graphical outputs from RTA, combined with the predicted tree species distribution maps in GIS, provide a powerful means of understanding the relationships among various factors associated with tree species distributions.

CURRENT AND POTENTIAL DISTRIBUTIONS OF SELECTED ANIMAL SPECIES

Paleontologists have dated the presence and location of certain mammal species back to the Pleistocene Epoch (approximately 10,000 - 11,000 years ago). Distribution ranges of species have been formed from this and other paleoenvironmental data to demonstrate range changes using the geologic clock. In Phase 5, habitats are being characterized for 10 of the mammals that have exhibited range changes due to historical changes in the environment and that currently populate OH, KY, IN, and IL. At the county level of scale, we are evaluating relationships between current distribution ranges of the mammals and the current environmental picture which includes the derived importance values of tree species as developed in phase 4. Land use and human population density will be evaluated for spatial patterns across the region that will help to geographically characterize mammal habitat. In an attempt to relate the habitat characterizations of current mammal ranges with historical and potential ranges, we will also factor temperature and precipitation into the analyses. Canonical correspondence analysis was used to relate mammal presence or absence data with the derived environmental factors since no single environmental factor has been shown to characterize mammal habitat.

PREDICTED DISTRIBUTION OF TREE AND SELECTED ANIMAL SPECIES UNDER GLOBAL CHANGE

In Phase 6, the general approach will be to initiate MOM/Z using Forest Inventory Analysis (FIA) plots, and run simulations using local climate estimates derived from mesoscale climate models of 2xCO₂ GCMs. Using these simulations, we will evaluate potential species shifts for each county. This effort, in conjunction with the effort to understand the role of fragmented habitats and potential distributions, will help elucidate likely patterns in tree species migration and associated ranges of mammal species.

CARBON BALANCE OF THE ALASKAN BOREAL FOREST

John Yarie and Tim Hammond¹

Determination of the carbon balance in a broad region like the Alaskan boreal forest requires the development of a number of important environmental classes (state factors) to allow for the estimation of carbon balances. We have used the following state factors to develop a regional classification of the Alaskan boreal forest:

- Mean monthly temperature May through September (Approximate growing season)
- Mean total precipitation May through September
- The domain, division and province levels of the ecoregions classification of Alaska (see Gallant et al. 1995)

In addition the following classifications to further subdivide and describe the boreal forest regions of Alaska are being developed:

- Land Cover is being developed by the USGS EROS field office in Anchorage
- Age structure of the vegetation in the forest areas

A forest dynamics model (GAFED) for the Alaskan boreal forest will be run to determine the effects of anticipated global change on the carbon dynamics within the regions of the biogeoclimatic classification. This approach should result in an accurate representation of the carbon dynamics of the forest within an area of land the size of Alaska.

INTRODUCTION

Calculations of carbon source/sink relationships for large land areas are often based on a simple calculation of the average land area represented by a relatively simple classification of landscape characteristics (e.g., coniferous forest). In this type of calculation, differences in carbon dynamics due to a large number of factors such as topography, soils, differences in climate, or variation in vegetation community types within a region, are not considered. The calculation would only be accurate if an appropriate landscape-weighted average was chosen for the region's carbon factor.

We propose to develop a geographically referenced data set that can be used to define biogeoclimatic groups across Alaska. These groups will then be used to parameterize GAFED and to define specific changes to the climate in the defined regions that are likely to occur due to global change. The model will be designed to work at all levels of spatial resolution, which is one advantage of incorporating it into ARC/INFO. Primary analysis will be developed for individual trees within a stand level of landscape resolution (one

square meter grid cell resolution). The biogeoclimatic classification for the state of Alaska will then be used to summarize stand level work to the landscape level (one hectare or greater grid cell resolution).

The primary milestone at completion of this work will be the development of a carbon balance map for the state of Alaska with current vegetation and average climate conditions. Changes in carbon dynamics can be estimated based on climate scenarios developed from mesoscale climate models. The biogeoclimatic classification should give us the ability to describe the appropriate level of landscape summarization for Alaska.

DEVELOPMENT OF THE STATE FACTOR BIOGEOCLIMATIC CLASSIFICATION

Currently a number of data sets are available for the state of Alaska. A 90 m digital elevation map (DEM) derived from USGS data sources is available. This data set can be used to derive relevant elevation, slope and aspect groupings. This data set has been summarized to 1000 m grid cell size (USGS EROS field office Anchorage) and was used to develop a topographic ARC/INFO coverage for Alaska (Figure 1).

The average climatic zones based on a May through September growing season have been determined using average monthly data sets available from NOAA (world wide web home page; <http://www.ncdc.noaa.gov>).

Work is close to completion on assembling all current vegetation data bases for the state. We will try to summarize this data set at the level IV groups for the Alaska Vegetation Classification (Viereck et al. 1992). The level IV category can be further summarized to broader groupings (e.g., needle-leaf forest, broadleaf forest, etc.) for comparison to datasets derived from other areas of the country. The level IV groupings will also give us the best approach for defining the four primary components of the carbon stores on the landscape. These components are: live and dead trees (above- and belowground), forest floor, mineral soil, and understory vegetation.

Surface temperature and moisture algorithms are being developed for application to daily AVHRR satellite coverage. This data set will give us the ability to validate the mapped climate zones for the state and be useful in determining the accuracy of results from mesoscale climate models. The mesoscale climate model can then be used to derive climate scenarios for the ecosystem forest dynamics model.

Model Structure and Conceptual Basis

The GAFED model is primarily a process model that will use the important limiting factors to drive forest growth and forest

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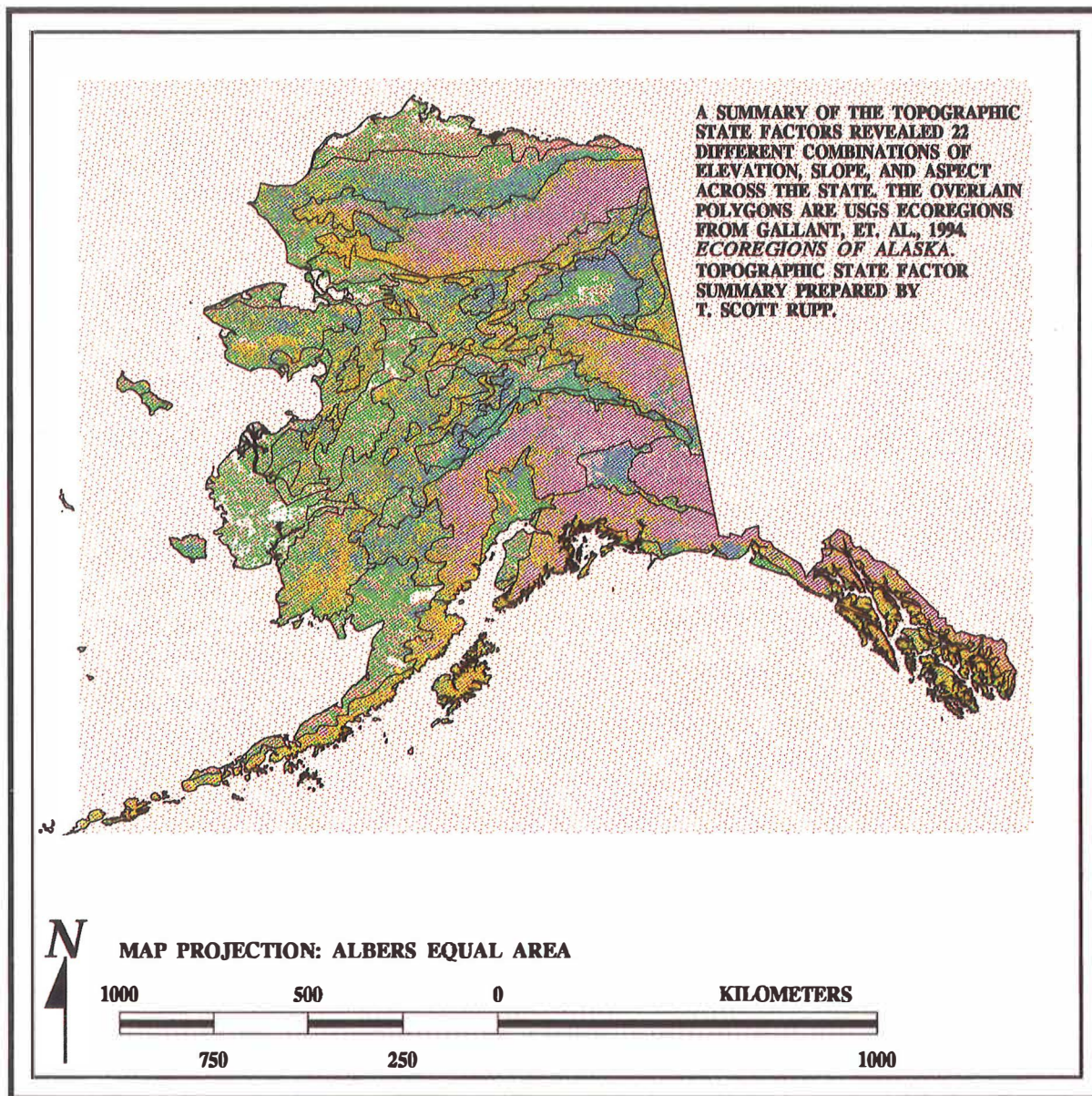


Figure 1.—Distribution of the topography state factor across Alaska. Topography was based on three aspects (none, North 310° to 70°, South 70° to 310°), three slopes (< 5 percent, > 5 percent to 100 percent, > 100 percent) and three elevation (0 to 150 m, 150 m to 750 m, > 750 m) ranges.

floor dynamic routines. The model is being developed as an AML within ARC/INFO GRID. The routines necessary for the model can be developed so that the grid cell size is not a limitation (Table 1). The majority of routines can be applied at either the individual tree (1 m grid cell size) or landscape representation (1 ha or above grid cell size).

Model validation will be carried out by using tree growth, forest floor and mineral soil dynamic variables that have been measured in the Fairbanks area for periods up to 25 years (depending on the variable). There is sufficient information available on tree growth and forest floor dynamics from the Bonanza Creek Long-Term Ecological

Research (LTER) site to evaluate the model behavior for soil temperature, moisture dynamics, carbon and nitrogen turnover, and tree growth across both upland and floodplain successional sequences.

Production

The nitrogen productivity concept (Ågren 1983) is defined as the amount of annual production per unit of foliar nitrogen. At steady state nutrition, the plant's growth rate is proportional to the amount of foliar nitrogen in the plant and the nitrogen productivity. The nitrogen productivity is at a maximum during the exponential growth phase and depends on a number of

Table 1.—Relationship Between Model Routines and Grid Cell Size.

Routines valid across all grid cell sizes	Routines that have cell size dependencies
Production	Litterfall
Decomposition	Regeneration
Climate	Single Tree Mortality
Disturbance by Fire	

plant properties, weather conditions, self-shading and aging. The nitrogen productivity can be calculated for individual seedlings (Ingestad 1979a, 1979b; Ingestad and Kahr 1985) and for stands of trees (Ågren 1983) as the calculation parameters are not specific for the size of the geographic unit. Therefore, it should be possible to use equation 2 for calculating the nitrogen productivity for a single tree and a stand of trees.

DEVELOPMENT OF NITROGEN PRODUCTIVITY CURVE

Individual Trees

The nitrogen productivity of individual trees within a stand was calculated using the 1989 tree chemistry and aboveground production dataset from the Bonanza Creek Experimental Forest (BNZ) LTER program (see the BNZ-LTER World Wide Web home page at <http://www.lter.alaska.edu>). A total of 239 white spruce, 21 aspen, 54 birch, and 107 balsam poplar trees were available. Because we were trying to estimate the maximum N-productivity for individual trees, 37 white spruce, 12 aspen, 8 birch, and 15 balsam poplar were selected for analysis. Individual tree N-productivity was then calculated by dividing the aboveground annual production by the aboveground foliar nitrogen content.

The comparative analysis between trees and stands was handled by placing all estimates of N-productivity and foliar nitrogen content on a simple unit area basis. The space occupancy of each individual tree was based on a calculation of tree density of a fully stocked stand if the diameter of the sample tree was the average diameter of the stand (Yarie 1983). The chemical analysis of the foliar material was performed as described by Yarie and Van Cleve (1996).

Stand Level

Calculation of the nitrogen productivity of stands of trees was based on data sets from Van Cleve et al. (1983) and the USFS Inventory of the Porcupine River Drainage (Setzer 1987, Yarie 1983). None of these stands contained any of the trees used for the individual tree calculations. The stands represented independent measurements of the nitrogen content and nitrogen productivity. The foliage quantity per unit area for each stand was again reduced to a one meter square basis.

Results indicate that the nitrogen productivity of trees and stands within interior Alaska can be estimated using a single

equation (figure 2). The model was able to predict the growth of white spruce and birch in an old-growth white spruce forest on the floodplain in interior Alaska. Diameter growth for white spruce between 1989 and 1993 averaged 0.9 cm. The model predicted an average of 1.1 cm for the same time period. Total biomass growth for the modeled tree species in this site was approximately 270 g/m². The aboveground portion was then approximately 135 g/m² which has been measured in other forest stands in interior Alaska (Yarie and Van Cleve 1983).

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Nitrogen Productivity (nprod)

$$\text{nprod} = 128.55 - 0.0413 \cdot \text{foliage}; \quad r^{**2} = 0.678$$

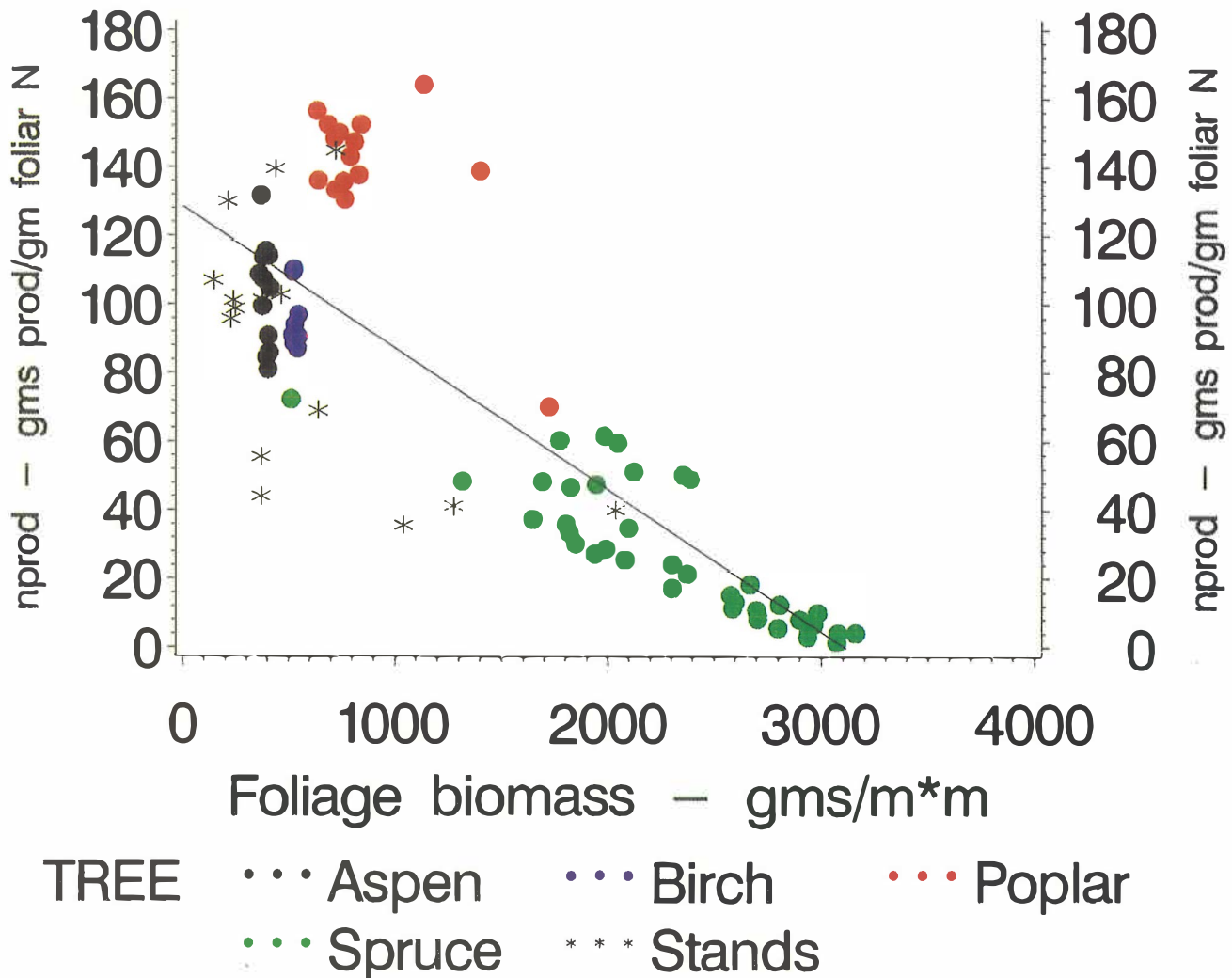


Figure 2.—Individual tree and stand nitrogen productivity relationship to foliar nitrogen quantity per square meter of surface area.

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Summarizes research findings of the USDA Forest Service's Global Change Research Program. Research highlights are presented at national and regional scales within the following topic areas: atmosphere/biosphere gas and energy exchange; ecosystem dynamics; disturbance ecology; and human activities and natural resource interactions. Selected topics are reviewed in depth with individual papers covering the global carbon cycle, climate scenarios, multiple stress studies, changes in vegetation distribution, the United States carbon budget, and the human dimensions of global change. Also included is a progress report on development of an integrated national model of the effects of global change on forests and people.



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