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Global Change Research Program Highlights: 1991-95

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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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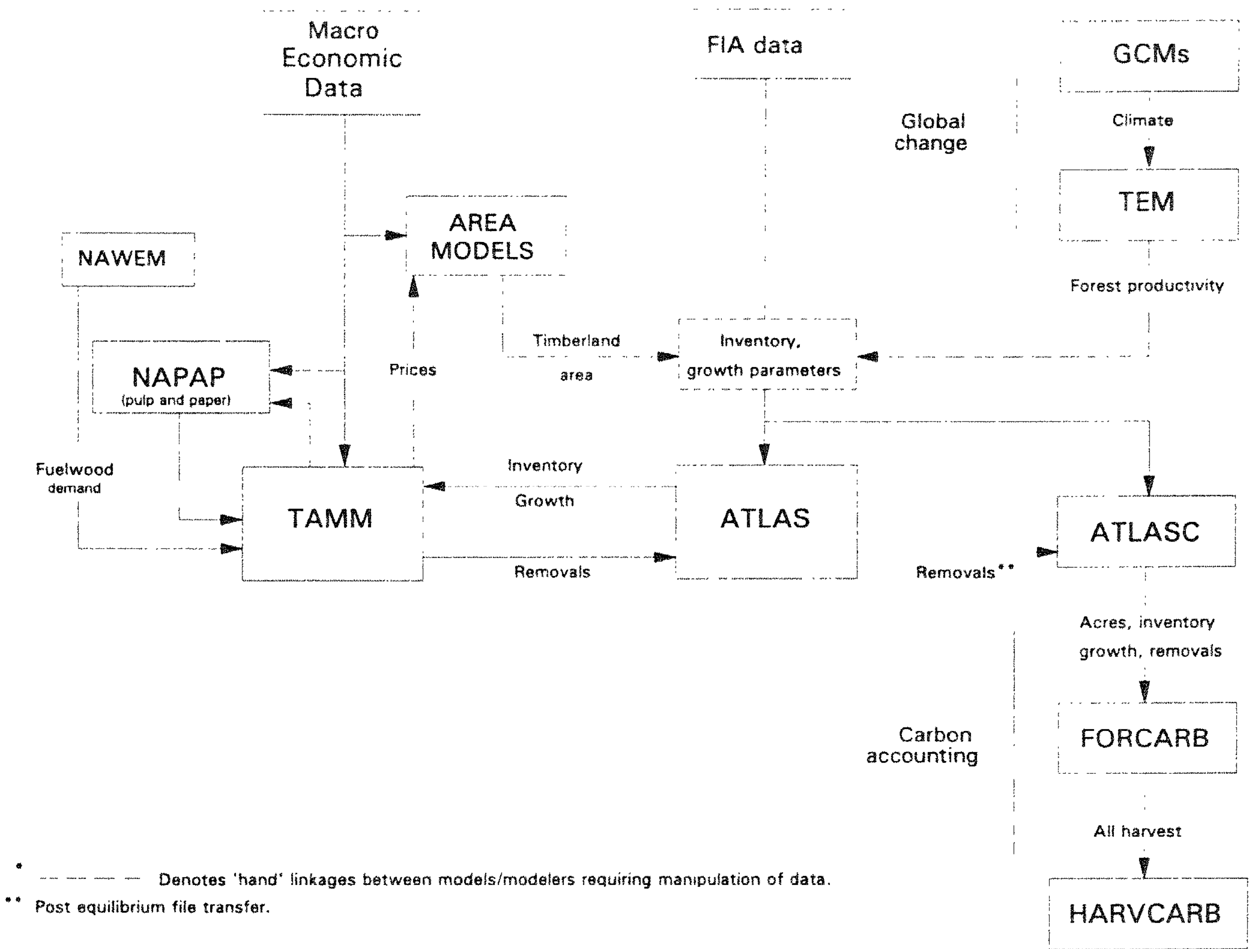

Figure 1.—Modeling system as used in the 1993 RPA Assessment Update.

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 CO_2, 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?

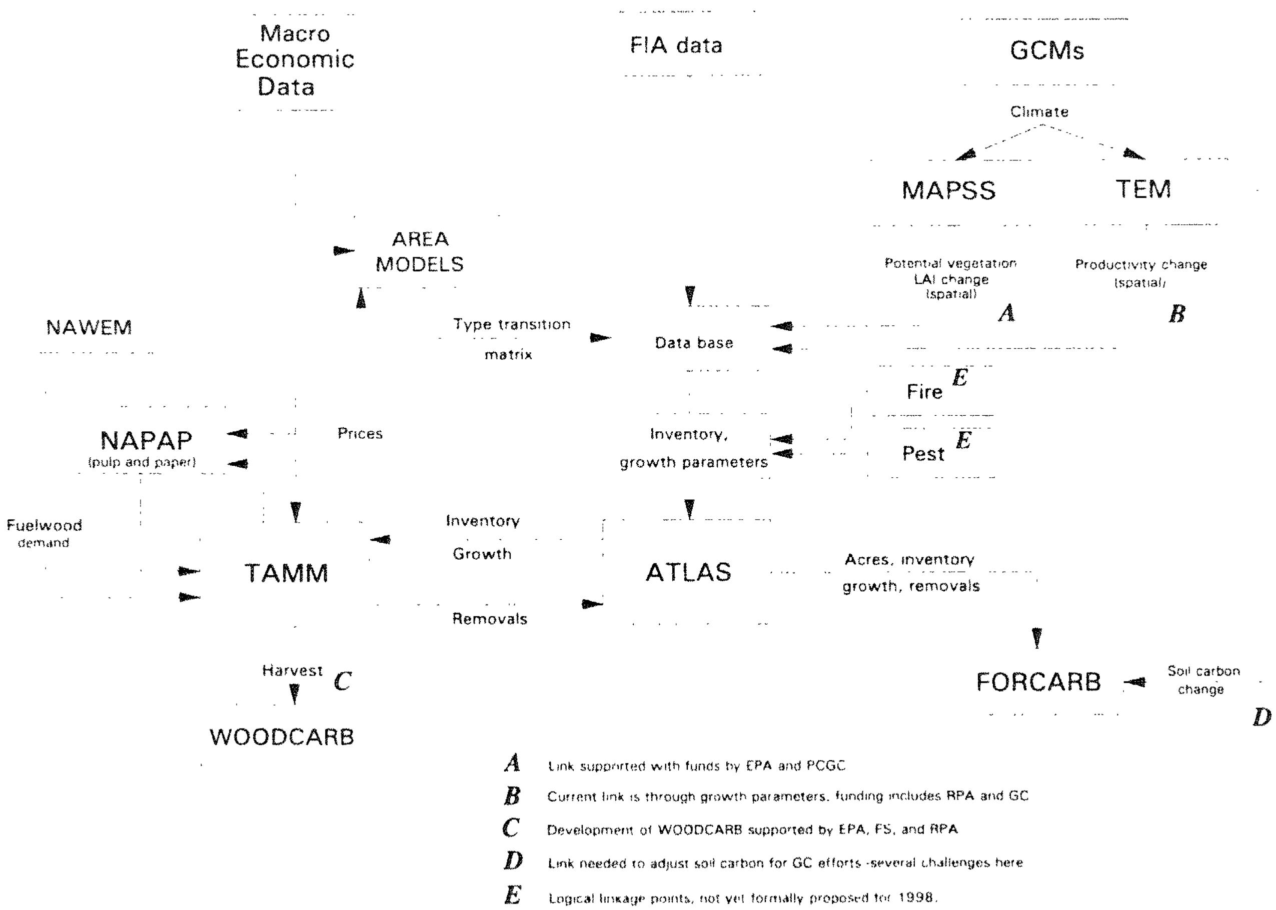

Figure 2.—Modeling system proposed for the 1998 RPA and GC Assessments.

Carbon Budget

What are the opportunities and costs of emissions mitigation using forest ecosystem management and forest products technologies?

What are the impacts of changes in disturbance regimes for fire and insects on atmospheric CO_2?

Human Interactions

What are the interactions between climate change effects and land management scenarios, harvest and regeneration alternatives, and land use/cover alternatives?

How might society adapt to the effects of global change on forests?

SCENARIOS FOR THE 1998 GLOBAL CHANGE ASSESSMENT

Climate, air pollution, and management scenarios are all under consideration as part of the integrated modeling effort. We have convened a climate scenario task force and cooperated with other Agencies and global change researchers to identify the best available continental-scale climate scenarios for the national modeling effort. Several efforts are underway within the regional programs to develop air pollution scenarios, and we are identifying national-scale efforts by the EPA. We intend to work within the RPA process to analyze broad management scenarios as developed for the 1998 RPA assessment. These management scenarios are issue-oriented, and may include climate change mitigation and/or adaptation actions such as outlined in the President's Climate Change Action Plan.

Our overall analytical design is a 2-stage process where various scenarios are tested with a subset of the integrated modelling system, and then a subset of the tested scenarios is selected for analysis with the whole integrated system using a complete or partial factorial design.

Climate scenarios

We intend to include some of the variability in projected climate by using the results of 2 or more General Circulation Models (GCMs), by comparing transient vs. equilibrium model outputs, and by comparing GCM results that are based on different levels of expected atmospheric CO_2. We will rely on analysis of climate scenarios for the VEMAP 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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VEMAP Members (J. M. Melillo, J. Borchers, J. Chaney, H. Fisher, S. Fox, A. Haxeltine, A. Janetos, D. W. Kicklighter, T. G. F. Kittel, A. D. McGuire, R. McKeown, R. Neilson, R. Nemani, D. S. Ojima, T. Painter, Y. Pan, W. J. Parton, L. Pierce, L. Pitelka, C. Prentice, B. Rizzo, N. A. Rosenbloom, S. Running, D. S. Schimel, S. Sitch, T. Smith, I. Woodward). 1995. **Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling.** Global Biogeochemical Cycles. 9(4): 407-437.

PRODUCTIVITY OF AMERICA'S FORESTS AND CLIMATE CHANGE

Linda A. Joyce[1]

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 affects 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 $m^{-2}yr^{-1}$ for boreal forests to 1113 gC $m^{-2}yr^{-1}$ 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 CO_2 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 (CO_2) (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 CO_2 the responses differed qualitatively in all regions between the models. With no change in temperature and an elevated CO_2 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 CO_2 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 CO_2 (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 CO_2 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

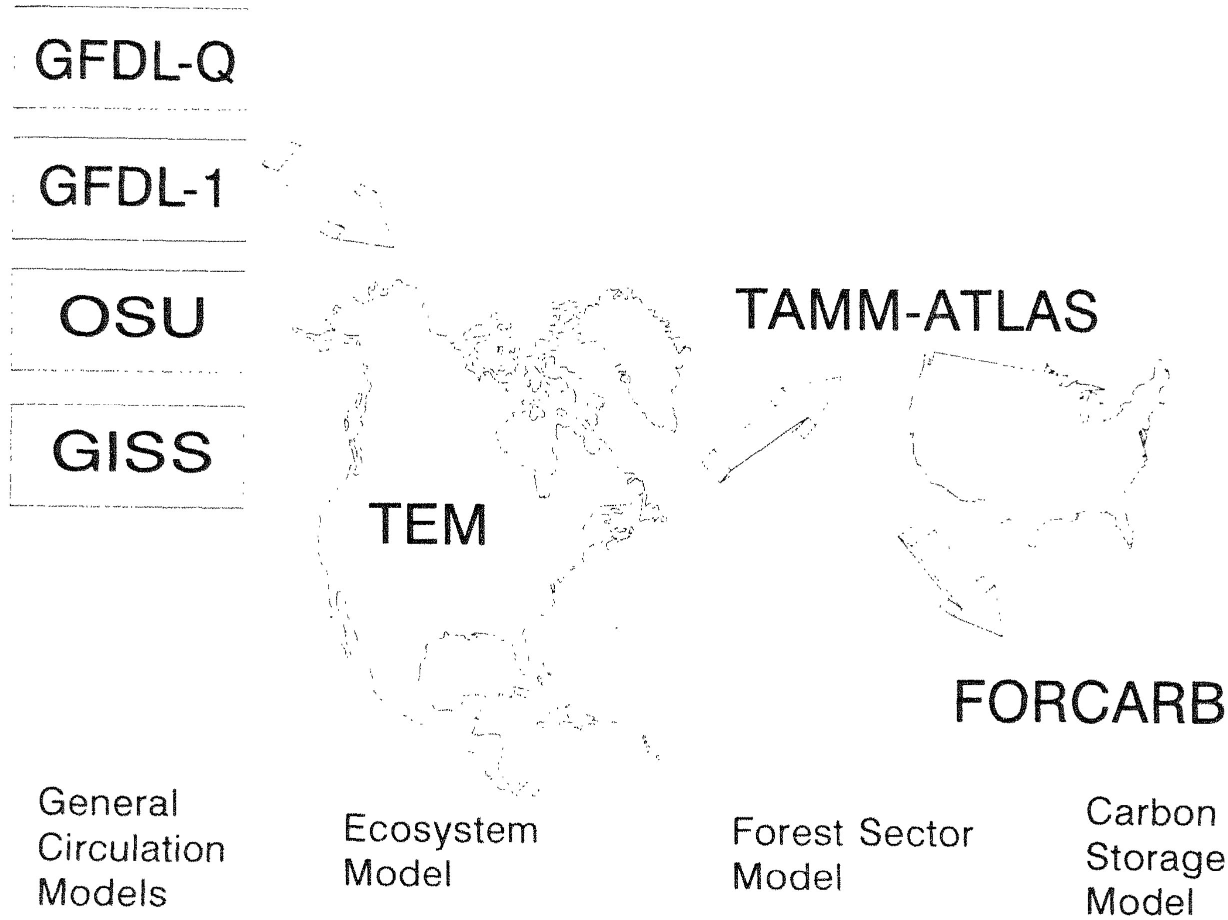

Figure 1.—Schema for analysis of climate change impacts on the forest sector: the Terrestrial Ecosystem Model (TEM), the Aggregate Timberland Assessment Model (ATLAS), the Timber Assessment Market Model (TAMM), and the Forest Carbon Model (FORCARB). The general circulation models are: GFDL-1 and GFDL-Q, 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.

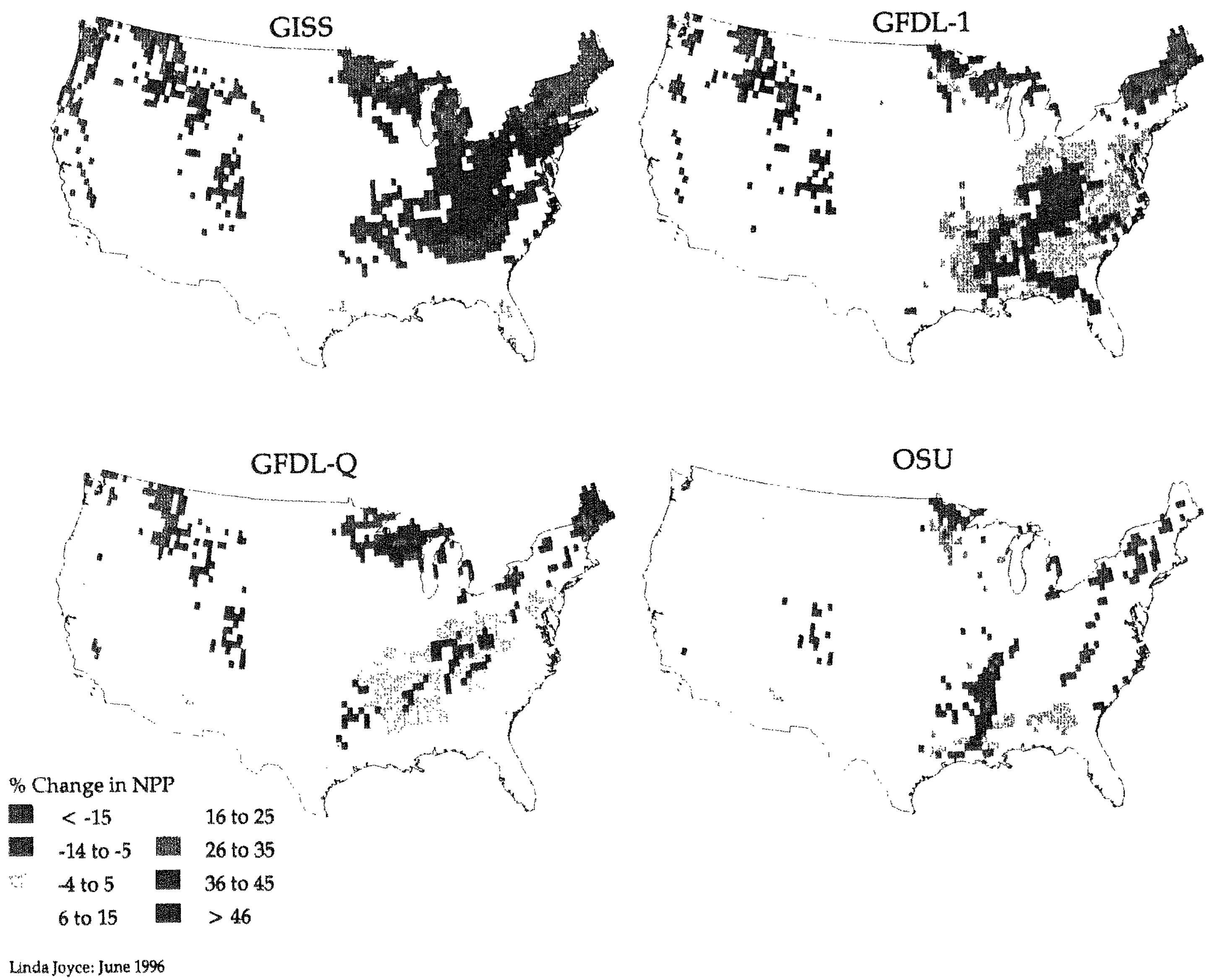

Figure 2.—Percent differences in net primary productivity from the baseline run (contemporary climate) and the four general circulation model scenarios. The general circulation models are: GFDL-1 and GFDL-Q, Geophysical Fluid Dynamics Lab, GISS, Goddard Institute for Space Studies, and OSU, Oregon State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

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 ($2XCO_2$). It was assumed $2XCO_2$ 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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[2]A 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).

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

[4]Areas 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.

[5]Public 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 scales[7]. 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.[6]

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 $2XCO_2$ projections were input to TEM. Using data on climate, soils, and vegetation,

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

[7]The 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 $2XCO_2$ projections. The percent change in NPP that occurred between the baseline and $2XCO_2$ 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 CO_2 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. Birdsey[1]

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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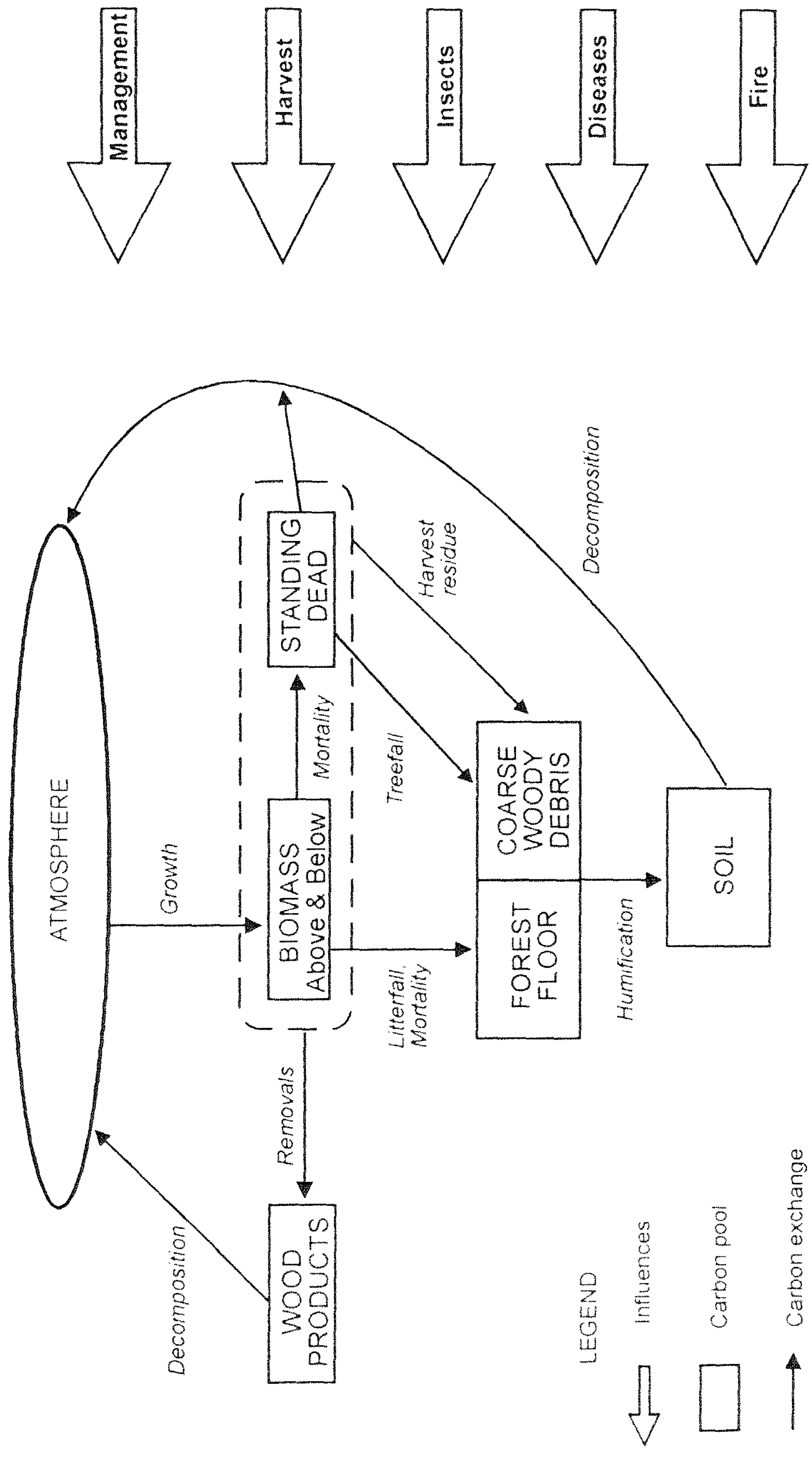

Figure 1.—Conceptual model of the net carbon budget of United States forest ecosystems.

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 Skog[1]

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 CO_2 or methane (CH_4) 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 CO_2 and CH_4 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 CO_2 or CH_4. 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 CO_2 rather as opposed to CH_4 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 CO_2 or CH_4 (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

David W. Williams[1] and Andrew M. Liebhold[2]

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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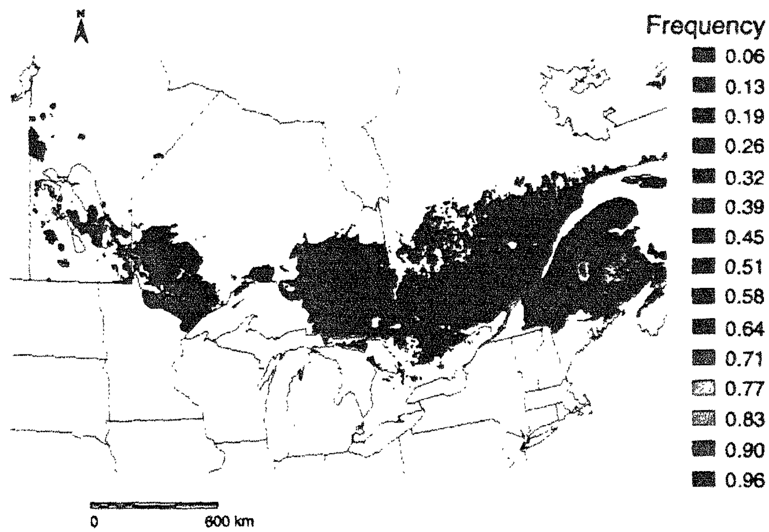

Figure 1.—Frequency of aerially detectable defoliation by spruce budworm in Eastern North America, 1954-80.

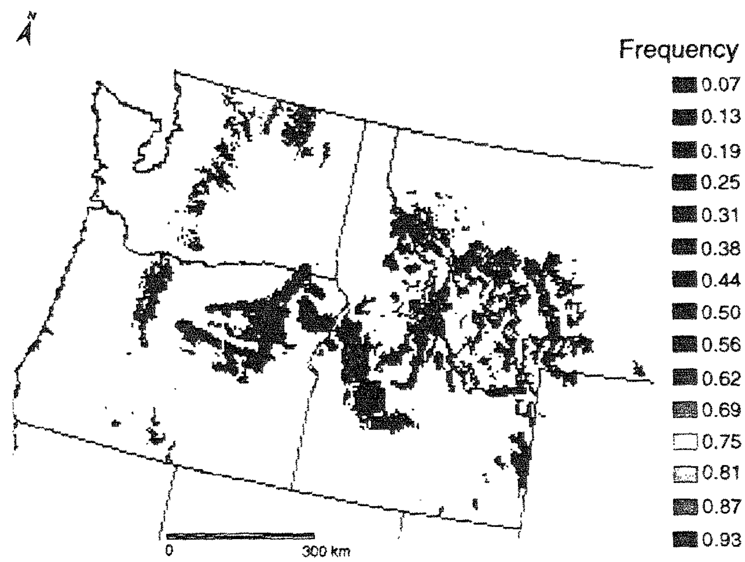

Figure 2.—Frequency of aerially detectable defoliation by western spruce budworm in Washington, Oregon, Idaho, and Montana, 1977-92.

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.

Elaine Kennedy Sutherland[1], Louis R. Iverson[1], Daniel A. Yaussy[1], Charles T. Scott[1], Betsy J. Hale[1], Anantha Prasad[1], Mark Schwartz[2], Hope R. Barrett[1]

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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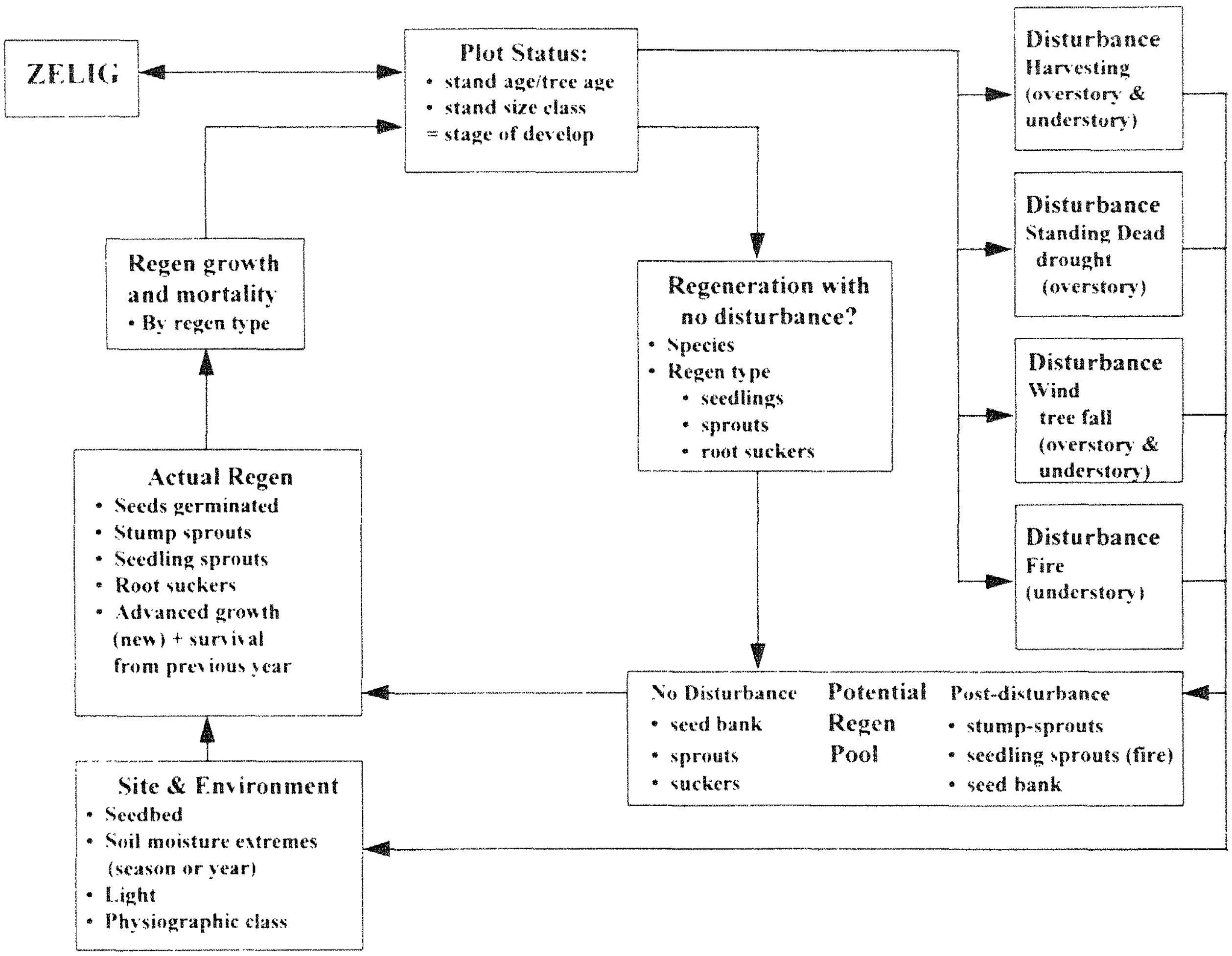

Figure 1.—Flow diagram of the Mechanistic Origination Model (MOM) to be used with the ZELIG gap-phase model modified to simulate disturbance events. ZELIG will provide plot status information that MOM requires (eg., quantity of light on the forest floor, seedbed condition, seed producing trees, sprouting-capable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

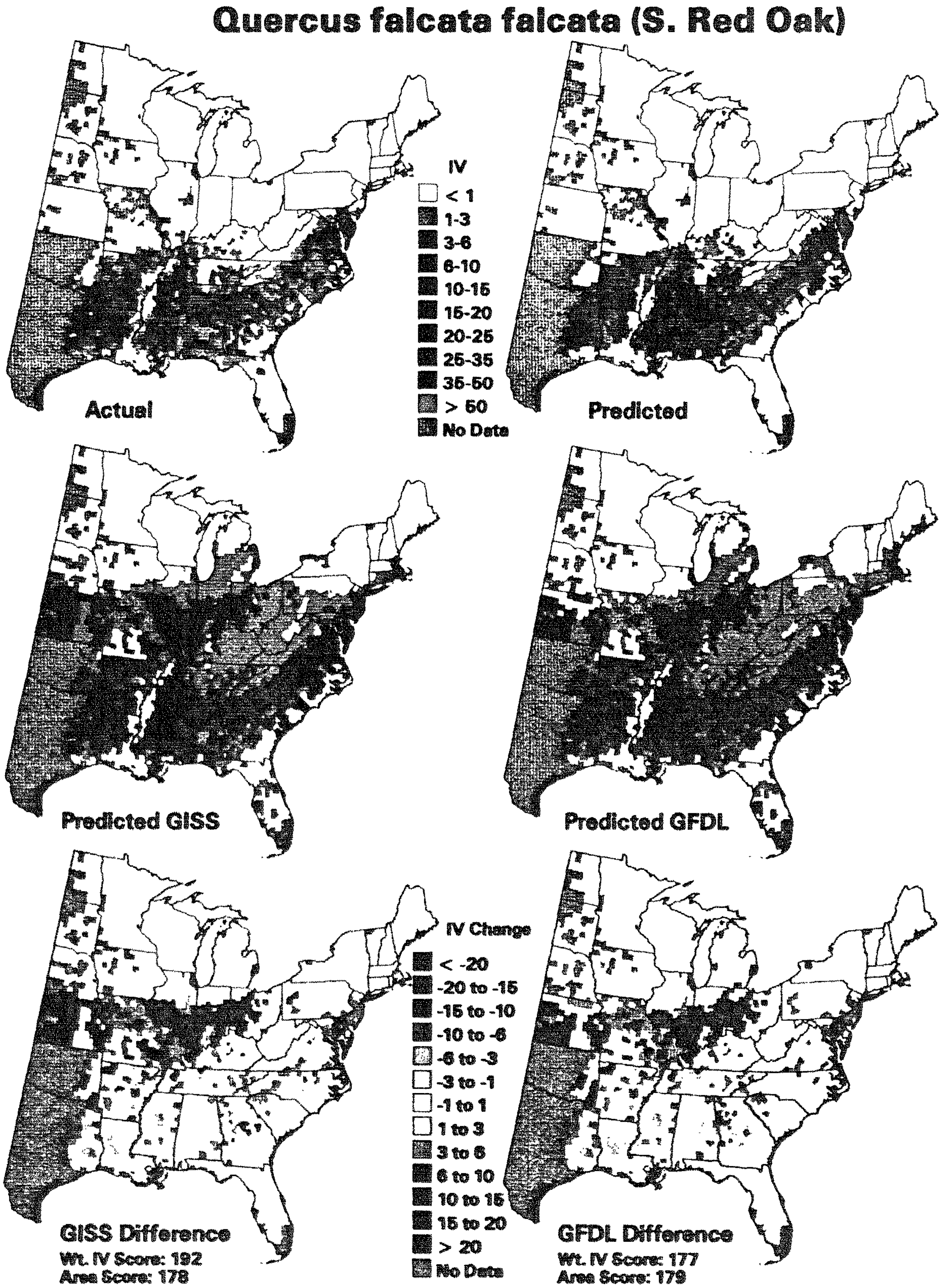

Figure 2.—Example model outputs for *Quercus falcata* var. *falcata* (southern red oak), including: a) actual county importance values as calculated from FIA data; b) predicted current importance values from the RTA model; c) predicted potential future importance values after climate change according 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 2xCO_2 (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 2xCO_2 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 Hammond[1]

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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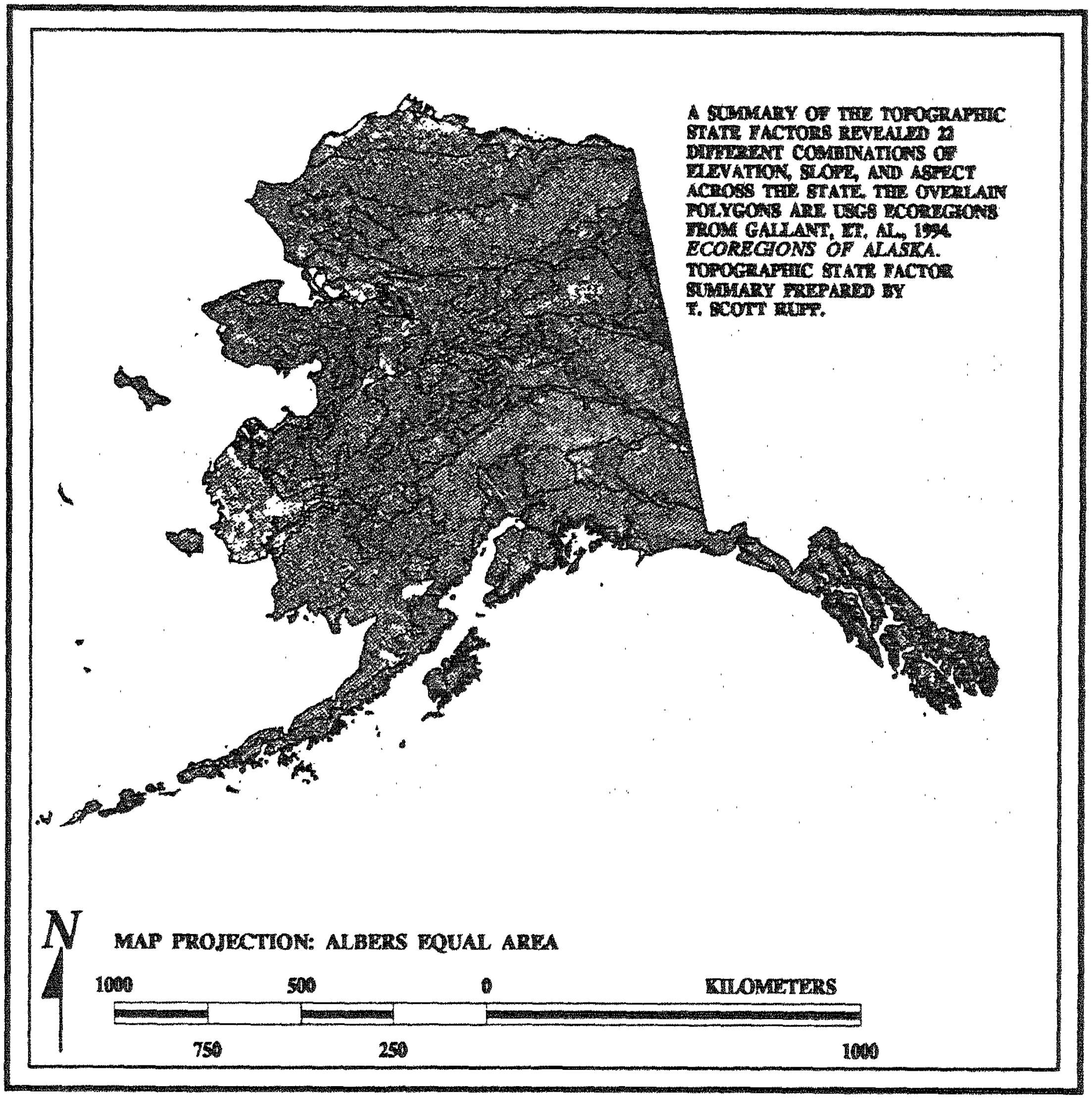

Figure 1.—Distribution of the topography state factor across Alaska. Topography was based on three aspects (none, North 310° to 70°, South 70° to 310°), three slopes (< 5 percent, > 5 percent to 100 percent, > 100 percent) and three elevation (0 to 150 m, 150 m to 750 m, > 750 m) ranges.

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/m^2. The aboveground portion was then approximately 135 g/m^2 which has been measured in other forest stands in interior Alaska (Yarie and Van Cleve 1983).

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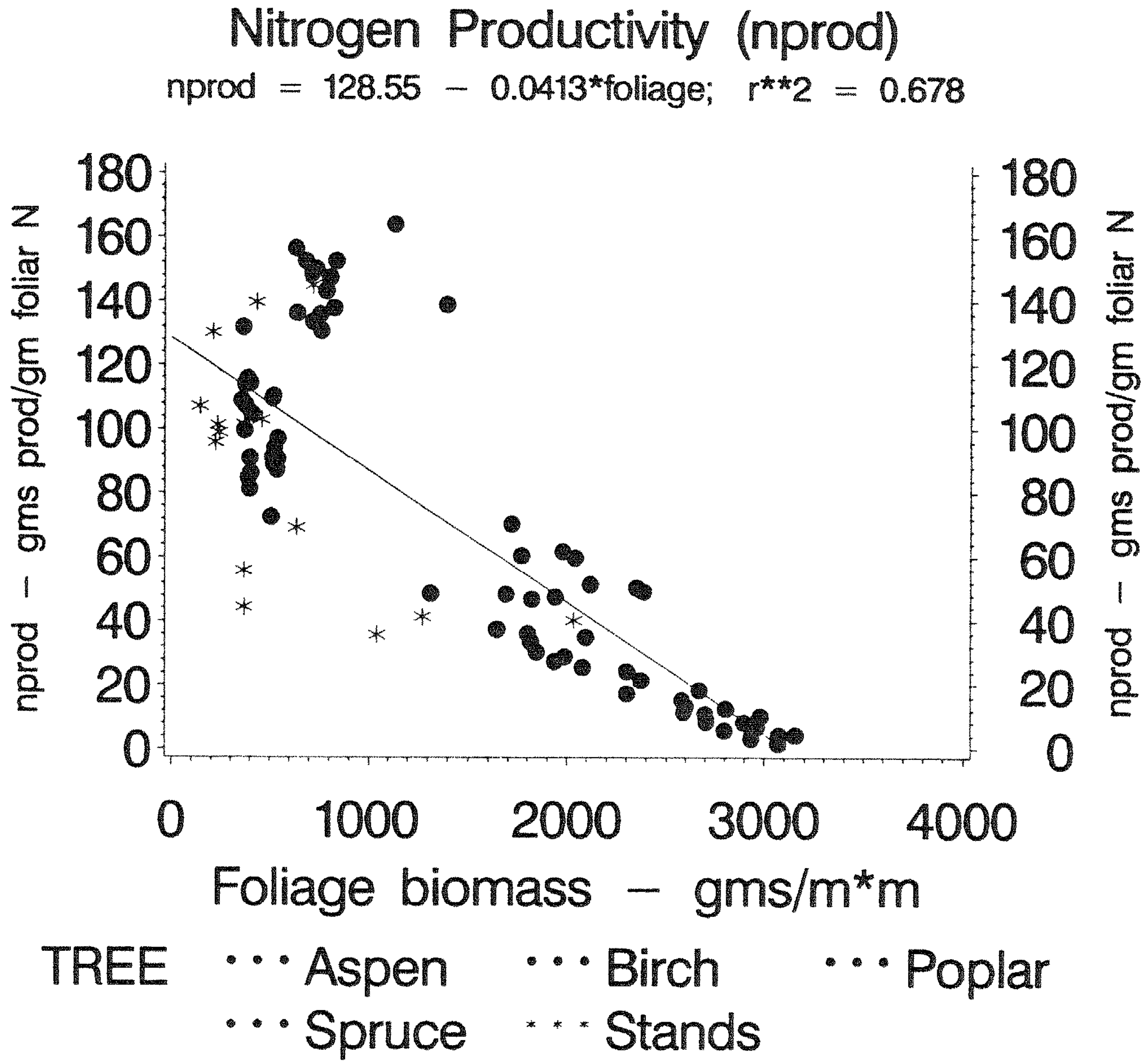

Figure 2.—Individual tree and stand nitrogen productivity relationship to foliar nitrogen quantity per square meter of surface area.

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