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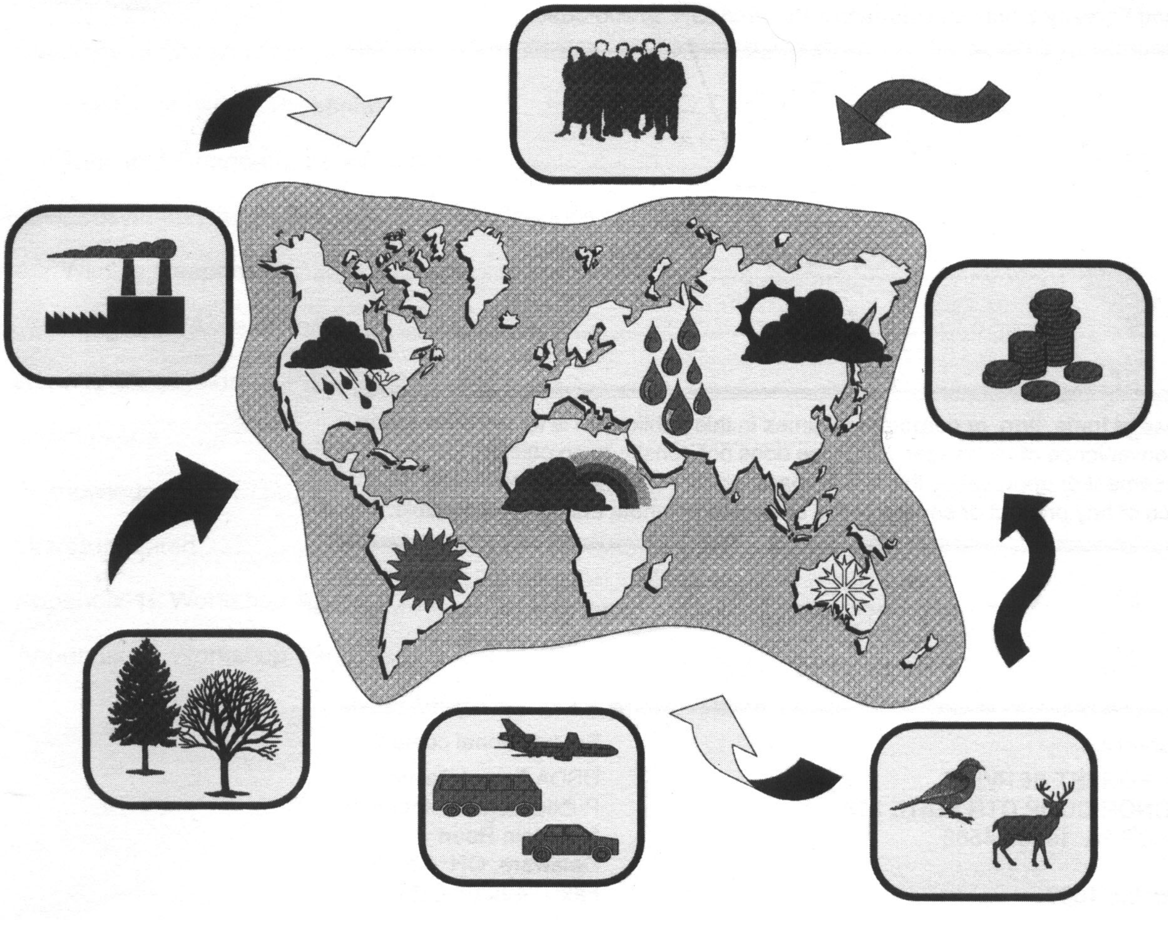
Multidisciplinary Views in Modeling Response to Climate Change: A Workshop Summary

James E. Smith
Linda S. Heath



Abstract

Summarizes presentations at a workshop jointly sponsored by the Interdisciplinary Climate Systems Section of the National Center for Atmospheric Research and the Northern Global Change Research Program of the USDA Forest Service. This was the 11th in a series of annual workshops that provide a forum for scientists from a wide range of disciplines to address issues of global climatic change processes and their interactions with forests and related ecosystems. This year's title was "Moving from Equilibrium to Transient GCMs (general circulation models): Linking Physiological Responses, Community Responses, and Ecological Rates of Change with Social-Economic Factors." Topics included global-scale climate simulations, continental-scale biotic models, ecosystem-level research, and issues associated with developing large-scale assessments.

The Authors

James E. Smith, is a Research Biologist with the USDA Forest Service, Pacific Northwest Research Station, Portland Forestry Sciences Laboratory, Portland, OR 97208-3890.

Linda S. Heath, is a Research Forester with the USDA Forest Service, Northeastern Research Station, located at: Pacific Northwest Research Station, Portland Forestry Sciences Laboratory, Portland, OR 97208-3890.

Multidisciplinary Views in Modeling Response to Climate Change: A Workshop Summary:

"Moving from Equilibrium to Transient GCMs: Linking Physiological Responses, Community Responses, and Ecological Rates of Change with Social-Economic Factors"

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Contents

Introduction

For the past 10 years, the Interdisciplinary Climate Systems Section of the National Center for Atmospheric Research (NCAR) and the USDA Forest Service have cosponsored annual workshops to develop multidisciplinary understanding between scientists and managers on issues of global climatic change processes and their interactions with forests and related ecosystems. The workshops have led to improved understanding of the interaction between terrestrial ecosystems and the atmosphere and have included analysis and discussion of human interaction with ecosystems in a global change context. This year the focus was on “Moving from Equilibrium to Transient GCMs: Linking Physiological Responses, Community Responses, and Ecological Rates of Change with Social-Economic Factors.”

The purpose of the workshop was to introduce scientists and managers to global change modeling issues from the perspective of other disciplines. Presentations are briefly summarized, with speakers identified in boldface type. We also discuss a number of issues that participants identified as hurdles to interdisciplinary understanding of ecosystem-atmospheric interactions and use of such information in forming policy.

Overview of Global Change Issues

Richard Birdsey, USDA Forest Service, Northern Global Change Research Program, opened the workshop with an overview of global change issues in a policy context.

Since 1991, the United States Global Change Research Program has sponsored research to enhance understanding of the nature and magnitude of past and future climate change, prospective impacts on ecosystems, and implications for society. In the spring of 1997, the United States Office of Science and Technology Policy, at the request of Vice President Gore, asked agencies of the U.S. Government to answer several questions about global change impacts on resources: (1) What are the conditions and stresses of resources today; (2) What additional future impacts does climate change pose for resources; (3) What resources (and where) are most vulnerable to climate change; (4) What socioeconomic impacts might ensue; and (5) What options for managing natural resources, in the face of such change, ought to be explored? These questions are the basis of a national assessment process to explore the consequences of climate change and climate variability on different regions of the United States and to engage stakeholders in exploring strategies to cope with impacts.

Ecosystems are continuously adapting to a variety of environmental changes: population growth; pollutants such as ozone, nitrate deposition, and greenhouse gases; invasions of exotic plants and animals; and increased risk of catastrophic fire due to fuel buildup from fire suppression. These factors affect forest growth, species composition (including whether vegetation is forest or non-forest), and mortality. Climate change and climate variability will interact in complex ways with other environmental factors to affect forest processes, with either positive or negative impacts. As the environment changes, some species may successfully adapt and others may not, and new “exotic” species may be introduced. The specific changes will determine the nature of the impacts on society. For example, northward migration of a key species such as sugar maple could have negative consequences for the maple syrup industry and tourism related to fall foliage in New England. Faster growth of loblolly pine due to increased atmospheric carbon dioxide (CO_2) concentration could benefit the timber industry in the South, yet increased temperature could result in northward migration.

Some proposed characteristics of vulnerable forest ecosystems include forests and trees growing near their ecological limits, forests already under stress, and forests with limited adaptive capability. Forest ecosystems that may be considered vulnerable include high-elevation eastern spruce-fir, loblolly pine, coastal oak-gum-cypress, western pines with high fuel loads, and boreal forests.

Climate models have changed from estimating future climate at a single hypothetical equilibrium to simulating transient changes over time; ecosystem models must also evolve in a similar fashion. Such evolutionary models must address the complexities of climate-induced successional vegetation changes. They also must assess likely interactions between effects of human impacts and climate on vegetation. And finally, to the extent that climate and anthropogenic influences affect the modeled system, simulations must include dynamic links with both transient climate and transient socioeconomic models. These are daunting challenges, not only because of complex model formulations and interactions, but also because of the lack of experimental or observational data to adequately parameterize and validate such models. It is practically impossible to design and conduct ecosystem-scale experiments that address the many interacting factors and their effects over long time periods. For example, the most ambitious ecosystem-scale experiment in place — a chamberless experiment in a northern hardwood ecosystem in Rhinelander, Wisconsin — addresses only two factors (CO_2 and tropospheric ozone) and their interactions. Sufficient replications are being done to detect responses after several years of fumigation. Such practical experimental limitations necessitate extrapolation of spatially and temporally small-scale data. Ecosystem models that are appropriately “scaled up” can be linked with climate and economic models to address the regional and national issues posed by global change.

Some examples of critical questions about ecosystem responses that ecological models must address despite a lack of evidence from experiments include:

- How will carbon allocation among ecosystem components change under increased temperature, increased or decreased precipitation, and increased CO_2? What is the likely trajectory of such change under a transient climate?
- To what extent will ecosystem processes be affected by the differential ability of individual species to adapt or migrate? How might adaptability affect succession after disturbance?

Some examples of critical questions that will challenge both ecosystem and socioeconomic modelers as they attempt to link models include:

- Given that timber harvesting is the dominant form of forest disturbance in the United States, how might the regional pattern of timber harvest change, and what would be the implications for forest ecosystems?
- How might society ameliorate potential negative effects of climate change by assisting species migration or mitigating the buildup of atmospheric CO_2?

Despite the inability to fully answer such fundamental questions, scientists are using the best available data and modeling technology to address the issues posed by the President’s Office of Science and Technology Policy. By continuing to challenge current analytical capability, researchers identify areas that need the most attention and steadily progress to more comprehensive and credible analyses.

Summaries of Invited Presentations

The four sessions were entitled: Transient Change at Large Scales, Ecosystem Processes and Transient Responses, Wildlife Responses, and Integrated Assessments. Summaries are in the same sequence as presentations at the workshop. The workshop agenda and titles of individual presentations are provided in Appendix 1; a list of participants is provided in Appendix 2.

Transient Change at Large Scales

Discussion centered mostly around development of transient climate scenarios and their inclusion in large-scale biome modeling. Issues addressed included: incorporation of carbon dioxide and sulfate emission scenarios in transient general circulation models (GCMs) with feedback between the atmosphere and biosphere adapting GCM output as climate scenario input to large-scale biosphere models, and spatial and temporal response of biomes to climate, as evidenced by the pollen record and projected by simulation modeling.

Highlighted progress included:
- Development of fully coupled transient GCMs as well as the computationally more efficient hybrid approximations that facilitate addressing uncertainties in carbon dioxide and sulfate scenarios
- Strategies to improve transient climate scenarios derived from GCM output
- Enhanced presentation of spatial and temporal scales of output from biogeographic models

Issues of current concern included:
- Uncertainties and increased computational efforts associated with including sulfate emission as inputs to transient GCMs
- The need for clear communication among researchers linking models at different scales — increased model complexity and volume of output make guessing the needs of other modelers, or running all permutations of a model, less viable options

General circulation models that incorporate transient changes in climate forcing and biotic feedbacks are expected to improve realism of predicted future climate and biosphere response to change. **Michael Schlesinger**, Head of the Climate Research Group at the University of Illinois, discussed modeling coupled transient GCM simulations as well as availability and limitations of climate projections. To construct geographical scenarios of greenhouse-gas and anthropogenic-sulfate-aerosol induced climate changes, the Climate Research Group performed a number of simulations with their atmospheric-general-circulation/mixed-layer-ocean (AGC/MLO) and energy-balance-climate/upwelling-diffusion-ocean (EBC/UDO) models.

Equilibrium climate simulations were performed with the AGC/MLO model for: the present climate (control); double the CO_2 concentration ($2\times CO_2$); the present worldwide emission of sulfur dioxide (SO_2) gas, which is converted to sulfate (SO_4) aerosol in the atmosphere; a tenfold increase in rate of sulfur dioxide emission ($10\times SO_4$); seven simulations for regional $10\times SO_4$ emissions (one each for Europe, North Africa, Russia, China, North America, the Southern Hemisphere, and all regions other than Europe); and joint $2\times CO_2$ and $5\times SO_4$ levels. Trajectories of future global-mean surface-air temperature were simulated for three scenarios of future CO_2 emission using the EBC/UDO model. The first simulation was the Intergovernmental Panel on Climate Change (IPCC) 1992 "Business-as-Usual" scenario (IS92a) (Folland and others 1992). Two additional scenarios stabilized atmospheric CO_2 concentration at 550 parts per million by volume, they were: one proposed by IPCC Working Group I (IPCC 1996a) which does not consider economics, and one by Wigley and others (1996), which does consider economics in an implicit manner. Geographical patterns of climate change for scenarios were constructed by multiplying the geographical patterns of equilibrium climate changes simulated by the AGC/MLO model, individually for increased CO_2 and SO_4 and normalized by their respective changes in annual global-mean surface-air temperature, by the change in this quantity simulated by the EBC/MLO model individually for the scenario of increased CO_2 and SO_4.

Simulations indicate that inclusion of sulfur dioxide emissions can have an effect in offsetting warming from greenhouse gases, yet considerable uncertainty exists in spatial and temporal specification of sulfate aerosols as inputs to these simulations. This uncertainty, together with the considerable storage requirements of GCM outputs, underscore the importance of communication between climate modelers and biosphere modelers to facilitate exchange of useful information among researchers. Additional information on the aforementioned simulations, research reports, and a large number of climatic quantities from these simulations are available at the Climate Research Group Internet site (http://crga.atmos.uiuc.edu/ [1998 May 7]) and in Lempert and others (1997), Schlesinger and others (1997), and Wigley and others (1996).

The next presentation examined issues related to biospheric responses to global change as well as biogeophysical and biogeochemical feedbacks to the climate system. Working Group I (IPCC 1996a) on biospheric feedbacks and Working Group II (IPCC 1996b) on impacts on many different ecosystems have been unsuccessful in identifying a coherent strategy for modeling such crucial responses. **Wolfgang Cramer** presented results of model simulations using transient climate change scenarios done at the Potsdam Institute for Climate Impact Research with colleagues Harald Bugmann and Alberte Bondeau. They assessed the potential of current broad-scale ecosystem models to make use of improved climate scenarios, particularly those from transient GCM simulations. They first identified the nature and extent of some critical errors in the control run from a recent transient coupled ocean-atmosphere model analysis (HadCM2 (Cullen 1993) run with observed and predicted CO_2 concentrations and sulphur aerosols), using a global vegetation model (BIOME3, Haxeltine and Prentice 1996) as a diagnostic tool. Control runs produced climate conditions of greater than observed cloudiness, and subsequent lower than observed incident radiation. Based on this, they proposed a simple correction scheme that should yield climate scenarios that are better suited to assess biospheric response.

Cramer and colleagues then tested the sensitivity of a sophisticated forest gap model (FORCLIM V2.9, Bugmann and Solomon[1]), across its applicable geographic range, to observed climatic trends as well as to the trend simulated by the climate model (Fig. 1). These tests showed that the correction scheme to construct climate model output was appropriate and necessary. However, global biospheric response assessments, which must involve time lags and feedbacks, require dynamic global vegetation models. Some prototypes of such models have been tested using the same climate model output. Preliminary results indicate the capacity of these models to show qualitatively plausible sensitivities, but the quantitative results are not yet reliable. For additional information on modeling forest response to climate gradients, see Bugmann (1996) and Bugmann and Cramer (1998).

Jon Bergengren, Climate and Global Dynamics Division at NCAR, presented a global model that simulated distribution of vegetation and productivity in response to transient climate change. The model included a large number of vegetation life forms that responded individually to climate. Thus, biomes, or sets of life forms, were emergent properties of the model. Climate and biosphere were fully interactive in model simulations, and this had a large effect on modeled global vegetation maps. The greatest effects of simulating climate change were alteration of vegetation at the edges of boreal regions and poleward migration of some biomes. Presentation of simulation results as animations of global vegetation cover enabled joint display of spatial and temporal characteristics of model output.

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[1] Bugmann, H. K. M.; Solomon, A. M. [In review]. Towards a unified gap model for the global temperate forests. Primary author at: Potsdam Institute for Climate Impact Research, Telegrafenberg, Building C4, D-144 12 Potsdam Germany, P.O. Box 60 12 03

Rates of change in species distribution that are expected to accompany climate change have important implications not only for conservation biology, but also for estimating transient effects of biophysical feedbacks to climate. **Thompson Webb III**, from Brown University, presented research on the pollen record of forests in eastern North America. The use of pollen records to map vegetation and changes in species distribution over time can be partly verified by comparing surface pollen samples with current and recent vegetation maps. Such a comparison of past climate and paleoecological indicators of forest change is useful for determining historic migration rates for a number of taxa.

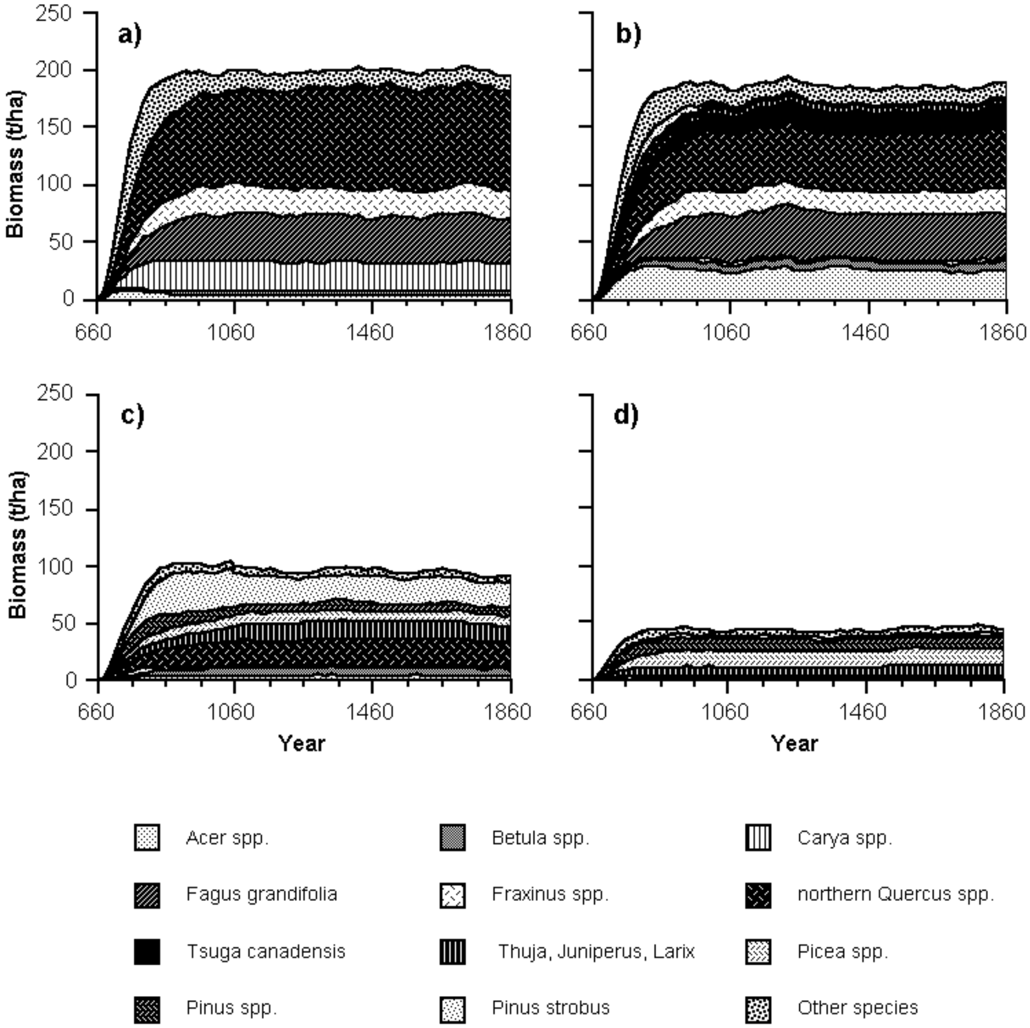

Figure 1.--"Spin-up" behavior of forests at the Stambaugh (Michigan) site simulated by the gap model ForClim V2.9 as the average of 200 forest patches across 1,200 years, starting from bare ground. Different sources for the monthly climatic input data are used, based on the period 1860-1889, which then are re-sampled to create a longer, steady-state time period (660-1860) using a weather generator: a) using the "uncorrected" GCM temperature and precipitation data; b) using GCM data corrected with respect to the climatic normals for the period 1931-1960; c) using "downscaled" GCM data (the same correction was applied but with respect to the climatic normals at the Stambaugh site); d) using observed climate data for the Stambaugh site from the Global Historical Climate Network.

Ecosystem Processes and Transient Responses

Presentations included large-scale modeling and analysis as well as ecosystem-level research. The central theme was identifying important inputs and assumptions for modeling response to transient changes in climate; this included discussion of the importance of the mechanisms and details in modeling water and nutrient cycles, vegetation types, and feedbacks within models. The considerable effects of human inputs, management, and resource use on ecosystems, and thus projections of the future, were also discussed.

Highlighted progress included:

- Equilibrium models are being improved and adapted for transient simulations
- Smaller scale experimental and historical data are contributing to larger scale modeling

Issues of current concern included:

- The need to review the appropriateness of model inputs and assumptions with respect to questions addressed by the model or assessment
- Temporal variability and uncertainty of inputs need to be reflected in model outputs

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provides a means of assessing model behavior by developing and comparing models using common data sets, thereby allowing the hypotheses implicit in the models to be compared. **David Schimel**, NCAR, presented a summary of some results from VEMAP as well as an overview of the next phase of the project. Estimates of ecosystem net primary productivity and carbon levels were presented for simulations of the BIOME-BGC (Running and Coughlan 1988, Running and Gower 1991), Century (Parton and others 1987), and TEM (McGuire and others 1992) models. The models were in general agreement in simulations under current climate and CO_2, but differed substantially under a range of climate change scenarios. Simulations showed the greatest variability when potential changes in vegetation distribution were included. Such comparisons are useful in evaluating differential sensitivities among model results with respect to the carbon, nitrogen, and water cycles incorporated into the simulation. In general, results emphasized: (1) the water cycle is of central importance; (2) the influence of different assumptions about allocation in such models was great and this process is poorly modeled; (3) biogeochemical responses are controlled by plant functional diversity as well as by climate and soils because of differences in allocation and litter chemistry; and (4) life-form competition may play an important role in the next generation of these models. A VEMAP data set of climate for the last 100 years is being prepared for use in evaluating effects of historical transient climate change on carbon storage as well as ecosystem structure and function. The next phase of the VEMAP project will focus on gradually increasing CO_2 concentration, use of climate models with aerosols included in scenarios, and trajectories toward stabilized CO_2 at a range of levels. Additional information regarding the VEMAP project is available at the VEMAP Internet site (http://www.cgd.ucar.edu/vemap [1998 May 7]) and in Kittel (1995), Kittel and others (1995, 1996a, 1996b, 1997), Pan and others (1996), Rosenbloom and Kittel (1996), Schimel and others (1997), and VEMAP members (1995).

Ron Neilson, USDA Forest Service, Pacific Northwest Research Station, discussed modeling issues associated with recent advances in biogeographic (vegetation distribution) simulations. Energy constraints and water and nitrogen cycles are important determinants in simulating transient vegetation conditions. In transient models, nitrogen inputs can constrain model results, whereas nitrogen is assumed to be non-limiting in most equilibrium biogeography models. Future climate inputs to biotic models can be strongly dependent on how changes in climate, based on GCM simulations, are expressed relative to the current climate (that is, whether as differences or ratios). Future projections from large-scale biogeographic models are changing with incorporation of results of transient GCMs and other model improvements such as increased resolution to incorporate topographic effects, use of vegetation density as a feedback in determining vegetation distribution, and incorporation of aerosols. An issue that needs to be addressed in the development of transient biogeographic modeling is the simulation of fine-scale processes (both spatial and temporal) with coarse-scale climate. So, effects of stressful years (for example, drought-induced dieback or fires) should not be imposed over entire gridcells, but should be reflected accurately without recourse to finer scale simulations.

Richard Haynes, USDA Forest Service, Pacific Northwest Research Station, discussed possible impacts of human populations on forests under climate change. Such factors are not normally considered with most climate change simulation models. He suggested that climate-change influences on U.S. timberlands will be mitigated by market feedbacks between the natural resource base and the production and consumption of forest products. As shown in Figure 2, the prospective impacts on the U.S. forest sector of climate change alone are likely to be overshadowed by other contemporary policy concerns. This raises questions about the often cited prospective "catastrophic ecological declines" associated with climate change and the accompanying specter of economic dislocation within the U.S. forest sector. This scenario needs to be examined in light of the extent and speed of changes induced by signals from timber markets.

Projections of timber markets require assumptions concerning future: (1) product demand, which is largely based on projected population and employment; (2) capacity, which is dependent on flexibility in location of production and profitability; and (3) available timber inventory. Other assumptions need to address the context surrounding forest sector issues. For example, worldwide assessments of human influence should incorporate different views on the use of forest resources. Specifically, developing countries tend to view forests as a source of food and fuel, whereas the United States and Canada view forests as a source of industrial wood products and a range of amenities.

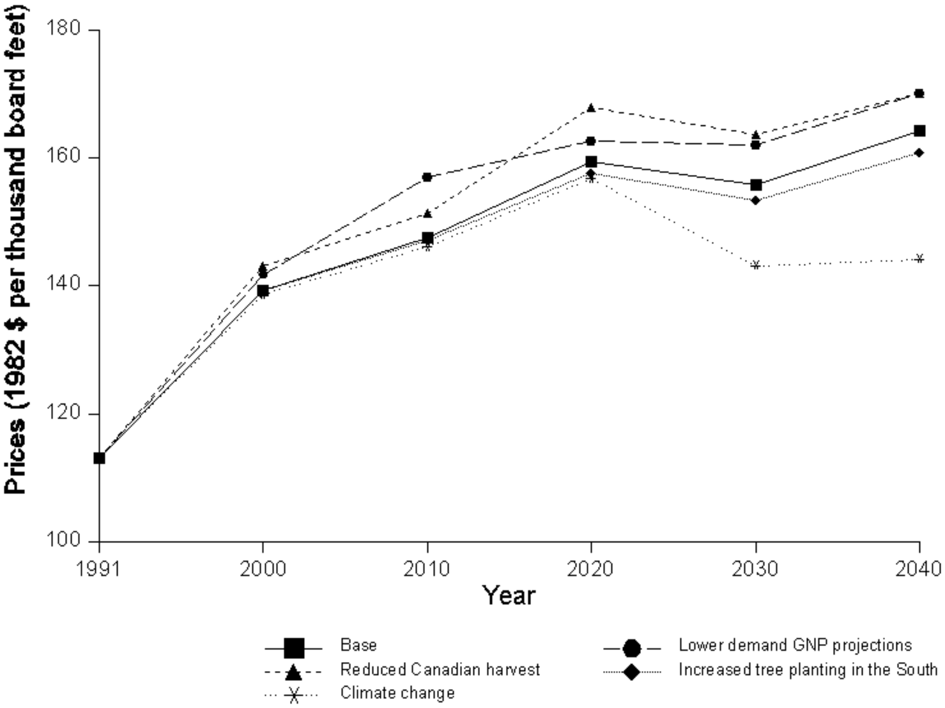

Figure 2.--Relative effect of alternate scenarios, including climate change, on projected softwood lumber price index. Based on information in Haynes and others (1995).

Product markets in the United States have grown 72 percent (1.4 percent per year) over the past four decades, while over the same time, forest resources have grown 28 percent. In the next five decades, we expect slowing in the growth of consumption and in forest resources. Prospective changes in prices signal changes in tastes, industry location, and incentives to landowners, all of which act to mitigate potential impacts of climate change. In developing assessments of forests with respect to climate change, include two important concepts: effects of humans as the most adaptable component of the system and distinctions between science and policy (or politics). For additional information on U.S. timber projections, see Haynes and others (1995).

Reliable estimates of carbon storage in terrestrial ecosystems have become increasingly important as nations move toward commitments in reducing CO_2 emissions. **James Smith**, USDA Forest Service, Pacific Northwest Research Station, discussed some of the work he and Linda Heath, USDA Forest Service, Northeastern Research Station, are doing to address how uncertainties in modeling forest carbon budgets can affect model projections. Such assessments are typically based on series of linked models including components describing social, physical, and biological processes (Fig. 3). Uncertainties in projections of future climate, forest management practices, demand for timber, and biological response are part of model inputs for carbon budget projections. Influences on model projections can change, for even a very simple model of forest carbon budgets, when the model simulates the progressive effect of many years versus the uncertainties for only a single year. Including quantitative descriptions of uncertainty with model output is important to most subsequent uses of model results, for example, in identifying effects of each component of a large-scale, multi-model, assessment. For additional information on carbon storage in U.S. forests, see Birdsey and Heath (1995), Heath and Birdsey (1993a, 1993b), and Heath and others (1996).

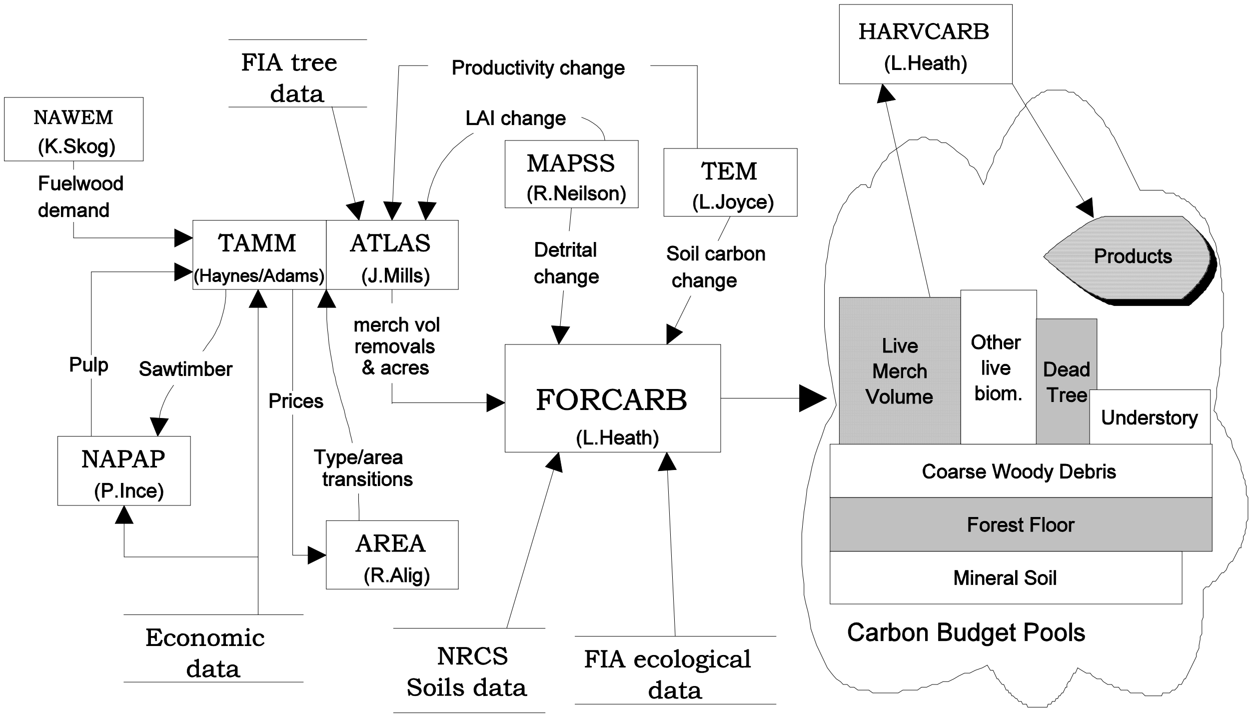

Figure 3. System of linked models used to estimate carbon budgets for U.S. forests. See Joyce (1995) for explanation of models and structure.

Jason Neff, from Stanford University, presented the results of simulations exploring the influence of the nitrogen cycle on ecosystem response to climatic variability. The work was based on the ideas that: (1) nutrient limitation can fundamentally alter response of ecosystems to climate change, and (2) the character of nutrient limitation matters. Nitrogen is lost from ecosystems via a variety of pathways, some of which are tightly regulated by system demand for N and others may occur despite nitrogen demand. Losses of nitrogen such as nitrate leaching and trace gas loss linked to denitrification and ammonia volitilization are closely regulated by system nitrogen demand. Other loss pathways such as dissolved organic nitrogen leaching and trace gas loss associated with organic matter turnover may occur despite high nitrogen demand in an ecosystem and act, in effect, as leaks of nitrogen from an ecosystem.

The Century model was used to compare the implications of these different loss pathways in the context of varying nitrogen input rates. Figure 4 shows the changes in tropical forest net ecosystem productivity (NEP) that occurred following a 20 percent increase in temperature and precipitation. The lines represent two types of forests including one that lost dissolved organic nitrogen, nitrate, and trace gases during turnover and following plant nitrogen demand (“leaky ecosystems”) and one that only lost nitrate and trace gas nitrogen following plant and microbial nitrogen use (“non-leaky”). The values, which range from 0.5 to 100 kg, represent yearly nitrogen deposition values in kg nitrogen per hectare. The figure shows that at low nitrogen input rates, leaks of nitrogen are important for ecosystem response to climatic variability. Thus, the approach taken to model the nitrogen cycle can affect simulated ecosystem response to climate.

Carole Coe Klopatek, USDA Forest Service, Rocky Mountain Research Station, presented results of climate influences on carbon storage and flux in a semiarid ecosystem. This research focused on controls over decomposition, particularly the relative strength of influence of temperature versus moisture. In the gradient between pinyon pine and juniper to ponderosa pine, moisture rather than temperature was most closely associated with decomposition. Further, initial N concentration of litter did not influence decomposition rates. These two results may be at odds with assumptions in some ecosystem models currently in use. Thus, such assumptions need closer examination before inclusion in models of such semiarid systems.

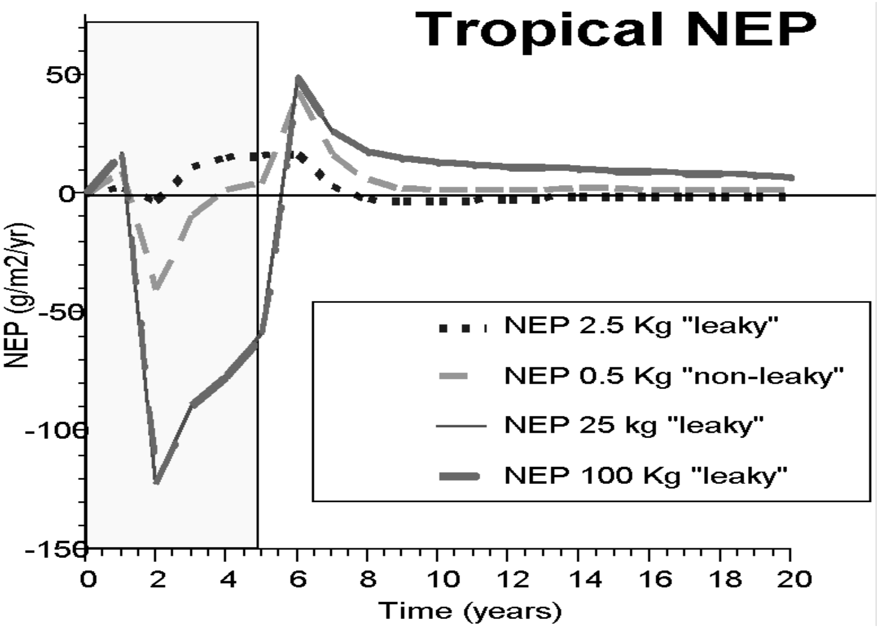

Figure 4.--Changes in tropical forest net ecosystem productivity (NEP) that occurred following a 20 percent increase in temperature and precipitation during the 0-5 year period (shaded box).

Paleoecological evidence of past climate and land use effects on an ecosystem may provide insights applicable in current assessment efforts. **Grace Brush**, from Johns Hopkins University, discussed this issue with respect to Chesapeake Bay. Over the past 250 to 300 years, the Chesapeake Bay watershed has been converted from an almost completely forested landscape to one which is now 60 percent forested. During this time, the shellfish and fishery resource in the estuary has been depleted. Analyses of sediment cores show that sedimentation rates over the past few centuries in the estuary and tributaries increased in proportion to the amount of land cleared. During the same time, estuarine biota changed from benthic to pelagic. This shift has had economic consequences, since many of the economically exploited species are benthic. There were no identifiable changes in the estuarine system until more than 25 percent of the land was deforested. Deforestation also has resulted in a decrease in salinity in the upper tributaries. On the other hand, the Medieval Warm Period, which preceded European settlement in the Chesapeake region by a few centuries, resulted in major shifts in forest species, increased fires, and high sedimentation rates in some tributaries, but very little if any change in the estuarine ecosystem. The difference in estuarine response to anthropogenic and natural disturbance may be related to the episodic character of disturbance related to climate, whereas land clearance has been a continuous process. A comparison of the spatial pattern of forests and their composition under different conditions of climate and land use with estuarine biology during similar time periods may provide guidelines for land management that would ensure conservation of both terrestrial and estuarine resources.

Wildlife Responses

Wildlife, and birds in particular, were presented as early indicators of changing ecosystems because of their relatively rapid response to change. Additionally, natural history examples of past surprises in how one population was affected by a disturbance to another point out the need for understanding community structure. Much of the discussion concerned the potential for climate and land use changes to differentially affect populations, and thus, disrupt community structure.

Highlighted progress included:

- Development of models examining spatial and temporal response to climate and land use
- Identification of mechanisms whereby climate change may alter communities

An issue of current concern was:

- The need to continue to identify cause and effect relationships that may result from disturbances

Jeff Price, American Bird Conservancy, discussed how birds are a colorful link between the public and the environment. In the United States alone, it is estimated that birdwatching is currently a $5.2 billion a year industry. Birds also play an integral role in servicing their ecosystems as pollinators, seed dispersers, and predators of harmful insect pests. As might be expected, projected global climate changes will impact many bird species. He presented results from spatial models developed to examine the relationship between climate and summer bird distributions in the United States and southern Canada. Data for many grassland species showed that some species shifted their distribution from year to year. The models suggest that these shifts are in relation to climate or climate mediated effects. These models were then analyzed using an equilibrium carbon dioxide doubling scenario. In this scenario, most of the species underwent changes in distribution. Models also were developed for the wood warblers, many of which are major predators on forest insects. Under one equilibrium scenario, the models predicted that forested areas in northern Minnesota and southern Ontario might contain 16 fewer warbler species than are currently present. The impact these changes might have on forest health in that area still needs to be examined.

Spatial scale may be an important factor to include when modeling wildlife response to changing climate. Data presented by **J. Russ Butler**, from the University of Michigan, suggests scale-independent associations between some breeding bird populations and land cover. Breeding bird presence or absence was recorded at 2,021 randomly selected roadside point counts over a 4-year period within a 4,000 km^2 area of north-central Tennessee. The study area was categorized into six spatial scales (Fig. 5). The breeding bird species were subdivided into neotropical migrant breeding birds, short-distance migrant breeding birds, and resident breeding birds. Land cover for the study area was derived by digitally classifying a recent Landsat thematic mapper satellite image.

When the number of species per time per scale unit was correlated with the proportion of urban and two rural land cover categories per each scale unit, both neotropical and short-distance migrant species were found to have greater land cover associations than resident breeding species (Table 1). Neotropical migrant breeding species were almost symmetrically inversely correlated across spatial scale: negatively correlated with urban land cover; positively correlated with forest land cover (Table 1). Understanding where scale-independent and scale-dependent ecosystem processes exist could facilitate large-scale modeling of wildlife response to climate change. For additional information on scale and landscape patterns of bird species see Butler (1996) and Flather and Sauer (1996).

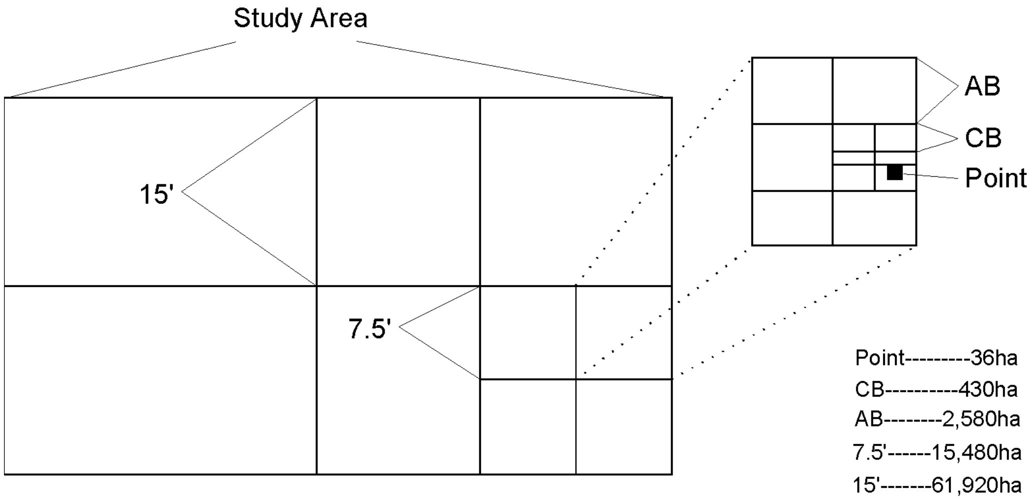

Figure 5.--Spatial scale subdivisions used in the spatial association analysis of breeding bird populations and land cover.

Continental scale studies may be most appropriate for examining responses of some populations to climate change. **Terry Root**, from the University of Michigan, summarized her research at the continental scale. Patterns of animals on landscapes are affected by land use, and this will likely be an important factor in their response to climate change. Forecasts of changes affecting animals need to account for such influences. Possible interactive effects of climate and land use change resulting in loss of breeding grounds may adversely affect populations of waterfowl that breed in the prairie pothole region (Northern Plains and Canada). A correlation was found between May breeding populations of ducks and the Palmer drought severity index. In drought years, populations shifted north to Canada where reproductive success dropped. In a second study, examining the range of wintering songbirds (lark buntings) in response to interannual variation in winter temperature, evidence suggested that the birds responded relatively quickly to temperature, with species ranges varying independently of one another. Research with animals suggests the importance of land use, as it may interact with climate change, potentially resulting in a decoupling of animal communities.

Table 1.--Significant correlation trends between breeding bird populations and land cover across spatial scales.

Breeding populations	Land cover	Spatial scale[a] Pts n=100	 CB n=100	 AB n=100	 7.5' n=32	 15' n=8
Total	Urban	-S[b]	-S	-S	-S	
	Field	+S	+S			
	Forest					
Resident	Urban					
	Field			+S		
	Forest		-S	-S		
Short-distance migrant	Urban	-S	-S			
	Field	+S	+S	+S	+S	+S
	Forest	-S		-S		
Neotropical migrant	Urban	-S	-S	-S	-S	-S
	Field					
	Forest	+S	+S	+S	+S	P=0.0132

[a] See Figure 5 for details on spatial scale.

[b] '-S' is a negative statistically significant result, '+S' is a positive statistically significant result, *P* less than or equal to 0.01.

Integrated Assessments

The final session concerned issues encountered in developing assessment models:

- No model is best or most applicable for all situations. Use depends upon the stated goals of the assessment.
- Appropriate level of complexity for models also depends in part on the stated goals of the assessment.
- Explicit details of approach to scaling and quantitative definitions of uncertainties should be included.
- Socioeconomic processes should be integrated with physical and biological models.

Models are major components of integrated assessments. **Steve Schneider**, from Stanford University, discussed modeling in this context. For models to be useful, feedback is needed from the "real world" to keep modelers informed of what really happens so they can update or correct the models. Feedback is available by monitoring actual policy analysis, implementation, and results of policies. Four research paradigms were identified as principal approaches to assessment modeling, these were described as: (1) bottom-up "laws", (2) top-down "reduced forms", (3) bottom-up with embedded top-down "parameterization", and (4) strategic cyclical scaling. Top-down models are primarily useful for identifying associations, while bottom-up approaches are aimed at identifying likely effects of processes. Mechanistic models with parameterization of subgrid-scale processes characterize most global change simulation models. Strategic cyclical scaling is what Root and Schneider (1993) labeled the continuous process of cycling between top-down and bottom-up studies to understand salient problems (that is, the "strategic" part). All models applicable to assessments need parameterization to some extent; therefore, some degree of independent validation is necessary. Assessment models are most appropriately evaluated by testing at a scale equal to, or larger than, the scale of the lowest resolution element of the model. Recommendations for approaching modeling vis-à-vis assessments were to: (1) take hierarchical approaches, spatially explicit comprehensive process models that contain many parameterizations can be appropriate for high resolution regional assessments while tractable, or highly “transparent” forms, may be more appropriate at very aggregated scales; (2) use sensitivity analyses to expose logical consequences of explicit (process or policy) assumptions; (3) search for synergisms and surprises, people usually do not make decisions simply on the basis of mean expectation; and (4) evaluate processes and simulations with respect to observations. Often, process is the important product of assessment modeling, that is, learning about the system and its relative sensitivities and resiliences to a plausible array of disturbances. For an overview of issues relevant to assessing global change, see Schneider (1997).

Large-scale integrated assessment models that incorporate both transient climate scenarios and biosphere feedbacks to climate are currently being developed. **Michiel Schaeffer**, National Institute of Public Health and the Environment, The Netherlands, gave an overview of considerations in such modeling with specific reference to the IMAGE 2 project (Fig. 6) and work done in collaboration with Rik Leemans. Impact assessment models that use climatologies and climate anomalies based on long-term averages (climatic normals) do not generally consider climate variability or infrequent extreme events. Moreover, land use and land-use change are not yet adequately considered in many models. A comprehensive assessment of the impacts of climate change, mitigation, and adaptation

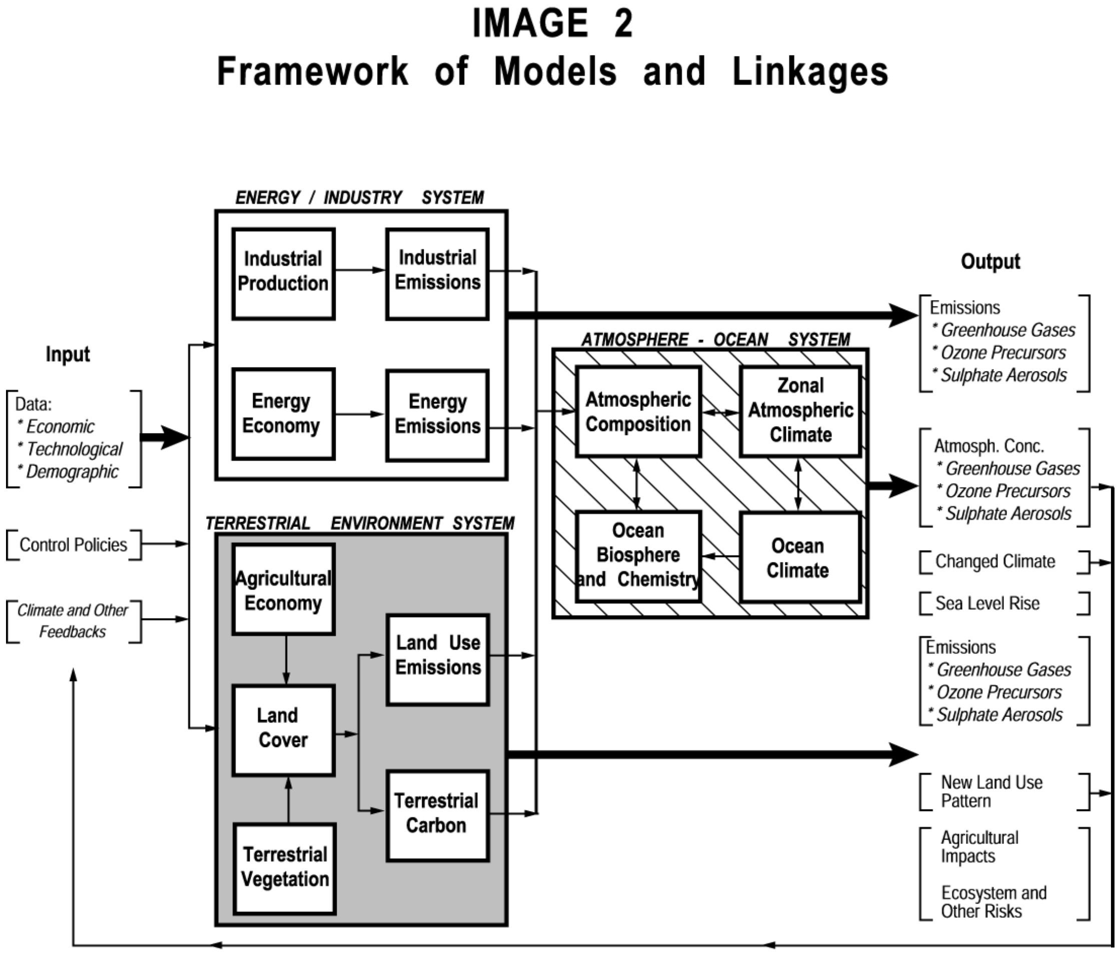

Figure 6.--Organization of IMAGE 2. See Alcamo (1994) for additional information on details of figure.

potential requires the incorporation of interactions and feedbacks in transient scenarios. IMAGE 2 (Fig. 6) considers several important feedback processes between climate, atmospheric composition, and ecosystems. This model explicitly contains a representation of land-use and land-cover dynamics. Therefore, it facilitates identification of the relative importance of environmental, land use, and socioeconomic issues. A coupled atmosphere-ocean-cryosphere climate model of intermediate complexity is currently under development and will become an integral part of IMAGE. The explicit aim is to study climate variability and climatic feedbacks in an integrated assessment modeling framework. Our understanding of individual components and all interactions is not yet fully developed. However, such an integrative approach is crucial from a policy perspective, for only in this way can the importance and interactions of different components be fully addressed with respect to evaluating different policy paths. For additional information on this integrated modeling approach, see also Alcamo (1994) and Alcamo and others (1996, In press).

Linda Joyce, USDA Forest Service, Rocky Mountain Research Station, discussed linking models. The current approach to assessing the impact of climate change on forests is to link separate climate, ecological, and forest sector models. Climate information is passed from the GCMs to ecological models in the form of “deltas,” that is, changes in variables such as temperature and precipitation. Forest productivity is predicted using ecological models under a climate similar to the recent past and under a climate driven by these deltas. Forest productivity deltas are passed to the forest sector models where impacts on timber supply and demand are examined. The deltas are the information about the climate change effect that is passed between climate, ecological, and forest sector models. In the case of GCMs, the delta reflects the change in the climatic variable at the scale of the GCM. Ecological models typically do not use the same baseline climate as the GCMs. Thus, the delta allows the use of site specific or 30-year normal data in the ecological model. In addition, ecological models typically use a much finer spatial scale for model resolution. Forest sector models represent a further scale difference in that forest growth is represented by empirical growth functions based on inventory plots aggregated across large geographic areas. To examine the effect of scale on deltas, Joyce and colleagues varied the resolution scale of input variables (for example, climate or vegetation) to an ecological model predicting forest productivity.

Bridging between ecological and forest sector models as the analysis framework moves from equilibrium to transient models will require a close examination of the assumptions currently made in assessments. Ecological models currently focus on potential vegetation; only recently are successional changes being included. Forest sector models assume no effect of climate on regeneration, production of merchantable wood, and mortality. Timber inventory models compute growth empirically as the average of tree growth across wide ecological variability. Although current assessments impose a climate-driven ecological variability on this average growth, the complexity of site differences within a geographic region has yet to be captured in the forest sector models. Nor is it understood that this complexity will impact the results of the climate change analyses. Timber trade influences were shown to be large in previous assessments, suggesting the need to carefully examine the potential to increase or decrease capacity within the forest sector. For additional information, see Joyce and others (1995), McGuire and Joyce (1995), and Nungesser and others[2].

Bob Luxmoore, Oak Ridge National Laboratory, described an integrated modeling project involving cooperation among investigators from several institutions. A USDA Forest Service funded project in the Southern Global Change Program was designed to assess forest responses to changing climate, air quality, and land use in 13 southeastern states of the United States. This assessment addresses forest responses over the next several decades by combining several scales of computer simulation

[2] Nungesser, M. K.; Joyce, L. A.; McGuire, A. D. [In review]. Effects of spatial aggregation on predictions of forest climate change response. Primary author at: Rocky Mountain Research Station, 240 West Prospect, Fort Collins, CO 80529

with geographic information system capability. Luxmoore and colleagues are developing information transfer among seven simulators ranging from canopy photosynthesis (MAESTRO, Wang and Jarvis 1990) and soil nutrient dynamics (NUCM) to plantation management (PTARDA2, Burkhart and others 1987) (Fig. 7). Each selected result (response signal) passed between two models has a mean and variance from the application of uncertainty analysis, which propagates variability of soil and plant inputs through each model. Simulations are generated for combinations of atmospheric CO_2, ozone, nitrogen deposition, temperature, and precipitation representative of the current and anticipated

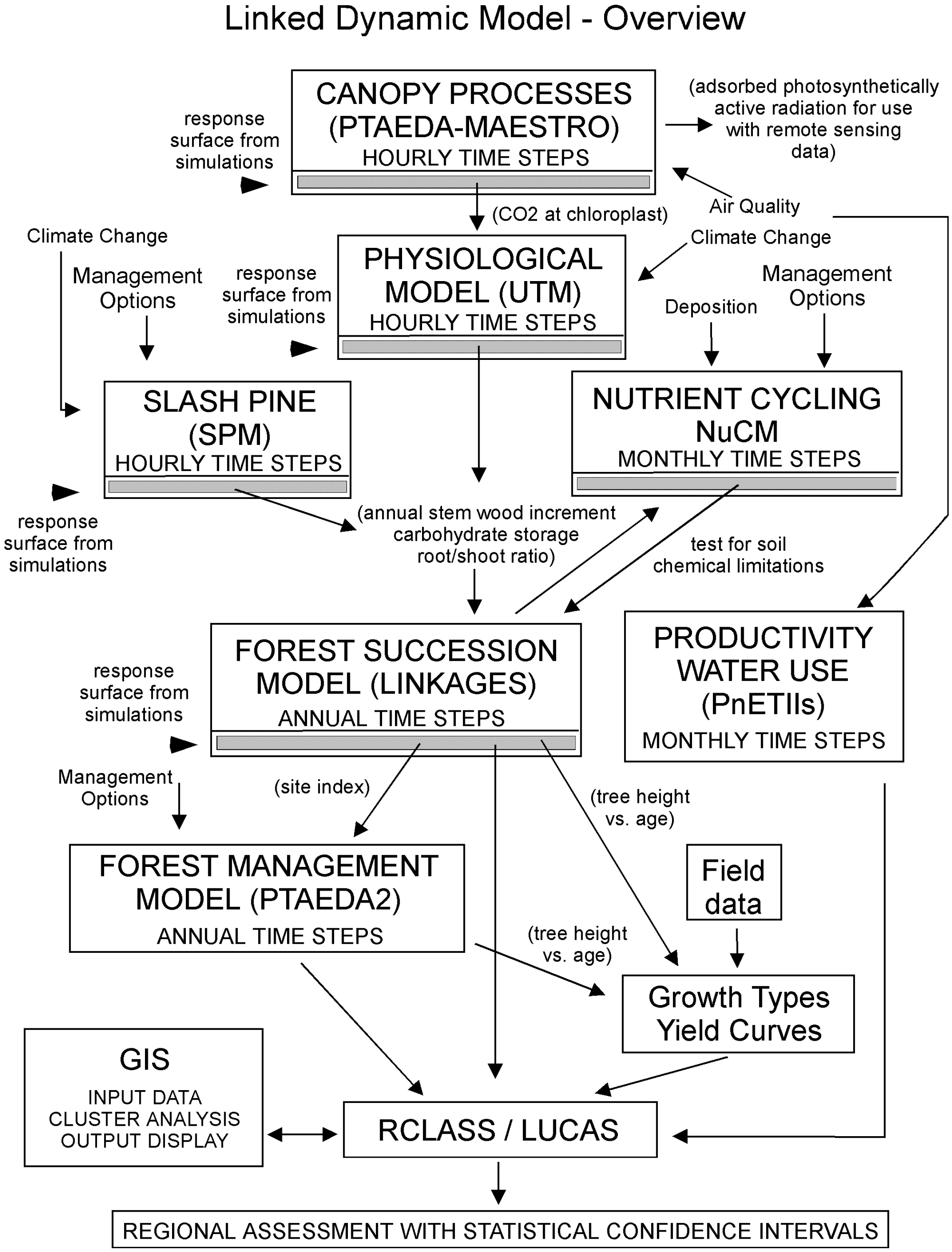

Figure 7.--Organization of regional integrated modeling project. See Integrated Modeling Project Internet site for information on details of figure.

future conditions in the whole region. Selected results are stored in response surfaces as normalized values relative to results from calibration sites. The response surface files are used in assessment simulations. GIS databases are used to characterize plant, soil, and climate attributes for each of the 2.2 million square km pixels of the region. Cluster analysis aggregates these attributes, each as a mean and variance, into about 1,000 clusters. Forest assessments are simulated with uncertainty analysis for all clusters with either the Regional Cluster Assessment System (for environmental stress impacts) or the Land Use Change and Analysis System (for land use change impacts) using interpolated response surface values stored at each node of a parallel processing computer network. Interpolations are determined by the requirements of selected scenarios. As an example of the signal passing approach, loblolly pine responses to multiple environmental stresses are simulated with an ecophysiological model (UTM) to generate stem wood increment responses which are passed to a stand succession model (LINKAGES) for modification of its tree diameter growth calculations. The succession model simulates tree height as a function of stand age for each cluster of the region containing loblolly pine. The height of dominant trees at an index age of 25 years (site index) now incorporates the stress impacts and is passed to the PTAEDA2 model for simulation of impacts on plantation productivity. This method allows site index to be dynamic in response to multiple environmental stresses. The regional assessment is developed for investigation of southern pine species and eastern deciduous forests. Outputs, such as forest production, evapotranspiration, and carbon pools, may be compared statistically for alternative equilibrium or transient scenarios. Additional information regarding the integrated modeling system and its components is available at the Integrated Modeling Project and Land Use Change Analysis System (LUCAS) Internet sites (http://www.cs.utk.edu/~imp/ and http://www.cs.utk.edu/~lucas/, respectively [1998 May 7]) and in Luxmoore (1992), and Berry and others (1996).

Projections of area changes for major land uses are developed and incorporated into a series of models used in natural resource assessments. **Ralph Alig**, USDA Forest Service, Pacific Northwest Research Station, discussed applications of such projections in forest sector modeling. A combination of biophysical, ecological, and socioeconomic forces influences the amount of land allocated to major land uses and forest cover types in the United States. Population is the major factor influencing conversion of forest land to developed uses, which greatly reduces aggregate amounts of forest carbon on those areas. Approximately 6 million acres of non-federal forest in the coterminous United States were converted to urban and developed uses between 1982 and 1992, according to estimates by the USDA Natural Resources Conservation Service (1996). Another 4 million acres of forest were converted to agricultural uses.

A linked model of the forest and agricultural sectors was developed to aid in policy analysis for global change mitigation strategies (Fig. 8). Applications of the linked model included analysis of market impacts of forest carbon sequestration programs and examination of the dimensions of economic impacts due to hypothetical biological responses to global climate change. A group of submodels incorporated projections of land allocation, progression of forest inventory, harvest flows, and expected regional investments.

Incorporating land use changes is an important consideration in choosing forestry instruments to achieve goals of climate change mitigation, as greenhouse-gas mitigation efforts can include activities that sequester carbon in trees and other biomass. Policy-induced land use changes may generate compensating land use shifts by other sectors through markets. Land use shifts to meet policy targets need not be permanent. Implementation of land use and management changes in a smooth or regular fashion over time may not be optimal. For additional information on linked economic and forest models, see Alig and others (1997, In press).

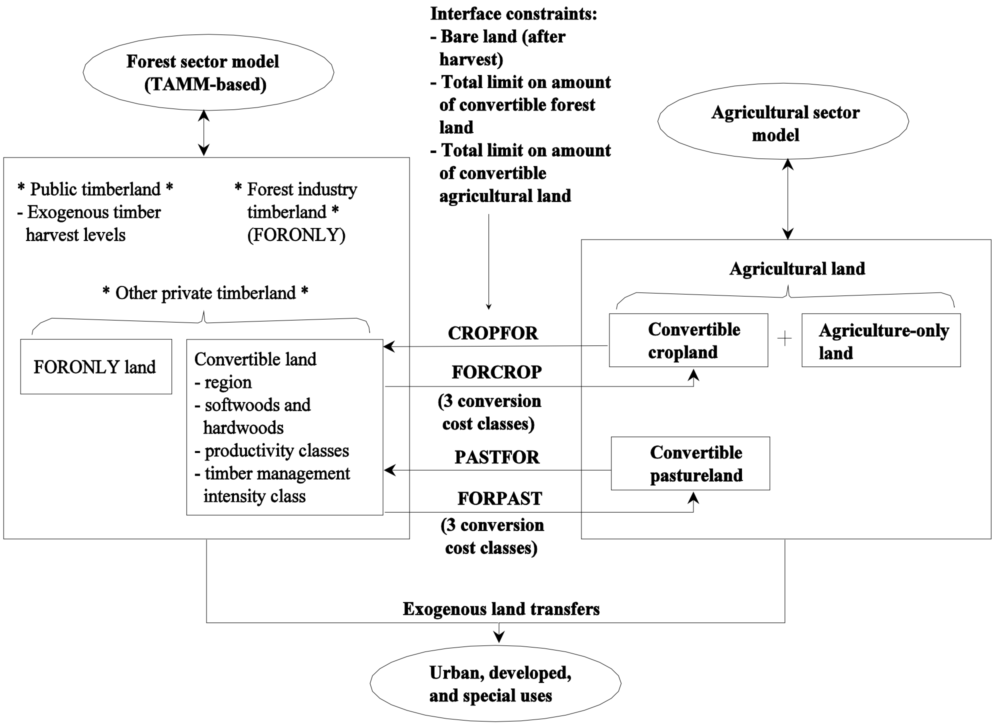

Figure 8.--Linked model of forest and agricultural sectors. See Adams and others (1996) for information on details of figure.

General Discussion by Panel of Participants

Schlesinger started the general discussion by suggesting that the greatest advance in climate modeling would come when time-dependent geographic distributions were incorporated into the models making climate impact projections. The intermediate hybrid approximations of GCMs are currently useful alternatives to the computationally intensive transient GCM simulations. He recommended the use of three transient scenarios: IS92a (“Business-as-Usual”, Folland and others 1992), the 550ppm IPCC version (IPCC 1996a), and the 550ppm version by Wigley and others (1996) that looked at economics. He also emphasized that the great amount of effort needed to produce and save results of GCM simulations underscores the importance of communication in the exchange of information between climate modelers and climate-impact modelers. Climate modelers need to know which outputs are useful to the climate-impact modelers. Output from GCM simulations can require considerable amounts of storage because many of the quantities are nonlinear and information is lost by only saving summary variables. Finally, Schlesinger addressed the importance of remembering and using uncertainty in projections and discussed approaches to incorporate model uncertainty in an adaptive decisionmaking policy process (see Lempert and others 1997).

Cramer also stressed the importance of communication among researchers and discussed the problems with not clearly stating what information is included in the model and how it is used. The ecological modeling community needs to convey what they want from the climate modeling community. Biosphere models are inconsistent in their use of climatic data. For this reason, it is often difficult to evaluate ecosystem or biosphere models. Cramer urged an international view and effort in modeling. Models confined by national boundaries are not addressing the whole story – climate issues are international in scope.

Haynes, with experience in science, policy, and regional assessments, shared several observations about the workshop. Humans are commonly left out of models intended to represent likely response to climate change, yet they are the most changeable part of ecosystems. Common protocols are needed for multidiscipline research so that scientists can talk to each other and more effectively access useful information. Well-defined goals are often missing from assessments; he feels that integrated work cannot be done without integrated questions. Resources should be spent to determine what the questions are. With respect to assessment results, we need to recognize that there is a difference between data and information. Scientists must translate data to tractable information and then present it. In this way, public perceptions, and thus policy, may better reflect the science. A final challenge is getting science into the context of ecosystem management.

Brush was very pleased that paleoecology records are being examined because those records provide hard evidence of changes on the global level. She also pointed out that coastal regions may be much less resilient to disturbance than interior areas.

Additional group discussion focused on uncertainties in ecosystem-to-landscape level models. Improved confidence in predictive capabilities is expected as important processes are identified and better represented in the models. Obviously this is an ongoing and iterative process as evidenced by the fact that such models are constantly being updated and refined to reflect results of ecosystem-level experimentation (e.g., presentations by Neff, Klopatek, and Brush). Neilson indicated that resolution of some issues surrounding nitrogen dynamics and water use is crucial to model improvement. Luxmoore suggested that the expected night-day differential in warming may prove to be a critical factor that is currently omitted from many ecophysiological modeling assessments of global change. Schimel pointed out the importance of incorporating aboveground and belowground allocation.

Birdsey contributed a list of issues that needs to be addressed as part of an assessment of likely response of U.S. forests to global change.

- Large-scale, long-term experiments are needed because ecosystem-scale physiology is poorly understood.
- Equilibrium ecosystem models should become fully transient and include both natural and human disturbances.
- Climate, ecosystem, and socioeconomic models should be fully coupled with feedbacks.
- Ecosystem models need to address effects at multiple scales, from leaf to landscape.
- Fill in major gaps in underlying data. For example, little is known about peatland responses, Alaska/boreal forest responses, and species adaptability.
- Model validation and uncertainty analysis need increased attention.

Some final comments included the importance of getting away from point estimates as the final output of models and assessments. Quantitative expressions of uncertainty should be included as part of model results. However, there are no simple formula for estimating and expressing uncertainty. The best approach is to consider the goals and users of the information. Despite the uncertainty, models are critical because the alternative is to make decisions heuristically. Finally, as Schneider pointed out, the process is often the most important product of models and assessments.

Conclusions

Discussions during the four sessions and at the conclusion of the workshop were wide-ranging with respect to global change issues. However, most of the discussion focused on topics such as implementation of transient scenarios of global change, current successes and difficulties of integrated research in understanding climate change issues, and assessment of biotic response to climate at multiple scales. Four themes were highlighted throughout the workshop; that is, each was reiterated in at least a few of the presentations:

1. There is a need for communication among those working at different scales and in different disciplines.
2. Well-defined model goals, explicit statements of assumptions, and incorporation of uncertainty in model output can facilitate flow of useful information across disciplines.
3. Uncertainties can affect subsequent uses of information and should be explicitly addressed.
4. Assessment work is not simply the summing up of a set of numbers – the process may be the most important product.

Acknowledgments

The workshop was organized and co-sponsored by the Northern Global Change Program of the USDA Forest Service and the National Center for Atmospheric Research. Katarina Kivel, Linda Mearns, Ligea Rice, and Holly Howard helped provide preliminary organization or local site support. The three workshop chairs were Steve Schneider, Terry Root, and John Hom. Workshop participants provided figures and summaries of research. We also thank Steven McNulty, Brent Sohngen, and Dave Williams for their reviews of the workshop summary.

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Appendix 1: Workshop Agenda

USDA Forest Service - NCAR Workshop. Moving from Equilibrium to Transient GCMs: Linking Physiological Responses, Community Responses, and Ecological Rates of Change with Social-Economic Factors

Walter Orr Roberts Board Room, NCAR Mesa Laboratory, Boulder, CO
June 3 and 4, 1997

Workshop Organizers:
John Hom, USDA Forest Service
Terry Root, University of Michigan
Steve Schneider, Stanford University

Welcome by John Hom and Stephen H. Schneider

Richard Birdsey, William Sommers, and Marla Emery - Impacts of climate change on U.S. forests, and opportunities for adaptation and mitigation

Session I: Transient Change at Large Scales - Chair: Stephen H. Schneider

Michael Schlesinger - Transient climate models: a hybrid strategy (or: Geographical scenarios of greenhouse-gas and anthropogenic-sulfate-aerosol induced climate changes)

Wolfgang Cramer, Harald Bugmann, and Alberte Bondeau - The impact of transient climate change scenarios on broad-scale ecosystem dynamics

Jon Bergengren - Modeling the effects of vegetation change on climate sensitivity

Thompson Webb III - How fast have climate and ecosystems changed: The Ice Age-Interglacial record

Session II: Ecosystem Processes and Transient Responses - Chair: John Hom

David Schimel - VEMAP and transients

Ron Neilson - Some conceptual issues in the spatially explicit simulation of dynamic global vegetation change

Richard Haynes - Will forest product markets change fast enough to alleviate prospective “catastrophic ecological declines”?

James Smith and Linda Heath - A discussion of system influences in estimating forest carbon budgets in the United States

Jason Neff - Some missing linkages among climate, carbon and nutrient cycling

Carole Coe Klopatek - The effects of potential climate change on carbon storage, turnover, and flux in semiarid ecosystems

Grace Brush - Forests and the economic resource: the Chesapeake Bay

Session III: Wildlife Responses - Chair: Terry Root

Jeff Price - Potential impacts of global climate change on the summer distribution of some North American birds

J. Russ Butler - Local to regional scaling of biological processing: a North American bird case study

Terry Root - Forecasting possible ecological consequences of climate change: where have all the ducks gone?

Session IV: Integrated Assessments - Chair: Richard Birdsey

Stephen Schneider - Integrated assessment modeling: a hierarchical approach

Michiel Schaeffer and Rik Leemans - Developing transient scenarios with integrated assessment models, which include feedbacks and responses of the terrestrial biosphere

Linda Joyce - Bridging between ecological and economic models: The implications of averages

Robert Luxmoore and the Integrated Modeling Project Team - Toward modeling regional forest responses to changing climate, air quality, and land use.

Ralph Alig - Projecting area changes for major land uses and forest cover types in macro assessments: Global climate change as a modeling issue

General Discussion, Panel of Participants

Appendix 2: Workshop Participants

Ralph Alig, USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Lab, 3200 Southwest Jefferson Way, Corvallis, OR 97331, Email: aligr@fsl.orst.edu

Jon Bergengren, NCAR Climate and Global Dynamics Division, P.O. Box 3000, Boulder, CO 80307, Phone: 303-497-1340, Fax: 303-497-1348, Email: jcb@ucar.edu

Richard Birdsey, USDA Forest Service, Northeastern Research Station, 100 Matsonford Road, 5 Radnor Corp Ctr, Radnor, PA 19087-4585, Phone: 610-975-4092, Fax: 610-975-4095, Email: Richard.Birdsey/ne@fs.fed.us

Grace Brush, Johns Hopkins University, Department of Geography and Environmental Engineering, 3400 North Charles Street, Baltimore, MD 21218, Phone: 410-516-7107, Fax: 410-516-8996, Email: gbrush@jhu.edu

J. Russ Butler, University of Michigan, School of Natural Resources and the Environment, 430 East University, Ann Arbor, MI 48109-1115, Phone: 313-764-1415, Email: jrussb@umich.edu

Wolfgang Cramer, Potsdam Institute for Climate Impact Research, Telegrafenberg, Building C4, D-144 12 Potsdam Germany, P.O. Box 60 12 03, Phone: 49-331-288-2521, Fax: 49-331-288-2600, Email: cramer@pik-potsdam.de

Pru Foster, Okayama University, Misasa, Tottori-ken, 682-01 Japan, Phone: 81-858-43-1215, Fax: 81-858-43-3450, Email: walter@misasa.okayama-u.ac.jp

Richard Haynes, USDA Forest Service, Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208-3890, Phone: 503-808-2002, FAX: 503-808-2033, Email: rhaynes/r6pnw_portland@fs.fed.us

Linda Heath, USDA Forest Service, Northeastern Research Station, located at: Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208-3890, Phone: 503-808-2008, Fax: 503-808-2020, Email: lheath/r6pnw_portland@fs.fed.us

John Hom, USDA Forest Service, Northeastern Research Station, 5 Radnor Corp Ctr, 100 Matsonford Road, Radnor, PA 19087-4585, Phone: 610-975-4097, Fax: 610-975-4095, Email: John.Hom/ne@fs.fed.us

Linda Joyce, USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect, Fort Collins, CO 80529, Phone: 970-498-2560, Fax: 970-498-1314, Email: ljoyce@lamar.colostate.edu

Carole Coe Klopatek, USDA Forest Service, Southwest Forest Science Complex, 2500 S. Pine Knoll, Flagstaff, AZ 86001-6381, Phone: 602-965-9757

Bob Luxmoore, Oak Ridge National Laboratory, Environmental Sciences Division, P.O. Box 2008, Oak Ridge, TN 37831-6038, Phone: 423-574-7357, Fax: 423-576-8646, Email: rjl@ornl.gov

Steven McNulty, Southern Global Change Program, 1509 Varsity Drive, Raleigh, NC 27606, Phone: 919-515-9489, Fax: 919-515-3593, Email: mcnulty@arrc.ncsu.edu

Jason Neff, Stanford University, Department of Biological Sciences, Stanford, CA 94305-5020, Phone: 650-725-1856, Fax: 650-725-1856, Email: jneff@kukuau.stanford.edu

Ron Neilson, USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Lab, 3200 Southwest Jefferson Way, Corvallis, OR 97331, Phone: 541-750-7303, Fax: 503-750-7329, Email: neilsonr@fsl.orst.edu

Jeff Price, 7394 Glacier View Road, Longmont, CO 80503, Phone: 303-530-7239, Fax: 303-530-7604, Email: jprice@mho.net

Terry Root, University of Michigan, School of Natural Resources and Environment, 430 East University, Ann Arbor, MI 48109-1115, Phone: 313-763-5945, Fax: 313-763-5945, Email: tlroot@umich.edu

Michiel Schaeffer, National Institute of Public Health and the Environment, Department of Global Environmental Assessments, P.O. Box 1, NL-3720 BA Bilthoven, The Netherlands, Phone: 31-30-274-4056, Fax: 31-30-274-4435, Email: michiel.schaeffer@rivm.nl

David Schimel, NCAR, P.O. Box 3000, Boulder, CO 80307, Phone: 303-497-1610, Fax: 303-497-1646, Email: schimel@ncar.ucar.edu

Michael Schlesinger, University of Illinois at Urbana-Champaign, Department of Atmospheric Sciences, 105 South Gregory Avenue, Urbana, IL 61801, Phone: 217-333-2192, Fax: 217-244-4393, Email: schlesin@uiatma.atmos.uiuc.edu

Stephen Schneider, Stanford University, Department of Biological Sciences, Stanford, CA 94304-5020, Phone: 414-725-9978, Fax: 415-725-4387, Email: shs@leland.stanford.edu

Herman Sievering, University of Colorado - Denver, Center for Environmental Sciences, Denver, CO, Phone: 303-556-4277, Fax: 303-556-4292, Email: hsieveri@carbon.cudenver.edu

James Smith, USDA Forest Service, Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208-3890, Phone: 503-808-2068, Fax: 503-808-2020, Email: jsmith/r6pnw_portland@fs.fed.us

Thompson Webb III, Brown University, Department of Geological Sciences, Providence, RI 02912-1846, Phone: 401-863-3128, Fax:401-863-2058, Email: Thompson_Webb_III@brown.edu