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Assessing the Impacts of Climate Change on
Natural Resource Systems

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Integrated Assessments of the Impacts of Climate Change on Natural Resources

An Introductory Editorial

by

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Resources for the Future

Washington, D.C.

Concerns about the possibility of an anthropogenically-induced greenhouse warming have prompted a growing body of research designed to understand the likely biological and physical impacts of climate change on terrestrial and aquatic ecosystems and the social and economic consequences of these impacts. Relatively few studies, however, have integrated both the biophysical and the socioeconomic aspects or considered the linkages between them. The publication of this volume culminates a project designed to encourage and, hopefully, facilitate future integrated assessments of the social, economic, and environmental impacts of climate change on terrestrial and freshwater ecosystems. Specific project objectives include: (1) characterizing the current state of natural science and socioeconomic modeling of the impacts of climate change and current climate variability on forests, grasslands, and water; (2) identifying what can be done currently with impact assessments and how to undertake such assessments; (3) identifying impediments to linking biophysical and socioeconomic models into integrated assessments for policy purposes; (4) recommending research activities that will improve the state of the art and remove impediments to model integration.

This introductory essay provides some background on the issues motivating the project, the steps involved in doing climate impact assessments, their potential use for formulating mitigation and adaptation policies, and the particular challenges of

undertaking integrated assessments of the impacts of climate change on natural resources. The first eight papers in this volume were presented at a workshop in San Diego, California from February 28 to March 3, 1993. The final paper discusses some of the principal issues addressed during the workshop and a few of the major findings of the workshop papers. The focus of the papers is on forests, grasslands, and water resources. Other ecosystems such as agriculture, wetlands, tundra, deserts, and arid rangelands are not covered because of the limited resources available for the task.

Vulnerability of natural resource systems

Natural resource systems such as forests, rangelands, tundra, water resources, wetlands, and estuaries are affected by human activities. Indeed, few of these resource systems are truly natural. Most have been altered significantly by human intervention, modified by management practices such as fire suppression, or otherwise advertently or inadvertently impacted by human activities.

From the perspective of human welfare, the implications of these changes have been mixed. On the positive side, former forests, grasslands, and wetlands have been converted into highly productive agricultural lands and urban settlements. Streams have been controlled and managed to reduce flooding, overcome droughts, and provide reliable water supplies for a variety of human uses. On the other hand, loss of forests, grasslands, and wetlands contributes to flooding, loss of habitat, and consequent loss of biological diversity. Agricultural and urban activities can degrade land and water resources, and controlling streams to limit floods and supply irrigators and other offstream water users can sacrifice instream values such as fish and wildlife habitat.

While increases in population and economic activity will continue to affect natural resource systems, the prospect of anthropogenically-induced climate change adds a new element of uncertainty and potential stress. Climate changes of the rates and magnitudes suggested by the general circulation models (GCMs) could have substantial future impacts

on forests, rangelands, water resources, and other resource systems. Projections of the global average annual changes likely to result from an equivalent doubling of atmospheric carbon dioxide (CO₂) from the preindustrial level range from +2 to +5° C for temperature and +7 to +15 percent for precipitation. The ranges for probable average annual regional changes are much broader: -3 to +10° C for temperature and -20 to +20 percent for precipitation (Schneider, Gleick, and Mearns, 1990). Recent projections of fossil fuel consumption indicate that an equivalent doubling of greenhouse gas concentrations in the atmosphere may occur between 2020 and 2080, followed by an increase in globally averaged temperature to the equivalent equilibrium value over the next few decades. Consequently, significant anthropogenically-induced climate changes could occur within several decades (National Research Council, 1987, Intergovernmental Panel on Climate Change, 1991).

Problems stemming from a greenhouse-induced climate change might result from several factors - the potential magnitude and the uncertainty as to the nature of the changes, the uncertainty as to the ability of these resource systems to adapt either naturally or through managed intervention to these changes, and insufficient economic incentives to manage these lands in ways that might facilitate their adaptation to a different climate. The vulnerability of these resource systems to future climate change must necessarily be placed in the context of the growing demands on the systems that are associated with future increases in population and economic activities.

Unlike agricultural lands, the incremental market values associated with managing many landscapes are too low to warrant investing much time or effort purposefully intervening to alter their natural adjustments to climate change. Moreover, when valued by standard measures such as gross national product or national income, the economic implications of the effects of climate change on resource systems are likely (at least in the short and medium terms) to be small even if the biophysical effects on these resources are significant (National Academy of Sciences, 1992, Nordhaus, 1992). Measures of national

income are useful for studying fluctuations in employment or in the demand for goods and services. But they understate humankind's stake in the health of natural resource systems. Efforts to adjust the standard accounts for changes in environmental assets suggest the values associated with natural ecosystems are significant (Repetto, et al., 1989).

Recent assessments suggest that the unmanaged systems may be more vulnerable and possibly less amenable to adaptation to climate change (Intergovernmental Panel on Climate Change, 1991, National Academy of Sciences, 1992). And many people believe that the more extreme GCM scenarios present major risks to natural systems and human welfare. The members of the National Commission on the Environment gave the following strong endorsement to this view.

We, the members of the National Commission on the Environment, are convinced that the natural processes that support life on Earth are increasingly at risk and that by choosing to act or not to act to confront this risk now, our country is choosing between two very different futures. If America continues down its current path, primarily reacting to environmental injuries and trying to repair them, the quality of our environment will continue to deteriorate, and eventually our economy will decline as well. If, however, our country pioneers new technologies, shifts its policies, makes bold economic changes, and embraces a new ethic of environmentally responsible behavior, it is far more likely that the coming years will bring a higher quality of life, a healthier environment, and a more vibrant economy for all Americans. (National Commission on the Environment, 1992, v.)

While individual incentives to develop and introduce mitigation and adaptation measures may understate society's interests in such actions, social action has also been stymied in part by the large uncertainties as to what is at risk and when it will be at risk. Integrated assessments of the ecological and socio/economic implications of climate change on natural resource systems can reduce these uncertainties, help identify and quantify the values potentially at risk, and assist policymakers in evaluating options for mitigating and adapting to climate change. Such assessments can also help identify the areas of research most likely to bear fruit in terms of reducing critical uncertainties that vex policy formulation in this complex area.

Undertaking climate impact assessments

Figure 1 presents a flow diagram of the steps involved in assessing the impacts of climate change scenarios and policy responses that would mitigate the anthropogenically-induced climate changes or facilitate adaptation to them. This approach is consistent with the general framework for conducting a climate impact assessment developed by Working Group II of the Intergovernmental Panel on Climate Change (1992). However, several steps of the analysis have been modified to emphasize that an assessment of the impacts of climate change implies comparing at least two future situations, one with and one without climate change, and that automatic adaptations should be incorporated into both future situations to account for any normal human responses to the projected changes. The modifications are also intended to make the impact assessment process more readily understandable to practitioners and users.

After the problem is defined (step 1), the method of analysis selected (step 2) and tested (step 3), the current climatological, environmental, and socioeconomic conditions must be established (step 4). Once the current situation is determined, step 5 involves establishing one or more future baselines that describe the area in the absence of any anthropogenically-induced changes in the climate.

Defining a future baseline entails projecting technological, demographic, social, political, and economic changes over periods of several decades or more (i.e., periods of sufficient length that significant climate changes are likely); determining the impacts of these changes on natural resource systems and socioeconomic factors; and making allowance for automatic or normal human adaptations that are likely to occur in response to these other changes. Comparisons of past projections with actual energy, mineral, and water use suggest the speculative nature of future baseline projections (Rogers, this volume, Goklany 1992). Changes in the non-climate variables and the responses to them are likely to be far more important than the anticipated climate changes for the

Figure 1**IMPACT ASSESSMENT FLOW DIAGRAM**

socioeconomic and ecological future of a study area (Intergovernmental Panel on Climate Change, 1991, Goklany, 1992). Moreover, uncertainties as to the nature and magnitude of the changes in these non-climate factors are likely to be greater than those surrounding the climate. The importance of the non-climate variables is evident in the United States where enormous changes in the nation's forests, rangelands, and water resources have resulted in response to changing population, economic, and technological pressures (Frederick and Sedjo, 1991). Past trends in the condition of forests in the coterminous United States illustrate that the impacts of these variables on the resources have been neither unidirectional nor readily predictable. Warnings of impending timber shortages date back to the nineteenth century and became more frequent and urgent during the first two decades of this century. By 1920 hundreds of millions of acres of the original forest had been cleared to meet demands for fuelwood and timber and to convert the land to agriculture. Since then, however, the overall condition of the forests has actually improved in spite of the continued rapid population and economic growth. The improvements are attributable in large part to the introduction of improved forest management techniques, new environmental policies protecting forests, and development of substitutes for fuel and industrial wood and yield-increasing agricultural technologies that have reduced pressures to clear forested land (Frederick and Sedjo, 1991).

After the future baseline is established, the task (step 6) is to determine how the projected change in the climate (or alternative climate scenarios) is likely to affect natural resource systems and how changes in these systems together with the direct climate impacts affect socioeconomic and environmental factors. These socioeconomic and environmental effects would result in turn in automatic adaptations designed to reduce and/or take advantage of these effects. These adaptations should be incorporated into this step of the analysis. The papers in this volume reference an extensive literature that assesses individually the ecological and economic impacts of climate change on forests, grasslands, and water. Only a few attempts, however, have been made to produce an

integrated assessment accounting for the linkages between the ecological and economic impacts. And no attempts have been made to determine how the ecological and economic changes might then feedback to alter the climate.

The initial climate projections underlying the analysis in step 6 assume that the surface biosphere remains unchanged under the new climate. However, if the analysis indicates that the change in the climate is likely to result in significant changes in vegetation and other factors that influence the climate, step 7 would incorporate the net impacts on the climate of the projected changes in the biosphere. These revised climate projections would then be used to reassess the future with climate change (step 6).

Once the future situation with climate change is established (ideally incorporating an iterative process to account for both the linkages from the biosphere to the climate and any automatic adaptations), assessing the impacts of climate change on the region (step 8) involves comparing the future situations with and without climate change. This assessment may raise questions as to the desirability of developing and implementing mitigation and adaptation strategies. Thus, step 9 is an assessment of various policy options. In general, a policy option would consist of a mix of adaptation and mitigation measures. The adaptation measures considered here are those that would be in addition to the automatic or normal adaptations introduced into the future baseline in step 6. If the policies under evaluation provide effective mitigation or adaptation, they would alter and require a reevaluation of the situation with climate change. Evaluation of a specific policy response implies comparing two alternative futures, one with climate change but no policy response and another with the policy option under consideration. The following paper by Mendelsohn and Rosenberg describes in some detail seven components of a generic model for assessing policy responses to climate change.

Developing assessments for policy purposes

The appropriate scale and nature of an assessment designed for policy evaluation may differ depending on what questions it is designed to answer. Mitigation involves international or national issues; the atmosphere is a global commons, and the anthropogenic forces that are altering its composition and influencing the climate are global in nature. Individuals have no economic incentive to incur costs solely to benefit the global commons even when they have much to lose from climate change. Even for the United States, the world's largest contributor of greenhouse gases, the national benefits of adopting unilateral mitigation measures fall well short of the global benefits. Consequently, in the absence of an international perspective and accounting of the potential benefits, mitigation efforts based on cost-effectiveness criteria would fall well short of an efficient global mitigation strategy. However, because the climate, geography, social, economic, and ecological conditions vary widely around the world, local information is critical for understanding some implications of climate change. For example, determining if a species might go extinct or how the productivity of an ecosystem might change would require a local evaluation. Assessments of the national and international risks and possible benefits and costs associated with climate change may have to be largely induced from the results of many local and regional studies.

Uncertainty is another factor in the development and acceptance of a policy response. Although there is broad agreement among the results of the GCMs that increasing concentrations of greenhouse gases in the atmosphere will increase global average temperatures, the magnitude and timing of such increases are matters of debate. More importantly, there is wide uncertainty as to the likely changes in regional climates. Furthermore, the ecological and socioeconomic implications that would be associated with any climate change are highly uncertain. In view of these uncertainties, policy is likely to be driven by rough estimates of the risks and the magnitude of the impacts of climate change rather than by any detailed accounting of the global benefits of specific actions.

Even without great detail and complexity, climate impact assessments might provide insights into the ramifications of selected policies by addressing such questions as:

- How will the overall system (physical - biological - economic) respond to various imposed stressors?
- How do the uncertainties in the component models add up to give an overall system response uncertainty?
- Is society being made more vulnerable to extreme natural events either by changing those events or by reducing human ability to respond with corrective action?
- How likely is it that the consequences of climate change will be severe or catastrophic?
- What is at risk and when is it at risk?
- What are the likely impacts on the landscape and hydrologic system?
- How might the boundary conditions and the overall productivity of the forests, grasslands, and other rangelands be affected?
- How might increasing carbon dioxide levels affect crops and food supplies for humans, livestock, and wildlife?
- What are the socioeconomic consequences of these physical and biological changes?
- What are the likely consequences for ecosystems of mitigation actions?
- Can the costs associated with climate change be reduced through natural adaptation of ecosystems or policy-initiated adaptation?

The accumulated results of many regional and local climate impact assessments may help provide informed answers to these questions. Nevertheless, the uncertainties surrounding both the nature and the impacts of any future climate change are likely to remain very large, precluding precise estimates of the net benefits associated with alternative policy responses. Even if the range of uncertainty were diminished, it might still be difficult to justify specific measures on narrow economic grounds because (as

noted above) the impacts on natural resource systems are apt to be poorly reflected in standard benefit-cost analysis. Thus, for instance, mitigation investments may have to be justified as a means for reducing the risk of major and even catastrophic changes in natural resource ecosystems and for buying time to allow for adaptation.

The rate at which the climate changes and the expected timing of the climate-induced impacts are important policy considerations for two reasons. The more gradual and distant in time the changes are expected to be, the more future costs will be discounted and the greater the opportunities for adaptation. Discounting over time horizons of 50 to 100 years that are typically associated with climate change reduces the present value of future benefits and costs to insignificance. This is apparent when one considers that the present value of \$1,000 fifty years hence is \$1,000 without discounting (i.e., a 0 interest rate), \$87.20 at 5 percent, and only \$8.52 at 10 percent. Discounting, however, is controversial when applied to irreversible damages to natural resource systems. Indeed, some environmentalists argue that any discounting is inappropriate for evaluating the impacts of policies that deplete the resource base over time or impose risks on future generations.

In view of the uncertainties as to the timing and nature of climate change, one approach to adaptation is to develop strategies that make the system more flexible and responsive to change. Some such changes may be possible at little or no cost and may be warranted to stimulate economic growth and technological change even in the absence of climate change. Examples include institutional changes that facilitate the reallocation of water in response to supply and demand changes and development of drought resistant crop, tree, and grass cultivars. The threat of anthropogenic climate change provides additional justification for adopting such measures even in the absence of any detailed assessment.

Strategies for adding flexibility that involve significant costs would be warranted only when the prospect of specific climatic events is high. Detailed assessments of

regional climate impacts might be useful in making decisions about long-term investments that will still be operational within the time frame when significant changes in the climate are expected. Possible examples include the sizing of dams, the location of nuclear facilities, and the construction of facilities to protect coastal zones. Decisions regarding these facilities are based in part on expectations regarding extreme events such as floods and storm surges that likely would be altered by climate change.

Climate affects a number of management decisions such as the optimal level of fire protection, the allowable level of grazing, and the operation of dams for flood control or drought protection. However, the current variability of the climate independent of any long-term changes in climate averages are likely to dominate such management decisions for the foreseeable future. Indeed, Peter Rogers argues in this volume that climate change has little relevance for water management and investment decisions.

Toward integrated assessments

Figure 2 (the framework of an integrated global change assessment model being developed at Battelle/Pacific Northwest Laboratories by J.E. Edmonds, H. Pitcher, and N.J. Rosenberg) provides a schematic for conceptualizing the processes associated with

Figure 2: Schematic for an integrated assessment

the causes, nature, and implications of anthropogenically-induced climate change. This scheme differentiates among four components - socioeconomic, ecosystems, atmospheric chemistry, and the climate. To illustrate the linkages among these components, the socioeconomic component includes human activities that affect greenhouse gas emissions (e.g., fossil fuel combustion) and carbon sinks and reservoirs (e.g., land use and land cover modifications). The resulting changes in atmospheric chemistry affect the climate, and both of these components affect the productivity of ecosystems and human activities. For example, the climate affects space heating and cooling and water use; the growth of cities and other anthropogenic changes in the landscape affect the climate; atmospheric concentrations of CO₂ and climate variables such as temperature and precipitation influence agriculture and forestry activities; and changes in forest, grassland, and water resource ecosystems affect a variety of human activities. Of course, socioeconomic factors such as growing human population determine the demand for products of the land as well as energy and other natural resources.

An integrated assessment takes account of the important linkages and feedbacks among two or more of these components. "It seeks to encompass the hierarchies of interactions that occur within sectors, interactions between sectors, and feedbacks, including adjustments that may mitigate or exploit the effects of a climatic event." (Intergovernmental Panel on Climate Change, 1992, p.4). The Holy Grail would be a closed system, either a fully integrated model or set of linked models, that accounts for all important linkages and feedbacks among all four components of the system. Such a system would provide a turn-key set of linked, nested models and modules capable of answering all relevant policy questions about the implications of climate change (Stakhiv, 1993).

As with the Holy Grail, a fully integrated assessment is likely to remain elusive for the foreseeable future. In the meantime, integrated assessments involving selected components of the overall system can enhance our understanding as to the likelihood and

possible nature of climate change, the biophysical and socioeconomic implications of an assumed climate change, or the policy alternatives for mitigating and adapting to climate change. Research in all of these areas can help move us closer to the ideal fully integrated system.

A major focus of the research to date has been to model the atmospheric chemistry and climate components through general circulation models (GCMs). In addition, a substantial literature assesses the impacts of given climate scenarios (often based on the outputs of the GCMs) on natural resource sectors such as forests, grasslands, and water. The papers in this volume by Dale and Rauscher on forests; Parton, Schimel, and Ojima on grasslands; and Leavesley on water discuss and reference this literature. The papers by Binkley and van Kooten on forests, Conner on grasslands, and Rogers on water discuss and reference the growing literature that attempts to determine the socioeconomic impacts of climate change and current climate variability on these resources.

The Global Change Assessment Model under development at Battelle/Pacific Northwest Laboratories represents one of the few attempts to date to integrate across resource sectors to determine how the climate might affect the competition for land and water among agriculture, forestry, range, and other uses. Climate-change modeling has generally assumed land use would remain unchanged even though the results of some ecological and socioeconomic modeling suggest that climate change could substantially alter the ability of the land to sustain existing uses. Integrating among and within resource sectors to better understand the potential implications for land use and land cover is a major challenge for future climate assessments and a necessary task for evaluating feedback linkages from the biosphere to the climate (step 7 in the impact assessment procedure illustrated in figure 1).

Introduction to this volume

Robert Mendelsohn and Norman Rosenberg review the science issues underlying global climate change and its possible impacts on water and ecology and how analysts have attempted integrated assessments of what these impacts and their consequences might be. They do this through an exploration of seven natural science questions linking climate change to its impacts and three questions of how the importance of the climate change issue to society can be valued.

William Riebsame, William Meyer, and B.L. Turner II describe on-going work analyzing long-term changes in land use and land cover and suggest new approaches that could help establish land use and land cover baselines both with and without anthropogenically-induced climate change. The absence of analysis that integrates the biophysical and socioeconomic effects has been a major shortcoming of past efforts to model land-use and land cover changes in a changing climate. Biophysical modeling of the effects of climate change on vegetation cover fail to account for the direct human effects resulting from factors such as population, economics, technology, and policy. Socioeconomic modeling, on the other hand, tends to focus on the readily quantifiable factors such as population and market demand while neglecting climate change as well as potentially important policy changes that might result from changing values and attitudes. The authors also note the need for models that account for the interactions among multiple resources and that provide better ways to assess the cumulative effects of multiple stresses and of a single stress over time. Although they suggest that the first step toward better integrated assessments should be to link existing models, they indicate that new modeling approaches are needed to better deal with uncertainty and complexity.

These first two papers provide background for the following three pairs of papers that address the ecological and the socioeconomic impacts of climate change on forests, grasslands, and water resources. The first paper in each pair reviews the state of the art of modeling the biological and physical impacts of the climate on the respective resource.

The second paper in each pair reviews research on the social and economic implications of possible changes in the respective resource systems. Taken together, these six papers discuss analyses undertaken to date and identify the obstacles to and the opportunities for developing integrated assessments of the ecological and socioeconomic impacts of climate change on these resources.

Virginia Dale and H. Michael Rauscher review the state of modeling of the impacts of climate change on forests, including changes in the distribution and abundance of various species of trees. Models at four different scales (global, landscape or regional, community, and tree) are compared for their ability to provide the types of information that managers need to assess the impacts of climate change on forests. Although no single type of model can provide all the answers, landscape transition models and regional vegetation and land-use models are the most useful for examining the impacts of the climate on forests. The authors suggest ways for adapting risk assessment methodologies to deal with the impacts of climate change at various spatial and temporal scales. Recommended areas for future research are linking socioeconomic and ecological models, interfacing forest models at different scales, obtaining data on species-specific susceptibility to climate variables, and relating information from models that operate at different scales.

Clark Binkley and G. Cornelis van Kooten examine efforts to model the socioeconomic impacts of climate change on both the timber and nontimber outputs of the forests. The research to date is limited as economists have yet to effectively exploit the rich set of ecological models of the forests discussed by Dale and Rauscher. Much of the work that has been done focuses on the timber values of the forest and suggests that the net economic impacts are likely to be small because management regimes should be able to adapt to a changing climate. This sanguine outlook, however, does not extend to other products of forest ecosystems such as recreation and the distribution and abundance of animals and nontimber plants. Because trees sequester large quantities of carbon, forests

play a potentially important role in designing strategies to mitigate a greenhouse warming. Binkley and van Kooten examine how forest management might change if the full value of the carbon sequestration were incorporated in management decisions.

William Parton, David Schimel, and Dennis Ojima review the use of ecosystem models for assessing the impacts of climatic changes on grasslands. They present several reasons for suspecting that grasslands would be very sensitive to the types of changes associated with a greenhouse warming. First, the quantity and seasonal distribution of precipitation are very important in controlling the productivity and distribution of grasslands. Second, reductions in precipitation and increases in temperature may accelerate human-caused degradation of arid and semiarid ecosystems. Third, higher temperatures generally imply a decline in soil organic matter which is likely to lead to nutrient loss in the long term, degraded soil structure, increased erosion, and a release of CO₂ to the atmosphere. Fourth, an increase in plant productivity and water use efficiency associated with the CO₂ fertilization effect might offset some, if not all, of the negative effects likely to be associated with reduced precipitation and increased temperature. On the other hand, the CO₂ fertilization effect may accelerate the prevailing trend from the more productive grasses (many of which are C₄ plants) to woody plants (which all use the C₃ pathway). Current assessments of the geographical impacts of climate change on grasslands are limited by the lack of adequate model validations; lack of the needed spatially distributed input data on soils, topography, climate, and land use; and the coarse resolution of the output of the GCMs which does not approach the ecosystem scale. Despite the potential importance of climate changes on grasslands, the authors note that land use changes associated with direct human interventions will greatly modify and may overwhelm the climate-induced changes.

Richard Conner examines past efforts to assess the socioeconomic impacts of climate change on grasslands and discusses the obstacles to achieving more policy-relevant assessments. The inherent spatial and temporal variations in the productivity of native

grasslands pose problems in aggregating over economic regions the results of biophysical simulation models that do not accurately incorporate the heterogeneity and dynamics of the region's forage types. Another obstacle to assessing the implications of climate change is that animal performance models based on diets of known quantity and quality fail to describe the variable feeding conditions confronted by grazing animals. The difficulties of incorporating institutional and technological changes into future baselines with and without climate change are discussed. In concluding, Conner suggests a strategy for improving the efficiency and reliability of linking several current models to assess the socioeconomic impacts of climate change on grasslands for a specific region.

George Leavesley characterizes the current state of water resource modeling for use in simulating the effects of climate change and current climate variability. The methodologies and the deficiencies of four modeling approaches -- empirical, water balance, conceptual lumped-parameter, and process-based distributed-parameter -- that have been used to assess the effects of climate change are reviewed. These approaches have a number of problems in common that results in a large degree of uncertainty in the ability of current models to be climatically and geographically transferable. Leavesley identifies a number of research needs to address these problems. These involve developing (1) a more physically based understanding of hydrologic processes and their interactions, (2) an improved ability to measure and estimate parameters across the wide range of scales over which climate change impacts will be assessed, (3) quantitative measures of uncertainty in model parameters and results, (4) improved methodologies to develop climate change scenarios, (5) detailed data sets in a variety of climatic and physiographic regions, and (6) modular modeling systems to facilitate interdisciplinary research.

Peter Rogers notes that the weak point in water resource assessments is dealing with uncertainty in estimating the future supply and demand for water. The prospect of future climate change adds to the many uncertainties faced by water planners, but the outputs of

the GCMs are too coarse to help planners reduce these additional uncertainties. However, Rogers concludes that even if the climate models provided perfect predictions of basin hydrology forty or more years in the future, they would have little relevance for current water resource planning. Socioeconomic assessments of the factors affecting water resources suggest that even with the prospect of a significant greenhouse warming the uncertainties regarding factors such as population growth, income levels, and institutional changes are likely to be much greater than those surrounding the hydrologic variables, with or without climate change. A review of three case studies suggests that while human systems have considerable capacity to adapt to limit the adverse economic impacts of hydrologic changes, aquatic ecosystems may be more vulnerable to climate change.

The final paper summarizes some of the major conclusions of the papers and presents some conclusions, unresolved issues, and recommended next steps.

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FRAMEWORK FOR INTEGRATED ASSESSMENTS
OF GLOBAL WARMING IMPACTS

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An integrated assessment of global warming impacts requires coordinated and defensible inputs of natural science and economics in order to provide meaningful feedback to policy makers. This document reviews the structure of the assessment of greenhouse gases and summarizes current understanding of emissions and climate changes. The paper then highlights key issues which are particularly relevant to measuring the ecological impacts of climate change.

I. INTEGRATED ASSESSMENTS AND THE PROBLEM AT HAND

Alarming discussions of vast areas turned to desert or of coastal cities overwhelmed by rising tides have raised public interest in understanding the impacts of greenhouse gases on the earth. Hampering quick mitigative action in this area is the expectation of the large sacrifice required to slow the accumulation of greenhouse gases. In order to assess the strength of the steps needed to curb the growth of greenhouse gases, it is critical we begin to understand the consequences of greenhouse gases over time. Unfortunately, greenhouse warming is so complicated that there are few people in the world who comprehend all of its even most important dimensions.

The central purpose of integrated assessment models is to organize complex technical information across disciplines. Although a precise definition of an integrated assessment model has not yet been developed, it is clear that such a model should contain all the relevant information needed to address a specific problem. For example, if the problem was to determine the root causes of desertification, the model would need to include purely natural science information about climate, hydrology, soils, and ecosystems and also human behavior (such as land use and groundwater use) which might induce deserts to grow or contract.

In this paper, we wish to organize the vast technical information concerning greenhouse gases in order to determine whether additional control efforts are worth the cost. Thus, we develop a cost benefit approach to integrated assessment and explore its application to the general problem of controlling greenhouse gases.

A brief review of the science of greenhouse gases is presented in Section II. By its very nature, the greenhouse gas problem is interdisciplinary and global requiring close cooperation from numerous specialties including climatology, biology, and economics and requiring a scope of analysis which extends far beyond the traditional small region or setting. Integrated assessments provide a framework within which the needed cooperative work can be organized. The framework clarifies the logic of the overall analysis, assures that the analysis is comprehensive, identifies the links between associated processes, and provides clear assignments for each specialty.

There have been several attempts at building integrated assessments of various aspects of the global warming problem. Nordhaus (1991) was the first to build a fully integrated model, although he focuses solely on market impacts. Peck and Teisberg [1992], Nordhaus [1993], Falk and Mendelsohn [1993], and Manne, Mendelsohn, and Richels [1993] have completed dynamic versions of

greenhouse gas accumulation but their models remain simplistic. Other projects have examined pieces of the global warming problem in more detail but without addressing the entire issue. In the MINK (Missouri, Iowa, Nebraska, Kansas) study (see Rosenberg et al [1991]), a general methodology was developed for assessing the possible regional-scale impacts of climate change on natural resources, the possible responses to these impacts, and the possible overall effect of the impacts and responses on the regional economy. However, the MINK study provided information on only a single region and for only a single scenario of climate change. Edmonds and Reilly (1985) and Manne and Richels (1992) provide considerable detail concerning the energy sector of economies and how these sectors would react to different policies; yet these studies completely ignore the impacts of greenhouse warming. Currently, the Electric Power Research Institute (EPRI) is funding three groups--Carnegie Mellon, MIT, and Battelle/Pacific Northwest Laboratories--to build new forms of integrated assessments for greenhouse warming.

Integrated assessments of climate change impacts on regional and global economies are in their infancy and no one model yet exists that can be recommended for general use. Nonetheless, there are some key features which all the models must address. These features are clear and distinct enough to guide what science will be needed to make any assessment comprehensive. In sections III and IV of this paper we present the general framework for a generic model of an integrated assessment.

The quantification of possible climate change effects on ecosystems is one of the issues that has received the least attention in the overall greenhouse gas literature. Most of the resources in natural science have focused on atmospheric science and most of the policy work on natural systems has focused on natural systems as means of controlling ambient methane and carbon dioxide. The uncertainty surrounding the ecosystem effects component remains one of the largest in the model. In Section V, we discuss key issues which the ecological and water resource research communities must address as we work to develop truly integrated assessments.

II. GLOBAL WARMING AND CO₂-FERTILIZATION: THE SCIENCE BACKGROUND

II.1. The Radiation Balance and Greenhouse Warming

The mean flux density of solar radiation at the top of the atmosphere for the earth as a whole is 340 W m^{-2} . On entry to the atmosphere, a portion of this radiation is reflected (see figure 2) and a portion is absorbed, but the largest amount reaches the surface of the earth because the gases of the atmosphere are quite transparent to the visible radiation (0.4-0.7 micrometers) which predominates in the solar spectrum. The atmosphere, far cooler than the sun, emits radiation in the longwave or thermal band (8.0--14 micrometers) and some of this radiation is also directed toward earth.

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Figure 1. Schematic illustration of the earth's radiation and energy balances.

(Source: Figure 2-1 in S.H. Schneider and N.J. Rosenberg, 1989)..

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Figure 1. Schematic illustration of the earth's radiation and energy balances. (Source:

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A considerable fraction of the shortwave solar radiation that reaches the surface is reflected in the direction of space. The remainder of the shortwave and most of the impinging longwave radiation is absorbed by the land, vegetation and bodies of water. The energy not absorbed or consumed in evapotranspiration or photosynthesis is transferred back to space as longwave thermal radiation. However, natural constituents of the atmosphere – water vapor, carbon dioxide, methane, nitrous oxide and ozone – and some manufactured substances, such as the CFCs,

are partially opaque to the longer wavelength thermal radiation and trap a portion of it. A portion of the energy absorbed by these so-called 'greenhouse gases' is retained in the lower layers of the atmosphere raising its temperature. Were it not for this natural 'greenhouse effect' the atmosphere would be about 33 °C cooler on average than it now is.

Thus the radiation balance of the earth-atmosphere system is determined by the exchange of shortwave visible and longwave thermal radiation. This balance can change with changes in solar luminosity, variations in earth-sun orbital relations, volcanic activity and other events such as dust storms that alter atmospheric turbidity. Here, however, we are concerned with changes in the radiation balance induced by human activity that can lead to changes in climate. There are two avenues for this kind of change: changes in land surface conditions, especially albedo (reflectivity) for solar radiation and changes in atmospheric composition that alter its transparency, particularly to longwave radiation.

Land Use: The albedo (reflectivity) of earth's surfaces varies: for forest it is about 0.18 (18% reflectivity); for grassland about 0.24; for a lake about 0.10; for desert about 0.50 (Rosenberg *et al.*, 1983). Thus changes in land use, if on a large enough scale, can alter global climate by altering the amount of solar radiation retained at the surface. Land use change can also alter temperatures at the earth's surface and, hence, the emission of longwave thermal radiation which varies with the fourth power of the surface temperature.

Composition of the Atmosphere: Increases in the concentration of natural gases and industrial compounds such as the CFCs that have greenhouse properties have the potential to raise the temperature of the lower portion of the atmosphere – the troposphere. Atmospheric radiative transfer models indicate that a doubling in concentration of the greenhouse gas carbon dioxide (CO_2) would increase the net global average radiative flux at the top of the troposphere by 4.4 W m^{-2} – about 1.3% of the incoming solar flux at the top of the atmosphere. Other greenhouse gases – methane, nitrous oxide, ozone in the troposphere and the CFCs – also contribute to this potential for altering radiative flux. Warming increases the capacity of the atmosphere to hold water vapor which is, itself, one of the more potent greenhouse gases.

Other substances that derive from industrial and/or agricultural and biological systems can affect turbidity and cloud formation and these processes may augment or counteract the warming effects of the greenhouse gases. Some details on greenhouse gases and other climatic changing mechanisms are given below.

2.2. The Greenhouse Gases

The demands of this volume are best served by confining discussion to the greenhouse gases CO_2 , CH_4 and N_2O and to tropospheric ozone that originate, at least

in part, through biological processes and that directly affect biological/ecological processes. These gases are increasing in their atmospheric concentrations at rates that could lead to significant warming of the atmosphere in the coming century. The 1990 and 1992 IPCC reports provide information on their pre-industrial atmospheric concentrations, present day concentrations and current rates of increase.

2.2.1. Carbon Dioxide

Carbon dioxide had risen in concentration from a pre-industrial concentration of 280 ppmv to 355 ppmv in 1991 and continues to increase at about 0.5% or 1.8 ppmv per annum. IPCC estimates that CO₂ contributed 55% to the increase in radiative forcing caused by all the greenhouse gases between 1980 and 1990.

Annual emissions of CO₂ are estimated at 6.0 $\pm$ 0.5 GtC (gigatons of carbon) from fossil fuel use and from 1.6 $\pm$ 1.0 GtC from deforestation (IPCC, 1992). But the 1.8 ppmv/annum concentration increase in the atmosphere is equivalent to only about 3.8 GtC of the 6.3–8.5 GtC, assuming total emissions at the mid-point of the 6.1–9.1 GtC range. A major uncertainty about CO₂ is the exact disposition of the carbon emitted into but not retained in the atmosphere. Clearly, however, that 'missing' CO₂ must be taken up by terrestrial and oceanic sinks. The oceans until recently had been thought to be the major sink.

2.2.2. Methane

Methane is the greenhouse gas next in importance to CO₂ in radiative forcing. Its concentration has increased from a pre-industrial 0.8 ppmv to 1.72 ppmv in 1990, and is increasing now at a rate that has diminished during the past decade from about 20 ppbv (about 1.3%) to as little as 10 ppbv (0.6%) per annum. The IPCC (1990) estimated methane contributions to radiative forcing in the last decade at 15%. Current understanding suggests that a given quantity of methane emitted

into the atmosphere today will, after 20 years, be about 60 times more effective in warming the atmosphere than an equal mass of carbon dioxide emitted today.

Sources of methane are both industrial and biogenic.

Industrial sources include leakage from natural gas transmission and distribution systems and escape from coal mines and oil and natural gas wells. Biogenic emissions are the result of anaerobic decomposition of organic matter in natural wetlands, rice paddies and landfills. Methane is also produced as a by-product of animal digestion, particularly in ruminants and by termites and other insects.

According to Crutzen (1991) the total annual source of methane is 550 ± 105 Tg/yr. About 100 ± 20 Tg/yr comes from fossil fuels and methane hydrates.² If so, another 405 Tg/yr($\pm$) must come from biogenic sources. The IPCC (1990) scientific assessment estimates the range of current methane emissions (all in units of Tg/yr) as follows: 100-200 from natural wetlands; 25-170 from rice paddies; 65-100 by enteric fermentation (animals); 10-100 by termites; 20-70 from landfills; 20-80 from biomass burning; 1-25 from freshwater; 5-20 from oceans.

²According to Svensson et al., (1991) gas hydrates may be present under certain temperature-pressure conditions found in permafrost regions and in sea sediments of the outer continental margins. These hydrates are solids composed of water molecules with large amounts of gas (mainly methane) trapped in them.

This wide range of estimates indicates the state of our knowledge concerning biogenic emissions of methane. Lemon, Katz and Rosenberg (1991) have assessed the reasons for this great uncertainty. Emissions estimates are uncertain because of problems associated with 1) the measurement or estimation of gaseous fluxes, 2) the measurement or estimation of areas of the emitting ecosystems or populations of the emitting organisms or 3) systematic problems in integrating from a very limited observational base to the global scale.

Uncertainties of flux measurements stem from shortcomings in the instrumentation employed and from inadequate spatial and temporal sampling. Flux of methane is controlled by soil temperature, moisture content, aeration and acidity and other rate controlling factors. Correlations between these factors and rates of emission make generalizations from the very limited numbers of measurements very difficult. It is also now clear that soils provide a strong sink for methane (e.g. Whalen et al., 1991). IPCC (1992) puts this sink at 15-45 Tg CH₄ per annum.

Uncertainties in knowledge of the 'area factor' stem from inadequate definition of sub-ecosystem variations that affect emissions and from difficulties in accurately mapping land areas according to those distinctions. In the case of methane emitting domestic animals, difficulties arise in assembling accurate statistics on population and nutritional status, especially (but

not only) in developing countries. Difficulties are still greater in counting wild ruminants and in establishing the populations, by kind, of methane emitting insects.

II.2.3. *Nitrous Oxide*

Nitrous oxide has increased from its pre-industrial atmospheric concentration of 288 ppbv to 310 ppbv in 1990. Its current rate of increase is 0.20 and 0.30% per annum. Even though it is accumulating more slowly than CO₂ or CH₄, according to IPCC (1990) its effective warming potential per unit mass emitted today will, after 20 years, be about 270 times greater than that of carbon dioxide.

It now appears that nitrous oxide emissions are primarily biogenic in origin; previous estimates of large industrial sources having been due to measurement error. The biogenic emissions stem from biomass burning, natural, disturbed and cultivated soils and, possibly, from nitrogen-containing groundwater and the oceans.

According to the IPCC's 1992 estimates industrial processes including combustion account for only 0.8-1.8 Tg N/yr out of a possible total of 10.0-17.5 Tg N/yr. Biogenic sources account for the remainder. Wet forests produce 2.2-3.7 and other forests 0.05-2.0 Tg N per annum ; biomass burning produces 0.2-1.0; cultivated soils 0.03-3.0; and oceans, 1.4-2.6 Tg N/yr. One

estimate puts emissions from groundwater at 0.8-1.7 Tg of N_2O (Ronen et al., 1988).

Uncertainty of the estimates of biogenic N_2O emissions stem from the same causes as with methane: inadequate measurements, uncertain estimates of the areas of ecosystems involved and difficulties of integrating up from a very limited data base to the global scale.

Other Atmospheric Gases

As was pointed out above, ozone is a strong radiatively active atmospheric trace gas. Its concentration in the stratosphere is declining; however, in the first 10 km of the troposphere its concentration has increased by about 10% in each of the last two decades (IPCC, 1992). Precursors to ozone formation in the troposphere include carbon monoxide (CO), oxides of nitrogen (NOx), methane and non-methane hydrocarbons (NMHC). The concentration of tropospheric ozone varies greatly around the world. It is greatest in densely populated and/or industrialized regions.

II.2.4. Climate Consequences of Greenhouse Warming

What might be the climatic consequences of the rising atmospheric concentrations of CO_2 , CH_4 , N_2O and other greenhouse gases? While much can be learned about natural climate changes from paleoclimatic and modern records, theoretical models that

consider all components of the climate system--atmosphere, oceans, cryosphere, land-masses and biosphere provide the best means of predicting how natural and man-made phenomena can alter the workings of the climate system.

The general circulation model (GCM) is one such tool. A publication of Lawrence Livermore Labs (LLNL, 1990) describes the GCM in this way:

"GCMs divide the global atmosphere into tens of thousands of discrete boxes and use the dynamical equations of motion, energy and mass to predict the changes in winds, pressure, and water vapor mixing ratio (humidity). The vertical domain of GCMs typically extends from the Earth's surface to about 35 km; this distance is divided from two to twenty computational levels. The horizontal domain covers the globe with grid cells, each of which is several hundreds of kilometers on a side."

A survey of models reported in IPCC (1990) and reviewed in IPCC (1992) indicates "with high confidence" that an equilibrium climate change due to a doubling of CO₂ or its radiative equivalent due to all the greenhouse gases will warm the lower atmosphere (troposphere) and cool the stratosphere and that global average tropospheric warming will range between 1.5 and

4.5 C with 2.5 C as the 'best guess'.³ Rate of temperature increase could range from 0.2 to 0.5 C per decade with the 'best guess' at 0.3 C. Global average precipitation will increase as will evapotranspiration and the more the warming, the greater the increase for both. Global average precipitation and evapotranspiration are estimated to increase by 3 to 15%.

The changes described above will not be uniformly distributed around the globe. IPCC indicates, with a lesser degree of certainty than attributed to global mean temperature, that high latitudes will warm more than the global average in winter but less in summer, and that surface warming and its seasonal variation will be least in the tropics. Precipitation is projected to increase in the high latitudes throughout the year and in the mid-latitudes in winter. Zonal mean precipitation will increase in the tropics although there will be areas of decrease as well. Models differ considerably in the shifts of tropical rainbands that they predict. Little change is expected in precipitation in the subtropical arid regions. As a consequence of the above, soil moisture should increase in the high latitudes and decrease in the mid-latitudes of northern hemisphere continents in summer. The areas of sea ice and seasonal snow cover should diminish.

³This range was estimated prior to the recent evidence of a negligible or even slightly negative net radiative forcing by CFCs 11 and 12.

II.3. With What Confidence the Climate Change?

None of the twenty or so GCMs in current use can produce acceptably accurate representations of even current climatic conditions. While all are of basically the same design and derive in many ways from one another, the changes in climate they project for the future as the result of any particular change in atmospheric conditions (say a doubling of the pre-industrial CO₂ concentration or its radiative equivalent in all the greenhouse gases) differ in their estimates of global mean climate change and, particularly, in the regional distributions of change.

There are a number of reasons for the different results that emanate from current models and the general concern for their reliability. Grid cells in the current models are too large to allow important processes with global implications such as those controlling cloud size and amount to be captured. The treatment of cloud physics and effective coupling of atmospheric and oceanic dynamics needs to be improved. The GCMs also require improved parameterization of terrestrial conditions (plant growth, vegetation cover and roughness, for example). In general, a better understanding and parameterization of feedback processes is needed.

Perhaps most important is the current lack of understanding of feedbacks that can either amplify or dampen the climate response to additional greenhouse gases. Some possible climatic feedbacks to greenhouse warming are:

- 1) because of increased evaporation, water vapor increases in the atmosphere as it warms; water vapor is a strong greenhouse gas: positive feedback.
- 2) snow and ice melt as the atmosphere warms; snow and ice have high albedo; less solar radiation is reflected to space, more is absorbed: positive feedback.
- 3) the oceans warm; CO_2 dissolved in the upper layers is released to the atmosphere further increasing its CO_2 concentration and greenhouse forcing: positive feedback.
- 4) warming causes melting of permafrost in the arctic exposing organic materials to respiratory decay and release of CO_2 into the atmosphere: positive feedback
- 5) warming in high latitudes causes the release of methane trapped in hydrates: positive feedback
- 6) but warming dries the soil; dry soils are a sink for methane and can lower its concentration in the atmosphere: negative feedback
- 7) warming and increased water vapor in the atmosphere lead to changes in cloud amount, cloud altitude and cloud water content: both positive and negative feedbacks are possible
- 8) dimethyl sulfide (DMS), a gas released by certain species of marine phytoplankton and bacteria, is oxidized in the atmosphere to form compounds that act as cloud condensation nuclei (CCNs). Under warm conditions, the marine organisms produce more DMS increasing cloudiness--particularly low stratiform clouds--over the oceans: negative feedback
- 9) rising CO_2 concentration stimulates photosynthesis and reduces water use extending the extent of healthy green ground cover. More carbon is sequestered: negative feedback; albedo decreases: positive feedback
- 10) decomposition of soil organic matter increases with rising temperature: positive feedback

II.4. What Does the Record Show about Global Warming?

Available data do not yet show conclusively that climate changes of the kind predicted by the GCMs have in fact occurred. According to IPCC (1990) the global mean temperature according to IPCC (1990) has increased by 0.3- 0.6 C over the past century--an increase that is consistent with expected greenhouse warming, but not in itself evidence of it.

The observed warming, if due entirely to an anthropogenic greenhouse effect, would be near the lower end of the range predicted by GCMs for the radiative forcing of greenhouse gases added to the atmosphere in the past 100 years. If natural variability accounts for some of the observed warming, then the climate sensitivity would be still lower. IPCC (1990) suggests the possibility that larger greenhouse warming could have been offset in part by natural variability (on the cooling side) and by other factors, also perhaps anthropogenic.

Interestingly, studies of the climate record for the 48 contiguous states (Karl, 1991; Hanson et al. 1989) show no long term trend in annual mean temperatures. Although the 48 states comprise a very small fraction of the earth's total surface this region has one of the most dense and reliable weather networks. Even more interesting from the point of view of biological processes, the records reveal that while mean temperatures have

not risen, nighttime temperatures have risen slightly (Karl et al., 1991). Observations in the Soviet Union and China confirm these results. Such an effect is consistent with increased atmospheric water vapor content and/or increased cloudiness both of which reduce the escape of thermal radiation to space. Increasing global haze provides another possible damper on the warming that GCMs indicate should already have been observed and may also account partially for the increase in nighttime temperatures. Sulfur emitted from smokestacks is oxidized to sulphuric acid droplets which are capable of reflecting sunlight back to space. Shading by a sulfate haze could be counteracting almost half of the Northern Hemisphere temperature rise that would have occurred as the result of increases in concentrations of all the greenhouse gases added to the atmosphere since pre-industrial times (Kerr, 1992; Charlson et al., 1992).

II.5. Direct Effects of CO₂ on Plants

II.5.1. *Fertilization and Water Use*

We turn now to a different subject but one closely related to greenhouse warming. It is a well-known and demonstrable fact that plants, when exposed to increased concentrations of carbon dioxide, respond with an increased rate of photosynthesis. Such increases in photosynthesis normally lead to larger and more vigorous plants and to higher yields of total dry matter (roots, shoots, leaves) and often of fruits, grains, etc. The behavior

described here is demonstrated particularly by plants of the C_3 category which includes most of the world's small grains, legumes, root crops, cool season grasses, and trees. Another category of plants, the C_4 or tropical grasses such as corn, sorghum, millet, and sugar cane, are naturally more efficient photosynthesizers than the C_3 plants. They too respond, but less markedly, to increases in atmospheric carbon dioxide.

The C_4 plants, however, show another interesting response to increased carbon dioxide in the atmosphere: their consumption of water by transpiration is reduced because of partial closure of the leaf stomata (pores) induced by high carbon dioxide concentration. This effect occurs also in C_3 plants. The reduction in transpiration is not accompanied by any significant loss in instantaneous photosynthesis and usually results in greater total photosynthesis where moisture savings occur.

Agronomic experiments for the most part support the statements made above. For example, Chaudhuri et al. (1990) grew winter wheat over three growing seasons at 340 (ambient), 485, 660, and 925 ppmv of CO_2 at both high and low levels of water supply. Yields of wheat increased in both water regimes and at all levels of CO_2 above the ambient. In this experiment water requirement was reduced by elevated CO_2 with the greatest reduction in almost all cases with the first increment of added CO_2 . Water use efficiency (production per unit of water

consumed) was increased because of reduced transpiration and increased photosynthesis.

If the findings from laboratory, greenhouse and open chambers upon which the above statements are based can be extrapolated to the open field agriculture, we may expect important benefits from the increasing concentration of carbon dioxide in the atmosphere--increased photosynthesis in many important species and decreased water consumption in most species. Further, laboratory, controlled environment and open-top chamber experiments have shown that CO₂-enrichment of the atmosphere actually reduces the impacts of moisture and salinity stress on plants (Rosenberg et al., 1990). A summary by Allen et al. (1990) shows that high temperature stress is also alleviated by CO₂-fertilization. The effects on nutrient stress remain less clear at this writing. We still do not know whether these laboratory-demonstrable CO₂ effects on photosynthesis and transpiration do now or will occur in the future in the field where temperature, moisture and nutrients are the factors that normally limit plant productivity.

The evidence suggests that increased capture of CO₂ by the terrestrial biosphere (including agricultural ecosystems) should be occurring. One item of evidence supports this view. The amplitude of the annual CO₂ concentration wave at Mauna Loa is observed to be increasing. This suggests that total global

biomass, total global photosynthesis, or both are increasing (Kohlmaier et al. 1987). Either effect could be due to CO_2 -stimulation of plant growth and would be consistent with the assertion by Tans et al. (1990) that more of the 'missing carbon' has been and is being captured by vegetation on land and less by the oceans.

CO_2 -enrichment of the atmosphere could also lead to some troublesome effects. Because of the special benefit that C_3 plants derive from elevated CO_2 , C_3 weeds may become more dominant where they grow in association with C_4 plants. Additionally, the C:N ratio increases in leaves of plants fertilized with CO_2 . Some short-term studies show that herbivory increases as insects consume more vegetation to satisfy their nutritional needs (Lincoln et al., 1984). Later studies suggest more complicated outcomes, however. Over longer periods, the population of insects feeding on plants stimulated by higher CO_2 would likely decline in response to the diminished proportion of nitrogen in the plant tissues. As pest populations decline so too would the populations of their predators (Fajer et al., 1989). The long-term ecological changes that might follow from increasing CO_2 concentration in the atmosphere are difficult to predict (Bazzaz and Fajer, 1992). However, the impacts on agriculture of changes in weed competition and insect activity would probably be less profound than they would be in ecosystems that are unmanaged (Rosenberg, 1992).

The foregoing information on plant responses to CO₂-enrichment has been derived almost entirely from agronomic and horticultural experiments under controlled environment conditions or in a few cases with chambers enclosing small clusters of plants in a crop field. Only a very few studies have been conducted in natural ecosystems under ambient conditions and most of those, too, have involved the use of chambers enclosing clumps of vegetation. In most of the recent studies chambers are opened at the top so that artificiality of the chamber environment is minimized.

Results of two studies in widely contrasting unmanaged ecosystems are particularly interesting. Tissue and Oeschel (1987) studied the response of tundra vegetation in Alaska to CO₂ enrichment over a number of years. Despite an initial positive growth response to CO₂ enrichment in one type of tussock grass, overall the species studied grew no better than plants exposed to unenriched air. Low temperatures and photosynthate accumulation (lack of capacity of the plant to store increased photosynthate) may be responsible for these results.

On the other hand, Drake (1989 and personal communication⁴) has found that marsh vegetation enclosed in open top chambers on

⁴Personal communication, B.G. Drake, Smithsonian Institution, Edgewater, MD, May 1991.

the shore of the Chesapeake Bay responds positively to CO₂ fertilization. This response continues after five years of observation and is greater for *Scirpus olneyi* (a C₃-plant) than for *Spartina patens* (a C₄-plant). The reasons for the different outcomes of the Alaska tundra and Chesapeake marsh experiments are not yet clear although differences in climate are probably involved. There is evidence that response to CO₂-enrichment is limited by low temperature (Idso et al., 1987; Allen et al., 1990).

Because of the many complicating factors induced by the artificiality of experimental environments it will be some time before we have definitive answers on whether CO₂ fertilization will actually affect photosynthesis in totally natural open-air environments. Attempts to measure open-air responses began in the 1970s in experiments where CO₂ was released directly into crop fields (Harper et al., 1973a, 1973b for cotton; Allen et al., 1974 for corn). These experiments failed to provide definitive results, primarily because of the difficulty of maintaining elevated CO₂ concentrations in the air surrounding plants in the face of normal atmospheric turbulence which tended to remove it rapidly.

Since then technological advances have made open air CO₂ enrichment research possible. In a program called FACE (Free Air Carbon Dioxide Enrichment) sponsored by the U.S. Dept. of Energy

and conducted by the U.S. Dept. of Agriculture, equipment has been developed to maintain an elevated level of CO₂ in the air within and above crops for the duration of entire growing seasons (Hendrey and Kimball, 1990). The FACE system was originally tested in a Mississippi cotton field using industrial by-product CO₂ and is now working in a field near Phoenix, Arizona. Cotton crops have been grown for two years with CO₂ held at a concentration of about 550 ppm.⁵ Cotton growth and yield has been about 40% greater with CO₂ enrichment. Seasonal water use may not have been affected although use appears to have been greater early in the season because of more rapid crop growth while the stomatal closure effect reduced use later in the season. Water use efficiency was improved in direct proportion to the increase in yield.

The CO₂-fertilization effect adds one more layer of uncertainty onto our analysis of the potential impacts of anthropogenic greenhouse gas emissions. For agriculture and managed forests, on the one hand, the fertilization effect is more likely than not to be beneficial because of direct stimulation of the photosynthetic mechanism and suppression of transpiration. Other effects that might be counter-productive in agriculture such as stimulation of the growth of C₃ weeds or increased herbivory because of reduced nutritional quality of the

⁵Personal communication, Dr. Bruce Kimball, USDA/Water Conservation Laboratory, Phoenix, AZ., February 1992.

plant leaves can be overcome by means of readily available management techniques. For unmanaged ecosystems, however, the longterm effects of CO₂-fertilization are far less clear. Most of us would consider it inappropriate to apply management tools, even if available, to unmanaged ecosystems. Application of a chemical pesticide to contend with a CO₂-induced increase in the population of a particular plant or insect species can set in train all manner of changes in the dynamics of the hitherto unmanaged ecosystem. Add to this the difficulty of knowing how the greenhouse forced climate change *per se* affects population and spatial distribution of individual species and interspecific dynamics and we realize how complicated the outcomes may be for unmanaged ecosystems. This unpredictability of climate change and CO₂-fertilization impacts on unmanaged ecosystems is, perhaps, the strongest justification for trying to halt or, at least, moderate the flow of radiative trace gases into the atmosphere.

II.6. Summary

Driven by a variety of natural causes, climate is continually changing. Now, however, human activities, particularly land use change and the emissions of greenhouse gases into the atmosphere, appear likely to induce other changes in climate and at an unprecedented rate. The most likely change is a general warming of the lower layers of the atmosphere due to

enhancement of the planet's natural greenhouse effect. This will be forced by the rising concentrations in the atmosphere of carbon dioxide, methane, nitrous oxide and the CFCs. But predicting when, where and by how much not only temperature but also precipitation, windiness, cloudiness, soil moisture, etc. will change and what the consequences of these changes might be is extremely difficult. Current projections made with general circulation models encompass great uncertainties because of the complexity of climate dynamics and the many feedback processes that greenhouse warming might invoke.

Of the greenhouse gases now increasing in atmospheric concentration because of human activity carbon dioxide is the most important from the point of view of radiative forcing. Increased atmospheric concentration of CO₂ has also been shown to increase plant growth and reduce water use in agricultural crops and it likely does so in other terrestrial ecosystems, as well. While supporting evidence is difficult to obtain, it seems likely that the CO₂-fertilization effect is already being expressed and is responsible for the sequestration in terrestrial ecosystems of a large portion of the CO₂ emitted into the atmosphere by fossil fuel combustion and deforestation. These direct (non-climatic) effects of CO₂ will be beneficial to agriculture and forestry. It is not at all clear, however, that the changes that occur in the dynamics, species distribution or provenance of unmanaged ecosystems because of CO₂-fertilization would be beneficial.

III. FRAMEWORK OF AN INTEGRATED ASSESSMENT

An integrated assessment model is a tool in the policy process to help understand the implications of taking a specific action or failing to take any action. In this case, we imagine the model being given a set of policies to analyze. For example, the model could analyze a set of control policies. Each policy results in a path of emissions and certain implementation costs. The model then follows these emissions through the environment and predicts the effects which emanate from this initial disturbance. The final result is a set of damage estimates which are expected to occur if that policy were undertaken. The policy process, using the integrated assessment model to evaluate competing alternatives, can then select the most desirable policy.

Although policy formulation is not a formal part of an integrated assessment model, it is helpful to know the range of policies being considered in order to design a model. Conceivable policies for coping with greenhouse warming might range from doing nothing at all, controlling the demand for or the supply of energy, to changing the ways in which land is used. Actions to control emissions will impose costs on society. In turn, these actions will change the path of emissions which could modify the rate and or direction of climate change and the consequent environmental effects.

What follows is a generic model for integrated assessments: it is not the only blueprint for this purpose. The nomenclature we apply to the framework components may not be congenial to each and every analyst and, therefore, these components may justifiably be labelled differently by others. However, while their names are subject to negotiation their inclusion in the integrated assessment in some form is not.

The integrated assessment model in this paper evaluates the consequences of alternative policies to control greenhouse gases. The model has seven component parts, as shown in Figure 2: ECONOMIC RESPONSE, DISPERSION, CLIMATE CHANGE, ECOSYSTEM EFFECTS, ECOLOGICAL VALUATION, HUMAN SYSTEM IMPACTS, and HUMAN IMPACT VALUATION. These components logically follow one another in a chain of causation. Each component part tends to fall within the competence of a specific discipline.

The model has a clear flow associated with the consequences of one action upon another. Possible feedback loops from later components back to earlier ones are not shown in the diagram. For example, it is possible that the ecosystem effects due to climate change may alter the carbon cycle which in turn could affect the ambient concentration of carbon dioxide in the atmosphere. If such feedbacks turn out to be important, the figure would have to be amended to take these feedbacks into account.

FIGURE 2
SCHEMATIC OF AN INTEGRATED ASSESSMENT MODEL

Note that the overall purpose of the integrated assessment is to display the consequences of any policy in a manner accessible to and understandable by the policy maker. The framework displayed in the figure divides consequences into two categories: implementation costs (e.g. costs of reducing emissions) and benefits (reduced negative impacts). It should be stressed that the framework allows for consideration of market and nonmarket impacts of climate change. For example, impacts on items sold in markets such as food, energy, and coastal structures are measured and valued. Items valued by society but not bought and sold in markets should also be counted such as health effects, wildlife, preferences for warmer climates, endangered species, and ecosystem boundaries. Valuing these nonmarket services is an exciting new area in economics.

The schematic may give the misleading impression that the model is deterministic. An important aspect of global warming is that substantial uncertainties surround the sign and magnitude of the final impacts that result from greenhouse warming. The degree of uncertainty may be important in determining which policies are prudent and which are not. The integrated assessment should consequently make provision for the inclusion of some measure of uncertainty in the construction of each framework component. Results should be expressed in terms of both an expected value and a variance. (Scientists who sometimes feel reluctant to convey an uncertain value can thus express

their concern by revealing the uncertainties associated with any estimate). Policy makers, rather than being overwhelmed by the precision of a highly uncertain number, will be able to give that number the weight it deserves given its reliability.

Figure 2 is also deficient in its representation of time. Figure 2 may give the misleading impression that greenhouse gas policies and impacts involve a single period. However, an important characteristic of the greenhouse gas problem is that it involves a very slow accumulation problem. The optimal policies designed for this problem and the resulting consequences are long-lasting and dynamic. A more robust representation would need to convey this intertemporal dimension of the model.

IV. OUR INTEGRATED ASSESSMENT FRAMEWORK

The initial input into the model is a specific set of regulations or actions which provide incentives or disincentives to which the economy responds. These policies, by changing behavior in one way or another, affect the behavior of the integrated assessment model. For example, abatement policies affect economic activity which in turn alters emission paths. Policies which increase or inhibit adaptation may result in changing the physical impacts and their value for an otherwise identical emission trajectory.

COMPONENT 1: ECONOMIC ACTIVITY

The economic activity component describes activities of society which have led to greenhouse gas emissions. Man-made emissions are due primarily to energy use and the ways in which land is used. The economic activity model examines these two sources and sinks and links these activities with emissions. There are two important outputs from this component. First, the economic response model will evaluate how emissions will change as a result of abatement. For example, a particular rule may be promulgated to tax energy. The effect of this rule on energy use and greenhouse gas emissions would be predicted by this component. The consequence of this reduction could then be explored by running the rest of the model with this changed element. Second, the economic response model will also generate an estimate of the cost of abatement. This is an important output since the cost of abatement is one of the key final outputs of the integrated assessment.

A key issue to raise with respect to this component is the need for a complete accounting of what society loses by adopting any particular policy. Clearly this accounting would include consideration of increased out-of-pocket expenses such as the use of more expensive fuels or increased capital outlays. However, there may be other costs to consider. First, policies to deal with global warming may cause prices to change in some markets especially those for energy. The costs of these price changes

should be evaluated using consumer surplus estimates. The consumer surplus is the area underneath demand functions. It captures the value of changing quantities which result in changing prices.

Second, the costs of regulations are sometimes borne in lost qualities or attributes, not necessarily additional expenses. For example, forcing people to drive lighter, more fuel efficient cars could increase the risk of injury while also decreasing performance of the car, e.g. rougher ride, reduced speed of acceleration. Mileage standards may lead to lower cost cars but the buyers may feel they are losing aspects of automotive quality that they are willing to pay for. To the extent that these lost opportunities are realized, they must be quantified and included as costs.

COMPONENT 2: DISPERSION/ATMOSPHERIC CHEMISTRY

From the projected emissions of greenhouse gases derived in the Economic Activity component, the Dispersion component predicts atmospheric concentrations of each relevant greenhouse gas. To accomplish this task requires contributions from several disciplines. First, there is the simple physics of accumulation. Ambient concentrations also involve complex chemical reactions involving atmospheric chemistry. Finally, there are sinks and sources of greenhouse gases in nature which could interact with the man-made emissions. Understanding the methane, nitrogen

oxide, and carbon dioxide cycles involves a host of biological and physical sciences.

One of the most sensitive issues requiring consideration in the Dispersion component is whether the natural sources and sinks of the greenhouse gases themselves respond to changes in atmospheric concentrations or in climate. As is shown in the following section, subtle effects on the natural cycles and biogenic emissions could be very significant and possibly overwhelm the anthropogenic contributions.

COMPONENT 3: CLIMATE CHANGE

The Climate Change component predicts the relationship between climate and ambient concentrations of greenhouse gases as is explained in Section III in greater detail. These models, starting from radiative forcing, must take into account heat and water transport in the earth's atmosphere and predict how climate will eventually be changed as a result of these higher concentrations. At present, our vision of how climate might change is based on the results of three-dimensional GCM (General Circulation Model) "experiments".

Although substantial resources have been devoted to calibrating and building GCM's, there remains substantial uncertainty about many of their integral parts. Concerns about the role of clouds, the generation of precipitation, the role of

ice, the interaction with oceans, soils, and the biosphere, and the role of other gases in the atmosphere remain unresolved. Further, the models still struggle to reproduce the current regional climates of earth.

The key output of the climate change component is a detailed geographic distribution of climate across the terrestrial portions of the earth's surface given the ambient concentrations of greenhouse gases. In addition to predicting changes in the average temperature of the earth, it is helpful for the models to predict credible geographical distributions of temperature change. Specifically, the model's should include predictions of the ground level temperature and precipitation level in each of four seasons on a finer geographical scale than currently available from GCM's.

However to drive impact analyses, other measures may also be needed. For example, episodes of extreme weather may yield health effects (Kalkstein 1991), year-to-year variance in temperature and precipitation may affect agriculture (Shaw, Mendelsohn, and Nordhaus 1994), and changes in the intensity, frequency, or geographic distribution of storms may have serious coastal impacts. Sea level changes from melting sea ice and ocean expansion are also items of concern (Titus 1992).

COMPONENT 4: ECOSYSTEM EFFECTS

The Ecosystem Effects component of the integrated analysis framework is likely to be of great importance for two reasons. First, it is possible that the reaction by natural systems to climate change will provide feedbacks to the methane, carbon, and nitrogen cycles. Since the absolute levels of emissions from these sources and sinks greatly outweigh human emissions, even subtle changes in the natural cycle can be of great importance. Second, the impacts of climate change and carbon dioxide on ecosystems might be substantial. Natural systems may adjust poorly to rapid climate change leading to major disruptions such as species loss, boundary shifts, and population shifts.

Over the last decade, several teams of scientists have begun developing models of ecological responses to climate change. To date, however, none of the integrated assessment models of climate change have incorporated these models. There are several reasons why this has not yet been accomplished. First, existing integrated assessment models have not carried sufficient geographic detail in their climate components to motivate ecological models. Second, it is not clear what outputs from ecological models are important. Third, the ecological models tend to be long run equilibrium models whereas most of the integrated assessment models need a dynamic ecological model.

As a first step towards bringing ecological models into integrated assessment frameworks, it is helpful to outline what role the ecological model is to serve. In Figure 3, we illustrate how a simple ecological model would function in an integrated assessment framework. This is at least one version of what the framework would want from ecological models. Several experimenters have already integrated climate and ecological models although the temporal and spatial aspects of this connection need to be developed. What has been left untouched is the connection between the ecological model and impacts. Not only has this connection yet to be quantified, few scientists have even volunteered what should be measured. In this section, we explore a select list of desired outputs from the ecological model.

The ecosystem model begins with climate outcomes at each location and derives changes in ecosystem levels which matter to people. This derivation is complicated and involves many equilibrating forces. It begins with a direct interaction between the climate and a large set of living things (a dose response relationship). Some of these plants and animals are sensitive to climate change and will become more or less productive (capable of surviving). This initial dose response drives the ecosystem to change. The ecosystem model must capture both this initial response as well as the ecological response to this disturbance of equilibrium.

In Figure 3 we characterize the equilibrating forces of the ecosystem using two activities: a food chain link and a competition link. The purpose of presenting these activities is to convey the likelihood of indirect ecological changes (see Root and Schneider 1993). The reduction of a basic food source because of the climate change, for example, will tend to limit the populations which feed on that specific source. Similarly, the reduction in productivity of a particular plant may allow competing plants to flourish. It is important to model these indirect consequences. First, it is only through the indirect consequences that many of nature's creatures manifest their importance to man. For example, virtually all organisms involved in decay processes are of no direct interest to man. They are, however, valuable because of their role in disposing dead biomass, thereby allowing ecosystems to renew themselves. Since we value the renewability of the ecosystem we indirectly value the decomposers. Second, a substantial fraction of the changes which occur to plants and animals which are of direct interest to humans will probably come through indirect ecosystem effects rather than direct dose response effects. For example, deer may

FIGURE 3
ECOSYSTEM EFFECTS MODEL

be sensitive to both direct changes in climate as well as the resulting change in food supply and cover. Song birds may be affected directly by temperature changes but also by changes in their habitat (see Root and Schneider 1993).

It is important to specify what products the integrated assessment requires of the Ecosystem component. The outputs should be in terms of ecosystem changes that matter to society. Ecosystem services may matter to society because they affect the economy directly (market goods) as in the case of altered timber supplies or fisheries productivity, because people directly rely on them for favored activities such as with fishing and hunting, or because people simply care about an ecosystem or a specific species through indirect activities such as hiking, passing by, or reading.

It is relatively clear which outputs fall into the category of market products. Market goods such as timber and grazing lands are readily bought and sold and then used as inputs by the economy. It is also clear from analyses of outdoor activities that species such as game and recreational fish populations used for consumptive activities are valuable services of ecosystems. The ecosystem outputs which are more difficult to identify concern services which involve only passive use or no use at all. For example, what features of a forest are important to automobile riders as they drive by nature? What do people want

saved when they support wilderness areas in a region of the country they tend not to visit? What are the ecosystem outputs that ecological management is supposed to produce?

Before delving into the details of final outputs, it is helpful to distinguish between intermediate products of the Ecosystem component and its final outputs. The final outputs are changes in the ecosystem that matter to people. Intermediate products include measures of phenomena affected by climate change that in turn affect the overall functioning of the ecosystem. Intermediate products tend to be readily quantified and they are important for deciphering how the ecosystem functions. However, intermediate products should not be confused with final outputs. Intermediate products such as ecosystem primary productivity, photosynthetic rates, and biomass per acre are all measures of ecosystem productivity but they do not clearly correspond in and of themselves to something society values. Generally, another connection needs to be made to link these intermediate products with something society wants.

The final outputs of the ecosystem component can be divided into four key types: changes in productivity per unit land area, ecosystem boundary shifts, species extinction, and feedback loops to climate change. Productivity changes should be focused on key species of direct interest to man. The productivity of market inputs are clearly important. What is needed is specific

information on sustainable harvest levels which are tied to average growth rates of market species. In timber, this would be reflected by average growth of the bole of each commercial tree species. With fisheries, it would be measured in terms of the average growth rate of the population of each commercial fish species.

The productivity of nonmarket species which society wants is also important. For example, the sustainable harvest level of game and recreational fish species would be relevant measures. The sustainable population size of watchable wildlife such as grizzly bears, elk, great herons, eagles, and song birds are all potential measures. More subtle measures such as the growth rates of undergrowth or noncommercial tree species may eventually prove significant as well. However, these latter measures are not developed as yet and it is not clear that they will ever be of the same significance as the measures already listed.

The public has been exposed to visions of entire lush natural ecosystems collapsing and turning into moonscapes as the result of climate change. Similarly, scientists could show pictures of the earth spinning and turning ever more green with a warmer, wetter, and CO₂ enhanced environment. While these visions may never come to pass, one cannot easily dismiss the possibility (perhaps, likelihood) of significant changes in the boundaries and community structure of major ecosystems. Whether

subtle, as the shift from an oak-hickory forest to a mixed hardwood spruce forest, or dramatic, as the movement from Pacific Northwest Douglas fir forest to Northern Californian grass lands, possible shifts in ecosystem boundaries (landscapes) should be described in quantitative terms, so far as possible.

Boundary shifts will tend to impact both market goods and nonmarket goods. For example, boundary shifts will alter the possibilities for growing specific commercial tree species in specific areas. Boundary shifts will also change recreational opportunities, wildlife abundance and scenic vistas. Boundary shifts could result from changes in sea level and incidence of storms, as well.

Through both changes in relative productivity of different species and wholesale ecosystem boundary changes, some species will inevitably be driven into endangered status or lost entirely while some currently endangered species may improve. Depending upon the rate of climate change, some poor dispersing plants for example may not be able to migrate fast enough. Even relatively mobile species can be caught by the increased fragmentation of ecosystems neighboring their current territory. Existing programs to protect existing habitats become ineffective strategies as climate change forces changes in land use patterns not conservation of existing land use.

Special efforts will be needed to measure just what species and how many will be affected by climate change. Clearly, there are biologists who view all species as equally important. However, studies of human preferences, such as the work by Steve Kellert, indicate that the general population values more highly developed species (antelopes over ants; lodgepole pine over lichens). From the perspective of the ecosystem component, this fact suggests that lumping all species together would be inappropriate. Separate measures should be computed for all of the lower order creatures. As one approaches higher order animals, counts should become more refined including individually listing and quantifying all mammals which might be affected.

Most of ecological modeling, like climate change modeling, has focused as a first cut on describing new equilibria which would occur as a result of climate change. This work is helpful in describing the magnitude of change likely from climate scenarios as well as the type of changes. However, most of the ecological equilibrium work focuses on impacts which will occur several centuries in the future. Short of future catastrophes, the shorter term impacts will be more important from a policy perspective.

More insight is needed in describing the short term ecosystem dynamics. First, the dynamics or transient conditions may be more important than equilibria because it take so long to

reach new equilibria. Second, the process of climate change is expected to continue for centuries. Thus the initial stimulus will continue changing. The ecosystems are unlikely to reach equilibria while climate continues to change. Third, the level of services during transitional periods may not simply be a weighted average of the initial and final states. Whole mature systems may yield to a world dominated for a time by early succession species. Modeling this dynamic process explicitly can reveal a very different picture compared to analyses of equilibria.

The Ecosystem component must produce a set of products linking ecological feedbacks to the other components of the framework. Changing climates are likely to affect the growth rates of plants in terrestrial and marine environments. These changes could profoundly impact upon the methane, carbon, and nitrogen cycles. The ecosystem component must explore the extent to which greenhouse-forced climate change and increased atmospheric CO₂ concentration would alter the major sources and sinks for these greenhouse gases. Because albedo of the surface affects climate dynamics, the ecosystem component must also report back to the climate component on how the landscape changes as ecosystem boundaries shift.

The ecosystem component should take changes in precipitation and temperature patterns and predict the direct impacts on water systems. There are two measures of direct interest: water flows

(runoff) and water temperature. The flows are important in water scarce regions such as the American West. They may also be important in restricted systems such as eastern reservoirs where water is stored for municipal uses. Finally, flows can be important if they change the frequency or magnitude of floods or droughts. In order to capture all of these effects, efforts to link precipitation to flows must be done in enough representative water systems to provide regional predictions for every region.

Information is needed on more than just the average annual flows. Depending upon the final user, the seasonality of water flows is important. Thus, at a minimum, one would want average flows by season. However, to capture flood and drought concerns and storage issues, the probability of different levels of daily flows is also important.

In addition to examining flows, changes in water temperature are also important. Temperature affects cooling water efficiency in power generation. Temperature also affects profoundly the productivity of fisheries, especially cold water fisheries. Slightly higher water temperatures could drive miles of cold water habitat into strictly warm water fisheries.

COMPONENT 5: VALUING ECOLOGICAL EFFECTS

The value of changes in the ecosystem must take into account natural and economic adaptation. For example, some of the

natural shifts which would occur in forests could be resisted using forest management. Species which are disadvantaged by climate change could be assisted with active habitat management. Losses of water flows could be dealt with by conservation, reallocation of water shares, or building new physical storage capacity. None of these solutions will completely eliminate climate impacts nor are they cost free. However, large scale adaptation can significantly mitigate the effects of ecological responses to climate change. In particular, it is likely that the parts of the ecosystem which are managed for market goods such as commercial forests can be readily adapted to climate change.

Another important adaptation question concerns whether human institutions will adapt to climate change. Some changes in climate will increase pressure to change both the quantity and use of natural resources. For example, if warming resulted in increased shortages of water in the West, there would be increased pressure for Western water to be allocated more efficiently. Such changes, however, are not automatic and political realities may postpone change indefinitely. Many existing institutions which control water allocation are designed to prevent change. If these institutions resist or even postpone reforms, they will increase the damage from climate change.

Policy changes must be modeled as part of the general adaptation by society. They can be treated either as part of the overall process of adaptation (internal to the model) or as an explicit policy option (an input to the model).

The value of changes in market outputs from ecosystems are readily measured given available data. Small changes in market outputs such as timber and fish can be valued at the price that producers pay for such goods. For example, timber should be valued at its stumpage price and fish should be valued at ex-vessel price minus marginal harvest costs. Large changes in market outputs will cause the price to change so no single price can be used for valuation. Large price changes should be valued using consumer surplus methods.

Consumer surplus methods calculate the area underneath demand functions in order to reflect the changing prices associated with a large change in quantities. For example, in Figure 4, the value of a reduction of water from Q_0 to Q_1 is shown. Given a flow of Q_0 , we observe that a marginal unit of water is worth P_0 . With a reduction in water flow to Q_1 , prices rise to P_1 . The original price P_0 , multiplied by the change in quantity, would understate the value of this reduction of water. Similarly, using the final price P_1 , would overstate its value. The shaded area under the demand function values each unit of

water at what its price would have been. This shaded price is the correct measure for the water loss.

Nonmarket goods that people use directly can be measured by means of a number of behavioral methods. These methods reflect what people do, not what they say they would do. In practice they appear to provide excellent measures of the value of goods and services which are not traded in the market but which people directly enjoy. For example, one can value ecosystems using the hedonic travel cost method (see Brown and Mendelsohn 1984 and Englin and Mendelsohn 1991). Similarly access to public spaces and other natural amenities near homes can be valued using the hedonic property method (see Freeman 1979). Hedonic methods estimate the value of characteristics when a good is purchased. If the value of the surrounding ecosystem is a characteristic of a home purchase, their value should be reflected in house prices.

The visitation value of ecosystems can be measured using various travel cost methods. Specific site attributes such as old growth forests (Englin and Mendelsohn 1991), game population densities (Mendelsohn 1984) or water quality (Smith and Desvousges 1985) can be valued using advanced travel cost methods such as hedonic travel cost, generalized travel cost, and discrete choice techniques.

How to value nonmarket goods that people do not experience (nonuse values) or which they have not yet experienced is more controversial. Contingent valuation or attitudinal methods are used most often in such circumstances. People are surveyed and asked to place value on specific resources, i.e. what they would be willing to pay to assure the continued existence of the resource. Although this approach may seem simple, two decades of research on contingent valuation has revealed that in this context contingent valuation remains complex and contentious (see Cummings et. al. 1986).

Aesthetic values (use or nonuse) that the public places on ecosystems have not been systematically quantified. Research to date has tended to focus on valuing specific places rather than types of ecosystems or site characteristics. The few studies which have delved into the value of site characteristics yield reasonable responses but these studies are not comprehensive. For example, it is clear that hunters and fishermen value catch per unit of effort which is a proxy for population density (although it can be influenced by other factors such as cover). In special cases, such users also value trophy individuals, catch of unusual size or special species. However, the desired composition of most forest, range, or wetland systems, preferences for growth rates, and preferences for change or stability have not yet been measured. It is important that such valuation studies begin immediately so that at least initial values are available for immediate policy decisions.

COMPONENT 6: HUMAN SYSTEM EFFECTS

In addition to altering ecosystems, climate change will directly impact human activities. Significant impacts on aesthetics, agriculture, energy, coastal lands, and health are possible. In the context of this paper we consider agriculture under human system effects rather than ecosystem effects because humans exert extensive control over farmland. Health effects are also listed on the human system side although they too involve a natural science component.

One approach to modeling human system effects on, for example, agriculture and health, is to model all the physical linkages between climate, the directly affected system, its response, and then valuation. For example, one could model climate impacts on soil, water, pests and crops, measure the resulting change in productivity, examine how these effects alter farmer decisions, and then model the change in agricultural supply. The appeal of this approach is the linkage between cause and effect. The problem is that it is often difficult to understand all the linkages and responses between climate and outputs. Consequently, it is also useful to explore how existing human systems have reacted to surviving in different climates across space. This simple empirical analysis can highlight what effects are important and what are trivial. Of course, cross sectional studies such as these can also be misleading if other factors vary in concert with climate.

Climate change can have a number of quantifiable impacts on humans. Agricultural yields can change for various species. Heating and cooling days will shift by region. Mortality and morbidity rates by age and sex could be affected. Each of these can be studied using carefully controlled natural experiments.

These direct impacts, however, must be analyzed carefully in order to estimate measures of damage. With respect to all of the effects listed above, people can adapt and thereby change the resulting damages. For example, human health effects would be quite different were people to continue behaving as though the weather was cool after it had warmed up considerably. However, once people adjust their clothing, housing stocks, health care, and behavior, the altered climate may have much less of an impact. The same phenomenon applies to farming and energy. Farmers could adapt to new climates by changing their choice of crops, planting dates, rotations, and fertilization and tillage practices. Energy consumers could adapt to warmer environments by changing their insulation, clothing, and habits. It is essential that all efforts to measure direct impacts of climate change on human systems consider the potential for economic adaptation. Otherwise these efforts will lead to serious and unrealistic overestimates of the damages of climate change.

Observations about how readily economies adapt to long run change provide another interesting insight into climate change.

To the extent that climate change can be viewed as a steady smooth transition from one climate regime to another, it is likely that most human systems will adapt. However, if the transition is instead characterized as a set of wild swings dampening to a new equilibrium, adaptation will be far more difficult and there will be far greater costs. Similarly, the mean precipitation and temperature of a new equilibrium climate may actually be less important than the variance associated with the climate. Initial work on agriculture suggests that changes in diurnal and year-to-year variance of temperature may be more important than mean temperatures (Shaw, Mendelsohn, and Nordhaus 1994).

COMPONENT 7: HUMAN EFFECT VALUATION

Because the phenomena used as measures of human effects are often market goods, valuation of these effects is relatively advanced. If they are small, changes in agriculture and energy can be valued by means of existing prices. Large changes can be quantified using consumer surplus and existing demand functions for each good.

Analyses of differences in rents of agricultural lands located in different climates can reveal the final impact of climate on agriculture. This Ricardian approach has been successfully implemented by Mendelsohn, Nordhaus and Shaw, 1993, for US agriculture. Similarly analyses linking energy

expenditure to climate could be used to determine effects of climate on energy demand.

Nonmarket human effects have also received substantial attention. Mortality rates have been valued using the hedonic wage method. The wages of similar people living in different climates are compared. If one climate is preferred to another by wage earners, theory suggests that firms in such an area could pay lower wages than similar firms in more undesirable climates. The differential in wages is a "second paycheck" reflecting people's preferences for living in one climate rather than another. Initial work in this area suggests that people prefer warmer climates across the United States.

Contingent valuation has also been used to value health effects. People have been asked how much they would pay for small reductions in their probability of dying each year. Contingent valuation has also been used to place a value on morbidity. Morbidity, unfortunately, is a complex phenomenon involving various levels of discomfort, duration, and future health scenarios. Further, the value of morbidity to an individual will depend upon guaranteed sick days, health insurance, and the psychological costs of illness. Thus, morbidity values are difficult to quantify.

An additional measure which could be used concerns awards given in legal cases. Accidental deaths and injuries often leads to liability suits with resulting monetary awards. These awards, however, often involve more than just the value of the damage. Quite often attorneys press for punitive damages which are meant more as punishment than compensation. Further, people tend to be more sympathetic with a specific person who has been injured than they are to an unknown statistical person. Thus, a jury may award a large figure to compensate for the loss of a specific father to an attractive family but yet hesitate to support that level of expenditure on safety programs to protect unknown future victims. To the extent that people turn to court awards for measures of value, they must carefully weigh these other factors.

V. KEY ISSUES FOR ECOLOGY/WATER

The review of the integrated assessment and science in Sections II and III raises a number of uncertainties with respect to global warming effects in the area of ecology and water. In this chapter, we highlight these issues. Seven are natural science questions which link the initial climate stimulus to important final effects. Three key issues are valuation exercises which measure the importance of the issue to society. For each of these questions, we need to develop a clear list of methodologies, data requirements, and studies which should be

undertaken to resolve them. The papers in this volume provide a modest movement in this direction.

- 1) Do changes in ecosystems provide important feedbacks to the natural carbon, nitrogen, and methane cycles? For example, will the natural sinks or emitters be affected by changing precipitation, temperature, and CO₂ levels?
- 2) What are the appropriate output measures of ecosystem component models? What are the ecological effects of climate change that policy analyst can use to determine the importance of an ecosystem change?
- 3) What climate change-driven shifts in ecosystem boundaries can be predicted? Will these effects be subtle and small or large and dramatic and over what time frame and spatial dimensions?
- 4) Will climate change cause a change in the productivity of valuable market or nonmarket species? For example, to what extent will some forests grow more quickly or more slowly? Will desired nonmarket species such as bear, elk, and bald eagles be more or less plentiful?
- 5) What species could be lost with rapid climate changes? How do the vulnerable species break down by type and geographic

distribution? How should conservation policies adapt to a world requiring change?

- 6) How are ecosystems likely to change as the climate evolves over time? Will there be a large increase in early succession species and where?
- 7) How will average flows in rivers change with greenhouse warming? How will these flows change over seasons? Will the probabilities of catastrophic events change?
- 8) What values do people assign to the changes in ecosystems caused by climate change? Which changes are important and which are minor? Can a value be assigned to nonuse?
- 9) How much should society be willing to pay to reduce the probability of losing specific species? If different scenarios favor different species, how should society trade between these outcomes?
- 10) What impact do ecosystem changes have upon the economy? For example, how will climate change affect grazing, commercial fishing, timber, or commercial tourism?

This introduction serves as a starting point for the investigation of ecological/water effects from greenhouse gases.

A comprehensive framework has been developed and a number of difficult questions have been asked. We end with a challenge to provide defensible answers.

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Modeling Land Use and Cover as Part of
Global Environmental Change

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ABSTRACT

Land use and cover change are important elements of the larger problem of global environmental change. Land use patterns result in land cover changes that cumulatively affect the global biosphere and climate. We describe efforts to analyze the driving forces behind land transformations and to create land use models that can be linked to other types of global change models. Two efforts to model land use in the U.S. are described, one projects aggregate agricultural, forest, and range land, and the other attempts to model forest land use change at the parcel scale in two mountain landscapes. We conclude with suggestions for new approaches that could clarify the role of land use/cover change in global change and in natural resources management.

INTRODUCTION

Land use and cover change are important elements of the larger problem of global environmental change. Land use

patterns, driven by a variety of social causes, result in land cover changes that affect biodiversity, water and radiation budgets, trace gas emissions and other processes that, cumulatively, affect global climate and biosphere. Moreover, the mix of land use/cover in a place affects its sensitivity to climate change: e.g., dryland farming areas may be more sensitive than irrigated areas. While most attention in global change research has been on the causes and impacts of climate change, any conception of global change must include the pervasive influence of human action on land surface conditions and processes. Work is needed to create historical reconstructions of land use/cover, to analyze the social driving forces behind land transformations, and to create land use modeling approaches that can be linked to other types of global change models, especially climate models (Jacobson and Price, 1991, Committee on Earth and Environmental Sciences, 1991, Stern et al., 1992), and to efforts to model biodiversity change.

Conceptual models of land transformation, eventually to be operationalized into simulation models, are beginning to appear as a new International Geosphere-Biosphere Program/Human Dimensions Program (IGBP-HDP) "core project" on global land use/cover change is planned (Turner et al., 1993). But researchers delving into this seemingly simple aspect of nature and society interaction quickly realize that land use/cover is a complex phenomenon reflecting a wide range of social and natural processes (Meyer and Turner, in press; Riebsame et al. 1994).

Understanding, modeling, and projecting land use/cover is as difficult, and as important, as modeling ecosystems or global climate.

We describe selected efforts to model land use/cover not as an exhaustive review, but as a way to identify strengths and weaknesses, and challenges, in the field. Our choice of examples is driven by our goal of citing efforts to integrate economic, ecological, and social factors even if all factors cannot be handled quantitatively.

LAND USE AND LAND COVER

Land use and land cover are distinct but closely linked characteristics of the earth's surface. Agriculture, logging, grazing, and urban development are land uses; crops, forests, grasslands, and roads and buildings are categories of cover, as are soil, ice, and water. Land use affects land cover, and changes in land cover affect land use. A change in either, however, is not necessarily the product of the other. Cultivation may be abandoned on a particular tract--a change in use--because market conditions have made farming unprofitable, or because land quality has been so degraded as to make continued cropping unprofitable or environmentally unacceptable. Land cover may likewise be altered by forces other than human use (e.g., weather and climatic fluctuations, ecosystem dynamics, air pollution, and so on).

Changes in land cover driven by land use can be divided into two types: modification and conversion. Modification is a change

of condition within a cover type (from, say, unmanaged forest to a forest managed by selective cutting). Conversion is a change from one cover type to another (e.g., deforestation to create cropland or grassland). This paper draws mainly on examples of conversion, which has been the focus in land use analysis; additional work is needed on the effects of modification, especially in the United States where major land cover patterns are relatively stable, but significant modifications occur within these patterns.

LAND TRANSFORMATION: A LONG-TERM VIEW

Data on land use/cover are highly variable in coverage and quality according to the area, time period, and purpose for which they are sought. Statistics for the U.S. are much more reliable and detailed than for most of the rest of the world, but still fall short of the quality needed for detailed study of land transformation. We address the need for more spatially explicit data later in the paper.

Data problems notwithstanding, some global generalizations are possible about major forms and trends of land use/cover change, especially for cropland, forest, grassland, and settlement or urban area (Table 1). Cropland has expanded dramatically over the past three centuries, perhaps the most extensive and outstanding anthropogenic transformation. However, cropland has declined in parts of Europe and North America, allowing some forest expansion and illustrating how global or even national statistics can hide significant regional trends.

World forest area has diminished some 15-20% in post-glacial times. Most of the net clearance has occurred since the mid-nineteenth century. The global trend since 1950 has been continued loss due to rapid clearance in the developing countries, and stability or increases in forest area in most of the developed countries (Williams, 1990). Further variation is apparent, though, at finer scales of analysis; the United States as a whole, unlike most other affluent developed nations, has experienced a modest decrease in forest cover since the 1950s (Platt, 1991, 7-8). Significant forest expansion in the rural Northeast has been overshadowed by timber harvesting in the Northwest and clearance near cities in the East.

The net global area of grassland has remained largely constant over the past three centuries (Richards, 1990) and the past several decades (Graetz in press). Yet large areas of grassland have been created by deforestation (especially in Latin America) and others have been converted to cropland (especially in North America and Southeast Asia). Thus, this global conservation of grasslands conceals major land use change and regional variation.

Globally, urban areas have grown in size, actually becoming less densely settled in affluent countries where suburbanization has taken place. Only some 2% of the earth's surface can be considered "urban", and perhaps only a tenth of this is densely built-up (Meyer and Turner 1992). Yet this area now holds half the global population.

Overall, land use historians find a long-term global trend toward greater intensity of particular uses and the replacement of less intensive by more intensive uses (expansion of cropland and settlement at the expense of forest, grassland, and "wastelands"). Most analysts attribute these broad land use trends to the monolithic trend of increasing global development. But land use/cover changes have not occurred in a linear or globally uniform fashion, and represent instead the aggregation of different trends varying widely by time and place. Land use does not display a simple association with broad trends in society and economy, despite efforts to link it to monolithic variables, like population, production, and consumption. Land-use/cover changes in the Western U.S., for example, are as much related to national and international markets and policies (e.g., trade agreements, commodity prices, federal lands policy) as to local/regional socioeconomic changes (e.g., changing labor demands in agriculture). Accounting for this variability is an important challenge to land modeling.

MODEL TYPES AND TOOLS

Conceptual models, some operationalized into computer simulations, can aid inquiry into the complexities of land use and cover change. Land use models have pursued several (to some extent overlapping) goals: description (detailed or simplified inventory and assessment of land use and cover); explanation (connecting patterns of use and cover to their social and physical causes); projection or prediction (forecasts of future

conditions, based on extrapolation or theories of process and assumptions about social and ecological contexts of those processes), and prescription (planning and policy based on normative criteria and social goals, such as preservation, economic efficiency, or social equity).

A recurrent problem with land use/cover modeling (and modeling in general) is that the assumptions and goals of a given study are often neglected in interpreting the results. For example, prescriptions (what uses should be made of a parcel of land) may be misinterpreted as predictions (what uses will be made of it), as descriptions (what uses are being made of it), or as explanations (why certain uses are being or will be made of it). This is not to argue against any of these modeling goals, but rather to point out that confusing them leads to confused interpretations, and that analysts must be cognizant of these different goals in employing any one kind of model or in attempting to link multiple models.

BIO-PHYSICAL MODELING

Our focus in this paper is on social modeling, but a brief examination of methods for modeling bio-physical land cover illustrates some theory-driven predictive approaches and their interpretation.

Vegetation cover modeling is often highly abstract and normative; that is, vegetation is mapped not according to empirical patterns, but in terms of "potential" or "climax" plant communities--those that would exist at a site if it were not

disturbed (e.g., cultivated or covered with concrete) over a sufficiently long time. In climate impact assessment, vegetation cover is often synonymous with natural or unmanaged terrestrial plant communities, whether they exist in reality or not (Tegart et al., 1990; Panel on the Policy Implications of Greenhouse Warming, 1992, 575). Large-scale natural vegetation has traditionally been extrapolated from indices of temperature, precipitation, and evapotranspiration (e.g., the Holdridge Life Zone Classification system--see Shugart et al., 1986). Thus, projections of vegetation change under climate change are often just maps of a climate derivative, with other factors (e.g., soil and pests) assumed to be constant. Such climate-correlative methods do not necessarily simulate actual vegetation cover in the current or future climate; rather, they offer a norm to which actual vegetation can be compared. In reality, potential natural cover rarely exists, chiefly because of its disturbance or removal in any area with a significant human presence.

The most sophisticated projections of vegetation cover come from simulations of the biological dynamics of vegetation change, in concert with abiotic factors such as soils and topography. Species demographic and growth models are replacing climate-correlative approaches. Solomon and West (1987) modeled growth factors such as nutrient uptake, competition, birth and death, and moisture utilization to project how eastern forest species would respond to climate warming. In similar work, Shugart and West (1980) used demographic process models (termed "gap models")

in which each plant is modeled as a unique entity and tracked over time through normal or disturbed life cycles. The aggregation of species-specific outcomes yields maps of vegetation communities. Smith et al. (1992) applied this approach to global and regional projections of climate change. Increasingly realistic pictures of future vegetation cover should emerge as modelers enlarge their efforts to multiple species and their interactions, thus creating simulations of possibly totally new vegetation complexes. Unfortunately, such modeling requires so much information about species behavior and driving forces that only small areas and numbers of species can be modeled and mapped.

The stochastic nature of vegetation change raises some questions about model validity, and a combination of descriptive and theory-driven modeling has emerged in range science to better account for non-linear thresholds in vegetation change. The traditional successional model is being replaced by "state and transition" models (Westoby et al., 1989; Laycock, 1991; Committee on Rangeland Classification, 1994) conceptualized as multiple possible vegetative states connected by transition probabilities. Of particular interest in terms of land use and cover in this new thinking is that human interventions might change the probability of transitions over time, or might create one-way transitions into new landscapes that do not re-cycle in the classic successional sense. These sinks or "black hole" states, from which the vegetation cannot transit given current

climate, have exciting conceptual implications, linking notions of landscape robustness and resilience to emerging concepts like chaos and complexity. We return to these ideas in the final section of the paper.

SOCIOECONOMIC MODELING OF LAND USE

Many trends in social modeling of land use parallel the biophysical modeling; correlative methods are being replaced by theory-driven algorithms. The dominant emerging approach to predicting (and explaining) land transformation is the notion of "social driving forces," especially population and consumption. Correlative links between driving forces and land use are combined with projections of driving force change (e.g., population growth) to predict changes in land uses in a given area.

Macro-scale Models

The simplest and best-known attempt to bring together multiple social driving forces of environmental change is the "I = PAT" formula, which equates environmental impact (I) with the product of population (P), affluence (A), and technology (T) (Ehrlich and Ehrlich 1990). In one form, this simply partitions the components of production: pollution emissions, for example, are identified as the product of the number of consumers, resource demand per capita, and pollution emissions per unit of resource use. More generally, it can be taken to suggest that impact is directly related to human numbers and wealth, and is either amplified or diminished by technology.

Employed mainly by natural scientists and engineers addressing the abiding population and resource issue (e.g., Commoner, 1989; Ehrlich and Ehrlich, 1990), the $I = PAT$ formula has not, for a variety of reasons, been widely accepted by social scientists (Sage, in press). It is not seen as offering much insight beyond a restatement of the overall human dimensions of change. Critics also argue that to represent impact as a direct function of affluence ignores situations in which poverty drives unsustainable resource use and others in which affluence actually aids environmental protection. Population and resource equations also routinely fall into the "ecological fallacy" of ascribing characteristics of the whole to the parts: e.g., a high level of population growth may accompany environmental degradation, suggesting a situation of population-driven damage, yet the damage might be the work of a small fraction of the population (e.g., political or economic elites) that is growing not in numbers but in influence. The equation also does not address the location of impact, though, in a global economy, demands and impacts are often experienced far from their origin and the seriousness of their impact depends in part on where they are manifest.

These objections point to the need for incorporating social science knowledge about such variables as politics, economics, culture, and the geographical patterns of human activity, all widely identified as important influences on environmental change. The roster of driving forces has been divided into five

categories: population change, technological change, affluence/poverty, political-economic structure, and beliefs and attitudes (Meyer and Turner, 1992; Stern et al., 1992). Existing macro-scale models do not at present appear adequate to capture this social complexity.

Meso-scale Models

Specific meso-scale models developed for studies of particular regions and land uses do incorporate some of the richness of multiple social causes. The traditional focus of this work has been on economic forces controlling urban land value based on the theory of land rent originating with Ricardo and von Thünen (Hall, 1966; Kim 1986). Most such models rest on the assumption that land managers attempt to maximize their economic returns, and little attention is paid to other socio-cultural goals. Economic land use models assume competitive land markets, as exist in cities and some prime agricultural areas (Hazell and Norton, 1986), but such assumptions probably do not hold for deeply rural or wild areas. Indeed, the long history and relative sophistication of urban land-use modeling (e.g., stands in sharp contrast to the state of modeling of rural lands (Birch 1968), with which this paper is principally concerned. The gap between urban and rural land-use modeling skills must be narrowed if we are to understand better the state of land cover over most of the world's surface area.

Nevertheless, classical economic models offer an explicit social theory of land use that can be examined in detailed cases.

In theory, any parcel of land, given its physical qualities and location, will be used in the way that earns the highest rent. The driving forces of change operate through their integrated effect on the net return of alternative uses of the land. An individual land manager's decision to undertake investments or transformations will be determined by comparison of discounted benefits and costs (including opportunity costs). Many such studies simulate land use for specific industries (e.g., coal mining or dairying), and, in theory, these patterns can be aggregated across economic sectors in a traditional input-output model (Abler et al. 1971). Alternatively, given sufficient data, land rent analyses can be dis-aggregated down to individual parcels and owners, where the returns of different uses can be calculated and compared directly (Kim, 1986).

Econometric approaches may not reliably reconstruct land use, however, because significant spatial externalities exist in any case where social and institutional factors reduce the power of individuals to optimize returns. Non-market values, satisficing rather than optimizing behavior, and non-user benefits are likely to be important in many land use situations, especially where extensive public lands exist or where particular externalities of land use are generated (non-point source pollution in agricultural regions). The modeler's toolbox for including such factors includes hedonic price assessment methods and more controversial approaches such as contingent valuation and other survey tools (Mitchell and Carson 1989).

Even these methods remain more or less within an overall paradigm of optimum economic utility (Etzioni 1988). Challenges to such traditional elements of economic modeling as the use of market interest rates for discounting (see Lind 1982; Page 1988) have raised further questions as to the compatibility between the optimizing norm and other concerns such as sustainability and intergenerational equity. Especially in cases of large public land holdings, economic approaches will have to be supplemented with ones informed by theory from the other social sciences. Political science and political economy, for example, have developed theories of managerial and regulatory behavior that can be applied to land use: how land management agencies might be "captured" by land user groups being regulated, how cycles of institutional forms and attention affect oversight, and how institutional structure affects land use outcomes. Blaikie and Brookfield (1987) use the term "political ecology" to refer to such processes, and show how they play out in cases of land degradation. But, land use models have not so far incorporated these processes to any significant extent.

EXAMPLES OF LAND USE MODELING

Two examples of rural land use modeling in the U.S. illustrate some of the approaches just discussed. The first falls under the category of aggregate economic modeling, in this case an attempt to predict future commercial forest area. Such natural resource modeling is mostly based on national or regional

aggregate data de-coupled from their geographic characteristics (e.g., location, shape, and spatial linkages). Some of this spatial de-coupling occurs at higher levels of analysis, while the original data retain land unit addresses. Much of it, however, occurs at the primary level, where field data are collected and accumulated to larger units, making it difficult in the future to dis-aggregate the analysis into geographically-explicit studies.

The second example illustrates landscape scale (or "spatially-explicit") land use/cover modeling in which parcels of land are addressed individually at or near the scale of field data collection or logical units (e.g., ownership, habitat, etc.), and where the geographical characteristics of land units (e.g., location and spatial relationships) are explicitly factored into the analysis.

Aggregate Approaches: The Resource Planning Act Assessments

A major effort to assess and project natural resource conditions in the U.S., including aggregate land cover and use, emerged in the last decade, chiefly within U.S. Department of Agriculture agencies. Spurred by several pieces of legislation--the 1976 National Forest Management Act (NFMA), the 1977 Resource Conservation Act (RCA), and the 1989 Resource Planning Act (RPA), the U.S. Forest Service (USFS) was required to analyze supply and demand for forest and range land resources and to project these 50 years into the future (in keeping with Forest Service planning horizons under NFMA). This yielded the most comprehensive

assessment and modeling of aggregate land cover and use in U.S. history.

The RPA placed a new emphasis on land cover and land use modeling rather than the traditional practice of static land use mapping, though a large initial effort was still needed to reconcile land inventories developed by various federal agencies (USDA Forest Service, 1989a). Projection approaches included a mixture of extrapolation, expert opinion, and econometric modeling of agricultural, forest, and range lands (USDA Forest Service, 1989a, 6). We focus here on the forest studies.

RPA Land Modeling Approaches. The first round of RPA assessments relied mostly on expert opinion to project changes in major land uses. The 1989 (second) assessment used a combination of econometric and ecological modeling and expert opinion. Expert opinion was needed, the analysts argued, because land ownership patterns and the behavior of many actors--public land managers and private land owners--was simply too difficult to model in a realistic way. The experts provided trends and constraints on changes to guide the more narrow economic models--in essence the human mind was asked to conduct the integrated, qualitative modeling of individual and collective behavior that was required, but could not be computerized.

The second RPA assessment used expert opinion and econometric models that allowed dynamic simulation of competing uses and resulting changes (USDA Forest Service, 1989a, 72). Baselines, constraints, and trends of land use and forest and

range land ownership were first evaluated by canvassing regional expert opinion for guidelines used to initialize and constrain the economic models. The core econometric model was developed by Alig (1986; see also Alig et al., 1983) and applied regionally- and nationally-aggregated land use data. Alig's model projected land area changes as a function of regional population growth, income, resource demand, and a set of national driving forces. When applied to private land, the model assumes maximization of economic benefit as discussed earlier (Alig, 1986, 120-22). Expert opinion was used to guide the models when logic suggested that landowners would not seek to maximize profits (e.g., government agencies seeking to meet other mandates such as habitat preservation, or environmentally-committed land owners).

Driving Forces and Assumptions. The RPA assessments are useful examples not only for their use of expert opinion, but for the way that assumptions were made about macro-forces that will shape future resource demand over the next 50 years. In a sense, a form of the I=PAT equation was used, and a set of key factors was distilled from the many forces acting on land use: population, GNP and related income and capital, energy costs, red meat consumption (for rangeland projections), and institutional and technological change (USDA Forest Service, 1989b). The RPA analysts took a conservative approach in assessing these social contexts, arguing that the forces affecting resource demand "are shaped by massive social, political, technological and institutional forces that are not easily or quickly changed.

Recent trends are likely to persist over the long run with some short-term fluctuations" (USDA Forest Service, 1989b, 2). This conservatism shows up in assumptions about, for example, capital availability (judged to be similar to the past), population (Bureau of the Census "middle series" estimates, though with a relatively high immigration factor), and assumptions that public lands policy will change little over the next 50 years.

Some Results: Forest Land in the U.S. Based on the driving assumptions, expert opinion, and Alig's econometric modeling at the regional level, forest area change was projected to 2040 (Figure 1). It may have been inevitable that the decrease in forest area observed since the 1960s would continue, given assumptions about population and income growth which set the demand for residential and commercial land development. It is also assumed that suburbanization near cities drives conversion of forest land to crops in other regions, but this geographical pattern was not explicitly modeled. Rangeland (not shown) increases slightly, as cropland reverts to grassland due either to economic forces (modeled explicitly) or federal conservation programs (constraints based on expert opinion). Perhaps the most striking result of this study is the projected stability of the land base. While some countries are converting forests to other uses by several percent per year, the U.S. projections are for only a 4% reduction in forest area and a 5% increase in rangeland over 50 years.

Some of this stability is a reflection of constraints forced

into the economic model from the survey of expert opinion. But, it may not be safe, for example, to assume that federal land management will change little over the next fifty years. Only about 3% of the forest land of the U.S. is reserved from timbering (as wilderness or parks), and most of that is on the 28% of forest land in public ownership. While it is reasonable to suppose that no major changes will occur in the gross land area of public forests over the next several decades, some of the same forces driving land conversion on private forests (increasing population and income) are likely to drive increasingly preservationist policy on public lands. This will, in turn, affect demand on private lands. Other factors that contribute to the relative stability projected by the RPA assessments include assumptions that harvested land is successfully reforested and that no major ecological or environmental changes will occur. Nevertheless, such approaches as translating expert opinion into model constraints is the only currently operational way to entrain many cultural and institutional forces into quantitative models (Riebsame et al. 1994) and deserve more attention as a modeling strategy.

Landscape-Scale Approaches

Although aggregated data and modeling of, say, demand for crop or range land at a regional scale, may be suitable for national policy analysis, it will not elucidate patterns of land transformation at the landscape or land parcel scales important to many ecological and social processes. The RPA modelers want to

extend the work to landscape scale studies, but the only region thus far modeled parcel-by-parcel is the southeastern U.S. (see Parks, 1988; Parks has started similar work in the Pacific Northwest).

In landscape scale modeling, discrete land units are mapped in a geographic data base and their transformations simulated through time as they are influenced by social and ecological forces. Several landscape scale approaches to land cover modeling exist, but few studies of land use at this scale, outside of cities, can be identified. The GAP models discussed earlier are one example, as is the Coastal Ecological Landscape Spatial Simulation (CELSS) Model developed by Costanza et al. (1990). CELSS simulates biotic and abiotic dynamics of marsh and estuarine complexes in southern Louisiana. It maps out detailed coastal dynamics based on human interventions (chiefly canal and levee construction), but does not explicitly model the social driving forces behind those interventions.

In another landscape-scale study, Lee et al. (1992) have developed a conceptual and operational framework for modeling forest landscape change based on ecological variables and social driving forces. They are attempting to integrate the environmental, economic, and cultural forces acting on individual land parcels (defined chiefly by ownership and represented in a geographic information system--GIS) for study areas in the Great Smokey Mountains and the Olympic Peninsula. The key social driving forces include: 1) land and timber markets; 2)

institutional and locational factors; and 3) landowner characteristics and knowledge. Market forces are included in the orthodox way, but attempts to include institutional and individual behavior are more innovative. Institutions include government policies, tax structures, and social movements (e.g., environmental activism) that can affect land use. Locational characteristics (e.g., proximity to current suburbs), and land owner/manager knowledge and perceptions (e.g., conservation attitudes), are also assumed to affect parcel use.

Like the RPA modelers, Lee et al. call on regional expertise and other sources to translate regional socioeconomic knowledge into a land use transition probability matrix that acts as the core to a modeling process (Figure 2). Transition probabilities appear to be a useful way to deal with uncertainty and complexity in landscape change (Parks, 1991; Turner, 1988; and Burnham, 1973). First, land use/cover types are mapped, then transition probabilities are used to simulate future land use structure, and this, in turn, is matched to ecological knowledge to simulate the effects of the new use pattern. The map of ecological effects then feeds back to the land cover data base for a new iteration. As in the RPA models, land is assumed to move to the most economically efficient use, subject to constraints such as jurisdiction (e.g., preserved public lands do not switch), location (e.g., distance to markets), ownership characteristics and other factors distilled from expert knowledge.

The main goal was to assess biodiversity effects of land-use

change, so new land use patterns are interpreted according to principles of landscape ecology (e.g., patch size, corridors), parameterized for a target species (e.g., bears) or habitat type (critical winter range). At each iteration, alternative land-use policies and decisions can be explored, and the model is designed more for this type of "what if" analysis than to predict land use per se.

THE POTENTIAL FOR ASSESSING CLIMATE CHANGE IMPACTS ON LAND USE AND COVER

Where do these modeling approaches leave us in terms of ability to assess the effects of climate change? Much of the recent work on biophysical modeling of land cover has been driven by concerns over greenhouse warming. This line of research is obviously improving our ability to project potential surface vegetation under a wide range of climate scenarios. Certainly as the climate projections improve, so will the land-cover models. The great weakness here, however, is that most projections of vegetation cover fail to account for direct human effects. The loblolly pine forests of the Southeast, for example, may not be able to migrate in ways postulated by even the most sophisticated forest dynamics model if there are human barriers like cropland and cities in their way, or if air, land, and water pollution reduce their ability to adapt to climate pressures.

Global warming impacts on land use/cover, while "rapid" compared to natural climate change, may actually be rather slow compared to direct impacts of economic, social, and policy

change. For example, millions of acres of Great Plains crop land has switched to grass land since mid-1980s legislation introduced new incentives for conservation. Realistic modeling of land cover change in a changing climate, thus requires joint modeling of land use change, and the modeling must be spatially-explicit at a landscape scale. Such integrated modeling has not, to our knowledge, been attempted, although efforts to develop it are underway (Riebsame et al. 1994; Turner et al., 1993). Moreover, land-use modelers have tended to neglect climate change, though they could certainly incorporate its effects, which may be no more uncertain than many of the projected factors (like timber demand) now incorporated in their models. Thus, in our view, there exists good potential, but only a very limited current capacity, for modeling land use/cover change in a changing climate.

NEW DIRECTIONS IN MODELING LAND USE/COVER

Several questions suggest themselves as we appraise the existing tools for integrated assessment of how changes in environment and society affect land resources. Contemporary resource policy questions, such as how to protect endangered species, what levels of resource extraction are sustainable, how to meet changing social demands, and, of course, how to respond to the threat of global climate change, all inculcate a daunting complexity to which traditional assessment and management methods are ill suited. What are the great forces that affect land use, and what surprises might emerge in the next several decades?

What is needed to achieve better modeling? Can we find more holistic approaches to land modeling that offer better insights and better projections?

The challenge in land use/cover modeling, as in most elements of environmental research and practice, is to achieve more integrated analysis. Biological models camouflage the fact that direct human intervention is a key, and often dominant, landscape force in the U.S. and, indeed, much of the world. For its part, social modeling of non-urban land use is too immature and tends to focus on quantifiable factors like population growth and market demand, neglecting politics, perceptions, and beliefs--factors that land use researchers agree are important. Additionally, biophysical and social modelers rarely work together, and we simply do not yet have interactive society/resource models (Riebsame et al. 1994). Moreover, most process models (social and biological) are not yet coupled to spatially explicit land data-bases, and the spatial patterns of, and interactions among, elements are largely ignored.

In this final section, we make some suggestions for improved, integrated land use/cover modeling.

Approaches to Integrating Socio-Cultural Factors

The first and most obvious step toward better land use/cover modeling is to link ecological and social models, thus coupling social driving forces with their ecological ramifications and feedbacks to society. As a first step in this direction, we should be linking and modifying existing models. Linkage can be

computational, such that the models are actually fused in software, or might be accomplished simply by jointly running the models and passing data back and forth manually.

Riebsame et al. (1994) are trying to integrate existing ecological and econometric farm management models for the Great Plains. But they are also modifying both kinds of models to incorporate more behavioral and cultural factors. Changing priorities of land management in the U.S. make such modification particularly important; commodity production is being supplemented by other social and ecological goals, including biodiversity, equity, aesthetics, and even mitigation of global climate change (e.g., through carbon sequestering). A growing public role in resources management may mean rejecting the use of optimization as an explanatory or a planning paradigm. We know that people do not optimize, that real systems are highly complex, and that cultural goals can rarely be characterized by such simple norms. Ideas about how people's perceptions and values affect their land-use decisions have been addressed mostly in regard to natural hazards (see Whyte, 1986), and efforts are needed to include perceptions and attitudes in more general land use situations.

Modeling Resource Interactions

Another facet of integration is the need for models of multiple resource interactions. Joyce et al. (1986) and Hof and Baltic (1988) argued that our poor understanding of resource interactions weakens any projections of land conditions because

the land accumulates multiple resource uses and impacts. They described a land-based system for resource interactions analysis, and Fosberg et al. (1992) showed how such a system could be used to assess the impacts of global climate change.

As described in the forest modeling case, current models only minimally assess how changes in land area or resource production feed back into various resource sectors. Hof and Baltic developed the National Forest System Resource Interactions Model to assess such feedbacks, but this start must be expanded and moved beyond the initial range of resources and beyond purely econometric approaches.

Modeling Cumulative Effects

A critical need in land use/cover modeling is better ways to assess cumulative effects, either of a particular stress over time (e.g., logging, air pollution, etc.) or of multiple stresses (Westman, 1985). Cumulative impact assessment models must be especially tuned to potential thresholds when land characteristics change rapidly. Some analysts have suggested that slow, cumulative desertification has little apparent effect until some threshold is reached, whereupon the landscape degrades rapidly. Others have suggested that effects of, say farming on the western Great Plains, will accumulate until some external event, like a major drought, causes a total and irreparable collapse of regional carrying capacity (Pimentel et al., 1976; Lockeretz, 1978 and 1981; Worster, 1979; Popper and Popper 1988). The most vocal critics of current Great Plains land use believe

that agricultural collapse is inevitable without a profound change in human use patterns. Cumulative effects modeling frameworks are needed to assess the veracity of such assertions.

A similar argument rages over the western rangelands, which, depending on whose interpretation is accepted, are either recovering from historical overgrazing (Hess, 1992) or undergoing severe and widespread desertification (Dregne, 1992; Jacobs, 1992). A recent National Research Council committee report stresses that difficult-to-monitor cumulative effects, and threshold dynamics in vegetation communities, make it difficult to assess the health, stability or sustainability of rangeland ecosystems (Committee on Rangeland Classification 1994).

Dealing with Surprise

Land use/cover modeling must be more open to unusual conditions, rapid change, and potential surprises. Surprises may come from the environment (e.g., very rapid climate warming) or society (new energy sources, or rapid changes in attitudes toward public lands). Though history shows that dramatic changes in such factors are possible (even likely), projections like those in the forest land assessment are anchored in an abiding uniformitarianism of trend and process. New approaches are needed to incorporate the possibilities of step-functional changes, extreme events, and surprises.

Brooks (1986) has suggested a conceptual framework for paying more attention to surprise in the modeling of future social trends. His typology of surprise distinguishes: 1)

unexpected discrete events (e.g., the Three Mile Island nuclear accident); 2) discontinuities in long-term trends (e.g., recent declines in U.S. water withdrawal); and 3) emergence of new political consciousness (e.g., awareness of the prospect of global warming and ozone depletion). He prescribes strategies aimed at coping with surprises: the cultivation of greater institutional flexibility and more diverse "response pools" that sacrifice some degree of efficiency in handling short-term problems to effect greater capacity for dealing with the unexpected.

Yet, how might we also try to anticipate them better? Of course, it is a truism that "surprise" cannot be anticipated, but post-audits of past surprises (e.g., Pearl Harbor or the 1988 Yellowstone fires) almost always yield clues that, seen in a different light, could have helped managers anticipate the dramatic events that befell them--or at least realize that they were dealing with a system approaching a potentially dramatic behavior threshold. On the other hand, such post-audits may evince a false sense that signals of the surprise's approach must have been visible, a problem captured in the saying that "hindsight is 20/20". We do not call for clairvoyance, for it will not come, but modelers and resource managers should consider how they might be more sensitive to conditions approaching thresholds of change (especially degradation) and how they might alter their monitoring, assessment, and decision-making when conditions appear poised for rapid, surprising change.

A New Modeling Framework: Dealing with Landscape Complexity.

Theoretical and operational limits of existing models will still restrict their ability, in linked or cumulative mode, to simulate a derivative property of the earth's surface as complex as land use. Thus, we also need new modeling approaches. Model integration requires new modeling architectures and software tolerant of different levels of specification (quantitative to qualitative) and different scales of analysis. An especially important characteristic needed in future models is overall ability to deal better with complexity.

Our limited ability to simulate realistic land-use patterns is not just a modeling problem, but a reflection of the complexity of the real world. In the western U.S., for example, federal lands (managed by different agencies stressing commodity production, preservation, or multiple use) mix with private lands, municipal lands, and so on. In broad terms, the landscape ecology of the West is structured so that the Forest Service has the forested mountains, the Bureau of Land Management has the grasslands, farmers and ranchers own the riparian strips, the National Park Service has especially spectacular parcels of wild habitat, and cities have the valley-bottoms, and, by the way, most economic and political power. These patterns and interactions, and the forces influencing each set of actors, must somehow be considered if we are to model landscape changes (with or without climate change).

Perhaps we can get at such patterns by developing more

subtle notions of landscape ecology. For example, some way of conceptualizing the complex "social ecology" of land tenure is needed. The concept of social landscape ecology would combine the complicated human patterns of jurisdiction and ownership with physical characteristics to create a new view of landscape structure. Better appreciation for social factors will help us predict how environmental and social driving forces play out on a parcel of land or over a regional landscape.

Yet any attempt to model something as complex as land use requires a discerning parsimony. While it is appealing to argue that we simply need more data, more detail, and better resolution (as is frequently argued in global climate modeling), this traditional reaction to complex problems may be leading us in the wrong direction. Perhaps we need a different paradigm for dealing with the complexity of interacting terrestrial and social systems (Waldrup, 1992). A new modeling method that should be useful in this regard is "cellular automata" an object-oriented programming approach that subjects parcels of land or other landscape units and agents (e.g., land owners) to various rules governing their behavior (Itami 1988). Even simple rules about spatial interactions or state changes in such models result in complex patterns, much as in the real world.

Another aspect of complexity is the contextuality of land use/cover processes. The factors of change in one region will be different from those in another because of different social and environmental backgrounds against which they operate. Such is

the case at all scales of analysis; within the global scale, there is regional variation; within a region, local variation. One way to deal with contextuality is not to develop a single model for the aggregate conditions of what one is analyzing, but rather to develop and aggregate sub-models or "local models" depicting different situations within a realm of concern. This is a pragmatic, not an absolute, choice; the range of sub-situations to be examined will depend on the increment of understanding relative to that of effort involved in increasing their number.

Yet, while no model should fully recapitulate reality, it would be equally unwise to give up the notions of holism and integration. The challenge to land use and cover modeling, which is nothing short of a "science of the earth's surface," is to develop new insights into the essential patterns and processes, and to encapsulate the key processes in new model architectures that help us visualize and understand change. Our sense right now, however, is that we have neglected too many important social processes.

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Figure Captions:

Figure 1. Forest area in the U.S. by region as projected by the U.S. Department of Agriculture Forest Service (1989a).

Figure 2. A flow chart of steps for modeling land use change based on probabilities assigned to individual land parcels in a land use data base (modified from Lee et al. 1992).

Table 1: Global land use and cover changes (after Meyer and Turner, 1992)

Cover	Date	Area 10 ⁶ km ²	Date	Area 10 ⁶ km ²	% Change
Cropland	1700	2.65	1980	15.01	+466
Irrigated cropland	1800	0.08	1989	2.00	+2400
Closed forest	<1700	46.28	1983	39.27	-15.1
Woodland	<1700	61.51	1983	52.37	-14.9
Grassland	1700	68.60	1980	67.88	-1
Europe					-27
North America					-27
S.E. Asia					-26
Africa					+10
Latin America					+26
Urban			1985	2.47	

U.S. Forest Area

Assessing Impacts of Climate Change on Forests: the State of Biological Modeling

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Abstract. Models that address the impacts of climate change on forests are reviewed at four levels of biological organization: global, regional or landscape, community, and tree. The models are compared for their ability to assess changes in fluxes of biogenic greenhouse gases, land use, patterns of forest type or species composition, forest resource productivity, forest health, biodiversity, and wildlife habitat. No one model can address all of these impacts, but landscape transition models and regional vegetation and land-use models have been used to consider more impacts than the other models. The development of landscape vegetation dynamics models of functional groups is suggested as a means to integrate the theory of both landscape ecology and individual tree responses to climate change. Risk assessment methodologies can be adapted to deal with the impacts of climate change at various spatial and temporal scales. Four areas of research needing additional effort are identified: (1) linking socioeconomic and ecologic models, (2) interfacing forest models at different scales, (3) obtaining data on susceptibility of trees and forest to changes in climate and disturbance regimes, and (4) relating information from different scales.

INTRODUCTION

Projected climate alterations will produce changes in forests at a variety of temporal and spatial scales (Graham *et al.*, 1990) (as shown in Table I). Global responses to climate change involve alterations in the energy, carbon, or water fluxes of vegetation. At the biome level, species respond to climate change through evolution, migration, extinction, or adaptation to new disturbance regimes. Landscape responses to climate changes take years to centuries and occur via nutrient cycling, production, water use, succession, competition, and response to changes in disturbance regimes. The response of individual trees to climate change occurs through phenological, reproductive, and physiological processes on time scales ranging from minutes to decades and spatial scales ranging from cells to that of a large tree. Human activities must be considered in evaluating effects of climate

change on forest systems. At the most basic level, human use of fossil fuels and forest clearing are responsible for the increased concentration of CO₂ in the atmosphere. On the other hand, human activities may mitigate effects of climate change on forests. For example, species unable to migrate to those regions where appropriate habitats develop because of climate change could be intentionally planted.

Historical and paleoecological evidence shows that the effects on forests of climate change have been significant. Species responses have been complex. For example, with climate warming, intact forest ecosystems have not moved northward as a unit; instead, species have responded individually (Davis, 1989). Different combinations of tree species occur today than in the past (Davis, 1981; Webb, 1987). Also, the order of species entry into an ecosystem has been unique. For example, hemlock arrived before beech in northern Michigan and several thousand years after beech in the lower Peninsula (Davis *et al.*, 1986). Furthermore, biological responses have occurred with time lags. For example, with temperature increases in northern Europe about 10,000 years ago, beetles responded to the warmer temperature about 500 years before the forest response as indicated by the development of a birch woodland (Pennington, 1986). Multiple impacts can be expected to produce species assemblages different from any that we see today (possibly resulting from a combination of changes in climate and atmospheric chemistry). Therefore, it is necessary to acquire a functional understanding of the response of species to multiple impacts (Davis, 1989).

Although historical and paleoecological studies of effects of climate change on forests provide much information about responses in the past, their results cannot be directly applied to future conditions for two reasons. First, the current size, age, and species composition of temperate forests are unique and have been strongly affected by human activities. Second, global temperatures are predicted to increase at an unprecedented rate. Understanding how current forests will respond to transient patterns of global temperature, precipitation solar radiation, etc. requires reliance on

computer models that can deal with some of the complexities of the forest and climate systems. Because human activities are an important determinant of many forest systems, the influence of humans must be included in some of the modeling studies. Human use of the forests is largely influenced by available resources and social and economic conditions, so socioeconomic models paired with ecological models are needed to understand the complex functioning of modern forest systems.

In this paper we review models that can be used for assessing impacts of climate change on forest resources. Models exist at a variety of spatial and temporal scales and address processes and responses pertinent to those scales. Thus, a conceptual framework for using models that operate at a variety of scales is presented and related to forest features at risk. When landscape or larger spatial scales are considered, human activities must be included. Therefore, we also consider existing interfaces between socioeconomic and ecological models of forest resources. Additionally we identify research needed to assist the development of linkages among existing forest models that operate at different scales and among forest and socioeconomic models of land-use change. This paper differs from previous reviews (Ågren *et al.*, 1991; Shugart *et al.*, 1992; Malanson 1993) in that it is both comprehensive in the types of models considered and analytic in terms of comparing the models to assessment needs.

ASSESSING RISKS

Risk assessment methodologies need to be adapted to deal with the impacts of climate change at various temporal and spatial scales. Traditional risk assessment and management approaches have been developed to deal with regional issues (Hunsaker *et al.*, 1990), and these approaches could be applied to climate-change effects (Table II). This application requires consideration of risk endpoints (entities of concern) that have both ecological and human value. Furthermore, the regional risk approach is a systems perspective with no one component of the approach given undue weight. Thus,

the disturbance, endpoint, source terms, reference environment, and exposure must all be defined in order for the approach to be useful.

The risk assessment process is generally an exercise in extrapolation (Barnthouse, 1992). There are three basic uses of models in science. Models used for **prediction** make quantitative statements that can be tested by experiments or observations. Models used for **explanation** interpret an observed phenomenon in terms of underlying causes. Models used for **extrapolation** make projections in time or space that may not be directly testable. For climate change, the extrapolation issues deal with connecting information across different levels of biological organization. There are two main challenges: relating predicted global climate changes to landscape and regional scales, and relating effects of climate change on individual trees to landscape or regional scales.

Extrapolation can occur via a hierarchical approach, direct extrapolation, or spatially explicit models. A hierarchical approach involves the nesting of models (or of models and data) with information at finer resolution being aggregated to a broader scale (e.g., King, 1991). Direct extrapolation involves using information from sample points or running the models at set locations and averaging or using some other metric to summarize results (e.g., Solomon, 1986). Spatially explicit models include the spatial complexity in model projections (e.g., Turner et al., 1991).

The accuracy of predicting risks to forests resulting from climate change is unknown as are the true risks from any other health or environmental stress (Barnthouse, 1992). For this reason, models cannot be validated. However, Barnthouse (1992) points out that confidence in risk model projections is an issue of credibility rather than validity. The credibility of models can be established by experimental testing of the model, successful use in other applications, and supporting material found in peer-reviewed publications (Barnthouse, 1992). For example, based on these criteria, the community vegetation dynamics models are highly credible. These models have been tested using past conditions including effects on forest structure and growth of pathogens (Shugart and West, 1977),

historic land use (Dale and Doyle, 1987), hurricanes (Doyle, 1981), and anthropogenic pollution (Dale and Gardner, 1987). The community vegetation dynamics model structure has been applied to 25 locations throughout the world, and there have been over 50 peer-reviewed publications on the model (Shugart *et al.*, 1992). However, it must be pointed out that these models were not developed to simulate climate effects and need further sensitivity analysis (e.g., Botkin and Nisbet, 1992) and possible modifications (Pacala and Hurtt, 1993).

Factors other than credibility also determine whether a model is appropriate for assessing climate change impacts. Candidate models need to be evaluated as to whether they incorporate parameters and processes of concern (e.g., susceptibility of the forests to disturbance or climate change, socioeconomic factors, or land-use change). The degree to which critical feedbacks are included in the model or sets of models should also be considered. Another important factor concerns whether the model output is at the temporal and spatial resolution of interest. Finally, the model's level of detail should be evaluated as to its appropriateness to the question.

The assessment of risks of climate change to forest can best be explored by scenario analysis. Scenario analysis can bracket ranges of potential responses, enumerate risk factors, and identify the risk-contributing components of the forest system. For example, Dale and Gardner (1987) used a community dynamics model to estimate effects of changes in tree growth rate on productivity in Vermont forests. Their results indicated little change in projected volume by climate division or forest type. However, age structure did change in that the volume of small sugar maples declined by 50%. The 60-year duration of the simulation did not allow small trees, which are most affected by the growth changes, to have an impact upon stem volume. This factor holds implications for the integration of ecologic and socioeconomic models, because the economic model in which these forest projections were to be used did not provide for consideration of age or species structure. In other words, the most sensitive features of the forest projections could not be translated to the economic

projections. This example emphasizes the importance of transferring critical information between models.

Uncertainty and sensitivity analysis are key components of the risk assessment process that help in the identification of sensitive parameters and characterization of implications of uncertainties in a system. Uncertainty analysis of the Dale and Gardner (1987) example above shows that direct extrapolation from a few plots to a region is most affected by those forest types that have the greatest projected volume per area and the greatest land area. Analysis can also indicate those parameters most sensitive to perturbations (Dale *et al.*, 1988).

Models provide a means to assess the implications of gaps in information. These gaps can be dealt with by (1) assuming processes excluded from models have no effect, (2) hypothesizing a relationship between the process and some model parameters and using the model to test for sensitivity of the system, (3) assuming an exogenous value, or (4) using output from a different model. For example, the unknown effect of increased CO₂ concentration on mature trees is ignored in most models, but hypotheses concerning its effect could be explored by using a combination of scenario and sensitivity analysis.

Another aspect of risk assessment is developing an appropriate conceptual framework for considering risk impacts. This framework should facilitate the exchange of information among researchers studying different levels of biological organization and among researchers and policy analysts. The framework should also provide general guidance to program managers, individual researchers, and data management groups, so that the information needed at different biological scales and enterprise levels is generally understood and can be considered in the design of research. We do not suggest that one large, centralized modeling effort or data base be developed. Rather, modeling research should be conducted independently at the necessary levels of biological organization and for different purposes.

Because no one model encompasses all of the processes of importance or all of the biological levels of interest, the conceptual framework for assessing impacts of climate change of forests includes models that operate at different scales. The framework given in Fig. 1 focuses on interactions between biological levels of organization that occur along a space-time continuum. Working down the temporal and spatial diagonal in Fig. 1, global models provide information on climate conditions for the region and smaller scales. Regional models provide information on the natural and policy constraints for the landscape. The landscape-scale biological interactions result in changes in reflectance, evapotranspiration, land cover, and vegetation distribution for the region. In this conceptual diagram, management, large-scale disturbances, and species movement are assumed to occur at the landscape level as a function of the pattern of species composition, size and age distribution, biomass and numbers of organisms. Thus landscape dynamics provide information to the community on migration patterns, climate and water constraints, natural disturbance regimes, and management effects that have direct impacts on forest communities. Community properties that influence individual trees include costs (e.g., from predator activities), constraints (e.g., prevailing light conditions) and benefits (e.g., symbiotic activities). Individual tree models provide information on carbon and nitrogen fluxes, leaf area, and growth, death, and reproduction rates. Thus, processes that operate at a number of scales should be considered when assessing impacts of climate change on forests.

The conceptual framework should allow for consideration of all major perturbations in forest function that may be caused by global change. These perturbations can be grouped into four categories: climate change, land use/land management change, natural disturbances, and anthropogenic pollution. Climate change involves both natural climatic variations and those due to anthropogenic effects such as may be induced by rising atmospheric concentrations of greenhouse

gases. Furthermore, the perturbations categorized above can be interactive. For example, climate change affects the dispersal and scavenging of atmospheric pollutants.

Each type of perturbation can occur at a variety of temporal and spatial scales (Delcourt and Delcourt, 1988) and can have a range of effects upon the forest ecosystem. The relevant characteristics of the perturbation are partially determined by the level of biological organization being considered and the questions being asked. For example, factors to examine when considering vegetation and soil interactions include cloudiness, precipitation (amount, temporal and spatial distribution, storminess, frontal locations), temperature (mean, diurnal, and seasonal), humidity, and atmospheric deposition of pollutants. The impacts of these changes are constrained by prevailing nutrient status, moisture, temperature, soil erosion and deposition, bedrock depth, and weathering. These factors may (or may not) be relevant when investigating a particular perturbation. For example, these factors are crucial when considering direct effects of soil moisture change but are less important for analyzing tree mortality due to the spread of introduced pests, such as the gypsy moth.

MODEL REVIEW

The conceptual framework of forest impacts from global change (Fig. 1) is used to organize this review. Models are discussed with regard to the spatial and temporal scales that they represent.

A. Global-scale models

Global vegetation dynamics models predict the kinds and rates of alterations in global vegetation biomes in response to climate change (Table III). Their output can be used to assess global impacts of climate change and determine carbon storage patterns, both of which are critical to understanding the role of terrestrial systems in the global carbon cycle. Climate change scenarios

have been provided for these models in three ways. One approach uses mesoscale climate models to predict regional climate processes, such as the location of the arctic frontal zone, which is a good predictor of the boundaries of the boreal forest biome (Michaels and Hayden, 1987). A second approach is to scale up the community demographic model approach by using functional plant groups instead of species because the number of species that would need to be simulated on a global scale is overwhelming (Prentice *et al.*, 1989). Functional plant types are groups of species that germinate and grow under similar sets of environmental conditions (e.g., dry-deciduous sclerophyll).

The third approach correlates projected empirical models of climate and vegetation in a spatial context by using the Holdridge life zone classification system (Emanuel *et al.*, 1985). The Holdridge Life Zone classification (Holdridge *et al.*, 1971) has been used to examine potential global shifts in major ecosystems with climate change (Emanuel *et al.*, 1985; Lashof, 1987; Prentice and Fung, 1990; and Smith *et al.*, 1992). The Holdridge classification scheme relates the distribution of major ecosystem complexes to mean annual biotemperature, mean annual precipitation, and ratio of potential evapotranspiration to precipitation. Smith *et al.* (1992) compare potential impacts on vegetation distribution of climate change projections from four GCMs (global climate models). All four climate change scenarios suggest a decrease in the area of tundra and desert and an increase in grassland area. Forest areas also increase toward the poles with all scenarios having an increase in the extent of tropical forests into areas that are now occupied by subtropical or warm temperate forests and a shift of the boreal forest zone into area now occupied by tundra. All scenarios suggest an increase in terrestrial carbon storage ranging from 8.5 Gt to 180.5 Gt. Using the Holdridge classification approach to estimate effects of climate change on vegetation assumes that vegetation complexes move as a fixed unit in time and space, vegetation distribution is solely correlated to climate (e.g., soils are not considered), and that equilibrium solutions exist (e.g., there are no transient dynamics in either climate or vegetation) (Smith *et al.*, 1992).

B. Landscape and regional models

Landscape and regional scale models can be classified into three groups based on their driving variables : (1) socioeconomic driven land-use models, (2) models based on correlations with environmental drivers, and (3) landscape transition models based on spatial rules or neighborhood interactions (Table IV). Socioeconomic driven land-use models focus on how changes in the regional patterns of forests affect forest properties (Table IV). Land-use changes frequently contribute more to overall estimation errors than do errors associated with the available information on carbon dynamics within a single land-type unit. In Grainger's (1990) national-scale approach, the area of agricultural land and, hence, the rate of deforestation are assumed to depend upon (1) the population growth rate, (2) the rate of increase in food consumption per capita, (3) the rate of increase in yield per hectare, and (4) the availability of forest land and agricultural land. Alternatively, spatially-explicit models at the farm-lot scale include such specifics as soil, vegetation, and land-use practices and can simulate feedbacks between environmental conditions, land-use practices, future opportunities, and sustainability (Southworth *et al.*, 1991; Dale *et al.*, 1993a). These spatially-explicit models have a direct link between human choices and consequences of deforestation and carbon release. These models can be used to assess impacts of disturbances to the extent that vegetation pattern affects susceptibility to disturbances. Similarly, the vegetation patterns can influence animal movements.

Models based on correlations with environmental drivers project patterns of vegetation types given the spatial distribution of soils, topography, and climate (Table IV). Applying the environmental correlation approach to the topographically diverse landscape of Switzerland, Brzeziecki *et al.* (1993) use 12 environmental variables (including climatic conditions, topography, and soil parameters) to predict vegetation patterns for over one million pixels of size 250 m². Neilson (1993) has developed a global environmental correlation model that predicts vegetation patterns

under particular hydrologic scenarios. Iverson *et al.* (1993) use Weck's climatic index (Weck, 1970) in combination with data on topography and soils to model potential vegetation biomass in South and Southeast Asia. A climate index empirically relates potential biomass density to climatic factors. Because Weck's index uses readily available data, it can be applied world-wide.

Landscape transition models are based on spatial rules or neighborhood interactions. They estimate patterns of forest and other land uses in the face of climate change (Table IV). These models use a cellular automata approach to explore effects of changes in the location, size, shape, and composition of forest boundaries. The cellular automata approach tracks interactions within and between each location in the spatial model. The potential for migration or extinction in the face of changing landscape patterns can be examined with such models. For example, Turner *et al.* (1991) modeled a unidirectional change in the extent of suitable habitat such as might occur with climate change. They found that communities with a low probability of extinction and a low probability of colonization would successfully colonize a new habitat only if the rates of habitat movement were slow. Such an approach is useful for characterizing those species for which climate change poses a risk. For example, Schwartz (1992) used two dispersal models within the cellular automata design to predict a failure of many northern hemisphere temperate tree species to respond to climate change through range expansion. Effects of disturbance and management policies can also be projected (Gardner *et al.*, 1993). Landscape transition models provide the opportunity to combine broad-scale changes in forest patterns with site-specific processes (e.g., birth, death, and seed dispersal). The models provide an opportunity to examine how animal movements or the potential for disturbance are affected by the vegetation patterns resulting from climate change scenarios (Gardner *et al.*, 1992; 1993).

C. Community-scale models

Community models can be categorized into five groups: (1) demographic simulators, (2) statistical models of forest stand yield, and compartment flow models of (3) forest ecosystem fluxes, (4) organic matter decomposition, and (5) water balance (Table V). The vegetation dynamics models are dominated by the JABOWA/FORET family of models (Shugart, 1984; Shugart *et al.*, 1992). These models are capable of simulating species changes by considering the differential birth, growth, and death of individual trees as a function of species response to temperature, moisture, light, and nutrients. The computer code for these models is readily available, the system is clearly modularized, and the documentation is extensive (Botkin, 1992). Species composition, size and age structure for particular regions can be projected under climate change scenarios. Versions of the model have been applied to most forested regions of North America and to many temperate forests of the world (Shugart *et al.*, 1992). There is some question about the general applicability of the regeneration system, which depends on a gap size of 1/10 ha and introduction of saplings rather than seeds or seedlings (Pacala and Hurtt, 1993). Such a gap size may not be adequate for the effective regeneration of some species. Also, Urban *et al.* (1993) recognize the artificiality of having an upper temperature limit on species occurrence. The models are not sensitive to small errors in climate parameter estimation (Botkin and Nisbet, 1992). These models were the first to show dramatic vegetation shifts as a response to climate change (Solomon, 1986). Effects of soil conditions on patterns of vegetation change have also been illustrated with vegetation dynamics models (Pastor and Post, 1988). These models suggest that temperature increases do not cause changes in the role of forests as a major storage location of terrestrial carbon in some regions (Dale and Franklin, 1989). These vegetation demographic models are useful for examining effects of climate change on animals to the extent that animals respond to vegetation size and age structure (Botkin and Nisbet, 1992; Shugart and Smith, 1992). However, they cannot assess impacts on animals that may result from changes in spatial pattern of the forests (e.g., the availability of food and shelter within a certain distance).

Statistical models of forest stand yield are used to assess the yield of managed forests under prescribed conditions and usually require large calibration data sets (Table V). These models are generally derived from extensive growth records using regression analysis. The equations may replicate the data and display statistical significance with no basis in biological processes. Such growth functions usually predict the expected tree diameter increment under given site and stand conditions. Forest growth models are included in this review because they project the data needed for economic timber yield models and are well documented. Although there have been attempts to use these models to assess impacts of air pollutants on forests, they are not appropriate for assessing climate change impacts. Forest yield models are designed to be used under climate conditions identical to those under which the model parameters were derived (Dale *et al.*, 1985) and climate is not a variable in the models.

Compartment flow models include forest ecosystem fluxes, organic matter decomposition, and water balance models that are all based on a mass-balance approach (Table V). Their respective functions are to estimate above- and below-ground biomass and production, explain decomposition processes, and balance the water budget for specific sites. Species change is not allowed by these models during the course of a model run. There are numerous models in this class with a large variation in code availability, model structure, and documentation of algorithms used. Schimel (1993) refers to this category as models of physical processes that are influenced by biology (e.g., stomatal resistance or vegetation structure effects on evapotranspiration or albedo). In these models transpiration rates are linked to photosynthesis via stomatal conductance (e.g., Collatz *et al.*, 1991) or leaf area (Running *et al.*, 1989).

A comparison of compartment models against standard data sets provides a means to evaluate their usefulness for studies of climate change impacts (Ryan *et al.*, 1994a; 1994b). The prime advantage of these models is that the spatial and temporal scales are closer to those at which field

and laboratory experiments are conducted to examine effects of climate change. Procedures are being developed to link these physiologically based models to vegetation dynamic models (Luxmoore *et al.*, 1991; Friend *et al.*, 1991) so that succession, competition, and other community processes can be studied. Such nesting addresses the difficulties of using these mass-balance models to assess questions of climate change impacts on the regional scale.

D. Physiological models

There are two groups of models that simulate physiology on a small scale — whole tree and soil microcosm models (Table VI). These models are used to predict the impact of climate change on the physiology of tree growth and development or the detailed dynamics of the rhizosphere. Tree models have not yet evolved to the point where they can simulate an entire growing cycle from birth to death. Soil microcosm models treat the rhizosphere with the same degree of detail that ecophysiological models treat individual plants. Experimental and laboratory results at this scale are readily related to the parameter values used in these models. Instrumentation has been developed to measure most gaseous, liquid, and solid fluxes at this scale. Confidence bands can generally be developed for the model results. Few models exist at this scale, and those few have been developed only recently.

USING FOREST MODELS TO ASSESS CLIMATE CHANGE IMPACTS

The models being used to assess climate change impacts should be able to consider forests features at risk as a result of climate change. An assessment of the major categories of information needed for forest managers from research on global climate change impacts to forests, based on preliminary information from the USDA Forest Service (Birdsey, personal communication), is

summarized below. Ojima et al. (1991) provide a more detailed discussion of critical issues for understanding global change effects.

1. Predictions of expected changes in land use. How might changes in population and nonforest land uses affect land remaining in forest cover under global change?
2. Compilations of maps of forest type distribution. Where and when will forest type distributions be altered in response to climate change?
3. Compilations of maps of species composition changes. What changes are expected in spatial patterns of species distribution that reflect changes in the relative abundance of species?
4. Estimates of changes in forest resource productivity. Within broad forest ecosystems, what changes are expected in timber and biomass production and in the quality and quantity of runoff and groundwater?
5. Estimates of expected changes in forest health. Which ecosystems are most sensitive to global change, and which are most resilient? What changes can be expected in the incidence of damage and mortality from fire, insects, disease, and weather?
6. Estimates of potential effect on biological diversity. How are genetic, species, ecosystem, and land-use diversity expected to change?
7. Predictions of effects on wildlife habitat. Will climate change cause loss of nesting and forage areas or affect fragmentation and aggregation of forest types in ways that affect wildlife habitat?

These ultimate goals of the climate change research are expected to be of critical importance to policy makers and land managers.

Comparison of these research needs with the forest models (Table VII) shows that no one model meets all the needs although many climate change impacts on forests will be observed at the landscape and regional scales. For example, changes in land use and species composition may derive from community interactions, but their effects are observable at the landscape scale. Similarly, changes in forest productivity, forest health, and ecosystem and land-use diversity, as well as subsequent effects on wildlife habitat, will also occur at the landscape or regional level. This association means that model output related to climate change should be interpreted for landscapes

or regions. Of all the models, the landscape transition models and the regional vegetation and land-use models address the greatest number of research needs. Nevertheless, an understanding of the processes at other scales is frequently necessary for landscape or regional interpretation.

New Directions in Global Change Research

The spatial and temporal complexity of the global change issues as well as the need to deal with both ecological phenomena and human activities requires innovative and integrative research. Future research should explore ways to interface models and explore questions specific to global change issues.

A. Linking socioeconomic and ecologic models

Links between forest and socioeconomic models have largely been one-way and not fully integrated. Feedbacks have not been emphasized. Frequently, forest models are used to set initial conditions for the economic models, or specific land-use history sets the background for forest models. Forest growth models simulate timber yield, which can feed directly into forest economic models. A few applications of vegetation dynamic models have considered management regimes as scenarios (Dale and Gardner, 1987; Dale and Doyle, 1987). Dale (1987) discusses the importance of selecting appropriate scales and attributes when interfacing vegetation dynamics models with economic models. Landscape transition models have also incorporated forest management (e.g., Gardner *et al.*, 1993).

These one-way links between forest and socioeconomic models do not always take advantage of the detailed data available from the forest models. To refer to a previous example, Dale and Gardner (1987) use a vegetation dynamics models to provide timber volume data appropriate for initializing a forest economic model and show that species composition and size structure can be

important in projecting timber volume for a region. In fact, this information is crucial for the linkage question because the most widely used forest economic models do not incorporate species composition or size and only consider volume by forest type groupings.

Frameworks have been proposed for linking socioeconomic and ecological models (Lee *et al.*, 1993; Fosberg *et al.*, 1992), but examples are needed. The next step beyond models that have a one-way link is to integrate models. For example, Southworth *et al.* (1991) developed an integrated socioeconomic and ecologic model that simulates human colonization and its effects on deforestation, land use, and associated carbon losses. The model was originally conceived as a linked model (i.e., flows of information occurred between the socioeconomic and ecological model), but, as the model code was written, it was apparent that the socioeconomic and ecological processes were so highly related that separation of the two phenomena was hampering model development. For example, the history of land use on a site (a socioeconomic process) affects potential future agricultural development, and both land use history and agricultural use affects forest regeneration. Currently, the model has feedbacks between existing carbon on the land (which is a surrogate for biomass and other forest attributes) and farmers' land use practices. Work is in progress to relate other environmental conditions to farmers' land-use choices (Dale *et al.*, 1993a; 1993b).

B. Interfacing models

Linked models offer one approach to dealing with the complexity of global change issues. The linkage can occur by nesting models of forest systems that operate at different scales or by coupling models that pertain to different processes (e.g., forest and human activities or forest and atmospheric processes). Identification of feedbacks is a major aspect of modeling that needs to be emphasized. Ideally, such identification can lead to simplification of models and identification of parameters that need to be measured accurately.

Nesting models involves embedding a higher resolution and more detailed model into a model that deals with critical features of the process at a coarser scale (Fig. 1). An example of such a nested model is hydrologic models being a component of community forest growth models (Luxmoore *et al.*, 1991). When the feedbacks between nested models are understood, the more detailed models may no longer be needed, as long as the pertinent relationships are included in the larger scale model.

Friend *et al.* (1993) have combined elements of a vegetation demographics model (Urban *et al.*, 1991) with a forest ecosystem flux model (Running and Coughlan, 1988). The model, HIBRID) simulates how individual trees fix and respire carbon, lose water, and partition carbon. The demographics model thus includes competition and physiology and, thus, provides insights into how demography interacts with physiology to produce changes in sapwood area.

Another example of nested models pertains to effects of climate on tree-feeding insects (Fig. 2). A Leslie matrix model (Leslie, 1945; 1948; Usher, 1966) that simulates changes in the number of individuals by age classes was used (Dale *et al.*, 1991). Leslie matrix models of Balsam-woolly-aphid (BWA) and fraser fir were coupled to simulate interactions between the parasitic insect and the tree, as well as the effects of climate variation along elevation gradients on tree survival. The BWA model operated as a 2-day time step and tracked the number of insects in five age classes. The fraser fir model operated on an annual basis and predicted the number of trees in five age classes. The effects of adult aphid density on fir survival were included in the tree model once a year. Because fir must be present for BWA survival, these models are obligately coupled. The BWA and fir models are nested within a vegetation dynamics model by projecting fir density under particular BWA initial densities and elevation gradients. The vegetation dynamics model projects how changes in fir density over time can affect the forest ecosystem. The new stand density of the fir results from competition with other species for light, nutrients, or moisture. One advantage of this nested

approach is that temperature effects on a small scale (that of the insect) can be related to the overall behavior of the forest ecosystem.

C. Research needs for data

The data needed for assessing climate change impacts on forests may come from either empirical or modeling studies, or, preferably, from both. For impact analysis, climate, land-surface characteristics, and land-use information are needed at appropriate resolutions. There is currently a gap in the climate projections at scales lower than global. Mesoscale climate models are being developed to address this deficiency. Nevertheless, obtaining climate scenarios that can be used in forest models remains an important issue.

Data are needed on species-specific susceptibility to temperature and moisture (over all life stages of trees, their competitors, and their consumers). It would be useful to have empirical studies that address forest responses to climate change at a variety of scales. The models can assist in designing empirical studies by suggesting the parameters most sensitive to climate change and identifying the sources of greatest uncertainty. Empirical studies should be designed to provide relevant information for the model that will be most useful in addressing the question of climate impact. For example, the community vegetation dynamics models "grow" trees by changing the diameter increment, so empirical data are needed on the responses of diameter growth to environmental conditions.

The frequency, intensity, and duration of natural disturbances can be affected by climate change (Franklin *et al.*, 1991; Overpeck *et al.*, 1990). Climate-induced increases in distribution frequency could significantly change forest biomass, composition, and the rate of response of forest to climate alterations (Overpeck *et al.*, 1990). The results emphasize the need to include appropriate disturbance regimes in models.

One of the critical problems with global, regional, and landscape scale models is that their parameter estimates are rarely based on experimental data (even survey data). For example, important rates such as the rate of land-use change for different land-use classes are usually based on incomplete historical records that are usually based on a specific location. A statistically valid sampling survey across the globe, region, or landscape would help this problem of the mis-match between existing ecological data and the scale of these models.

D. Research needs for forest models

Research should focus on ways to make model inputs and outputs relevant to biological models at different scales. For example, community models require information on carbon and nitrogen distribution, leaf area, and phenology on the scale of individual trees (Fig. 1). Thus, the research on individual trees should be directed toward identifying how those factors are affected by climate change. Similarly, community models should explore how climate change affects species composition, size and age distribution, biomass, and density (information that is needed for landscape models) (Fig. 1). Also, some attention should be given to the model formats to facilitate transfer of information between research occurring at different levels of biological organization. For example, landscape transition models can be developed using various taxonomic or functional groups, but the most appropriate group should be selected depending on information available at the community level and on the assessment needs.

Forest modeling research needs to be related to socioeconomic processes for two reasons. First, risk is generally measured in economic terms. Second, social, political, and market conditions affect human interactions with forests. Socioeconomic models provide information on the causes and patterns of land use, forest management, and anthropogenic pollution needed in forest research.

Forest models can indicate those forest features most susceptible to climate change for socioeconomic studies.

One research problem that must be addressed is how the information from fine scales (e.g., field or laboratory experiments conducted over a short time) can be used to predict responses that may not occur in the time frame or at the spatial resolution typical of experimental studies. The ability to make predictions about effects at more than one scale requires identification of the scales of interest, understanding of the importance of parameters at different scales, ability to translate information across scales, and sampling and experimentation at various scales (King, 1991). The nested insect-forest ecosystem model, discussed above, offers one such approach.

Research should focus on models at regional or landscape scales that have biologically-relevant and economically meaningful outputs because these models meet so many of the research needs articulated in Table VII. Many of the susceptible features of forests are measured at the individual tree or community level, while assessment questions are at the landscape or regional scale. Therefore, one suggested research direction is the integration of community and landscape models. Spatially explicit models of functional groups of forest trees could make use of theories in both community vegetation dynamics models and landscape ecology. The advantage of such a new functional group landscape model is that it could address questions concerning both size and species composition and the pattern of the forests over space. Thus, this new form of model could be used to address landscape and regional issues of climate change that deal with temporal and spatial forest dynamics.

E. Conclusions

There are a large set of models available for studying climate impacts to forests. However, assessment should focus on those models most appropriate for assessing climate-change impacts.

Many models are available for assessing impacts of climate change on forests. Because forest impacts will occur at different spatial scales, a set of models should be used to address the question of impacts. Landscape models of relatively recent development offer the opportunity to examine potential impacts at the regional and landscape levels.

Efforts to provide information at appropriate scales need to be continued. Data for model scenarios need to be specific to the scale for which the scenario is being developed. Further, the research emphasis should be on the level of biological organization at which the assessment questions occur.

Linking and integrating ecological and socioeconomic models should be encouraged. Currently, socioeconomic and ecological models of climate change effects on forest are poorly linked. Few integrated models exist, and the most progressive developments are in models of land-use change. Because human causes of climate change are so closely related to forest effects, linking socioeconomic and ecological models is of great importance.

A research framework should be adopted that promotes interfaces between empirical and modeling studies. This framework is truly essential if assessments of the impacts of global climate change are to be useful. Research should be performed in a collaborative and coordinated manner so that results from one study relate to other studies.

There is a need for a holistic research framework that considers all scales of forest impacts resulting from climate change within a regional risk approach to assessment. The framework suggested in this paper recognizes the ecological processes unique to each scale and promotes integration of research.

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Table I. Four biotic levels of organization that participate in forest response to climate and CO₂ change.

Level of organization	Spatial scale	Temporal scale	Major processes	Human activities
Biosphere	Global	Years to millennia	Energy, carbon, water fluxes	Deforestation, fossil fuel burning
Biome	Subcontinental	Years to millennia	Evolution/extinction, migration, disturbance	Plant breeding, land management, conservation
Landscape	10 -10 ⁴ ha	Years to centuries	Disturbance, nutrient cycling, production, water use, succession, competition	Pollution, exotic pests, fires suppression, flood control, forest management, soil management
Tree	10 ⁻² -10 ³ m ²	Minutes to decades	Phenology, reproduction, physiological processes	Fertilizing, watering, weeding, breeding

Source: Graham, R. L., Turner, M. G. and Dale, V. H.: 1990, 'How Increasing Atmospheric CO₂ and Climate Change Affect Forests', BioScience **40**, 575-587.

Table II. Regional risk assessment terms

Term	Definition	Example
Disturbance	Climate change and its disruptive influence on the ecosystem containing the endpoint*	Climate change effects on forest health in the Northeastern United States
Endpoint	Environmental and socioeconomic entities of concern and the descriptor forest or quality of the entity	Growth rate of selected species and effects on forest productivity and aesthetic conditions
Source terms	Qualitative and quantitative descriptions of the source of the disturbance	Increasing atmospheric concentration of greenhouse gases
Reference environment	Geographic location and temporal period	Northeastern United States in the next 10 years
Exposure	Intensity of exposure of an endpoint to a disturbance	Changes in prevailing temperature and precipitation conditions over the next 10 years in the Northeastern United States

*Equivalent to hazard in toxicological assessment.

Table III. Global-scale models

Model class	Time step	Objective	Examples*
Global vegetation dynamics models	Annual and interannual	Assess the rate and direction of changes of global vegetation biomes	Emanuel <u>et al.</u> 1985, Esser 1989, Overpeck <u>et al.</u> 1991, Prentice <u>et al.</u> 1989, 1992

*Complete citations can be found in the references.

Table IV. Landscape- or regional-scale models

Model class	Time step	Objective	Examples*
Socioeconomic driven models of land-use change	Yearly	Balance the carbon budget, examine effects of land use change on forests	Southworth <u>et al.</u> 1991, Dale <u>et al.</u> 1993a, Grainger 1990
Models correlating environmental variables with vegetation	Steady state	Project spatial patterns of vegetation based on given climate, topography and soils	Brzeziecki <u>et al.</u> 1993, Neilson 1993
Landscape transition models	Variable	Estimate landscape patterns and their effects	Turner <u>et al.</u> 1991, Schwartz 1992, Gardner <u>et al.</u> 1993

*Complete citations can be found in the references.

Table V. Community scale models

Model class	Time step	Objective	Examples*
Community vegetation demographics models	Annual	Assess the rate and direction of species changes resulting from changing climate	Botkin <i>et al.</i> 1972, Shugart 1984, Pastor and Post 1985, Solomon 1986, Prentice <i>et al.</i> 1991, Dale and Franklin 1989, Urban <i>et al.</i> 1993
Stand yield models	Annual	Regress empirical relationships between site index and forest growth and yield	Arney 1971, Belcher <i>et al.</i> 1982, Ek and Monserud 1974, Solomon 1981
Forest ecosystem flux models	Hourly-daily-annual	Assess ecosystem fluxes as a function of climate and soil nutrient and moisture availability	Mohren 1987, Bossel <i>et al.</i> 1991, Rastetter <i>et al.</i> 1991, Wang and Jarvis 1990, McMurtrie 1991, Running and Gower 1991, Luxmoore 1991, Liu <i>et al.</i> 1991
Organic matter decomposition models	Hourly -annual	Predict organic matter decomposition rates and the dynamics of soil carbon	Clay <i>et al.</i> 1985, Jenkinson <i>et al.</i> 1991, Van Veen <i>et al.</i> 1984, Molina <i>et al.</i> 1983
Water balance models	Hourly -annual	Predict moisture dynamics in the soil -vegetation complex and water yield from watersheds	Thiery 1983, USDA 1984, Geng 1988, Huff <i>et al.</i> 1977, Running <i>et al.</i> 1984, Luxmoore 1983, Protopapas and Bras 1988, Whitehead & Hinckley 1991, Rosenberg <i>et al.</i> 1989

*Complete citations can be found in the references.

Table VI. Single tree scale ecophysiological models

Model class	Time step	Objective	Examples*
Tree models	Hourly-daily	Assess the effect of environmental stresses on the physiology of tree growth and development	Rauscher <u>et al.</u> 1990 Weinstein <u>et al.</u> 1991 Ford and Kiester 1990 Schaefer <u>et al.</u> 1988 Webb 1991
Soil microcosm models	Hourly-daily	Assess the nutrient and moisture dynamics of the rhizosphere	Rutherford and Juma 1992

*Complete citations can be found in the references.

Table VII. Forest models address specific research needs for assessing impacts of climate change

	Global	Landscape or region			Community		Tree
	Global vegetation dynamics models	Socioeconomic driven models of land-use change	Models correlating environmental variables with vegetation	Landscape transition models	Community vegetation demographic models	Forest ecosystem flux models	Tree models
Changes in land use		X		X			
Maps of forest types	X	X	X	X	X		
Maps of species composition changes					X		
Changes in forest resource productivity		X			X	X	
Changes in forest health				X		X	X
Effects on biodiversity		X		X	X		
Effects on wildlife habitat		X		X	X		

Fig. 1. The conceptual framework shows the major processes that can be represented by models operating on different temporal and spatial scales.

Fig. 2. The interactions between spatial and temporal scales of forest systems used to assess climate changes on Balsam woolly aphid, which affects the spruce-fir ecosystem.

4

**INTEGRATING CLIMATIC CHANGE AND FORESTS:
ECONOMIC AND ECOLOGIC ASSESSMENTS**

by

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INTEGRATING CLIMATIC CHANGE AND FORESTS: ECONOMIC AND ECOLOGICAL ASSESSMENTS

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Abstract. Effective policies for dealing with anticipated climatic changes must reflect the two-way interactions between climate, forests and society. Considerable analysis has focused on one aspect of forests--timber production--at a local and regional scale, but no fully-integrated global studies have been conducted. The appropriate ecological and economic models appear to be available to do so. Nontimber aspects of forests dominate the social values provided by many forests, especially remote or unmanaged lands where the impacts of climatic change are apt to be most significant. Policy questions related to these issues and lands are much less well understood. Policy options related to afforestation are well studied, but other ways the forest sector can help ameliorate climatic change merit more extensive analysis. Promising possibilities include carbon taxes to influence the management of extant forests, and materials policies to lengthen the life of wood products or to encourage the substitution of CO₂-fixing wood products for ones manufactured from less benign materials.

1. Introduction

The ordinary problems of managing forests challenge the capacity of contemporary decision makers, institutions and science to integrate ecologic, economic and social information. Anticipated global changes in climate will further test our capacity to do so.

The fundamental problem is to describe and manage the structure and function of three complex and interlocked systems: climate; the terrestrial biosphere; and the forest sector broadly defined to include timber, wildlife, water, recreation and other environmental services provided by forests. Climate largely determines the location and growth of forests. Forests succor human material welfare and spiritual existence through the products and services they provide. In turn, such human activities as timber harvesting, silvicultural interventions and land clearing for habitation influence the extent of forests. These natural and social systems co-evolve through time, each providing feedbacks on the other (Norgaard, 1984). Throughout this paper, we use the term "forest sector" to capture in shorthand the natural and social systems related to forests.

Figure 1 illustrates the co-evolution of the forest sector with particular reference to the problems arising as a consequence of climatic change. The left hand side of the diagram encompasses the climatic system and the terrestrial biosphere. The forward linkages labelled I include the effects of changed levels and seasonal patterns of temperature and precipitation on forest growth, regeneration and mortality; the direct and indirect effects of elevated CO₂ levels on forest growth; and the effects of changes in disturbance regimes associated with insect predation and fires.

Gradually the global biogeochemical role of forests has become apparent. These

linkages, represented by the arrow labelled II, include the impact of forests on the global carbon cycle (Tans et al., 1990; Kauppi et al., 1992; Sedjo, 1992), and on albedo (Bonan et al., 1992). The paper by Dale and Rauscher in this volume covers the parts of Figure 1 that are labelled "Forest Ecology" and, therefore, they are not explicitly discussed here.

The right hand side of Figure 1 comprises the terrestrial biosphere and the socio-economic system related to the forest sector. Integrated forest sector models treat these linkages, and in increasingly sophisticated ways. Early analyses centered on the comparatively simple problems of the forest products markets. Examples include the Timber Assessment Market Model (TAMM) of Adams and Haynes (1980), the Global Trade Model (GTM) of Kallio et al. (1987), the refinements of the GTM implemented by the Center for International Trade in Forest Products at the University of Washington (Cardellichio et al. 1989), and the Timber Supply Model (TSM) of Sedjo and Lyon (1990). These economic models all include some representation of the forests themselves, ranging from simple stock-accounting equations for changes in forest inventory to elaborate area-based models that track comparatively small land units. Changes in the characteristics of the forest translate into movements of the timber supply function with consequent effects on the rest of the system. More recently concern has spread to include more of the "products" of the forest than timber alone (Joyce and Haynes, 1992). The recent proceedings by Lemaster (1993) provide a useful summary of current research in this area.

Rarely have the two sides of the diagram been linked in integrated assessments of how climatic change will affect the forest sector, and how developments in the forest sector may affect climate. This paper focuses on the limited number of studies that have done so,

and, based on this review, provides some suggestions about where further effort might be usefully applied.

Valued "forest products" include timber, water flows, forest-based recreation, aesthetically pleasing landscapes, forest-dwelling wildlife, and the myriad of organisms the comprise the immense biological diversity harboured by forests. Integrated assessments seek to understand the relationships between changes in climate and impacts on these values. The impacts are measured with respect to a reference case. Construction of the reference case is not trivial, and must include forecasts of a complex set of biophysical, social and economic variables; in the absence of climatic change, one must forecast forest development, population levels, GDPs in the regions of interest, and so on. Although the reference case is a key element of integrated assessments, it is not discussed further here.

Economic analysis implies valuation: assessment of the magnitude and distribution across society of the costs and benefits of both market and nonmarket goods and services. Economic analysis includes assessment of such effects as changes in employment and income distribution, but would not extend to such sociological issues as the impacts of climatic change on the social structure of human communities, or such political questions as how changes in economic values induce changes in institutions (e.g., property rights). These social and political effects are beyond the scope of this paper.

Within the class of integrated assessments, we distinguish *impact assessment* from *policy analysis*. The former asks how changes in climate affect the biosphere and the economic and social aspects of the forest sector. In terms of Figure 1, impact analyses begin with the arrow labelled I, and trace the effects through the rest of the system. Following

the Easterling et al. (1992) terminology for agriculture, analyses that comprise the linkages I and III can be called "dumb forester" models because they do not consider how changes in the biosphere or associated sector-level changes induce adaptive responses in forest management or policy. Models that include parts I, III and IV of the diagram incorporate endogenous adaptation in the system. By doing so, these models anticipate changes in the structure of the world's forest sector, so climatic change is imposed on a future world that may be quite different from today's. To the best of our knowledge, no studies have included all four linkages indicated in Figure 1. That is, none of the studies we review below has explicitly traced how policy-induced changes in the terrestrial biosphere will affect climate.

Impact assessments do not consider how specific interventions in the system can be used to control any deleterious effects that may be identified. In contrast, policy analysis explicitly focuses on the problems of controlling the biosphere and society. The policy intervention can be either direct (e.g., the Forest Service plants trees) or indirect (e.g., the government imposes carbon taxes and subsidies, and this affects the forest management decisions of individuals and companies). The scope for policy intervention is wide, operating either on the state variables or on the linkages. Policies can deal with ways to help the sector adapt to climatic change, or on ways to use the sector as a tool to help mitigate climatic change. Except for studies of afforestation schemes to sequester carbon, very little policy analysis work related to climatic change has been done for the forest sector.

This paper considers only research that links the climatic, ecological and economic components of an integrated forest sector analysis. We explicitly exclude related work on forest ecology *per se*, national or regional carbon budgets (e.g., Birdsey, 1992; Kurz et al.,

1992), and forest sector analysis that does not explicitly reference climate. The first section below treats impact assessments. The second discusses policy analysis. The final section assesses where the most significant gaps in knowledge seem to lie.

2. Assessments of the Impact of Climatic Change on the Forest Sector

Assessing the impact of climatic change on forests generally employs techniques similar to those used in agriculture (e.g., Adams, 1989; Adams et al., 1992, 1993), or those used to assess the impact of other large-scale environmental phenomena involving forests such as acid precipitation (e.g., Haynes and Adams, 1990). The biophysical system typically forms one component of the production function for the product of interest. The product might be timber or any of the enormous variety of nontimber products and services that forests provide. Our discussion first deals with research on timber and then with nontimber components.

This dichotomy does not necessarily reflect the relative values of the two classes of products, but rather the comparative abundance of research in these two areas. Indeed, on many landscapes the value of the nontimber products may exceed by a substantial margin the value of the timber. For example, the USDA Forest Service has examined the value of some of the different products and services of the national forests--lands that collectively encompass about one fifth of the "commercial timberland" in the United States, and a much larger fraction of the less productive forest land. The Forest Service calculated that, by 1995, nontimber "forest products" would comprise about 70% of the gross value of all national forests (32% in recreation, 23% in wildlife and fisheries values, 14% in minerals,

and 1% other) (USDA Forest Service, 1990, figure 6.32). On other lands, the relative values of these different outputs will differ considerably. Timber values would predominate on some private lands with nontimber values holding even larger importance in parks, preserves and other kinds of wildlands.

2.1 Assessment of Impacts on Timber Production

Assessments of the impact of climatic change on timber production generally employ econometric models of the forest sector--Kallio et al. (1987) and Haynes et al. (1992) review various approaches to forest sector models. These models may be either partial equilibrium models of the forest sector alone, or computable general equilibrium models that include at least rudimentary representations of capital and labour markets and other sectors of the economy. Trade may be omitted altogether, treated as exogenously-set levels of imports/exports, included via excess supply or demand equations, or handled endogenously through a complete set of trade linkages and regional production models. Forest sector models typically include four components: timber supply, timber demand derived from a product manufacturing sector, product supply, and product demand.

Climatic change works through the timber supply component of a forest sector model. In general, these models condition timber supply on the current--and possibly future--state of the forest. Changes in climate affect such key forest characteristics as net growth rates or land area. Policies to mitigate climatic change such as afforestation of agricultural areas might also affect these variables. Changes in timber supply produce changes in important economic variables: timber prices, harvest levels, product prices, output levels, consumption,

trade, consumer and producer surpluses, governmental revenue raised from the sector, employment, income, and secondary economic effects.

These models generally do not distinguish species beyond the broad groupings of "coniferous" and "nonconiferous". Some ecological models carry considerably more detail on the biomass increment for individual species. To link these detailed ecological models with economic models of the forest sector simply requires aggregating the detailed stand information into the broader groupings. On the other hand, if ecological models require feedback information at a higher level of detail (e.g., harvest levels by species), then some kind of disaggregation procedure must be developed, and doing so is not always straightforward.

Some forest sector models include endogenous elements of adaptation: investment/disinvestment in silviculture in response to future timber prices, shifts in processing capacity towards regions where timber is relatively plentiful, or changes in technology in response to changes in factor or product prices. However, silvicultural adaptations specifically tailored to deal with climatic change (vegetation control to offset drought, choice of genotype or species adapted to a specific climatic regime) generally must be assessed outside the forest sector model.

There has been little research on the economic effects of climatic change on the forest sector. Binkley (1988) apparently performed the first integrated assessment of climatic change on the forest sector. He used a simple regression model of the relationship between heat sum and forest growth (Kauppi and Posch, 1988) to predict the effects of a $2\times\text{CO}_2$ GISS climate scenario on the growth of the world's boreal forests. The changes in growth affected

the development of the forest inventory, which in turn influenced economic timber supply. Using a multi-region model of forest products trade (Kallio et al., 1987), he predicted the production, consumption, price and trade effects of the simulated climatic change. In these simulations, some regions benefited from the climatic change while others lost. Percentage changes in timber revenues relative to a base case ranged from +22.4% to -25.5%. Binkley found a total net positive effect of \$25-150 billion (\$US1980) depending on the choice of discount rate. The forest growth model used was exceedingly simple, changes in forest growth outside the boreal zone were not considered, and the possibilities for adaptation in those regions where climatic change reduced growth were ignored.

As part of Resources for the Future's MINK study, Bowes and Sedjo (1992, 1993) examined the impacts of climatic change on the forests of the U.S. Midwest. They used Solomon's (1986) detailed FORENA model to simulate the effects of a 1930s' climate on forest growth. Without using a formal economic model of the forest sector, they qualitatively assessed the impacts of the changes in the forest on the local economy, and concluded that these were apt to be small. Bowes and Sedjo went on to explore the possibilities for using silviculture to mitigate the effects of climatic change. They generally concluded that, because forest productivity and timber values in the MINK region are low, little active adaptation was likely to occur. They also examined the possibilities for adaptation by the industry, and again generally concluded that little was apt to be done unless the market for biomass increases the economic value of these forests. Their study used a realistic ecological model to simulate the effects of climatic change, but dealt with a relatively unimportant forest region, and, consequently, could not elucidate any of the

price effects or inter-regional shifts that one might expect if climatic change were to affect the world as a whole.

Hodges et al. (1989) examined the effects of climatic change on the forest sector in the southeastern United States (see also Hodges et al., 1992; Cabbage et al., 1987). They did not use a formal ecological model, but, instead, relied on ecological assessments made by others. Like Bowes and Sedjo, they did not consider price or trade effects. The impacts of a $2\times\text{CO}_2$ -warming amounted to only about 0.2% of the value of shipments even without considering the possibilities for adaptation.

Using information on elasticities of supply and demand for wood products in Canada and the U.S., van Kooten and Arthur (1989) (see also van Kooten 1990) constructed a partial equilibrium trade model to examine the welfare impacts of potential effects of climatic change on wood supply. The scenarios included increased Canadian supply of 7.5% and 5.0%, accompanied by changes in U.S. supply of 0%, +/- 5% and +/- 7.5%. In the model, increases in forest biomass that result in increased harvests will, in general, increase the welfare of both Canadian and U.S. consumers but decrease that of producers in both countries. The exceptions occur when annual U.S. timber harvests decline. Then Canadian producers are better off, but Canadian consumers are worse off. Likewise, U.S. consumers are less well off only when U.S. productivity declines. Interestingly, social welfare of Canadians does not unequivocally increase as a result of these climate-induced increases in forest productivity and harvests. The sum of Canadian consumer and producers' surpluses increases only when there is an increase in productivity of Canada's forests with either no response to climatic warming by U.S. forests or a decline in U.S. forest productivity and

harvests.

Joyce and Haynes (1992) outlined a method for assessing the effects of climatic change in the United States on that country's forest sector, proposing use of a large-scale, "big leaf" model of net primary productivity (McGuire et al., 1992) to simulate forest growth for the large grid cells used by GCMs. They plan to use the results of the large-scale ecological simulations to modify the growth functions of the area-based forest inventory model used by the USDA Forest Service. They can then trace the economic effects of climatic change using TAMM. Turner et al. (1993) used TAMM to project harvest levels under a CO₂-enhanced atmosphere, and then used ATLAS (Aggregate Timberland Assessment System) to allocate harvest among management units.

Research has also linked TAMM with the Agricultural Sector Model (ASM) to determine the economic costs of sequestering carbon in tree plantations on agricultural land (Adams et al., 1993) (see Section 3.1 below). The researchers are currently developing a Forest and Agriculture Sector Optimization Model (FASOM) as a dynamic link between forest and agricultural land uses (Callaway, 1994). These approaches should result in some of the most complete and detailed assessments of the effects of climatic change on the forest sector, although it does not appear that they will examine the full global effects of climatic change, either in terms of forest products trade or in terms of climatic changes outside the United States.

2.2 Assessment of Impacts on Nontimber Forest Products

As noted in the introduction to this section, forests produce valuable products and

services other than timber. In principle, each of the activities warrants the same kind of detailed analysis as timber production. This paper considers all such nontimber forest outputs together because so little work has been done on how climatic change might affect any of these important aspects of the forest. The possible set of important nontimber forest products is enormous; here we consider only water, wildlife, recreation and aesthetics. As with timber, the problem can be decomposed into two parts: predicting the biophysical effects and valuing them.

In this volume, Leavesley discusses the direct effects of climatic change on water flows, but notes that few of these analyses consider how the effects on water flow will be mediated by climate-induced changes in vegetation. Because the type of land cover affects evapotranspiration and runoff (Bosch and Hewlett, 1982), integration of forest ecosystem and hydrologic models would appear to be a useful area for further research.

Some wildlife species are locally rare or endangered as a consequence of their location at the margin of their ranges. In such circumstances, organisms may be particularly vulnerable to climatic change. To the extent that vegetation determines habitat requirements, the JABOWA-type (Botkin et al., 1972) models could be used to assess the effect of climatic change on wildlife. These models simulate the growth of individual trees based on (1) physiological responses to such key factors such as temperature, soil moisture and nutrient availability, and (2) competition, especially for light, among interacting individuals. Pastor (1993) has extended this type of model to simulate habitat for certain song birds, but has not yet applied the extended model to problems of climatic change. Botkin et al. (1991) used this type of model to examine the effect of a GISS 2xCO₂ climatic

change on habitat for the endangered Kirtland's warbler. In their simulations, the jack pine ecosystem that apparently comprises the critical habitat for this species becomes unsuitable within 30-60 years.

At a regional scale, Joyce's work for the US South (USDA Forest Service, 1988) could be applied to study climatic change. She linked models of population abundance with models of habitat to predict forage production and the abundance of several indicator species (white-tailed deer, wild turkey, red-cocaded woodpecker and trout) under several forest production scenarios. Measures of forest cover for comparatively small units of land described by forest type, age and ownership drove the habitat models. In principle, this same procedure could be used to model the regional effects of climatic change on the same species. For each of these land units, a JABOWA-type model could be used to predict the changes in forest cover that might arise from climatic change.

Changes in forest cover will affect the desirability of individual areas for recreational purposes or as the aesthetic backdrop for everyday life. Buyoff et al. (1979, 1981) and Brown and Daniel(1990) describe methods to quantify aesthetic ratings of landscapes. These methods have been widely used to measure the aesthetic impact of insect attacks on forests--examples include Hollenhorst et al. (1993) for gypsy moth defoliation, Buyoff et al. (1979) for southern pine beetle infestations, and Buyoff et al. (1982) for western pine beetle/spruce budworm defoliations--and could be linked to an ecological model to provide some insights into the aesthetic impact of climatic change. That analysis remains to be done.

Once the changes in habitat, population sizes or species abundance have been

predicted, the large body of information on valuation of nonmarket goods and services (Smith, 1993; Mitchell and Carson, 1989, pp. 307-15; Wilman, 1988) can be employed to quantify the value (positive or negative) to society associated with climate-induced changes in wildlife populations. The so-called hedonic travel cost method (Mendelsohn, 1984) is particularly useful in this activity because it permits one to determine the value of characteristics of an area (e.g., presence or absence of deer, the status of vegetation, or the kind of scenery) and not just the area itself.

3. Policy Analysis for Climatic Change and the Forest Sector

Because the world's forests process and sequester globally significant quantities of carbon, their management may play an important role in policies to mitigate or adapt to climatic change (Cubbage et al., 1992; Woodwell, 1989, 1991). Mitigation policies involving the forest sector logically fall into one of three categories: those that increase the standing inventory of forest biomass (and therefore of sequestered carbon), those that increase the storage of carbon in forest products (what Schelling called "pickling" carbon), and those that substitute wood products for other materials that emit more CO₂ in their manufacture, use or disposal.

The first of these policy responses includes schemes that reduce deforestation (responsible for between 15% and 35% of all carbon currently released to the atmosphere), increase afforestation, or change forest management regimes to reflect the value of carbon sequestration. Most attention has focused on the role of tropical deforestation, but more recently the release of carbon associated with harvest of old-growth temperate forests has

been noted (Harmon et al., 1990). The rationale for conserving primary forests throughout the world are complex, and generally only marginally related to climatic change. As a consequence, we do not discuss policy responses in this area. On the other hand, many studies have examined the prospects for afforesting (or, more correctly in most cases, reforesting) marginal farmland. This problem is discussed below. We also examine how forest management is likely to change if the full value of carbon sequestration is included in the analysis.

The second general policy approach is to extend the life of forest products. Comparatively little attention has been paid to this aspect of the problem, although it seems to be important (IPCC, 1990). For example, simulations by Haynes et al. (1992) indicate that increasing the use of recycled fibre from 41% to 45% of total raw material input for paper and board has about the same effect on total carbon held in the forest sector as a six million acre afforestation program. Although Row (1992) has extensively studied the relationship between product life and carbon sequestration, we have not seen any analysis that explicitly examines the aggregate potential for this policy approach.

The third area--substitution of wood for non-wood products--opens a wide range of possibilities that appear to be understood only for a few individual products. The use of wood products generally emits far smaller amounts of CO₂ than does the use of other substitute materials (steel or concrete). As a result, substituting wood for steel or concrete will reduce CO₂ emissions (Buchanan, 1990; Marcea and Lau, 1990; Koch, 1992). Because the combustion of biomass simply recycles atmospheric carbon, substituting biomass fuels for fossil fuels (wood for coal or oil in electricity generation; methanol derived from wood

for gasoline) would reduce the net emissions of CO_2 if the biomass is continually regenerated.

Although biomass fuels have been studied extensively (e.g. NAS, 1992, ch. 24), we know of no national assessment of the potential for reducing CO_2 emissions through appropriate choice of building systems or a national materials policy more broadly. The potential seems to be significant. In Canada, for example, cement production is second to fossil fuel consumption as a source of CO_2 . Wood products could substitute for concrete in many applications, thereby reducing CO_2 emissions. Little attention has been paid to such policy responses, and they are not discussed further in this section.

3.1 Afforestation

Expansion of plantation forests to fix atmospheric CO_2 has been proposed as a major policy response to climatic change (e.g., Sedjo, 1989). The idea is to replace grasslands or marginal croplands, where long-term rates of carbon sequestration are low, with forest plantations where they are high. As these new forests grow, they will fix carbon from the atmosphere and store some of it in permanent tissues (stemwood, branches, roots), thereby reducing the amount of carbon in the atmosphere.

Dudek and LeBlanc (1990) consider offsetting new CO_2 emissions in the U.S. by planting trees on land put into the Conservation Reserve Program under the Food Security Act of 1985. This option is estimated to cost between US \$6.64 and \$10.67 per ton (2,000 pounds) of CO_2 removed, or US\$26.75-\$43.00 per tonne, of carbon removed from the atmosphere. (By weight, carbon constitutes 27.3% of a CO_2 molecule. A metric ton (or

tonne) is approximately 2,200 pounds). Costs of removing CO₂ under other options ranged from \$5.44 to \$239.38 per tonne of carbon. Similar results were found for Canada by van Kooten et al. (1992). Using data from Moulton and Richards (1990), Richards (1992) finds marginal costs in the range of \$5-\$45/tonne. Including the opportunity cost of using agricultural land, Adams et al. (1992) find sequestration costs in the range of \$16.30-\$218.35/tonne, depending on the specific assumptions employed. All of these calculations presume that good agricultural lands as well as marginal ones will be available for planting trees.

One difficulty with this policy arises as the plantation forests mature. At some point, the rate of carbon sequestration will slow and the use of the plantations for commercial purposes will become increasingly attractive. If the trees are not harvested, the potential to offset carbon emissions from fossil fuel consumption will gradually be lost. If the trees are harvested, some of the carbon that has been fixed will be released (through the natural decomposition of logging slash, through increased oxidation of carbon in the soil and through carbon released as products are manufactured from the trees). As mentioned above, the wood could be used to substitute for fossil fuels or could be "pickled" either by direct burial or through subsidized use in applications that have long retention times (e.g., house construction).

If the wood enters conventional forest products' markets, the prices of timber products may be driven down to extremely low levels. A recent study by Haynes et al. (1993) indicates that by 2040 an afforestation program of 5.8 million acres would reduce stumpage prices in the South to "a small positive residual value, such as 2-4 dollars per

thousand board feet..." (p. 26). A larger, 9.9 million acre program would result in these low prices by 2030. Another study by Adams et al. (1993) estimates that timber harvests could increase by as much as seven times current U.S. harvests if trees are planted on agricultural land in order to sequester carbon; even ignoring losses to the forestry sector as a result of lower prices, such a policy could cost \$8/ton of carbon if 35 million tons are sequestered annually, and \$55/ton if 700 million tons are to be sequestered. (Also ignored is the increased cost of food because prices will rise when large amounts of agricultural land are taken out of production.) If afforestation policies are pursued, one would expect to observe much lower levels of private investment in silviculture with consequent effects on rates of carbon sequestration. One purpose of FASOM is to estimate changes in silvicultural investment and potential losses (or gains) to the forestry sector from increased fibre availability.

3.2 Forest Management

The vegetative cover of the globe is an important net sink for CO₂ (Jackson 1990, p.38; Bazzaz and Fajer, 1992). In contrast to the popular attention focused on tropical forests, the total carbon contained in the boreal forests (vegetation plus soils) exceeds that in the tropical moist forests (although the rates of net primary productivity are somewhat lower) (Table 1). As Kronberg and Fyfe (1992, p.73) put it, "boreal forests store significantly more carbon in their soils and associated peatlands than do tropical forests. This makes the boreal biome much more important as a global carbon sink."

A significant fraction of the forest land described in Table 1 is exploited

commercially for fuelwood or industrial wood products--perhaps half of the forest land in the United States and one third in Canada. A wide variety of management techniques that permit adaptation to some climatic change are available for these lands (Binkley, 1990). However, because the costs of carbon emissions and benefits of carbon sequestration are not marketed, the management of these lands proceeds without regard to the large role they have in the world's carbon budget. It is useful to ask how forest management might differ if carbon costs and benefits were internalized.

Imagine that a carbon tax were imposed so that the forest owner received an annual payment for each tonne of carbon fixed that year, but paid an equal tax when the trees were harvested and some of that carbon was released. How would management differ? Let us examine the most simple management decision of all, the choice of the economically optimal rotation age. We illustrate the potential importance of this policy option through two empirical examples referring to the boreal forest region of northern Alberta and the coastal region of British Columbia. Binkley and van Kooten (1993) provide the mathematical details of this analysis along with a more complete assessment of the "supply curve" for carbon absorption services available from forests managed jointly for timber production and carbon sequestration.

Table 2 provides the results for various assumptions regarding the net price of commercial timber (P_{tm}), the value of carbon (P_c) and the "pickling rate" (b)--i.e., the fraction of the timber harvested but going into long-term storage in structures and landfills (Row, 1992). Timber prices represent the net value of a cubic meter of wood after all expenses (stumpage value), and currently lie in the range of \$10-\$30 for the relevant regions

of British Columbia. The values for carbon are intended to reflect the social opportunity costs of emitting another tonne of carbon into the atmosphere, with \$20/tonne representing a reasonable value (van Kooten et al., 1993).¹ Rubin et al. (1992) found this to be the cost of CO₂ abatement for reductions in the 1-3 billion tonne range. Nordhaus (1992) finds this to be the long-run optimal level for a carbon tax in his optimal control model of greenhouse gas control.

Suppose that trees have no commercial value, but stands are managed for carbon sequestration benefits only. If, in addition, timber releases all of its stored carbon at the time of harvest ($b=0$), then it is optimal never to harvest trees (this result may be an artifact of the functional form--if the trees begin to deteriorate at some old age, it may be economic to harvest them even if carbon values alone are considered). The same is true if only one half of the stored carbon is subsequently pickled in landfills and structures. However, if all stored carbon can be pickled at harvest time, the optimal rotation age varies between 112 to 128 years for the coastal forest, and between 201 and 220 years for the boreal forest (the shorter rotation is for a carbon value of \$20/t, the longer rotation for a value of \$200/t). This compares with an optimal financial (Faustmann) rotation age in the absence of carbon uptake benefits of 37 years or less on the Coast and 43 years or less for the boreal forest. Rotations that take into account carbon uptake benefits are greater than ones that maximize

¹Some studies considered in this review used U.S. units of measurement, while others (e.g., van Kooten et al., 1992, 1993; Binkley and van Kooten, 1993) used metric measures. We report the data as provided by the authors of the original, unless comparisons are made across studies, in which case metric units are employed; the conversion factor is: 1 tonne = 2.2 tons. Values reported below are in Canadian currency, with \$C 1 $\approx$ \$US 0.80.

the physical yield of timber (i.e., culmination of mean annual increment), but shorter than rotation ages that maximize total standing volume.

As the value of carbon sequestration to society increases, the optimal length of time until trees are harvested increases, *ceteris paribus*. Indeed, in a scenario with low timber prices, a "pickling rate" $b < 1$, and a high carbon value, a profit-maximizing owner of forest land facing a carbon tax/subsidy might find it optimal not to harvest trees at all. An increase in either timber prices or the discount rate shortens the optimal rotation age, with the discount rate having the greater effect. On the other hand, an increase in the pickling rate reduces the rotation length because the tax penalty from releasing carbon at the time of harvest is lower (indeed, it is zero when $b = 1$).

At current levels of timber prices, realistic possibilities for a carbon tax, and our best estimate of the current "pickling factor" ($b = 0.50$), the impact of the carbon tax on the optimal rotation age is modest (about four years on the coast, and six-ten years in the boreal region).

4. Discussion

How complete is our extant knowledge base?

4.1 Timber Production

With respect to timber production, our best information resides at the regional scale. Both impact assessments and policy analyses are comparatively advanced, at least for the United States. Work currently underway to link a "big leaf" ecosystem model with TAMM,

as well as the development of FASOM and its silvicultural feedback effects on production, will move the state of science forward significantly. These efforts should be taken farther to estimate the joint effects of climatic change and harvesting on the carbon cycle (i.e., link II in Figure 1). Calculations by Kauppi et al. (1992) and Sedjo and Solomon (1989) suggest this feedback could be important.

Policy analysis at this scale is incomplete. While the afforestation option appears to be well understood, other possible responses are not. In particular, it is vital to reassess the effects of substitution between forest products and other materials in such key end uses as construction and packaging. The potential for extending the useful life of wood products does not appear to have been systematically studied. Policies in both of these areas will operate at the regional and national scales, although there may be potential for multi-national approaches.

Our literature review identified no examples of policy analysis at the global scale. In principle, the same kind of approach used for the United States could be extended to this scale. The "big leaf" models are readily adapted to any location in the world, and they could be linked to extant global forest sector models. In the global context, one could logically examine how economic responses in the forest sector might affect the world's carbon budget and hence its climate.

From an economic perspective, the global scale of forest sector analysis comprises a collection of regional-scale responses linked by trade flows and possibly by interactions induced by the forest sector's effect on climate. The analytical tasks at this scale include, in the first instance, placing the regional-scale analyses into a global economic context where

regions are linked by endogenous trade flows. In the second instance, they must account for the impact on global carbon balances of forest growth, harvest and consumption activities. Extant ecological knowledge of these phenomena has not been collated into a global economic assessment.

Surprisingly little attention has been paid to the stand and landscape scales of timber production. The simple policy analysis model developed in Section 3.2, above, could easily be extended to landscape-scale management models. A great deal of ecologic impact assessment work has been done with stand-level simulators of the JABOWA type, but extensions of this work to include economic factors is scant.

The JABOWA-type models of vegetation dynamics could be used to explore several interesting climate-related questions. For example, how would optimal economic management (harvest regimes, fertilization, thinning) differ between the current and the changed climate? How would a carbon tax affect forest management? Work by Larson et al. (1989) suggests that the response of the forest to climatic change depends on the assumed management regime, with harvesting facilitating more rapid adaptation to the changed climatic conditions.

In summary, economists have not effectively exploited the rich set of ecological models discussed by Dale and Rauscher elsewhere in this volume. Examples of opportunities for interesting and useful integrated ecological/economic assessments of climatic change and forests occur at all of the interesting geographic scales, from stands, to forest landscapes, to regions and the globe.

4.2 Ecosystem Function

Much of extant work on climatic change and the forest sector concludes that the net economic impacts of anticipated changes will be small. This finding derives from three facts.

- (i) The forest sector comprises only a small fraction of the formal economy in most developed countries.
- (ii) Trees currently grow in a wide range of climates. Although climatic change may initiate massive changes in the species composition of the forests in any one location, the likelihood that forest cover will be completely eliminated over a large area of North America appears to be small.
- (iii) For those forest lands that are actively managed, there is considerable capacity to adapt management regimes to some kinds of climatic change (e.g., increased drought). The forest products industry can adapt to ecosystem changes by salvaging dying trees, replanting with better-adapted genotypes or species, or moving to those places where timber becomes more abundant.

This generally sanguine outlook does not extend to the nontimber components of forest ecosystems (e.g., recreation, the distribution and abundance of animal and nontimber plant species, water, and aesthetics) that comprise the bulk of social value of many forested landscapes. Although the industrial aspects of the forest sector may be able to adapt to the anticipated changes in forest cover, many ecosystem functions are unlikely to remain intact. While many studies have examined the effects of climatic change on plants, comparatively little work has focused on the myriad of other life forms that comprise an ecosystem. A few studies discuss biological diversity in fairly broad terms (e.g., Peters and Lovejoy, 1990;

Peters, 1990; Parsons, 1991; Schwartz, 1992). Others note that shifts in ecotones associated with climatic change may affect the viability of populations living at the margins of vegetation zones. However, our literature review found no studies that examined the economics of these ecosystem components in the face of climatic change. The policy problems posed by these nonmarket ecological services may be particularly severe if, for example, climatic change makes preserves designated for maintaining certain species inimical to those organisms or the associated ecosystem.

Investigation of these important features of the forest should proceed along the lines suggested earlier in this paper. First, model the biophysical effects of climatic change on the forest ecosystem. Second, value these changes using the methods that have been widely developed for other purposes. Many kinds of nontimber ecosystem components could be treated in this manner, and this appears to be a fruitful area for further research. However, unlike the effects of climatic change on trees, the capacity to develop experimental evidence to support the ecosystem models appears to be quite limited.

4.3 Institutional Constraints

Several institutional factors constrain society's capacity to design and implement effective forest management and policy, and these are likely to hobble our capacity to respond to climatic change. First, as mentioned earlier, a great deal of the forested area is not actively managed for any purpose. Passive ownership, long distances from civilization, rugged terrain, and lack of infrastructure all contribute. For example, vast parts of the boreal forest in Russia and Canada--literally hundreds of millions of hectares--are wholly

inaccessible. Second, in many locations where active management is technically feasible, confused or perverse institutional arrangements stand in the way of effective actions. Examples include tenure systems that do not provide appropriate economic incentives to tenure holders, policies that keep timber prices below their world-market values, uncertainty over who actually holds ownership rights, and a nearly universal failure to internalize the nontimber values of forests in market-based decisions. In many forest settings, nonmarket values exceed by a wide margin the value of the timber. Even in those cases where adaptation to climatic change is biophysically possible, these and other institutional factors are apt to limit society's capacity to implement the needed changes. Strengthening the institutions that govern the world's forests is a necessary precursor to effective climatic change policy for the sector, but it is also needed for handling the prosaic daily problems we face right now.

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Table 1. Areas of Major Vegetation Types, Carbon in Vegetation and Soils, and Net Primary Productivity of Terrestrial Ecosystems.

Region (Description)	Area (10 ⁸ ha)	Carbon in Vegetation (10 ¹⁵ g)	Carbon in Soil (10 ¹⁵ g)	Total Carbon (10 ¹⁵ g)	Net Primary Productivity (10 ¹⁵ g C/yr)
1. Tropical wet & moist forest	10.4	156.0	138.7	294.7	8.3
2. Tropical dry forest	7.7	49.7	45.8	95.5	4.8
3. Temperate forest	9.2	73.3	104.3	177.6	6.0
4. Boreal forest	15.0	143.0	181.9	324.9	6.4
5. Tropical woodland & savanna	24.6	48.8	129.6	178.4	11.1
6. Temperate steppe	15.1	43.8	149.3	193.1	4.9
7. Desert	18.2	5.9	84.0	89.9	1.4
8. Tundra	11.0	9.0	191.8	200.8	1.4
9. Wetland	2.9	7.8	202.4	210.2	3.8
10. Cultivated land	15.9	21.5	167.5	189.0	12.1
11. Rock & Ice	15.2	0	0	0	0
GLOBAL TOTAL	145.2	558.8	1,395.3	1,954.1	60.2

Source: Jackson (1990, p. 39)

Table 2. Optimal Rotation Ages for Boreal and Coastal Forests when Carbon Taxes and Subsidies Taken into Account (Years)

Discount Rate 5%				10%			15%		
Price of Carbon (\$/tonne)									
	\$20/t	\$50/t	\$200/t	\$20/t	\$50/t	\$200/t	\$20/t	\$50/t	\$200/t
Coast Forest									
Faustmann Age				23			16		
$\beta=0$									
\$0/m ³									
P _{tm}	15	*	*	*	*	*	*	*	*
	25	44	63	28	45	*	21	35	*
	50	41	49	26	32	*	19	24	*
	200	39	42	24	26	57	17	19	46
$\beta=1/2$									
\$0/m ³									
P _{tm}	15	*	*	*	*	*	*	*	*
	25	43	54	27	37	196	20	28	274
	50	41	47	25	30	74	18	22	63
	200	39	42	24	26	40	17	19	31
$\beta=1$									
\$0/m ³									
P _{tm}	15	112	112	123	123	123	128	128	128
	25	43	50	27	33	54	20	24	43
	50	40	45	25	29	44	18	21	34
	200	39	41	24	26	35	17	19	26
Boreal Forest									
Faustmann Age				24			17		
$\beta=0$									
\$0/m ³									
P _{tm}	15	*	*	*	*	*	*	*	*
	25	55	93	32	62	*	24	47	*
	50	49	64	29	39	*	20	28	*
	200	46	51	26	30	89	19	21	70
$\beta=1/2$									
\$0/m ³									
P _{tm}	15	*	*	*	*	*	*	*	*
	25	53	72	31	45	*	22	33	*
	50	49	59	28	35	122	20	25	101
	200	46	50	26	29	51	18	21	37
$\beta=1$									
\$0/m ³									
P _{tm}	15	201	201	216	216	216	220	220	220
	25	51	63	30	39	71	21	28	54
	50	48	56	28	33	55	20	24	41
	200	46	50	26	29	41	18	20	30

* Indicates that rotation age is more than 300 years, and may be infinite.

Figure 1: Coevolutionary Development of the Climate, Terrestrial Biosphere and the Forest Sector

**ENVIRONMENTAL CHANGE IN GRASSLANDS:
ASSESSMENT USING MODELS**

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ABSTRACT

Modeling studies and observed data suggest that plant production, species distribution, disturbance regimes, grassland biome boundaries and secondary production (i.e., animal productivity) could be affected by potential climatic changes and changes in land use practices. Many studies have used computer models to assess the impact of climate changes in grassland ecosystems. A global assessment of the impact of climatic change on grassland ecosystems suggests that some will have higher plant production (humid temperate grasslands) while the production of extreme continental steppes (e.g., more arid regions of the temperate grasslands of North America and Eurasia) could be reduced substantially. All of the grassland systems studied are projected to lose soil carbon, with the greatest losses in the extreme continental grasslands systems. There are large differences in the projected changes in plant production for some regions, while soil C changes are relatively similar over a range of climate change projections drawn from various General Circulation Models (GCM's). The potential impact of climatic change on cattle weight gains is unclear. The results also suggest that the direct impact of CO₂ on photosynthesis and water use in grasslands needs to be included in ecosystem models and that these direct impacts could be as large as those due to climatic changes. In addition to direct effects of CO₂ on photosynthesis and water use, lower N content and reduced digestibility of the forage is indicated.

INTRODUCTION

Natural grasslands are among the most extensive biomes in the world. Prior to human modifications they covered 24 to 45% of the earth's land surface (Harlan 1956, Coupland 1979). Distribution of various grassland communities is controlled by temperature and precipitation regime (Lieth 1975, Bailey 1986, Whitaker 1975) (Figure 1). Walter (1973) suggests that the primary natural factors influencing vegetation dynamics and distribution are temperature, water (climatic factors), chemical and mechanical (soil) factors. The human dependence and utilization of grasslands, now and throughout human development, have also modified environmental factors of critical importance to the grasslands and cannot be ignored in the assessment of grassland dynamics (Riebsame 1990, Schlesinger et al. 1990, and OIES 1991). The distribution of grasslands in the U.S. is shown in Figure 2 (Risser et al. 1981), and the global distribution in Figure 3 (Bailey 1989).

The seasonal distribution of rainfall is a major determinant of plant production in many semiarid and arid regions. In the North American Great Plains, most of the rainfall occurs during the growing season, April through September. As a result biological productivity and evapotranspiration are greater and runoff is less than it would be were rainfall more evenly distributed throughout the year. Despite its modest annual precipitation (250-600 mm) a productive vegetative system exists in the Great Plains region. Many of the semiarid and arid regions share this characteristic. The Intergovernmental Panel on Climate Change (IPCC) estimates (based on UKMO general circulation model climate projections, Houghton et al. 1990) indicate that potential changes in seasonal rainfall and temperature patterns in central North America and the African Sahel will have a greater impact on biological response and feedback to climate than will changes in the overall amount of annual rainfall. Simulation of ecosystem responses to climate change in the Great Plains demonstrated sensitivity of soil carbon storage, plant production, and nitrogen mineralization to seasonal distribution of precipitation changes (Ojima et al. 1991).

Semiarid and arid ecosystems may be among the first to show the effects of climatic change (OIES 1991). Their sensitivity to climatic change may be due to the normal marginality of soil water and nutrient reserves. The drought of the 1930's and in the 1950's in the U.S., for example, changed plant production systems (Weaver and Albertson 1944, Albertson et al. 1957) and led to modifications of land surface characteristics. Human activities have also modified the land surface during this time period, as a result of extension of cropping into marginal areas and abandonment of these soils during the dry period (Riebsame 1990). These modifications are manifested in changes in plant community composition and structure, decreases in soil carbon and nitrogen, increases in soil erosion, and changes in overall energy and water exchange. Growing human populations will continue to exert pressure on terrestrial ecosystems as demands for food, fuel, fiber, water, and other resources increase to meet their needs. Land use change can influence local climate through changes in mass and energy balances at the land surface (Charney et al. 1975, Pielke and Avissar 1990). These human activities related to changes modify biological constraints (e.g., plant nutrients, grazing) and these will change at very different time scales from abiotic controls (e.g., light, water, temperature), leading to changes in the land surface feedbacks to the atmospheric system (Charney et al. 1975, Schimel et al. 1991, WCED 1987, Bolin et al. 1986, Schlesinger et al. 1990).

We do not yet understand how short-term adjustments (hours to days) of photosynthesis or stomatal dynamics would be affected by the long-term regulation of biological processes due to changing vegetation dynamics and resource availability. Biological factors, including plant community shifts, affecting N limitations on photosynthesis and biomass partitioning will change slowly (i.e., months to decades). Abiotic controls, on the other hand, regulate instantaneous rates and will change rapidly. This interdependence of short- and long- term regulation is important to understanding how an ecosystem will store or lose carbon in response to changing climatic conditions during periods of transient environmental change.

Given the sensitivity of grasslands to climatic and land use change, the objective of this paper is to review the use of grassland ecosystem models in environmental impact assessments. We incorporate information about the impact of environmental change at the ecosystem level (i.e., plant production and nutrient cycling), on geographical distribution of grasslands and their species composition. We also evaluate climatic and nutrient controls on grassland functions, production and the potential vulnerability of grasslands to changes in climate and land use. We will present a brief review of how grassland models have been used to evaluate the impact of different human controlled activities and management practices, however, we will primarily focus on the impacts of climatic changes that could result from greenhouse warming and on the potential direct impacts of increasing atmospheric CO₂ levels.

Biogeography of Grassland Ecosystems

The major grassland biome types in the U.S. include the tallgrass prairie, mixed grass prairie, shortgrass prairie, desert grassland, mixed prairie, bunchgrass steppe and annual grassland systems (Figure 2). All of these systems experience drought stress sometime during the year; however, the degree and timing of drought stress are very different between regions. Distribution of the different grassland types is closely correlated with such climatic factors as the seasonal distribution of mean monthly air temperature and precipitation and the ratio of precipitation to potential evapotranspiration (Köppen 1930, Thornthwaite 1948, and Trewartha 1961).

Most grasslands in the U.S. are located within the Central Grassland and Great Plains regions. These grasslands include shortgrass steppe, mixed-grass and tallgrass-prairie systems. Climate in this region is classified as northern temperate. Temperatures are lowest in January-February and highest in July-August. The rainfall patterns are characteristically continental with little precipitation in winter and most in the warm season. Total yearly precipitation generally decreases from more than 800 mm

in the eastern tallgrass prairie portion of the region to less than 250 mm in the western shortgrass steppe. The ratio of annual rainfall to potential evapotranspiration ranges from 0.7 to 0.9 in the tallgrass region, 0.3 to 0.7 for the intermediate mixed grass, and 0.2 to 0.3 for the shortgrass steppe showing the increase in aridity from east to west across the Great Plains.

Temperature patterns in the desert grasslands (Figure 3) are similar to those of the southern part of the Great Plains; however the annual precipitation is substantially lower and the annual distribution is bimodal with peaks in winter and summer. In addition, annual grasslands and bunchgrass ecosystems exist in warm and temperate regions where summers are dry and hot and winters wet with most of the annual precipitation received during that season.

The Bailey ecoregion map (Bailey, 1989), a simplified version which is shown in Figure 3, provides another useful classification of the world's grasslands. Seven general types are defined:

- (1) extreme continental dry steppe,
- (2) dry continental steppe,
- (3) humid temperate prairie,
- (4) dry tropical steppe,
- (5) seasonal humid savanna,
- (6) humid tallgrass savanna, and
- (7) mediterranean.

The major regions in the world that contain humid temperate prairies include the eastern part of the U.S. Great Plains, parts of Uruguay and Argentina and the western part of Russia. Dry tropical steppe is found in northern and southern Africa, South America and Australia. Most of the dry continental steppe regions are found in the southwestern part of the U.S. Great Plains and Argentina, while extreme continental dry steppes are located in central Asia. The major differences between the dry continental steppe region and the extreme dry continental steppes are lower winter precipitation and

much colder winters in the latter. The seasonal humid savannas and the humid tallgrass savannas are found in the tropics where temperatures fluctuate little, but where one or two dry periods occur during the year. The humid tallgrass savannas receives more precipitation. The mediterranean grasslands are found in California and around the Mediterranean Sea. The potential impact of different GCM climatic change scenarios for these grassland regions will be presented later in this paper.

Controls on Plant Production

The primary factors that limit plant growth in grasslands are (1) precipitation and (2) nutrient availability. Fire and grazing also play important roles in determining plant growth (Daubenmire 1968, Hobbs et al. 1991, Holland et al. 1992, Ojima et al. 1994). Lauenroth (1979) summarized data on aboveground plant production for different grassland sites. Figure 4 shows that plant production increases linearly with annual precipitation. This pattern, observed also by Sala et al. (1988) and Lauenroth and Sala (1992) suggests that precipitation is the major limiting factor for plant production in grasslands. Lauenroth and Dodd (1978) showed that adding N to a shortgrass steppe system in eastern Colorado (320 mm annual precipitation) increased plant production by up to 50%; irrigation increased production by up to 200%; combined irrigation and N application increased production by up to 600% (Figure 5). A similar study by Owensby et al. (1970) in an eastern Kansas tallgrass prairie (700 mm annual precipitation) showed a 100% increase in production due to N additions and relatively little response to irrigation. These results suggest that dry grasslands are limited more by precipitation and mesic grasslands are limited more by nutrient availability. However, both grasslands were observed to respond positively to additions of nitrogen. The strong correlation between annual precipitation and grassland plant production may result from two factors: (1) a decrease in drought stress and (2) an increase in the amount of nitrogenous compounds delivered to the ecosystem in rainwater (Parton et al. 1987).

Grasslands can be classified into cool-season or C_3 -type and warm-season or C_4 -type (Sims 1988). Warm-season grassland communities are found in tropical regions and in warm temperate regions with low summer precipitation; cool-season communities are dominant in the higher latitudes. The latitudinal distribution of C_3 and C_4 plants depicted in Figure 6 (from Ehleringer, 1978) shows that C_4 plants are much more productive than C_3 plants (represented in terms of daily carbon gain) in the tropics, but lose that advantage at the higher latitudes. Analysis of North American grasslands by Terri and Stowe (1976) indicated that few or no warm-season species are found where minimum July temperatures are below 8°C. In California and Central Europe warm season grasses are found where temperatures are high and soil moisture availability low. Warm-season grasses dominate in tropical and sub-tropical areas (Jones et al. 1992), except where bamboo forests exist.

Experiments comparing water use between C_3 -leaves and C_4 -leaves indicates that water-use-efficiency (photosynthate produced per unit of water transpired) of C_4 -species is nearly twice that of C_3 -species (Black 1973). The physiological differences between C_3 -and C_4 -grasses explains their geographic distribution under current climate and may lead in the future to a differential response of C_3 and C_4 grass communities to changes in climate and atmospheric CO_2 concentration.

Vulnerability of Grasslands to Climate Change and Drought

Grasslands and associated savannas and shrublands are clearly vulnerable to climate change and major episodic weather events. The sensitivity of grasslands to climate change can be ascertained from the historical observations of grassland response to long-term environmental changes and episodic droughts. The effects of the 1930s and 1950s droughts in the U.S. Central Grassland Region are well known (Weaver and Albertson 1944, Albertson et al. 1957), as are the consequences of Sahelian droughts since the 1960s (Hare 1977, Warren and Maizels 1977). Plant production increases linearly with annual precipitation (Figure 4) and the seasonal distribution of precipitation is very

important in controlling the distribution of grasslands (see Grassland Climate Section). The sensitivity of grasslands can be increased due to land use practices that may exacerbate the negative impacts of climate change (Schlesinger et al. 1990, Graetz 1991, Ellis and Galvin 1994). There are several ways in which changing climate may affect ecosystem function and structure of grasslands including human-related interactions, biogeochemical direct CO₂ effects, and structural changes resulting from woody expansion.

Human-caused degradation of arid and semiarid ecosystems to less productive states is occurring in many grassland regions (Dregne 1983, LeHouerou and Gillet 1986, Riebsame 1990, Schlesinger et al. 1990). This degradation can be accelerated by reductions in precipitation or increases in temperature and may lead to the replacement of grassland or savanna vegetation by desert-like ecosystems. It is generally difficult to separate the effect of human caused land degradation from the effect of climate change and drought. In general, grasslands and savannas are dominated by perennial grasses and woody plants. Desert or desert-like environments are characterized by a greater presence of woody canopy cover and a replacement of perennial grasses by annuals. The result may be a reduction in overall plant productivity and cover. Soil erosion rates may increase as plant cover decreases leading to loss of productive potential--a process that may be irreversible, or nearly so. The transitions are almost always exacerbated by intense human use of the land, as occurs in most grassland and savanna regions (OIES 1991, Archer in press). Grassland degradation can thus occur through both functional (e.g., reduced primary productivity) and structural (e.g., perennial -> annual vegetation) change.

Nutrient cycling in grasslands is largely related to climate although these rates may be modified by grazing and fire effects in particular grasslands. Rates of carbon gain and loss, decomposition and nutrient recycling are all sensitive to temperature and moisture conditions (Parton et al. 1987, Schimel et al. 1990). Soil organic matter is the primary reserve for nutrients in grasslands,

and its quantity is sensitive to temperature, generally decreasing with rising temperature. Thus, a global warming would likely decrease carbon storage in soils worldwide. A decline in soil organic matter would likely lead to nutrient loss in the long-term, and to degraded soil structure, decreased infiltration rate and increased erosion. Destruction of soil organic matter due to increases in temperature would release CO_2 to the atmosphere. The emissions of NO and N_2O would also increase as the soil N turnover is accelerated. As previously indicated, primary production in grasslands is related to precipitation. Any change in rainfall will likely lead to altered productivity, with declining rainfall and productivity likely to intensify any losses of soil organic matter occurring with temperature changes. Thus, carbon storage and nutrient cycling in grasslands could change significantly if climate changes.

The enrichment in atmospheric CO_2 known to be occurring (see the Mendelsohn-Rosenberg paper in this volume) may lead to a ' CO_2 fertilization effect', that can also alter grassland biogeochemistry, leading to increases in plant productivity, decreases in evapotranspiration and increased water use efficiency (Hunt et al. 1991, Owensby et al., 1993). The CO_2 fertilization effect may also reduce rates of decomposition by producing litter with lower N content resulting in lower litter quality (Shaver et al. 1992, see below). Changes in grassland biogeochemistry are largely changes in ecosystem function, but can lead to structural changes if, through competition for nutrients or water, changes in soil nutrient and organic matter dynamics favor one vegetation type over another.

Finally, the balance between herbaceous and woody vegetation is sensitive to climate in most grassland/savanna regions, and the productivity and utility of these systems is very sensitive to this balance. Analyses of the large scale relationships between climate and vegetation (e.g., Holdridge 1964) suggests that grasslands and associated woodlands, savannas, and shrublands exist in a rather narrow climatic zone, and that small climatic changes could lead to really large modifications of the balance between herbaceous and woody vegetation. In addition the extent of changes in vegetation

due to climate modifications would also be influenced by land use practices (Schlesinger 1990). The areal extent of shrublands and woodlands has changed considerably over the past century or so, and increases in woody vegetation usually decreases suitability for grazing by cattle. In areas dependent upon livestock for subsistence, or income, a change to woody vegetation is detrimental. It is not necessarily bad to increase woody cover if goats, camels or other browsers are present. However, there are few successful examples of such substitution (Ellis et al. 1990). While the most important driver for woodland expansion appears to be grazing or 'overgrazing', changes in climate (Archer in press, Schlesinger et al. 1990) and, possibly, increasing atmospheric CO₂ concentration (Johnson et al. 1992) could increase the rate or extent of grassland conversion to woody vegetation. This latter effect would occur since rising CO₂ would likely increase the productivity of C₃ photosynthetic pathway shrubs more than that of the C₄ pathway grasses.

There is considerable potential for biogeographic changes between grasslands and desert types through increases in woody vegetation. Two published analyses using Holdridge-type equilibrium biogeographic models have demonstrated significant rearrangement of grassland and allied desert and woodland/shrubland/savanna vegetation. The studies were carried out by Prentice and Fung (1990) (henceforth PF) and by Emmanuel et al. (1985) (ESS). In both studies, climate-vegetation relationships were developed from the Holdridge life zone system (Holdridge 1964). This system assumes that current life zones (or biomes) are in equilibrium with the current climate and that climate is the primary determinant of vegetation distribution. While this approach has its uses, it also has a number of weaknesses. First, the current vegetation may not be in equilibrium with climate. Second, as applied in climate change studies, the projected changes in vegetative cover occur instantaneously and no lags are accounted for, as would be expected by the term 'equilibrium model'. Third, the approach assumes that the life zones or biomes are fixed in number and that climate change will not cause the formation of new types. Fourth, as noted in PF, representation of the current vegetation is

only moderately successful; vegetation on 33% of the land is incorrectly predicted under current climates in the PF calculation. Fifth, no account is taken of land use. Finally, in comparing PF and ESS, it must be noted that the GCM climates used for a $2\times\text{CO}_2$ world in these studies were quite different. The PF study used the Goddard Institute for Space Studies (GISS) projections and the ESS study used Geophysical Fluid Dynamics Laboratory (GFDL) model projections for climate change, and neither addressed the direct CO_2 fertilization response.

What we can gain from these models is a sense of the likely direction of vegetation change in an altered climate, and a sense of the regions that may be affected. The PF and ESS studies use the Holdridge system in very different ways. Therefore, direct comparisons are difficult, and each study is assessed separately. PF show the equilibrium area of most grassland and desert types declines in response to a doubled equivalent CO_2 climate change. Specifically, arid grassland and shrubland decrease by 22%, desert area decreases by 62%, and mesic grassland decreases by 17%. On the other hand, savanna increases by 35% and drought-deciduous, drought-seasonal, and broadleafed forest increase by 21%. Minimal changes are predicted for mediterranean systems (+4%). Emmanuel et al. (1985) subdivided the Holdridge system in an entirely different way. They show that for a $2 \times \text{CO}_2$ GCM scenario grasslands increase in area by 65%, deserts increase by 17%, and tropical dry forest increase by 46%. Within the grassland category, cool, temperate steppe is projected to increase by 125%.

What can be learned from these analyses? First, the area occupied by grasslands, savannas, shrublands and arid woodlands is significant, covering as much as 45% of the Earth's land surface in the ESS study. Second, the grasslands are likely to be vulnerable to biogeographic change in both the ESS and PF analyses and areal extent of the changes may be significant. Third, the specific changes projected cannot be viewed with great confidence, as the magnitude and direction of projected changes do not agree well (e.g., -17% for mesic grassland in PF compared to +125% for cool temperate steppe

in ESS). Reasons for the different outcomes are difficult to diagnose. The studies used different versions of the Holdridge system as well as different GCM scenarios (Goddard Institute for Space Studies (PF) vs Geophysical Fluid Dynamics Laboratory (ESS) models of quite different 'generations'). Relationships between biome geography and climate regime may represent more than just correlational (Neilson et al. 1989). Climate controls the regional water budgets and thermal balances which determine such key hydrologic processes as ET, runoff and soil water drainage (Neilson et al. 1992).

In summary, grasslands are likely to be very sensitive to climate change. First, productivity and nutrient cycling are closely tied to climate and could change appreciably with altered climate. Second, grasslands exist where fairly small climatic changes could induce structural changes over large areas. These structural changes may result from 'desertification', and lead to a dramatic reduction in productive potential and suitability for human use. Changes can also result from encroachment of woody vegetation. Such a change is not necessarily deleterious, but to be exploited would require changes in grazing systems. Finally, because all woody plants use the C_3 pathway and many grasses are C_4 pathway, increases in atmospheric CO_2 concentration may accelerate an already-prevailing trend from grassland to woodland.

When we look at the potential impact of climate change on grasslands, it is important to compare these impacts to those of human induced land use changes. According to Burke et al. (1990) the impact of a $2 \times CO_2$ driven climate change scenario on grassland soil C levels in the southern Great Plains would be an order of magnitude smaller than the impact of plowing the grassland for crop production. Mosier et al. (1991) have shown that plowing and fertilization of grassland affects trace gas fluxes, increasing N_2O flux by 50% and decreasing consumption of CH_4 in soil by 50%. These impacts, too, are much larger than the potential effects of a $2 \times CO_2$ driven climate change (Burke et al. 1991); however, the two effects of climate and land use changes combined could lead to more rapid

changes than either would alone. Since our ability to predict human-induced land use change is quite limited, we will emphasize grassland models here and how potential changes in climate and atmospheric CO₂ concentrations might influence grassland systems. We consider the impact of climatic change on plant production, species distribution, grazing animal production, nutrient cycling, geographical distribution of grasslands and soil organic matter dynamics.

USE OF MODELS FOR IMPACT ASSESSMENT

Computerized ecosystem models have been used for environmental impact assessment over the past 20 years. The initial work in this area followed the first efforts to develop ecosystem computer models in 1970-75 in connection with the International Biological Program. Models were developed for the Grassland Biome (Innis 1978, Bledsoe et al. 1971), the Tundra Biome (Miller and Tieszen 1972, Timin et al. 1973), the Coniferous Forest Biome (Sollins et al. 1973), the Desert Biome (Goodall 1973, Goodall and Gist 1973) and the Deciduous Forest Biome (O'Neill et al. 1972). Initially, the use of models for impact assessment was limited primarily by scarcity of ecosystem models suitable for computers, lack of model validation, and limited computer speed (Parton and Wright 1977). During the last twenty years the development of modern computers, the greater range of available computer software and better tested ecosystem models have advanced the state-of-the-art in modeling. In this section we describe how grassland ecosystem models have been used for environmental impact assessment during the last 20 years. This discussion deals with: (1) site-specific modeling, (2) regional modeling, (3) modeling of biogeographical changes, and (4) integrated social-economic-biological modeling. Initially, impact assessment models dealt primarily with specific sites under changing environmental conditions. But, more recently the combination of fast computers, advanced software and Geographic Information Systems has allowed development and use of

ecosystem models for regional impact assessment. Integrated social-economic-biological models have also been developed (Ellis et al. 1990, Stafford-Smith and Foran 1990).

One of the major limitations of the use of ecosystem models for impact assessment is that models do not consider the change in species composition. The state and transition models proposed by Westoby et al (1989) are the type of model needed to predict changes in species composition. Unfortunately, these type of models are not generally linked to ecosystem models. Models that link dynamic vegetation state submodels to ecosystem models are now being developed (Pastor and Post 1988).

Site-Specific Impact Assessments

Models of grassland ecosystems have been used for assessments since the mid-1970s. It was suspected that the deployment of a fleet of super-sonic transports and cloud seeding for hail suppression might lead to climatic changes. One of the first uses of ecosystem models was to simulate the impact of such changes on grasslands. Parton and Smith (1974a,b) used the shortgrass steppe version of the ELM grassland model (Innis, 1978) to evaluate how the anticipated climatic changes would modify plant production, animal consumption and nutrient cycling on a shortgrass steppe in northern Colorado. Climatic records for the area were modified in accordance with projected changes in the climate and the computer model was run for 3-5 year periods. Results with the altered climate were compared to those of the control run. Model output variables analyzed included plant production, microbial respiration, and secondary production (animal production).

A similar modeling approach was applied to the Sahel region of Africa to determine the impact of overgrazing (Parton and Schnell 1975). The model used in this case allowed consideration of a possible interaction between grazing and precipitation. The hypothesis considered was that grazing could reduce numbers of biologically generated ice nuclei, thereby causing a reduction in

rainfall. de Ridder et al. (1982a,b) developed a simplified model for simulating the impact of grazing and other animal and plant production management practices in the Sahel region of Africa. The model was designed as a tool for training land use managers about controls on primary production in Sahelian ecosystems and the use of these systems by grazing animals. Other grassland ecosystem models have been used in impact assessments of strip-mine reclamation (Parton et al. 1979), grazing and fire management implications for a tallgrass prairie in Oklahoma (Parton et al. 1980, Parton and Risser 1980, Ojima et al. 1990, Holland et al. 1992), and evaluating the effect of grasshoppers and range caterpillars foraging on plant production and other ecosystem variables (Capinera et al. 1983ab).

More recently Hunt et al. (1991) used the Grassland Ecosystem Model (GEM), Schimel et al. (1990) used the CENTURY model and Hanson et al. (1992) used the SPUR model to simulate the impact of various $2 \times \text{CO}_2$ -driven climate change scenarios on plant production, nutrient cycling and animal production for a number of sites in the Great Plains. The Hunt et al. (1991) model also considered the direct impact of elevated CO_2 on plant production via effects on photosynthesis and water use. A general review of the use of ecosystem models, ranging from physiological to ecosystem-based concepts, for simulating the impact of climatic change on natural ecosystems is presented by Ågren et al. (1991). Hanson et al. (1984) also presents a comparison of grassland ecosystem models. Other grassland models that have been developed recently include the ERHYM-II model (White 1987) and the PHYGRO model (Vega 1991). These models include simplified plant production and hydrology models but do not deal with nutrient cycling.

This literature review shows that grassland ecosystem models have been used extensively to evaluate the environmental impacts of various management schemes, insect outbreaks and climatic patterns on grassland production, soil organic matter dynamics, nutrient cycling and secondary production. A comparison of the different studies is very difficult since different models have been employed and the studies have had differing objectives. Some of the models cited above deal with

total systems (including production, decomposition, nutrient cycling and herbivory), while others represent only parts of the system and complete feedback loops among plant production, nutrient cycling, animal production and soil water dynamics are not represented. Another important difference between the studies is the length of time represented in the computer runs. The initial use for impact assessment of the ELM model (Innis, 1978) provided 3-5 year runs because of limitations in computer power, while 486 PC computers allow the current version of the CENTURY model to produce runs for hundreds of years in length for numerous sites.

Regional Impact Assessment

Until recently, most of the ecosystem models used in impact assessments were developed for application to specific sites. Regional impact assessments are now of growing importance (Schimel et al. 1990, Burke et al. 1991, Schimel et al. 1991, Pastor and Post 1988). The use of ecosystem models at the regional scale had been limited by three factors:

- (1) lack of regional data for validating models such as plant production, N turnover, soil C dynamics and evapotranspiration rates.
- (2) inadequate computer hardware and software limitations, and
- (3) lack of regional information on model inputs or drivers as soils, climate, vegetation, and land use.

Most ecosystem models have been tested only at a limited number of sites. Relatively little effort has gone into testing them at multiple sites. The prospect of global climatic change has led to the development of regional data bases that can be used to test the predictive power of ecosystem models at regional scales. Regional, national and global databases of soil C, N and P levels, plant production, and plant species distribution are now under development. Satellite derived products have been useful in expanding global and regional data bases on vegetation distribution and productivity. The

development of Geographical Information Systems (GIS) and fast computers have already improved our ability to simulate the impact of environmental change at the regional and global levels greatly. However, linking ecosystem models to needed spatial time varying data (e.g., weather, land use, soil texture, etc.) is still awkward. Software packages that directly link modular versions of ecosystem models to GIS systems are now being developed.

Lack of data bases of regional climate, land use, and soils has been a major limitation in large scale assessments since these are needed as inputs for ecosystem models. The scientific community has reached no consensus on the issue of spatial and temporal resolution of regional data. Regional climatic data have been available for a long time; however, GCM output of projected regional climatic change has only recently been made available to users outside the GCM modeling community. Part of the problem was that GCMs modelers did not store the data needed to run ecosystem models and did not extrapolate the results from the lowest layer (10's of meters above the surface) to the surface. Also the spatial resolution of the current GCMs (e.g., grid cells of 100 to 300 km to a side) is much coarser than the normal distribution of landscape units within the grid cell. Therefore, matching the spatial and temporal dynamics of GCM output and ecosystem dynamics is not easily accomplished. Regional and global soil databases (soil depth, texture, pH, C, P, and N content) are needed to drive ecosystem models and help evaluate global environmental issues and are only now being developed. Land use data are not readily available at the present time; however, regional and global data sets on land use are now being developed for the U.S. (Loveland et al. 1991), and globally (Mathews 1983). Satellite imagery offers great potential for determining global land use patterns (Loveland et al. 1991). This is important since detailed data on land use is available only in the developed countries.

The grassland version of the CENTURY model (Parton et al. 1987) has been used to simulate regional patterns of plant production and soil C and N content in the Great Plains and to simulate the impact of various climatic change scenarios for the region. A first step in use of the CENTURY

model at the regional scale was to test the model output against regional data. It was first necessary to organize and analyze regional data bases on plant production (Sala et al. 1988) and soil C and N (Burke et al. 1989). The CENTURY model was validated using the Soil Conservation Service (SCS) data by running it to equilibrium conditions for a large number of sites in the Great Plains and comparing simulated values of plant production and soil C and N levels with simulated values (Parton et al. 1987). After the comparisons proved to be satisfactory, the model was used to simulate the current regional patterns of ecosystem properties (plant production, N gas fluxes, N mineralization, soil organic matter and decomposition) for the Great Plains (Schimel et al. 1990). It was then used to project impacts of climatic change on these properties at several sites in the region.

Burke et al. (1990) continued this regional analysis with a detailed simulation of regional ecosystem properties for northern Colorado. In this case, maps of soil texture were used to initialize soil physical properties for the simulation model. Results showed that over scales of 10s to 100s of km, plant production was primarily controlled by precipitation patterns, while soil C and N patterns were controlled primarily by spatial changes in soil texture. Burke et al. (1991) also showed that aggregating soil properties at spatial levels greater than the county level resulted in errors of 10-20% in soil C levels. They then extended the earlier work of Schimel et al. (1990) by simulating the impact of climatic change for the central Great Plains region. In the latter analysis they used regional soil texture data and data on mean annual climatic conditions to drive the model.

Two years of CENTURY simulated aboveground vegetation production was compared to the regional patterns of normalized difference vegetation index (NDVI - Asrar et al. 1984 and Gallo et al. 1985) from NASA imagery with fairly good results (Burke et al. 1992). The climatic change runs of the model suggested that soil C levels would decrease (approximately 3%) during the next 50 years with the projected changes in the climate. Schimel et al. (1991) and Hanson et al. (1992) simulated the impact of the same climatic change scenarios for the entire Great Plains region. Schimel et al.

(1991) showed that soil C levels decrease for all of the Great Plains (Figure 7), while aboveground plant production (Figure 8) increases for regions north of the Kansas-Oklahoma border and decreases in most of Texas and Oklahoma. In the Schimel et al. (1991) analysis, simulated regional patterns of plant production were compared with the 1983-86 averaged NDVI index (index of plant production) and showed that the patterns compared very well for the region. In Schimel et al. (1990, 1991), the whole region was assumed to be a native grassland and the long-term average monthly climatic data was applied to it. Attempts are being made to improve on this analysis by using data on actual land use in the region (a large portion of which is currently cropped) and monthly observed climatic data to produce more realistic impact assessment runs. Recently, the MINK project (Rosenberg and Crosson 1991) used the EPIC model (Williams et al. 1984) to do a detailed climatic change assessment for the Central Great Plains region using observed soils, climate and land use data. The approach used in the MINK project is an example of the type of detailed climatic change assessment that needs to be done for all of the Great Plains using a variety of different models.

In our recent regional modeling project (Ojima et al. 1993, Parton et al. in press) we simulated the impact of scenarios of potential climatic changes (Houghton et al. 1990, 1992) on temperate and tropical grasslands around the world. The impact was simulated for the major grassland biome types shown in Figure 3. The latest version of the CENTURY model (Parton et al., 1993) is being used for this analysis. This version of the model was validated against a multi-year, multi-site data set on plant production and soil C and N content in various grasslands (Parton et al., 1993). Long-term weather observations (25 years) were used to simulate equilibrium conditions at 31 sites and the changes in monthly means of precipitation and temperature projected by each of two 2 x CO₂ GCM model runs were used to create climate change scenarios. Climate change was treated as a transient process by assuming that precipitation and temperature changes from current climate linearly over a 50 year period and assuming no further changes thereafter. We used climatic change data from two different

GCM simulations the Canadian Climate Centre (CCC) and the Geophysical Fluid Dynamic Laboratory model (GFDL); Houghton et al. 1990, 1992) and a summary of the changes in climate for each of the grassland regions is shown in Table 1.

The aggregated effect of altering the climate on aboveground plant production and soil C levels for the major global grassland regions is presented in Table 2. Production increased and soil C levels decreased for the humid temperate grasslands. Plant production responses differed for the two climate change scenarios while soil C levels decreased consistently for the dry continental steppes. Both plant production and soil C decreased for the extreme continental steppes. There was relatively little change in plant production and soil C for dry savanna steppes, savannas and humid savannas. The simulations show that soil C is lost from most of the sites. However, soil C losses are greatest (5-7%) for the continental steppe sites and least for the tropical grassland sites (+0.3 to -0.2%). In general the results for the two climate change scenarios used in this study are similar for soil C; however, simulated plant production is quite different for some of the regions (e.g., production changes range from -12 to +15% for the dry continental steppe). The soil C losses simulated by CENTURY are much lower than those of Jenkinson (1991). The reason for the difference is that Jenkinson's model did not consider the interactive impact of climate on enhanced nutrient availability and the increased plant production allowing for greater plant C inputs into the soil. CENTURY results suggest that nutrient released from the soil organic matter during a climate warming scenario will increase plant production and inputs into the soil. This will partially compensate for the soil C losses due to climate warming alone.

We also evaluated the direct impact of increasing atmospheric CO₂ levels from 350 to 700 vppm on these grasslands (including changes in water and N-use-efficiency based on recent data from Owensby et al., in press). Results (also shown in Table 2) indicate that plant production and soil C content increased as a result of increasing CO₂ concentration. It appears that the potential direct CO₂

impacts are as important as the influence of climatic changes predicted for the GCM models (see Table 1). The combined impact of the climatic change scenario and the increasing CO₂ levels is to increase plant production and decrease soil C losses. A complete description of the results from this study are presented by Ojima et al. 1993.

Integrated Social-Economic-Ecological Modeling

During the last 20 years a number of total system models have been developed for impact assessment. The Regional Economic Resource Simulation Model (REFLOW - Jameson et al. 1977) was developed to examine how investments influence the total regional economy, and how these economic changes influence the population and natural resource base of the region. The major components of the model include a water model, demographic model, land model, range production model and economic activity model. More recently the RANGEPACK HerdEcon model was developed to simulate grazing herd dynamics and economic return for ranching systems (Stafford-Smith and Foran 1990). That model is designed to assist decision-making on livestock grazing enterprises and allows consideration of cattle, sheep, buffalo and goat systems. The model includes an economic component and plant and animal production submodels and considers spatial aspects of grazing management and the potential impact of grazing intensity, burning and pasture improvement.

Ellis et al. (1990) developed a pastoral ecosystem model for nomadic tribes in northern Kenya. The model includes submodels for ecological and social-economic effects. The ecological effects submodel simulates important ecological processes and follows the supply and demand of resources through drought and non- drought periods. The social-economics component simulates human decision-making processes and the allocation of available resources. Some of the major outputs include: plant production, milk production, human nutritional condition, and food requirements for famine relief.

Hanson et al. (1992) and Baker et al. (in press) have used a combined ecological-economic model to simulate the potential impact of climatic change on plant and animal production for grasslands and pasture systems in the U.S. The model considers different animal production systems (e.g., cow-calf and steer systems) and simulates changes in plant species composition. The model considers management variables such as grazing intensity and fire management. Baker et al. (in press) used the model to simulate the effect of three different 2 x CO₂ GCM climate change scenarios on the Great Plains region. In these simulations plant production and cattle weight gains increase in the northern Great Plains, while cattle weight gains are reduced in the southern Great Plains. This reduction in weight gains is due to reduced digestibility of the forage and the direct impact of higher temperatures on the animals physiological condition. The predicted negative impact on cattle weight gain would likely be less than the model predicted due to improvements in animal breeding and other management practices. The SPUR model deals with the direct effects of CO₂ on plant production and water use, but does not consider its direct effects on forage quality. The omission is important since Owensby et al. (submitted) have shown that increasing CO₂ from 340 ppm to 700 ppm results in a substantial decrease in N content (10-30%) of leaf material. Decreasing N content of vegetation causes a reduction in digestibility of the material and would result in lower weight gains for grazing animals.

A thorough review of social-economic-ecological integrated models is presented by Conner (1994) in this volume. He suggests that social-economic impact models for grasslands can be divided into (a) micro-level models, (b) macro-level models and (c) decision support models (DSS). He characterized micro-level models as those that are location specific, use similar mathematical tools (i.e., linear and non-linear programming) and use simple plant production models that do not consider the interactions and impacts of grazing on the plant-soil system. FLIPSIM (Richardson and Nixon

1986) is one of the most commonly used firm level income simulators and has been adapted for range-livestock production systems by Van Tassell et al. (1989).

Macro-level economic models have been used during the last ten years to evaluate social-economic impacts of environmental and technological changes at the regional and national levels. Such models have been developed primarily for agricultural crop systems and do not deal with changes that alter the nature of the grazingland system (i.e., overgrazing and erosion). The ASM model (Cheng and McCarl 1992) is a good example of a macro-level model that has been used to study the impacts of global change and agricultural technology on agricultural systems.

Much recent effort has gone into development of decision support systems (DSS) which link biological models with socio-economic models. Such models include RANGEPAK (Stafford-Smith and Foran 1991), Graz PLAN (Moore et al. 1991) BEEFMAN (Clewett et al. 1991), GLA (Stuth et al. 1991) and STOCKPOL (McCall et al. 1991). Conner (1994) suggests that many of these models are limited in the way they are developed for specific regions and use simple plant-soil production models; they do not respond to long-term changes in soil properties (e.g., soil organic matter and N and P cycling) or to climatic change. Conner (1994) also includes a review of existing models, their limitation and suggests how to develop better integrated models for social-economic-biological assessment. We agree that ecological models can be successfully linked to social-economic models, however, there are many spatial and temporal scaling issues that need to be resolved to effectively link the models.

CONCLUSIONS

Grasslands are sensitive to changes in environmental conditions associated with fire, grazing and land use history. Ecosystem models vary widely, from those based on physiological processes and population dynamics to those based on broad biogeochemical phenomena. Correlative models can be used to assess biogeographical distribution of biome-types given projected climate scenarios. The reliability of current assessments of the effect of climate change effects on grasslands is limited by the lack of adequate model validations, the lack of the needed spatially distributed input data on soils, climate, topography and land use, and by the resolution of current GCM output, which does not approach the ecosystem-scale (i.e., GCM output at 50 km scale rather than 200 to 500 km scale). Model structures are needed that allow for better testing of model subcomponents. A structure to link various earth system subcomponents such as climatic-hydrologic-ecosystemic-sociological model linkages are also needed to evaluate the dynamic feedbacks among submodels.

We know relatively little of what to expect from an altered climate in terms of grassland/shrubland/woodland/savanna biogeography. However, two analyses (Prentice and Fung 1990, Emmanuel et al. 1985) both indicate that these systems may be susceptible to significant structural reorganization in an altered climate. Case studies (reviewed in Archer, in press) also suggest that this can occur. Based on biogeographic model analyses, we might expect significant changes in the distribution of grasslands and arid lands worldwide if the climate changes. Specific changes will be determined by the details of the climate change, including changes in extreme events not well simulated in atmospheric models. Land use change and human interventions will greatly modify the expressions of climate change and may, indeed, overwhelm them. Model predictions about the potential impact of climatic change on grassland ecosystems need to consider how management practices would change in response to changes in the climate. The interactive evolution of

management practices, climatic change, vegetation structure, and ecosystem properties need to be considered in future assessments of the impact of climatic change.

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Table 1. Regional climate and projected climate perturbations.

Sites	Current Precipitation (mm)	CCC Average % Change in Precipitation	GFDL Average % Change in Precipitation	Mean Air Temperature (°C)	CCC Average Change in Air Temperature (°C)	GFDL Average Change in Air Temperature (°C)
Humid Temperate	700	2.7	5.7	9.3	4.4	4.4
Dry Continental Steppe	301	-1.8	17.5	10.2	3.6	4.1
Extreme Continental Steppe	299	7.2	2.8	-0.3	6.2	5.1
Dry Tropical Steppe	387	13.4	10.2	24.1	3.4	3.3
Seasonal Humid Savanna	788	1.8	7.4	23.4	2.8	3.1
Humid Tallgrass Savanna	1555	-2.6	1.8	27.4	2.3	2.5
Mediterranean	497	2.6	6.4	15.7	3.8	3.8

Table 2. Simulated change in aboveground plant production and soil C (average change during the 50-75 year period following initiation of climatic change) of altered climatic conditions and CO₂ levels (doubling in 50 years) using climate change scenarios derived from the CCC and GFDL GCM 2xCO₂ runs (Ojima et al. 1993).

Sites	Current Aboveground (g C m ⁻² y ⁻¹)		Plant Production (% change)			Current Soil C gT to 20 cm	Soil C (% change in 0-20 cm)		
	Area* 10 ⁶ km ²	Plant Production	CCC GCM	GFDL GCM	CO ₂		CCC GCM	GFDL GCM	CO ₂
Humid Temperate	3.958	133.8	+10.2	+ 8.4	+12.5	28.89	-1.8	-2.0	+1.4
Dry Continental Steppe	2.943	36.4	-12.4	+15.4	+14.0	7.72	-6.5	-6.9	+0.8
Extreme Continental Steppe	2.095	59.7	-16.5	-18.0	+22.0	12.65	-5.0	-4.6	+0.9
Dry Tropical Steppe	5.109	54.6	+ 5.9	+ 0.1	+13.0	12.79	0.0	+0.3	+0.2
Seasonal Humid Savanna	7.990	190.9	+ 1.3	+ 6.3	+10.0	39.46	-0.5	-0.3	+1.9
Humid Tallgrass Savanna	1.708	339.6	- 1.0	+ 3.3	+ 6.8	3.76	-2.2	-1.9	+4.4
Mediterranean	0.161	78.8	+ 4.8	+ 6.7	+11.6	0.25	-4.5	-4.5	+1.9

*Estimated using data from Bailey (1989)

FIGURE LEGENDS

- Figure 1. A climatogram showing the distribution of forest, grassland, tundra and desert as a function of mean annual temperature and annual precipitation (Lieth, 1975).
- Figure 2. Distribution of grassland types in the US (Risser et al. 1981).
- Figure 3. Distribution of grassland types throughout the world (modified from Bailey, 1989)
- Figure 4. Aboveground net primary production and mean annual precipitation at 52 grassland sites. North American grasslands are represented by dots, others by stars (Lauenroth, 1978).
- Figure 5. Aboveground net primary production as a function of water and nitrogen supply. Experimental data from Northeastern Colorado, 1970-1975 (Lauenroth and Dodd, 1978).
- Figure 6. Simulated total daily carbon gain during July for C_3 and C_4 grass canopies of equal leaf area index (LAI=4) at different latitudes within the Great plains of North America (Ehleringer, 1978).
- Figure 7. CENTURY-simulated aboveground net primary production under (a) current climate (left panel) and (b) change in production 50 years after a change to a doubled CO_2 climate (GISS - Hansen et al. 1984) for the North American Central Grasslands (Schimel et al. 1991).
- Figure 8. CENTURY-simulated total soil organic carbon in the 0-0.2m layer (a) under current climatic conditions and (b) after 50 years of climate change (Schimel et al. 1991).

Fig. 1

Fig. 2

- ☆ 1. Shortandy, Kazakhstan
- ☆ 2. Tummensogt, Monogolia
- ☆ 3. Tuva, Russia
- ☆ 4. Xilinhot, China
- 5. Comodoro Rivadavia, Argentina
- ☆ 6. CPER, USA
- ☆ 7. Havre, USA
- 8. Santa Rosa, Argentina
- 9. Sarmiento, Argentina
- ☆ 10. Khomutov, Ukraine
- ☆ 11. Konza, USA
- ☆ 12. Kursk, Russia
- ☆ 13. Otradnoye, Russia
- 14. Montevideo, Uruguay
- 15. Bari, Italy
- 16. Davis, USA
- 17. Kalgoorlie, Australia
- 18. Khartoum, Sudan
- 19. Menaka, Mali
- ☆ 20. Niamey, Niger
- 21. Charleville/Warra Australia
- 22. Ciudad Bolivar, Venezuela
- 23. Kurukshetra Ludhiana, India
- 24. Marondera, Zimbabwe
- 25. Nagpur, India
- ☆ 26. Nairobi, Kenya
- ☆ 27. Towoomba, South Africa
- 28. Calabozo/San Fernando, Venezuela
- 29. Carimagua, Colombia
- ☆ 30. Hat Yai, Thailand
- ☆ 31. Lamto, Ivory Coast

HUMID TEMPERATE/PRAIRIE	SAVANNA
DRY SANANNA/STEPPE	HUMID SAVANNA
DRY TEMPERATE/STEPPE	MEDITERRANEAN
DRY CONTINENTAL/STEPPE DESERT	

Fig. 3

Fig. 4

Fig. 5

Fig. 6

NET PRIMARY PRODUCTION ($\text{g C} / \text{m}^2 / \text{y}$)

ABOVEGROUND

EQUILIBRIUM

50 - YEAR CHANGE

Fig. 7

SOIL ORGANIC CARBON (gC / m²)

Fig. 8

ASSESSING THE SOCIO-ECONOMIC IMPACTS OF CLIMATE CHANGE ON GRAZINGLANDS

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ABSTRACT

This paper begins with an introduction to human/grazingland interaction, including its history and a description of the general problems in analyzing and assessing human use of this vast resource. The second section provides a review and synopsis of the current state of modeling the socio-economic aspects of grazinglands. Aspects of biophysical models which can provide useful information on grazingland ecology and variability in the associated resources and human habitat are discussed. Models assessing human activity in relation to grazinglands are reviewed and a few examples of linkage of biophysical and socio-economic models into integrated assessments for policy analysis are discussed. Modeling the socio-economic impacts of climate change is discussed in the last section of this report. Problems encountered in incorporating changes in technology and adaptation to such changes are delineated and a model (FLIPSIM) designed to incorporate technological change is discussed. Methods for incorporating technological change and natural adaptation after climate change are then explored with emphasis on use of macro models as a means of parameterizing region specific micro models. The degree of reliability and resolution needed for models to be useful to policy analysts are assessed and it is argued that coarser resolution models are more efficient. The paper ends with an illustration of one type of analysis of socio-economic impacts of climate change on grasslands that can be conducted with the current data and methodology using a series of models and a "representative firm" approach.

INTRODUCTION

According to the Food and Agricultural Organization (FAO) (1982) almost all of the world's land area is capable of supporting grazing animals. Even with cultivated land excluded, 70% of the earth's land area has the potential to support grazing by domestic livestock. Lands are generally grazed because they are deemed inappropriate for use as cropland due to characteristics related to topography, climate, soil depth, etc. For thousands of years humans have used grazing animals as a source of food, clothing and power. Grazing animals are uniquely able to convert the energy stored in grassland vegetation into a form of energy usable by humans (Briske and Heitschmidt, 1991).

On a world-wide basis, grazinglands provide about 70% of the feed for domestic ruminants and about 95% of the forage for wild ruminants (Holechek et al., 1989). Grazed lands are used directly by over 200 million people and, through marketed products, they are used indirectly by millions more (Schuster, 1989).

History of human/grazingland interactions

There is evidence that humans have used domestic grazing animals for at least 11,000 years and that by 3,000 B.C. the practice was common from the Nile to the Indus (Pearse, 1971). Pastoral cultures developed during this time and evolved to the point where some degree of ecological soundness and viability was maintained. However, the advent of modern technology and the accompanying removal of natural limits on human and/or animal populations often led to environmental degradation (Stoddart et al., 1975).

Increased human and livestock populations in the last two centuries have

significantly increased pressure on much of the world's grazinglands. The consequences have been many: declining vigor and abundance of plants palatable to livestock, increased abundance of less desirable plants (including woody species), decreased soil fertility and reduced soil water absorption. These changes resulted in a reduced capacity to support grazing livestock (Holechek et al., 1989). According to Stoddart et al. (1975) " It was the effect of technological man that necessitated the development of range management as a profession."

The application of scientific principles to the management of natural grazinglands began in the United States in the 1890's. By the 1920's several state and federal experiment stations were conducting research on the management of grazinglands and associated livestock and by 1925 several colleges were offering courses in range management (Holechek et al., 1989). In 1948, the Society for Range Management was formed and began publishing the Journal of Range Management (JRM) and in 1949, a seminal paper on the use of "quantitative ecology" as the basis for managing rangelands was published (Dyksterhuis, 1949).

Studies of the economics of extensive livestock ranching in the western U.S. were conducted as early as the 1870's. However, the range management subdiscipline "range economics", which, according to Workman (1986), "... grew out of the combined efforts of range scientists and agricultural and resource economists to solve mutual problems involved with the use of mixtures of private and public rangeland resources...", was not formally recognized until the 1950's. Since the early 1950's, a large number of economic analyses of micro-level problems related to the use of range-related resources have been

conducted. Most of these used contemporary analytical techniques including simulation models (Bernardo and Conner, 1990; Torell and Tanaka, 1990).

Problems in analyzing human/grassland interactions

Over the past half-century economists have analyzed a large number of issues related to human use of grasslands. Many of these studies have, however, failed to provide the reliability, robustness and usefulness for managers and policy makers that similar efforts directed at agronomic production have produced (Bernardo and Conner, 1990). Several factors contribute to this situation:

1. Solar energy is harnessed less efficiently for human use by grassland ecosystems than by agronomic systems because grazing herbivores are required as energy convertors. In economic terms, forage is only an intermediate product. Because of this longer food chain, grazed ecosystems are more difficult for humans to exploit than are agronomic production systems (Conner, 1993).
2. Grazinglands are spatially heterogeneous. Each management unit is characterized by a diverse set of plant species whose composition and productivity change both during and between production seasons. Because of this variation, results from analyses of site-specific resource parameters are not generally applicable to other management units.
3. Ecology is not an exact science. There are a large number of interactions and interdependencies among abiotic and biotic variables that make cause

and effect relationships difficult to delineate. Thus, ecological principles and their transfer to management practices have evolved slowly.

4. Temporal relationships are complex. Ecological concepts are difficult to demonstrate because many grassland ecosystem phenomena evolve over long time periods. By contrast resource managers sometimes aim to maximize production in the short-run (current year). Thus, the modelling of human - grassland interactions requires attention to the relationship between present managerial actions and their impacts on future productivity of the grassland.
5. Annual production on grazingland is highly variable. Climatic variation usually results in fluctuations in forage yields and, consequently, in animal production. Such production swings offer substantial challenges to people using grazinglands to sustain and/or enhance their quality of life.

Scope and organization of this paper

The next section of this paper provides a review and synopsis of the current state of modeling the socio-economics of grassland use. Aspects of biophysical models which can provide useful information on grazingland ecology and variability in the associated resources and human habitat are identified. Models assessing human activity in relation to grazinglands are reviewed and the linkage of biophysical and socio-economic models for integrated policy analysis are discussed.

Modeling the socio-economic impacts of climate change is discussed in the last section. Problems encountered in incorporating technological changes and adaptation to

such changes into models of future conditions are delineated. Methods for incorporating technological changes and natural adaptation to climate change into simulation models are then examined. The degree of reliability and resolution needed for models to be useful to policy analysts is also discussed. The paper concludes with a discussion of socio-economic impact analyses of climate change on grasslands that are feasible, given the current methodology and data availability.

CURRENT STATE OF MODELING SOCIO-ECONOMIC ASPECTS OF GRASSLANDS

Biophysical models and other sources of information on the variability of grazingland production

Socio-economic models of human uses of grasslands must consider the inherent variation in grassland productivity. Most previous attempts to model microeconomic aspects of grazingland - livestock production systems attempted to do so empirically (Halter and Dean, 1965; Beck *et al.*, 1982). According to Carlson *et al.* (1993), empirical models are attempts to establish only correlation between processes and controlling variables. They may be accurate, but inflexible, if the underlying algorithms are based on site-specific information. Alternatively, they may be relatively robust but less accurate if based on broad regional data.

During the past two decades interest has increased in the development and use of process models to characterize the interactions between climate, soil, and plant and animal production. Mechanistic or process models attempt to explain and reflect actual processes.

Compared to empirical models, process models are generally more complex and require more kinds of data as input. However, mechanistic models are more likely than empirical models to generate realistic predictions for locations and/or situations for which data are lacking or unavailable (Carlson *et al.*, 1993).

Several biophysical simulation models are available. They include:

1. Ekalaka Rangeland Hydrology and Yield Model (ERHYM-II) (Wight, 1987);
2. Simulation of Production and Utilization of Rangelands Model (SPUR) (Wight and Skiles, 1987);
3. Grassland Simulation Model (ELM) (Innis, 1978) and
4. Patch Hydrology and Growth Model (PHYGRO) (adapted from ERHYM-II) (Vega, 1991).

Detailed analyses of the capabilities, data requirements and information provided by these biophysical models are provided by Carlson *et al.* (1993). In addition, ELM is discussed in detail by Parton *et al.* (1994) in the preceding paper in this volume. Therefore, detailed descriptions of these models will not be provided in this paper. However, some general comments regarding their usefulness to socio-economic models as a source of information on variation in rangeland productivity is warranted.

Perhaps the most perplexing problem in using biophysical simulation models in economic analyses is the scale of focus. Some models provide high resolution (e.g. a single plant) which complicates aggregation for an economic unit given the heterogeneity of most native grasslands.

Another problem is the proclivity of animal and range scientists to undertake

independent modeling efforts. Most animal performance models are based on fixed diets of known quality and quantity. However, the diet of the grazing animal is determined by variation in available forage. Thus, most existing models cannot adequately represent the consequences of management interventions, such as stocking rate adjustments or supplemental feeding, on animal production.

While most existing models of grazingland ecosystems consider the impacts of variation in climatic factors such as rainfall and temperature on seasonal and annual plant growth, they do not adequately incorporate intertemporal impacts of climatic or management induced disturbances. That is, they assume no trend in ecological condition. Similarly, most current biophysical simulation models do not accurately model the heterogeneity and dynamics of forage types (grasses, forbs and shrubs) on grazinglands, nor do they accurately reflect the impacts of interrelated ecological and managerial factors such as grazing pressure, vegetation type, fire, or changes in soil condition due to erosion (Walker, 1992; Steffen *et al.*, 1992; McKeon and Howden, 1992).

Current models and other methods for characterizing human activity on grasslands

Micro-level analyses. Most analyses of socio-economic issues related to grazinglands conducted in the past four decades have been location specific and have included generic analytical methodologies; i.e., enterprise budgeting, capital budgeting, and linear programming (Bernardo and Conner, 1990; Torell and Tanaka, 1990). Many of these studies used long-term averages for grazingland production yields and resource and product prices; i.e., these factors were assumed to be deterministic and static. Robustness

of results were usually checked with sensitivity analyses by varying product prices and/or production levels.

In several studies, however, attempts were made to analyze the socio-economic impacts of grazing by using methods which allow incorporation of the stochastic and/or dynamic aspects of the problem (Bernardo and Conner, 1990). Burt (1971) used dynamic programming in an analysis of optimal timing of investments in pinyon-juniper control on rangeland. More recently, Karp and Pope (1984) used stochastic dynamic programming to simultaneously determine optimal stocking rates and frequency of brush control investments and Garoian *et al.* (1990) used the same methodology to determine optimal stocking rates and cow-yearling herd ratios. In both studies, specifications of transition matrices were based on location specific data which greatly restricted the generality of the optimal control rules derived.

More recently, Sandiford and Howitt (1992) developed a stochastic optimal control model to evaluate management strategies for firewood, beef-cattle and wildlife lease-hunting enterprises on hardwood rangelands in California. Equations of motion (changes from year to year) for oak density, forage production and stocking rate were estimated from empirical studies in the region, again limiting the general applicability of the results.

A few recent studies used empirical simulation models to characterize the stochastic and dynamic aspects of human interactions with grazinglands. Riechers *et al.* (1989) developed a model of a Texas cow-calf ranching enterprise to assess the economic consequences of alternative stocking-rate decision rules. The model considered climatic conditions and cattle prices as stochastic variables and incorporated empirical site-specific

functional relationships between climatic factors, forage and beef production and feeding costs.

The Firm Level Income and Policy Simulator (FLIPSIM) (Richardson and Nixon, 1986) is the most complete and adaptable firm-level simulation model available. FLIPSIM is a general empirical model designed to analyze policy, tax, marketing, production and firm growth factors for various crop and livestock enterprises. It is a dynamic, stochastic and recursive (each year's result is predicated on the result from the previous year) simulation model containing an optimization routine for selecting the enterprise (crop) mixes each year. Price and yield distributions and the physical and economic environment are exogenous to the model and must be specified by the user. These distributions can be based on historical observations or may be specified to represent changes from current or historical trends. Several versions have been used to analyze:

1. marketing strategy impacts on firm survival and growth (Bailey, 1983),
2. optimal tenure arrangements (Perry *et al.*, 1985) and
3. the effects of tax law changes on ranch firm survival and growth (Conner *et al.*, 1987).

VanTassell *et al.* (1989) adapted FLIPSIM to model range - livestock production systems. The modified FLIPSIM was used to evaluate the effects of implementing alternative range improvement and grazing management practices (technologies) on the survival and success of a ranch firm parameterized to represent a specific region in Texas. Results of this analysis applied only to the modeled region, but a subsequent modification of FLIPSIM allows it to be parameterized to represent ranch firms in any region of the

United States (Knutson et al, 1992).

Recently, Richardson et al. (1993) produced another modification of FLIPSIM; a Farm Level Technology Impact Evaluation System (TIES); which is designed for use on smallholder farms anywhere in the world. It was initially developed for evaluating alternative animal disease control technologies and explicitly accounts for on-farm consumption of crop and livestock products. A module in TIES simulates the annual production, consumption and marketing activities of a farmer for individual livestock and crop enterprises. The model is a Monte Carlo simulator in that exogenous variables influenced by weather and market forces are drawn at random to simulate the risk and uncertainty faced by farmers. The impacts of changes in production technologies and policies on the economic and nutritional sustainability of a representative smallholder farm are evaluated by simulating the farm before and after the change. More than 100 financial variables related to the economic viability of a farm can be compared for each technology simulated.

Macro-level models. During the past ten years several regional and national scale models have been developed to analyze the socio-economic impacts of institutional and/or environmental changes in the rural/agricultural sector. These models are primarily used for analyzing the impacts of changes in technology and economic policy on aggregate demand and supply and consumer, producer and tax-payer well-being. Two of the best known are AG-GEM (Penson and Taylor, 1992) and FAPRI (University of Missouri, 1992). Both are empirical econometric models which provide estimates of change in a wide array of economic variables over specified planning periods resulting from changes in policies

and/or regulations or from changes in technology as represented by changes in resource productivity. They were designed primarily for agronomic agriculture and therefore do not readily react to changes in grazingland availability or productivity.

Another macro-level model, The Agricultural Sector Model (ASM) (Cheng and McCarl, 1993) uses a quadratic programming algorithm to select optimal production levels and areas (regions) for a variety of agricultural commodities. It has been used mainly to analyze the impacts on socio-economic variables in the United States of changes in environmental regulations, technology and global climate. Socio-economic impacts are reported as changes in variables such as producer and consumer surplus and more specific changes like agricultural commodity prices, yields and production costs for specific regions. ASM can be made to react to changes affecting grazinglands if the impacts of the changes in grassland productivity can be exogenously interpreted to reflect changes in the livestock yields and production costs used as inputs to the model.

Linking biophysical and socio-economic models for policy analysis

Most work linking biophysical and socio-economic models into integrated assessment tools has been conducted to develop computerized decision support systems (DSS). DSS are designed to aid humans trying to make decisions about how to manage their resources to meet their goals (Conner, 1993). One example of a DSS, RANGEPAK (Stafford and Foran, 1991), is described in a preceding paper in this volume (Parton et al., 1994). One of the oldest and most complete bio-economic DSS is GrazPlan (Christian et al., 1978; Moore et al., 1991). This was initially a whole-farm simulation model designed

for use in research and has only recently been re-developed as a DSS. The system incorporates a hydrology-based process model of plant growth using a specified mixture of three functional groups; annuals, perennial grasses and perennial forbs. Also included are animal production models for cattle and sheep. Intake of forage is predicted from functions of available herbage and its digestibility (output from the plant module). Animal growth and reproduction are modeled as functions of intake, digestibility, and user specified parameterizations of such factors as genotype, age, season, etc. The management module of GrazPlan is a series of scheduled events such as breeding season, shearing of sheep, sale of animals, movement of animals between paddocks, and supplemental feeding. An optimization module can be used to select the subset of management activities which maximizes net returns to the firm.

Unfortunately, GrazPlan was developed for use only in the high-rainfall and Mediterranean environments of southern Australia. Likewise, BEEFMAN (Clewett *et al.*, 1991), an integrated series of DSS, was developed for use only in the eucalypt woodlands of central Queensland, Australia. Other DSS which provide linkages between forage production, animal production and socio-economic impacts include Grazing Land Applications (GLA) (Stuth *et al.*, 1991) and Stockpol (McCall *et al.*, 1991). But, to-date, the applicability of these models is restricted to specific regions and/or they are not yet linked to biophysical process models that would make them useful in modeling climatic impacts on forage production. Another characteristic of these DSSs is that their resolution is generally rather coarse; that is, they report change only at the landscape or management unit level. This contrasts with results being reported at the plant or plant community level

in most biophysical models that have been developed as research tools. However, the spatial scale of the DSSs is probably better suited to policy analysis and resource management than is that of the typical biophysical model.

Fortunately, some current efforts should soon provide the means for linking plant and animal production with socio-economic models and adapting them to a wide variety of geographic and institutional settings. For example, Blackburn and Kothman (1989, 1991) have developed models of forage dynamics and diet selection and have linked them with a sheep production model by Blackburn *et al.* (1987). Another effort involving USDA-ARS, Colorado State University (CSU) and The University of Wyoming will link the SPUR model, the CSU beef production simulation model and FLIPSIM (VanTassell, 1992).

The integration of macroeconomic models with biophysical simulation models is relatively rare. However, the Agricultural Sector Model has been used in conjunction with information on annual crop yields provided by the Erosion Productivity Calculator (EPIC, Williams *et al.*, 1984) and CERES (Ritchie and Otter, 1984) models to estimate climate change impacts (Adams *et al.*, 1990; McCarl *et al.*, 1993). While the study by McCarl *et al.* (1993) did not consider the impacts of climate change on grasslands directly, it did assume that pasture (grazingland) productivity would change by the average percentage change predicted for crops by the EPIC model.

Rosenberg and Crosson (1991) used a regional input-output model to assess the economic impacts of climate change in the MINK project. Again, EPIC was used to project changes in feed grain and forage production. Direct impacts on livestock

production due to changes in grazable forage yields were not estimated. However, indirect effects were estimated using production multipliers linking changes in feed grain production to changes in livestock production.

DEVELOPING MODELS OF SOCIO-ECONOMIC IMPACTS OF CLIMATE CHANGE

Incorporating changes in technology and adaptation in baseline scenarios

Incorporating institutional and technological changes into the simulation of firm performance in the future has been a fundamental problem in economic forecasting. This is usually done with outputs generated by other models to parameterize the firm performance simulator. For example, FLIPSIM uses output from FAPRI and AG-GEM to establish input and product price levels and interest and inflation rates for each year in the period for which firm performance is to be simulated. It also makes provisions for specifying changes in technology (annual output per unit of land or per animal) over the simulation period. Most estimates of technological change to-date have been based on simple extensions of historical trends, but some work has been done to develop estimates of technological change as a function of public investment in research (Cheng et al., 1991). FLIPSIM has incorporated routines for selecting the optimal enterprise mix each year. This allows the model to automatically adjust to technological and institutional changes.

Obviously, the biggest problem with building change into baseline scenarios is that the magnitude and direction of the expected changes must be estimated. Then, the array of implications to alternative enterprises and production practices must be anticipated so

that they can be programmed into the model for selection by the optimization routine, if warranted. Forecasting techniques which would systematize this task would clearly be an improvement.

Incorporating technology changes and natural adaptation after climate change

Incorporating institutional and technological change into climate change scenarios is more difficult than for baseline scenarios. This is because the global impacts of and responses to climate change are added sources of uncertainty. Obviously, the way that other regions (nations) are impacted by climate change will determine, in-part, how the area being analyzed will respond.

FLIMPSIM's parameterization scheme offers an approach to this problem. Output from large global models and macroeconomic models are used to parameterize technological and institutional change for the more region specific micro models. If needed, a recursive procedure can be used wherein the output of the region specific micro model is used to re-parameterize the macro model which is then used to re-generate parameters for the region specific model. While this is a time-consuming procedure, it may be useful in establishing reliable indications of the socio-economic impacts of climate change.

Reliability and resolution requirements for policy development

In this paper discussion of policy development is restricted to policies directed at controlling human use of grasslands. Walker (1992) and Steffen et al. (1992) indicate that,

for policy questions of this kind, indications of the impacts of climate change must be specific enough to reveal changes in:

1. distribution and composition of vegetation,
2. amounts and seasonal distribution of grazable forage,
3. susceptibility of the land to erosion and
4. implications for biological diversity.

Coarse resolution models such as PHYGRO, ERHYM-II, or those incorporated in GrazPlan would be adequate to provide such information and more efficient to use than the finer resolution models such as SPUR or ELM. With this type of information it would, for example, be possible to develop policies for optimal land use by altering the:

1. types of livestock, livestock - wildlife proportions, and total population sizes,
2. management practices such as prescribed burns to control woody species encroachment, and
3. selection of species and sites for inclusion in protective programs.

In addition to such biophysical data, policy makers would need information on the impacts of climate change and requisite adjustments on ranchers using the land, e.g. production efficiency, product quality, etc. This often requires the use of micro level, region specific socio-economic models.

Current models for analyses of socio-economic impacts of climate change on grasslands

With the independently developed and unintegrated models currently available, it

is possible to assess the socio-economic impacts of climate change on the grasslands of any specific region. An example of how this might be accomplished is illustrated in Figure 1 and Table 1. The procedure requires selection of representative firms or estimation of their characteristics, considering their variation across the dominant ecological and socio-economic zones for the region. This hypothetical study region is depicted in Figure 1 and considerations for selecting the representative firms to be modeled are described in "Step 1" of Table 1. Next, a biophysical model, like CENTURY (Parton *et al.*, 1994) or PHYGRO, can be calibrated and parameterized for each representative firm as described in "Step 2" (Table I). In the third step an animal production simulation model, such as the CSU beef cattle model, or a modified animal production module from GrazPlan or GLA, can be used to relate animal production to the output of the plant growth model. In the fourth step of the procedure a micro level model like FLIPSIM, TIES or a modification of the management and optimization modules in GrazPlan, can be used with the animal production model output to estimate firm performance over the baseline period (and the climate change period). Differences in the firm's performance during the two simulated periods would be expanded to the regional level in the fifth step of the procedure (Table 1). The expansion to the regional level would be based on the proportion of the region represented by each firm modeled. The final step of the procedure requires that steps 2 through 5 be repeated with the changed climate data and the results compared with those from the same steps run with the baseline climate data.

An alternative approach to the procedure outlined in Table 1 would involve using the output from steps 4 and 5 as input to a national scale (macro) economic model like

ASM. Adding this step would facilitate integration of results across regions and would allow for interregional impacts to be accounted for.

CONCLUSIONS

Obviously, if the procedure described in the previous subsection and Table 1 represents our current capability for assessing the socio-economic impacts of climate change on grazinglands, there is much need for improvement. A significant first step could be effected by integrating the forage, livestock and farm level economic models into a system similar to the GrazPlan DSS. While development of a system like GrazPlan that is generally adaptable for most of the grasslands of the world could be accomplished by adapting various components from currently existing models, it none-the-less represents a formidable undertaking.

Moreover, an integrated model which incorporates capabilities of the currently available biophysical and socio-economic models does not alleviate several serious constraints to achieving truly useful integrated assessments of the impacts of climate change on grazinglands. In order to get reliable estimates of land use changes due to climate change we need biophysical models that (a) relate forage production by class (grass, forbs, browse); (b) model transitions between dominant plant communities (like grass to shrub); and (c) integrate forage composition, quantity, and quality (nitrogen - carbon ratio) to animal carrying capacity/productivity by kind and class of animal. Equally constraining is the lack of techniques for reliably predicting socio-economic adaptation to

future change in either climate, institutions or technology. Given the complexity of the transition processes, in both plant and human communities, it is likely that models which reliably reflect their reactions to future climate change will be slow to develop.

Despite the imperfections of the current modeling technology, progress in the use of computer technology for biophysical and socio-economic assessments of grazingland performance and sustainability could be enhanced by model integration. Thus, projects designed to develop integrated models are urgently needed and would doubtlessly be welcomed in both research and policy development communities.

FIGURE 1: Example of a study region with the use of representative firms to model impacts of climate change.

STUDY REGION

Table I. Steps in Analysis of Socio-economic Impacts of Climate Change on Grasslands Using Current Models

*Step
Number*

1. Select representative firms for modeling.

Considerations:

Firms should be representative of resources, size and tenure of production units and production practices in a specified portion of the study area.

2. Run PHYGRO for each representative firm for each year in the planning period (also EPIC if the firm engages in crop production).

Considerations:

input data

- a. climate
- b. soils
- c. hydrology
- d. vegetation

outputs

forage production by type
(grass, forb, browse),
by season, by year
(crop yields if EPIC)

3. Run animal production model for each representative firm for each year in the planning period.

Considerations:

input data

- a. initial animal inventories
and characteristics
by kind and class
(including vegetation
preference ratings)
- b. husbandry practices
- c. production goals
- d. forage/feed availability
by type, by season, by
year (from PHYGRO
and/or EPIC)

outputs

animal production yield
and inventory by kind
and class by year

Table I. Continued

*Step
Number*

4. **Run FLIPSIM for each representative firm for each year in the planning period.**

Considerations:

input data

- a. beginning financial characteristics of firm
- b. annual institutional and macroeconomic parameters
- c. annual enterprise production requirements (factors) and product and factor prices and/or probability distributions
- d. annual animal products and inventories (from Step 3) (and crop yields if EPIC)

outputs

- a. end of planning period financial characteristics of firm
- b. annual cash flow
- c. probability of firm survival and/or growth over planning period
- d. animal and/or crop enterprises included in optimal mix for firm at the end of the planning period

5. **Aggregate across representative firms to produce region-wide estimates of end-of-planning period characteristics.**

Considerations:

inputs

- a. results from Step 4 for all representative firms

outputs

- a. enterprise types and amounts (acres, no. of head, etc.) and yields
- b. profitability of enterprises
- c. size and tenure status of production firms

6. **Repeat Steps 2-5 for planning period with new climatic data.**

Considerations:

Compare results (from Step 5) with and without climate change to determine impacts of climate change on future socio-economic characteristics of the study region

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MODELING THE EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES - A REVIEW

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ABSTRACT

Hydrologic models provide a framework in which to conceptualize and investigate the relationships between climate and water resources. A review of current studies that assess the impacts of climate change using hydrologic models indicates a number of problem areas common to the variety of models applied. These problem areas include parameter estimation, scale, model validation, climate scenario generation, and data. Research needs to address these problems include development of (1) a more physically based understanding of hydrologic processes and their interactions, (2) parameter measurement and estimation techniques for application over a range of spatial and temporal scales, (3) quantitative measures of uncertainty in model parameters and model results, (4) improved methodologies of climate scenario generation, (5) detailed data sets in a variety of climatic and physiographic regions, and (6) modular modeling tools to provide a framework to facilitate interdisciplinary research. Solutions to these problems would significantly improve the capability of models to assess the effects of climate change.

INTRODUCTION

Hydrologic models provide a framework in which to conceptualize and investigate the relationships between climate and water resources. These investigations can range from the evaluation of annual and seasonal streamflow variation using simple water balance models to the evaluation of variations in surface- and ground-water quantity, quality, and timing using complex distributed-parameter models that simulate a wide range of water, energy, and biogeochemical processes.

The scientific literature over the past decade contains a large number of reports detailing the application of hydrologic models to the assessment of the potential effects of climate change on a variety of water resource issues. The purpose of this paper is not to review the findings of these reports but to characterize the current state of water resource modeling for use in simulating the effects of climate change and current climate variability. Methodologies are reviewed, deficiencies are discussed, and additional research needs are identified.

MODELS

"Hydrologic modeling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle" (Dooge, 1992). This partitioning in its simplest form is expressed by the water balance equation:

$$Q = P - ET \pm \Delta S \quad (1)$$

where Q is runoff, P is precipitation, ET is evapotranspiration, and ΔS is the change in system storage. Equation (1) is common to all hydrologic models. The variety and number of hydrologic models developed to solve equation (1) reflect the wide range of modeling purposes, data constraints, and spatial and temporal scales that have influenced the conceptualization and parameterization of the processes in the equation.

Models can be classified using a number of different schemes (Woolhiser and Brakensiek, 1982; Becker and Serban, 1990; Dooge, 1992). Classification criteria include purpose of model application (e.g., real-time application, long-term prediction, process understanding), model structure (models based on fundamental laws of physics, conceptual models reflecting these laws in a simplified approximate manner, black-box or empirical analysis), spatial discretization (lumped parameter, distributed parameter), temporal scale (hourly, daily, monthly, annual), and spatial scale (point, field, basin, region, global). A variety of these types of models have been applied to the assessment of the effects of climate change. A review of some of these modeling approaches provides one measure of the state of the art of hydrologic modeling. This is not a comprehensive review of all model studies, but a review of selected models to indicate the variety of modeling approaches and range of applications. Models are grouped using the model structure and spatial discretization criteria.

CURRENT MODELING APPROACHES

Empirical Models

An empirical representation of equation (1) considers only the statistical relations among the components of the water balance. An empirical model developed by Langbein *et al.* (1949) that expressed the relationship among mean annual precipitation, temperature, and runoff was used by Stockton and Boggess (1979) to estimate changes in the average annual runoff of 18 designated regions throughout the United States for different climate change scenarios. Revelle and Waggoner (1983) used the same model as the basis for investigating the effects of climate change on runoff in the western United States.

Empirical models do not explicitly consider the governing physical laws of the processes involved, but only relate input to output through some transform function. As such, empirical models reflect only the relations between input and output for the climate and basin conditions during the time period in which they were developed. Extension of these relations to climate or basin conditions different from those used for development of the function is questionable.

Water Balance Models

Water balance models originated with the work of Thornthwaite (1948) and Thornthwaite and Mather (1955). These models are basically bookkeeping procedures used with equation (1) to account for the movement of water from the time it enters a basin as precipitation to the time it leaves the basin as runoff. The models vary in their degree of complexity based on the detail with which each component of equation (1) is considered. Most models account for direct runoff from rainfall and lagged runoff from basin storage in the computation of total runoff (Q). In addition, most models compute the ET term as some function of potential ET and the water available in storage (S). While water balance models can be applied at a daily, weekly, monthly, or annual time step, in climate studies they have been applied most frequently at the monthly time step.

A simple three-parameter monthly water balance model was applied by Arnell (1992) to 15 basins in the United Kingdom to estimate changes in the monthly river flow regimes and to investigate the factors controlling the effects of climate change on river flow regimes in a humid temperate climate. The three parameters, which were fitted to each individual basin, represent (1) the fraction of precipitation that contributes directly to runoff, (2) the maximum storage capacity of the basin, and (3) the basin lag for converting the water available for runoff to streamflow. Arnell (1992) also compared the water balance model with four different empirical models for the assumed climate changes. No one empirical formulation gave a consistently closer match to the water balance model estimates of climate change effects and differences among empirical models for the same scenario were large. It was noted that the results suggest that "estimates of possible change based on annual empirical models should be treated with extreme caution."

Gleick (1987a) developed a monthly water balance model for application to the Sacramento River basin in California. He began with a basic model similar to that used by Arnell (1992) but varied the parameter representing the fraction of precipitation that contributes to direct runoff by season. A snow accumulation and melt component was developed to account for the seasonal storage and release of water by a snowpack. The model was applied using 18 different climate-change scenarios to evaluate changes in runoff and soil moisture under this variety of assumed climate conditions (Gleick, 1987b). A monthly water balance model that also accounts for snow processes was developed and applied by Mimikou *et al.* (1991) for evaluating regional hydrologic effects of climate change in the central mountainous region of Greece.

Schaake (1990) developed a nonlinear monthly water balance model for the evaluation of regional changes in annual runoff associated with assumed changes in climate. The model was applied to 52 basins in the southeastern United States using a single set of model parameters for all basins. The storage term in equation (1) was recast as a deficit term where deficit is the difference between a parameter defined as the maximum limit of storage and the current storage. When the deficit is zero, water is assumed to evaporate and transpire at the potential rate and all precipitation is assumed to be direct runoff. Monthly potential ET was computed from the annual average potential ET using a sinusoidal relation to account for the variation of potential ET over the course of a year. Actual ET was computed as a function of potential ET and the moisture deficit. Runoff was computed as a function of precipitation, the moisture deficit, and actual ET.

Water balance models provide the ability to simulate average runoff for given precipitation over a range of basin conditions and to simulate the year to year variation in runoff as precipitation varies. Limitations include the need to calibrate parameters to observed conditions and the inability to adequately account for possible changes in individual storm runoff characteristics at the time steps they are applied.

Conceptual Lumped-Parameter Models

Conceptual lumped-parameter models are developed using approximations or simplifications of fundamental physical laws and may include some amount of empiricism. They attempt to account for the linear and nonlinear relations among the components of equation (1). As with water balance models, conceptual lumped-parameter models attempt to account for the movement of water from the time it enters the basin until it leaves as runoff. However, flow paths and residence times of water are considered in much greater detail and normally at time steps on the order of minutes, hours, or one day. Vertical and lateral flow processes may be considered. Vertical processes may include interception storage and evaporation, infiltration, soil moisture storage, evapotranspiration, ground-water recharge, and snow pack accumulation and melt. Lateral flow processes may include surface runoff, subsurface flow, ground-water flow, and streamflow. In addition, some models include the capability to simulate some associated sediment, chemical, and biological processes.

Processes usually are parameterized at the scale of an entire basin or for relatively large subareas of the basin. These areas often have a heterogeneous mix of vegetation, soils, and land use. Consequently, parameters are assumed to be effective values that are representative of the mix of conditions and normally must be calibrated using historic information. Some applications attempt to account for spatial variability in basin characteristics by making subarea delineations based on considerations such as land use or vegetation. The effect of elevation on climate characteristics such as temperature and precipitation are considered by dividing a basin into elevation bands.

One of the more frequently used models in this group is the Sacramento Soil Moisture Accounting Model (Burnash, Ferral, and McGuire, 1973). The Sacramento model simulates the movement and storage of soil moisture using five conceptual storage zones. The model has 17 parameters that define the capacities and flux rates to and from the storage zones. Nemec and Schaake (1982) used the Sacramento model to evaluate the effects of a moderate climate change on the sensitivity of water resource systems in an arid and a humid basin in the United States. Sensitivity was evaluated by simulating the variation in storage-yield relations of hypothetical reservoirs located in each basin.

The Sacramento model has been coupled with the Hydro-17 snow model (Anderson, 1973) by a number of investigators for application to basins dominated by snowmelt. Hydro-17 simulates the accumulation, storage, and melt of a snowpack at a 6-hr time step using a modified temperature index approach. The hydrologic sensitivities of four basins in California were evaluated by Lettenmaier and Gan (1990) using the Sacramento model coupled with Hydro-17. Changes in snowpack water equivalent, runoff, evapotranspiration, soil moisture, and flood frequency were examined. The same model was used by Schaake (1990) to evaluate the sensitivity of runoff to climate change in the Animas River basin, a subbasin of the Colorado River basin. Nash and Gleick (1991) used the model to evaluate runoff sensitivities in two additional headwater basins of the Colorado River. Cooley (1990) applied the model to a headwater basin in southwestern Montana. Panagoulia (1992) used the model to assess the effects of climate change on a basin in central Greece.

Several other models having a similar structure to the coupled Sacramento and Hydro-17 models, but with different process conceptualizations, have been used to assess the effects of climate change on many regions of the globe. The Institute Royal Meteorology Belgium (IRMB) model (Bultot and Dupriez, 1976) has been applied to basins in Belgium (Bultot *et al.*, 1988) and Switzerland (Bultot *et al.*, 1992). The HYDROLOG model (Porter and McMahon, 1971) was applied to two basins in south Australia (Nathan, McMahon, and Finlayson, 1988). The HBV model (Bergstrom, 1976) has been applied to basins in Finland (Vehvilainen and Lohvansuu, 1991). The Hydrologic Simulation Program - FORTRAN (HSPF) model (U.S. EPA, 1984) has been applied to a basin in Newfoundland, Canada (Ng and Marsalek, 1992).

The Erosion Productivity Impact Calculator (EPIC) is a coupled model that simulates hydrology, erosion and sedimentation, nutrient cycling, plant growth, tillage, soil temperature, and crop management (Williams, Jones, and Dyke, 1984). EPIC was modified to enable it to simulate the effects of atmospheric CO₂ and climate change on crop photosynthetic efficiency and water use (Stockle *et al.*, 1992a, b). This modified version was used to investigate the effects of rising atmospheric CO₂ concentrations and climate change on agricultural productivity in the four-state region of Missouri, Iowa, Nebraska, and Kansas (Easterling *et al.*, 1992a, b). Applications were made at the single hectare scale for 49 different representative sites throughout the region.

The more detailed process simulation capabilities and higher temporal resolution permitted by conceptual lumped-parameter models enables a more detailed assessment of the magnitude and timing of process responses to climate change. For example, increased resolution of precipitation timing and form (rain or snow) enable the estimation of streamflow timing and of the frequency and magnitude of flood peaks. However, these capabilities are accompanied by an increase in the number of process parameters that must be estimated or fitted, and in the amount and types of data needed to characterize the basins and needed as input to run the simulations.

Process-Based Distributed-Parameter Models

These models are firmly based in the understanding of the physics of the processes that control basin response. Process equations involve one or more space coordinates and have the capability of forecasting the spatial pattern of hydrologic conditions in a basin as well as basin storages and outflows (Beven, 1985). Spatial discretization of a basin to facilitate this detail in process simulation may be done using a grid-based approach or a topographically based delineation. In each case, process parameters are determined for each grid cell or topographic element.

The ability to simulate the spatial patterns of hydrologic response within a basin make this approach attractive for the development of models that couple hydrologic processes with a variety of physically based models of biological and chemical processes. The applicability of models of this type to assess the effects of climate change has been recognized (Beven, 1989; Bathurst and O'Connell, 1992), but few applications have been presented to date.

The FOREST-BGC (BioGeochemical Cycles) model is a process level ecosystem model that calculates the cycling of water, carbon, and nitrogen through forest ecosystems (Running and Coughlan, 1988). Running and Nemani (1991) used this model to examine climate change induced forest responses for a 1540 km² region in northwestern Montana using a grid resolution of 1.1 km². Changes in outflow of water from the soil zone, evapotranspiration, and photosynthesis were examined for the region and on individual grid cells.

Major limitations to the application of these models are the availability and quality of basin and climate data at the spatial and temporal resolution needed to estimate model parameters and validate model results at this level of detail. These data requirements may pose a limit to the size of basin in which these models are applied. However, the Systeme Hydrologique Europeen (SHE) model (Abbott *et al.*, 1986) is said to have been successfully applied to basins ranging from 30 m² to 5000 km² (Bathurst and O'Connell, 1992).

MODELING ISSUES

Most of the current modeling approaches have been built upon existing operational models with modifications as needed to extend the application to a wider range of basin conditions and to account for limited knowledge of basin and climate characteristics. While most report some measure of success and applicability of the methods developed, each also discusses a number of qualifying assumptions and limitations that affect the interpretation of model results. A number of these problems are common to all hydrologic modeling applications and are being addressed by a variety of research efforts in the hydrologic science community. A review of selected topical areas in which problems and limitations have been identified provides an additional measure of the state of the art.

Parameter Estimation

The variety of modeling approaches used reflects a number of factors, including assessment objectives, data constraints, and the spatial and temporal scales of application. While these models differ in their degree of complexity, they share a common problem. Each has a number of parameters that must be estimated or calibrated for model application. Some parameters are defined as being physically based and are assumed to be measurable from basin and climate characteristics. Many of the parameters are less well defined and are optimized or fitted.

Problems with the use of fitted parameters include limited length of historic data record, minimal or no information on reasonable values or acceptable ranges of values, incorporation of model and data errors in parameter values, and the effects of parameter intercorrelations. Intercorrelation can produce compensating errors that inadvertently improve the simulation. Underestimation in one parameter may be compensated for by overestimation in another parameter resulting in the right answer for the wrong reason.

Problems of parameter fitting in the use of the Sacramento Soil Moisture Model have been investigated in detail by several investigators. Sorooshian and Gupta (1983) noted that one of the most important problems faced in the calibration of this type of model is the inability to obtain unique and conceptually realistic parameter sets. The problems were demonstrated to be the result of inadequacies in the structure of the models and the automatic techniques used to calibrate them. In a comparison of seven conceptual rainfall-runoff models, including the Sacramento model, Franchini and Pacciani (1991) found that all the models produced similar and equally valid results in spite of the wide range of structural complexities among the models.

Gan and Burges (1990) examined the parameterization and model response of the Sacramento model for hypothetical basins. Their findings included that the model was unreliable in predicting hydrologic response from extreme rainfall and that the lumped parameters were climate sequence dependent. The authors note that "This finding should be heeded by modelers who use calibrated conceptual models to explore the hydrologic consequences of climate change."

While other lumped-parameter models may not have been examined in this detail, similar arguments could probably be made for many of the models in this class as well as most of the current process-based, distributed-parameter models. The frequent use of these models for climate change assessments given the noted problems casts a degree of uncertainty on the results and says a great deal about the state of the art of hydrologic modeling.

Problems with the use of fitted parameters in climate change studies are increased by the fact that the climate and basin characteristics used in the fitting may be different from the climate and basin characteristics that are representative of the period with modified climate. Basin characteristic changes may be due to both climate and anthropogenic causes and the ability to distinguish between the effects of each will be important. Criteria to determine the suitability of a model for application to the assessment of climate change have been developed by Klemes (1985). He suggested that the model structure must have a sound physical foundation, that each of the structural components must permit separate validation, and that it must be geographically and climatically transferable. Geographic transferability is accomplished through the adjustment of model parameters and climatic transferability is accomplished by modifying input data.

The strong physical foundation of the process-based distributed-parameter models provides the capabilities outlined in Klemes's criteria and suggests that these models would be most appropriate for climate change assessments. In addition they provide the spatial and temporal resolution needed to couple other water dependent processes such as biological and chemical processes. With increased model complexity, however, comes an increased number of parameters, extensive data requirements for parameter estimation and model validation, and a degree of uncertainty given the current knowledge of basin processes and process parameterization at this level of detail.

In a critical review of physically based modeling Beven (1989) argued that while the application of physically based models appeared to be rigorous in principle, there are fundamental problems in their application. The problems include unknowns in the system, overparameterization of the models, and the implicit lumping of subgrid processes inherent in the numerical approximations used. Grayson, Moore, and McMahon (1992) had similar criticisms and warned that "In developing and using complex models, there is a danger that computational and conceptual complexity is substituted for accurate representation of reality."

The development of process formulations whose parameters can be estimated from measurable basin and climate characteristics is a critical need in the development of models for use in climate change assessment. This need exists across the full range of model types. The research tasks outlined by Beven (1989) for distributed-parameter models are equally applicable for lumped-parameter models. These tasks include "the need for a theory of the lumping of subgrid scale processes, for closer correspondence in scale between model equations and field processes, and for the rigorous assessment of uncertainty in model predictions."

Scale

A major factor in the development of more physically based models, be they lumped- or distributed-parameter, is the consideration of scale. Interests in the assessment of hydrologic impacts range spatially from the local to regional to global scale, and temporally from minutes and hours to days, months, years, and longer. As noted by Klemes (1983), as one moves from small plots and hillslopes to large basin systems, different sets of physical laws dominate at each major scale. Physical laws at a larger scale tend to express averages or integrals of those dominant at smaller scales. For a given model, parameters estimated or fitted for small basins may not be representative for larger basins. Likewise, time is a consideration in parameter estimation in that parameters estimated for a daily flow simulation may not be representative for different simulation intervals. A variety of models and modeling approaches will be needed to address the large number of modeling objectives and scales of application.

Knowledge of physical processes is most extensive at the laboratory, point, and small plot scales. Extrapolation of this understanding to larger scales must consider the effects of spatial heterogeneity in the parameterization of processes at the larger scales. Work by Wood *et al.* (1988,1990) investigating the modeling of basin runoff suggests that at some scale, termed a "representative elementary area" (REA), knowledge of the pattern of heterogeneity within a spatial element is no longer necessary; only the statistical representation of the factors controlling runoff needs to be quantified. This raises questions regarding the validity of using "effective" parameter values to simulate a process over heterogenous areas. Research remains to be done to define and test the statistical formulations of spatial heterogeneity.

Model Validation

Currently, models used to assess the effects of climate change are evaluated on their ability to reproduce historic time series of observed streamflow or other hydrologic variables. However, for conditions that are representative of a potential climate change, observations will not be available a priori, and the climate, as well as the physical characteristics of a basin, may be significantly different from those used in the parameter calibration procedure. The problem of defining quantitative measures of model performance in terms of its ability to adequately simulate new conditions is formidable.

Klemes (1985, 1986) suggests a hierarchical scheme for the systematic testing of climatic and geographic transferability in hydrological simulation models. This scheme presents two tests for application under stationary conditions and two tests for nonstationary conditions. The nonstationary tests are those designed for testing models developed for climatic and geographic transferability.

The first test for nonstationary conditions is a differential split sample test and is used to evaluate climate transferability. In this test, two periods with different values of the climate parameter of interest are identified. For example, a wet and a dry period are identified if precipitation is being considered. If the model is to be used to simulate a wetter climate, it should be calibrated using the dry period and validated using the wet period. For intended model application to a dry period, the procedure is reversed.

The second test is intended to evaluate both climatic and geographic transferability and is a proxy-basin differential split-sample test. Two basins within a region are selected and, as in the previous test, two periods with different values of a climate parameter of interest are identified. Using the wet and dry example, the model would be calibrated on the wet period of each basin and evaluated on the dry period of the opposite basin. Calibration on the dry period and testing on the wet period using the same paired basin scheme provides an alternative application of this test. Acceptance in the nonstationary tests is based on model performance using the alternative climate and basin conditions.

Determination of the acceptability of test results is ultimately a subjective decision on the modeler's part based on some criteria (s)he establishes. Klemes (1986) explicitly points out that the testing scheme is intended for models whose outputs are for "use outside hydrology," which he defines as applications for planning and operational decisions. This is as opposed to models the purpose of which are to improve the understanding of hydrological processes. In addition, the testing procedures measure only the correctness of estimates of hydrological variables and not the structural adequacy of the model. These tests are considered a minimum requirement for the evaluation of a model's simulation capabilities.

A procedure for calibration and uncertainty estimation of distributed-parameter models was recently developed by Beven and Binley (1992) which provides a methodology to evaluate the uncertainty limits of the model for future events for which observed data are not available. The appeal of this approach is the calculation of quantitative measures of uncertainty that could be used in applying simulation results to water resources management questions. While this method addresses the problem of climate transferability, research remains to be done to evaluate uncertainty for changes in basin parameterization.

Climate Scenario Generation

The preferred source of data for use in the assessment of the impacts of climate change is the general circulation model (GCM). However, most GCMs simulate reasonable average annual and seasonal features of present climate over large geographic areas but are less reliable in simulating smaller spatial and temporal scale features that are relevant to impact assessment (Grotch and MacCracken, 1991). In addition, the output from different GCMs can vary significantly for some regions, posing the problem of which GCM to consider as correct.

Given these constraints, one of the most widely used methods of scenario generation has been to estimate average annual changes in precipitation and temperature for a region using one or more GCMs and then apply these estimates to adjust historic time series of precipitation and temperature. In the simplest procedure, the adjustment is made by multiplying the historic precipitation by a percentage change and adding an absolute change to the historic temperature. Hypothetical scenarios using personal estimates or historical measurements of change, instead of GCM results, can also be generated using this procedure.

These procedures account for changes in the mean of the historic time series but do not provide for a change in the variance. The frequency of extreme events is relatively more dependent on changes in the variability than in the mean of climate (Katz and Brown, 1992). In turn, the resulting changes in the frequency and magnitude of storms and droughts may have a larger impact on water resources than those resulting from only a change in the mean. Changes in variance have been implemented in some hydrologic assessments by varying the magnitude of temperature and precipitation changes on a monthly basis (Gleick, 1987; Bultot *et al.*, 1988; Arnell, 1992).

Climate scenario estimates developed from GCM results are based on an assumption of accuracy of the GCM which may or may not be warranted. Improved climate scenarios will be a function of both improved disaggregation techniques and improved simulation capabilities of the GCM. Development and testing of scenario estimation methodologies in all the major climatic and physiographic regions is needed to fully assess their capabilities, to define the more robust approaches, and to improve the resulting estimates of climate at the range of scales required by hydrologic models.

Data

A major limitation to process conceptualization and parameter estimation is the lack of sufficient data to improve our understanding of the fundamental hydrologic processes across a range of spatial and temporal scales. The development of field based data collection programs jointly with model development efforts has been cited by numerous researchers as a critical need in the research and development of improved physically based models (a sample includes Dunne, 1983; Beven, 1989; Dozier, 1992; Grayson, Moore, and McMahon, 1992).

To address the variability problem, a number of methods have been developed to disaggregate the GCM output for direct application in hydrologic models. Hay *et al.* (1992) developed a methodology to disaggregate GCM precipitation using 6 weather types, classified on the basis of wind direction and cloud cover, and the precipitation characteristics of each weather type. Variations in weather type frequencies and characteristics are determined from GCM output for current and future conditions and are used in a stochastic precipitation model to predict current and future precipitation.

Wilson, Lettermaier, and Skillingstad (1992) developed a stochastic model of weather states and concurrent daily precipitation at multiple precipitation stations. Weather states were computed using grid cells and grid variables from the National Meteorological Center grid point data set. Proposed applications of this procedure will use grid variables from GCMs to investigate the implications of alternative climates to both the weather states and to station precipitation.

A method to adapt stochastic weather generation models to generate synthetic daily time series of temperature, precipitation, and solar radiation, consistent with assumed future climates as modeled by GCMs is presented by Wilks (1992). Parameters defining the current daily stochastic process at a site are adjusted based on monthly GCM values to produce changed climate scenarios. The model is then run in a Monte-Carlo sense to produce streams of daily weather values for periods of arbitrary length.

A nested model approach was developed by Leavesley, Branson, and Hay (1992) to disaggregate large-scale model output for application in mountainous regions. Output from a coupled GCM-mesoscale atmospheric model is used as input to an orographic-precipitation model. The orographic-precipitation model output, at a resolution of 2.5, 5, or 10 km, is used as input to a distributed-parameter hydrologic model. The nested approach permits the simulation of the smaller-scale atmospheric processes and can reflect the changes in precipitation frequency, magnitude, and duration consistent with the GCM response.

One approach to addressing the field-based data needs has been the development and conduct of coordinated large-scale field experiments. A number of these types of studies have been organized. The International Satellite Surface Climatology Program (ISLSCP) was organized to monitor variables that govern climate and climate fluctuations at a range of scales from point and plot to regional and global. The First ISLSCP Field Experiment (FIFE) conducted at a tall-grass prairie site in Kansas investigated water and energy flux processes from a scale of cm at the individual plant level to 10's of km for a regional perspective. The Boreal Ecosystem Atmosphere Study (BOREAS) is a similar type study in two boreal forest regions of Canada that will be an interdisciplinary investigation of land-surface climatology, tropospheric chemistry, and terrestrial ecology.

The Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) will use the Mississippi River basin as a continental scale area in which to conduct a variety of coordinated studies. The objectives of these studies include determination of the time-space variability of hydrological and energy budgets over regional and continental scales, development and validation of macroscale hydrologic models and coupled hydrological/atmospheric models, and provision of a capability to translate the effects of a future climate into impacts on water resources on a regional basis (World Climate Programme, 1992).

A data area in which advances will have a significant effect on hydrologic modeling is remote sensing. Remote sensing offers the possibility of obtaining frequent hydrologic measurements over wide spatial scales. Data include presence or absence of vegetation, vegetation structure, vegetation moisture stress, soil type, snow cover, snowpack water equivalent, and soil moisture (Engman and Gurney, 1991; Dozier, 1992). Quantitative precipitation estimates at a spatial resolution of about 4 km and a temporal resolution of 5-6 minutes will be generated by the next generation weather radar (NEXRAD) and used to produce hourly, 3-hr, and storm total products (Alberty, Crum, and Toepfer, 1991).

Programs such as FIFE, BOREAS, and GCIP with extensive data bases of simultaneous observations from ground stations, atmospheric soundings, aircraft, and satellites will be an important source of the types of information needed to address the parameterization and scaling issues so critical to the improvement of the understanding and modeling of hydrologic, climatic, and biogeochemical processes. To maximize the benefits of data from these and other investigations, improved information management systems are needed to enable the integration of data collected at different scales and by different agencies, and to make these data available to the scientific community on a timely basis (Dozier, 1992).

Modeling Tools

The large number and variety of hydrologic models makes the selection of the "optimal" model for a specific application a difficult task. A few reviews have been published that compare the features and process parameterizations for selected models such as the WMO's intercomparison of conceptual models used in operational hydrological forecasting (WMO, 1975). A more quantitative approach was used in the WMO's intercomparison of models of snowmelt runoff (WMO, 1985). Here models were run using the same data sets and model performance was compared using a number of quantitative measures. A similar approach of using common data sets to compare models is being developed for the intercomparison of land-surface parameterization schemes used in regional to continental scale hydrology and atmospheric models (Henderson-Sellers and Brown, 1992).

Quantitative model comparisons provide valuable insight to model performance. However, given the increasing complexity of water and environmental problems, coupled with the potentially broad range of study objectives and data constraints, selecting the model with process parameterizations and assumptions most appropriate for the task, based on a comparative measure such as streamflow, is difficult at best. In some cases no single model may meet all the users' requirements. A better approach for model selection is to be able to selectively couple the most appropriate process algorithms to create an "optimal" model for the desired application.

One approach to providing this model building capability is being developed in what was formerly called the Modular Hydrologic Modeling System (MHMS) (Leavesley *et al.*, 1992) but is now called the Modular Modeling System (MMS). MMS is an integrated system of computer software that has been developed to provide the research and operational framework needed to support the development, testing, and evaluation of hydrologic process algorithms and to facilitate the integration of user-selected sets of algorithms into an operational model. MMS uses a master library that contains modules for simulating water, energy, and biogeochemical processes. A given process can have several modules in the library, each representing an alternative conceptualization or approach to simulating that process. Researchers in a variety of disciplines can develop and test model components to investigate questions in their own areas of expertise as well as work cooperatively on multidisciplinary problems without each researcher having to develop the complete modeling system.

A similar modular modeling approach is being used to develop a general ecosystem model to investigate the response of plants and ecosystems to elevated CO₂ and climate change (Reynolds *et al.*, 1992). Modules have been developed to simulate processes at the plant and ecosystem levels of scale, and questions of scale, heterogeneity, and process parameterization comparable to those faced in hydrologic models will be addressed with this system.

Continued advances in hydrology and related sciences, in computer technology, and in data resources will expand the need for a dynamic set of tools to incorporate these advances in a wide range of interdisciplinary research and operational applications. Modular system approaches provide the flexible framework in which to integrate these advances in both research and operational applications. In addition, these systems can be coupled with data bases, geographical information systems, and expert systems to provide an interactive modeling tool to assist users in processing data, initiating model runs, and analyzing model results using a variety of statistical and graphical techniques. A variety of resource management and risk analysis models could also be incorporated in the modular system for use in evaluating alternative resource management policies and in developing short- and long-term resource management plans.

DISCUSSION AND CONCLUSIONS

Numerous models and modeling approaches are currently being used to assess the impacts of climate change on water resources. Studies to date have been generally limited to the use of operational models that have been tested in a wide variety of geographic regions or extensively in the region of interest. Model choice is normally a function of problem objectives, data constraints, and the spatial and temporal scales of application. Empirical and water-balance type models have generally been applied to large-basin and regional analyses at time scales of months to seasons to years. More detailed conceptual lumped-parameter and process-based distributed-parameter models have generally been applied to smaller basins at time scales of 24 hr or less.

Empirical models have minimal data requirements but have questionable transfer value to basin and climate conditions different from those used to develop the input-output relations of the model. An increased range of simulation capabilities is provided as one moves from water-balance models to conceptual lumped-parameter models to process-based distributed parameter models. This is accompanied, however, by an increase in the number of model parameters and the number and types of data needed to support parameter estimation and model operation. Limited knowledge of the relations between parameter values and measurable basin and climate characteristics often results in many of the parameters being calibrated to measured data. The use of calibrated parameters provides a large degree of uncertainty in the ability of these types of models to be climatically and geographically transferable as well.

Assessments based on model results have generally been presented as best estimates given the uncertainties in GCM-based climate change scenarios and the assumptions and limitations associated with the parameterizations of the model applied. While these uncertainties are large across the full range of models, some consistency of results among different types of models has been demonstrated in some applications. An example is the predicted change in the timing of runoff in snowmelt basins resulting from an assumed increase in atmospheric CO₂. A shift to earlier and increased winter runoff and decreased spring and summer runoff was simulated by a range of water-balance models (Gleick, 1987; Mimikou et al., 1991) and conceptual lumped-parameter models (Lettenmaier and Gan, 1990; Nash and Gleick, 1991; Bultot et al., 1992) for different snowmelt basins of the globe.

A review of current modeling studies also indicates a number of problem areas common to the variety of models applied. These problem areas are related to a number of modeling issues, including parameter estimation, temporal and spatial scale of application, validation, climate-scenario generation, data, and modeling tools. Solutions to these problems would significantly improve the capability of models to assess the effects of climate change. Research needs to address these problems include:

1. A more physically based understanding of hydrologic processes and their interactions is needed. The complexities of the hydrologic system are such that process parameterizations will always represent an integration of the spatial heterogeneity of the factors that control these processes. However, when these parameterizations are based on the physics of the process, the ability to measure or estimate parameter values from climate and basin characteristics is improved. It is only through the use of parameterizations that do not require calibration that the problems of climatic and geographic transferability will be resolved.

2. Parameter measurement and estimation techniques must be developed for application over a range of spatial and temporal scales. In moving from the points to hillslopes to grid cells or small basins, different sets of physical laws may dominate at each of these scales. The variability and applicability of parameters and process formulations must be understood across the wide range of scales over which climate change impacts will be assessed.

3. Quantitative measures of uncertainty in model parameters and model results are needed. Uncertainty measures could provide an estimate of confidence limits on model results and would be of value in the application of these results in risk and policy analyses.

4. Improved methodologies to develop climate change scenarios are needed. Removing the uncertainties in current scenarios is dependent on improvements in both GCMs and scenario generation procedures. Scenarios must provide the spatial and temporal resolution required by assessment models and they must incorporate the simulated changes in mean and variability of the climate variables.
5. Simulation capabilities have generally exceeded available data bases. Detailed data sets in a variety of climatic and physiographic regions collected at a range of spatial and temporal scales are critical to improving our understanding of hydrologic processes and to testing and validating the more physically based models that are being developed.
6. Modular modeling systems need to be developed to facilitate interdisciplinary research on the full range of modeling problems and to provide a framework in which to apply solutions to the range of assessment questions. Maximum use of current and future advances in the fields of expert systems, geographical information systems, remote sensing, information management, and computer science should be made in the development of such systems.

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**Assessing the Socioeconomic Consequences of Climate Change
on Water Resources**

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Introduction

When dealing with water resources there are essentially three things to be known: the future availability of water, the future demand for water, and the consequences that both of these have on the environment. Climatic conditions influence all aspects of life on earth and shape the physical, biological, and socioeconomic environment, all of which in turn influence the state and composition of the atmosphere (and ultimately climate). In other words, strong interactions and feedback loops exist among the various components of the ecosystem. Human activities are influenced greatly by weather and climatic conditions, and man can intentionally or inadvertently modify weather, climate, the water cycle, and such geochemical cycles as the carbon cycle.

It is now fashionable to criticize the climate modelers; either at the naiveté of what is missing from their models or at the poor quality of their prediction of current climatic conditions. This paper is not another critique of climate models; the focus of the paper is on integrated assessments of the socioeconomic impacts of climate change upon water resources. As we will see later, even if the climate models were better grounded scientifically and their prediction of the starting conditions perfect, there is still a question of how relevant they are to practical decisions concerning the human use of water resources.

Water resources managers and planners generally consider two types of decisions: those dealing with the allocation of the resource among competing users and those dealing with the expansion of the supply to meet the needs of new or existing users. Both of these types of decisions generally involve new investments or modifying the operation and maintenance of existing systems. A third category which falls between these two, and which has recently become more important in the U.S., is that of investments which adapt the operational capacity of existing systems in order to both reallocate and expand the supply by means of conservation to meet new socioeconomic and environmental conditions.

In order to make these decisions rationally, information is needed about the future availability of water and the future demand for water. One should take care not to confuse these two concepts: availability deals with supply or the physical amounts of water accessible for use, and demand refers to the quantities of water users would want at alternative prices. While actual use cannot exceed availability, shortages arise

when the quantity demanded at the going price exceeds availability. Both availability and demand are affected by climate change. On the supply side, water planners and managers would like to know the predicted average precipitation and other climate factors and some estimates of their variability at a scale of small watersheds (about 30 km by 30 km)¹. On the demand side, they would like to know how water demand would be affected by climate and socioeconomic changes.

Time also plays an important part in water resources policy investment decisions. With an average lead time of 28 years from start of planning to completion of large multi-purpose projects in the United States, any water project currently under consideration with a project life of 50 years would still be viable in the year 2070. This is within the time frame when climate changes are predicted to become noticeable, and also beyond the time frame of any reasonable forecast of socioeconomic conditions. Hence, the dynamics of water supply and demand changes ought to be important.

In 1977, the National Research Council commissioned a study entitled *Climate, Climatic Change, and Water Supply*. What is quite surprising is the "shelf life" of the 1977 study. Several of the same panel members were commissioned by the American Association for the Advancement of Science to write a book, published in 1990, entitled *Climate Change and U.S. Water Resources*. What these two books show us is that in many areas we seem to be no further along than we were in 1977. More importantly, the climatological parameters that the 1977 authors wished they had are still, by and large, not available -- or not even on the horizon. For example, the intervening 16 years has not brought water planners and managers better estimates of potential changes in means and variances of precipitation. The 1990 book was still limited to assuming levels of precipitation change and restricted to "what if" types of statements: simulation rather than prediction.

The main thrust of this paper is that water resources management is not simply a value-free scientific activity; it is a broad political, economic, sociological, scientific, and technological endeavor. Hence, to assume a priori that the present and future quantity of available water is the only, or even the major,

¹Giorgi and Mearns (1991) indicate that it would currently take 2 days of computing time to simulate one day of global climate at this scale using a Cray X--MP computer and a typical GCM. A 50-year forecast would, hence, require 100 years of real time: not a very helpful situation.

determinant of the outcomes is incorrect. There are other drivers of socioeconomic change that contribute to uncertainty, such as the state of the national economy and the level of commitment to environmental quality, and their contributions are of such large magnitudes relative to the uncertainties in water supply that they, rather than water, should dominate the assessment of the choices for action. Climate change is just one of several factors that make precise prediction impossible. In the paper I call the reader's attention to a few case studies which show that predicted water availability should not necessarily be the most important parameter in water resources planning and management.

Growing Scarcity of Water

One does not need the threat of global climate change to predict an increasing scarcity of water. The ever increasing population and economic growth of the world provides enough stress on the system. An assessment of the global impacts of homo sapiens on water quantity and quality was attempted by L'Vovich et al., (1991). They provided information on water use by activity from 1680 to 1985. Their paper reported that by 1985 there were 2,357 large storage reservoirs, a total storage volume of 5,500 km³, a surface area of 590,000 km², and annual evaporation losses of 130 km³. There was 2.5 million km² of irrigated land for which 2,710 km³ of water were withdrawn per year. Withdrawals for domestic livestock amounted to 60 km³ per year. Out of 150,000 km² of wetlands, more than 7,000 km² had been drained and the annual rate of loss is between 1-2%. The domestic and industrial consumption of water has increased 40-fold over the past 300 years. And evaporation from the land surface was estimated to have increased by 2,470 km³ over the same period.

Globally we withdraw annually about 3,240 km³ out of the readily available 9,000-12,000 km³ water (World Resources Institute, 1992). In other words, at current rates of use we could double our total annual water withdrawals without encountering too much trouble in terms of gross amounts of available water. This is not a recommendation since long before that happened there would be major water crises in several regions of the world and we would experience severe in-stream problems everywhere else.

Considering the enormous amounts of water in the hydrosphere (1.37 billion km³ of all kinds of water and as much as 60 million km³ of fresh water), it is difficult to understand how there could possibly be a scarcity of water. Nevertheless, the fresh water available for human use at the present rates of use in the world's populated regions would be getting uncomfortably close to potential "needs" by the twenty-first century.

Hence, while there appears to be no scarcity of the current resource in aggregate, if use was doubled over the next twenty years and nothing was done to increase the stable runoff (safe yields from groundwater and surface impoundments), water scarcity could become quite serious. For example, L'Vovich et al. made a projection until the year 2080 which suggested that, even with the adoption of drastic pollution prevention methods, the total withdrawal would be slightly above 5,000 km³.

Moreover, the aggregate resource position disguises many serious instances of scarcity, even at the current level of human use at national or regional levels. For example, Africa's runoff per unit area is only about one-fifth that of South America and half the world average. This is because of lower precipitation and higher evapotranspiration than in other parts of the world. On a per capita basis, however, it is Asia that has only half the world's average water availability, and Africa is almost exactly at the world average of 8,562 m³/person/yr. Despite its low runoff per unit area, Oceania has six times the world's per capita level because of its low population. Latin America has almost four times the world's average per capita supply of water. This variability is even more pronounced when considered at the level of nation states.

It is difficult to make predictions about future water use in the face of a changing climate for two reasons: first, the demand for water is heavily influenced by economic and social forces which are themselves virtually impossible to forecast for more than a few years; second, both the availability of the resource itself and the demands for it will be influenced by the changing climate.

Assessing the Socioeconomic Consequences of Climate Change on Water Resources

The major manifestations of socioeconomic consequences of climate change on water resources, both quantity and quality, will be felt through shifts in the availability of the resource and in shifts in demand for the

resource. In addition to these direct effects there are also secondary impacts of socioeconomic change which will impact the aquatic system which, in turn, will impact upon climate, and which in turn will influence water availability. Climate will also directly influence economic uses of land and water use which will influence water availability and so forth. These potential interactions are shown schematically in Figure 1. In this figure, first order effects are the directly obvious effects of one change upon another. For example, an increase in precipitation causes a river to flood, this in turn floods out a part of a city. These are both first order effects. If, however, as a consequence of this flood the city builds extensive dikes and levees, then the water will be kept off the land and groundwater recharge will be reduced. This is a second order effect. The emissions of greenhouse gases emitted by urban areas in response to increased demand for air conditioning because of climate change are considered second order effects.

How far one should pursue these linkages depends upon the magnitude of the impacts and also upon the time scale of concern. For most practical decisions, consideration of only the direct (first order) effects is sufficient. For intermediate term decisions, consideration of the primary and secondary effects may suffice. For long term considerations, on the same order as the predicted CO₂ doubling, consideration of all three pathways may be in order.

FIGURE 1

Socioeconomic Consequences of Climate Change

As far as the socioeconomic system is concerned, climate change will be manifest through changes in temperature, precipitation, sea level rise, and storm frequency. For each of these effects how the mean behavior will change is important, but the change in variability, seasonality, and extremeness of the effects will be equally important. The frequency and intensity of storms; in particular, coastal storms and tidal surges have great potential for exacerbating or ameliorating damages depending upon which direction the effects will go. There are also other important effects which are derived as a consequence of changes in temperature and precipitation that are extremely important from a socioeconomic point of view. For example, soil moisture and evapotranspiration, which depend directly upon precipitation, temperature, and also upon soil

and vegetation type, determine how successful agriculture will be with, or without, irrigation. Since in many countries irrigation accounts for more than 80% of all consumptive uses, the impacts of climate change upon soil moisture and evapotranspiration will be the most critical impacts in assessing socioeconomic consequences of climate change.

As a result of over 40 years of economic research, it is a fairly easy task to assess the first order socioeconomic effects of climate change, provided that we have reliable forecasts of the means, the variances, and the skew coefficients for the various hydrological inputs. Several journals and many books give the details of the assessment methodology (see for instance, R.W. Kates, J.H. Ausubel, and M. Berberian, 1985). The weak point in the assessment methodology tends to be in dealing adequately with uncertainty in estimates of the economic and social input data to provide reliable forecasts into the future. As we will see later, much of the uncertainty arises from estimating the economic parameters -- not the hydrological ones. Despite the global averages, it is the temporal and spatial distributions of precipitation that are the major determinants of the habitability of land for human uses. For example, problems for agriculture and other settled human activities can arise where water availability is limited at certain times of the year and, in some cases, where precipitation varies greatly from year to year (particularly in the semiarid tropics). Spatial variability in precipitation also has great significance for ecosystem stability. The precise nature of the ecosystem impact depends on many factors and defies generalization, but in semiarid areas variability can be devastating. Worldwide, average annual rainfall varies from almost zero in some deserts to over 10,000 mm in parts of Hawaii. At Iquique in the Chilean desert, no rain fell during one fourteen-year period; at the other extreme, 22,000 mm has been recorded in a single year at Cherrapunji, India.

Climate Impacts on Hydrology and Water Resources

Revelle and Waggoner (1983) applied the Langbein's empirical relationship linking precipitation, temperature and runoff to demonstrate the possible impacts of climate change on water supplies in the western U.S. Gleick (1987) used a similar approach and adapted a water-balance modeling technique to examine the implications of alternative climate change scenarios on the hydrology of the Sacramento Basin

in California. Wolock and Hornberger (1991) employed TOPMODEL, a variable-source-area hydrological model, and concluded that uncertainties in climate predictions and the underlying natural variability in temperature and precipitation prevent detection of a statistically significant trend in runoff. Recently, Kuhl and Miller (1992) used output from a GCM to examine seasonal runoff for the world's largest rivers and concluded that large errors in estimating actual runoff were owing to inadequate parameterization of sub-grid scale physical processes (such as infiltration and evaporation).

1. Sea Level Rise

Sea level rise, which is one of the most predictable environmental changes associated with global warming (Wigley and Warrick, 1990), will compound society's greatest environmental vulnerability, namely storm impacts in the coastal region (Lancaster, 1991). Over half of the world's most populous cities lie in the coastal region where winds and flooding already cause extensive and expensive destruction. Thirty-three large deltaic regions world-wide may be particularly susceptible to sea level rise and storms; these include the Colorado and the Rio Grande and Mississippi deltas in the Gulf of Mexico (Bardach, 1989). The recent Hurricane Andrew, for instance, caused more than 30 deaths and over \$20 billion in damages, however, most of the damages were to inland communities since the landfall of the hurricane missed major settlements. Under climate change, combined impacts of storm surge, higher sea level, waves and increasing storm force could pose an even greater threat.

An 18 cm rise in mean sea level by year 2030 and a 44 cm rise by year 2070 is predicted (Warrick and Oerlemans, 1990), and it is plausible that cumulative sea level rise will exceed one meter during the 100 years following. Wigley and Raper (1992) calculated that sea level could rise between 15 and 90 cm by 2100, with a best estimate of 48 cm. Unchecked sea level rise will inundate and displace wetlands and lowlands (Leatherman, 1989), increase coastal erosion, drown barrier reefs, increase salt water intrusion into coastal groundwater supplies, alter tidal ranges in rivers and bays, and alter sedimentation patterns (IPCC, 1991).

2. Storm Impacts

Other physical effects can combine with sea level rise to increase impacts of coastal storms. Effects on wave heights from rising sea level are expected to be small for deep sloping shelves with shoreline recession, but in areas of shallow shelf and fixed shoreline, wave heights may increase by 5-10% for a 0.5 meter rise in sea level (Mehta and Cushman, 1989). The reach of storm surges may be increased by the rising mean sea level, again depending on the specific coastal morphology. Predicted increases in storm force from global warming (Emanuel, 1987) could add to storm surge, while greater erosion would remove wave protection. Higher sea level would slow drainage at the outlet of rivers flooding from watershed runoff. Increasing storm frequency could multiply the above effects. Sea level rise holds implications for hazardous waste sites and flood insurance of commercial and residential sites in the coastal floodplains (Flynn et al., 1984), where the expansion of the 100-year storm surge area may require costly floodproofing for sites now located just outside this zone.

Many case studies of climate change impacts on coastlines have been conducted (Titus et al., 1985; Broadus et al., 1987; and MacCracken et al., 1987), but these have yet to produce a set of assessment tools for general application or a methodology for integrating research on hydrological impacts within the coastal watershed with impacts on shorelines, estuaries and coastal aquifers. In the United States, case studies have included Charleston, South Carolina (Kana et al., 1984), Galveston, Texas (Gibbs, 1984; Leatherman, 1984), Sea Bright, New Jersey (Kyper and Sorenson, 1985), Delaware Bay (Hull and Titus, 1986), the Massachusetts coastline (Giese and Aubrey, 1987), Ocean City, Maryland (Leatherman, 1987), Long Beach Island, New Jersey (Titus, 1990) and Miami (Miller et al., 1989). The first nationwide assessment of the primary impacts of a 1 meter sea level rise on the United States has recently estimated that the costs will total \$270-475 billion, ignoring future development (Titus et al., 1991).

In 1986, Congress asked EPA to prepare two reports on global warming, one to be an examination of policy options to stabilize greenhouse gases and the other to examine health and environmental effects of climate change in the United States. This second report, The Potential Effects of Global Climate Change on the United States (Smith and Tirpak, 1989), examined potential changes in hydrology, sea level rise,

agriculture, forests, aquatic life, air quality, human health, and infrastructure in the Southeast, Great Lakes, California and Great Plains regions of the United States. Hydrological aspects of the models used in the EPA study are reviewed by Rind et al. (1992).

Current Literature on Economic Consequences

During the past ten years a fairly large literature has appeared on the interactions between economy and climate. Starting with Heal (1984) and McFadden (1984) through to Manne and Richels (1990) and Nordhaus (1991, 1992) the economics profession has provided a set of theoretical explorations of the interactions of climate change and economic change largely based upon the theory of economic behavior under uncertainty and the dynamics of savings and investments. The bulk of this literature is based upon the national economic response and is too general for analyzing specific sectors such as water resources. Jorgenson and Wilcoxon (1990) and McKibben and Wilcoxon (1992), however, have been able to broaden the scope of the models to include specific intersectoral allocations via embedded input/output models.

There is another strand to the literature, however, that deals with assessing the economic impacts of climate change at a regional scale. Kates, Ausubel and Berberian (1985), reviewing methodologies for assessing impacts from climate change, stressed that regional assessments are necessary because drainage basin impacts depend greatly on topography, local geology and vegetation characteristics. For instance, one sensitivity study (Karl and Riebsame, 1989) showed that the impacts, in terms of available water resources, of relatively small fluctuations in precipitation (about $\pm 10\%$) often are amplified by a factor of two or more, depending on basin and local climate characteristics. Karl and Riebsame showed the limitations of Langbein's (1949) original formulation which related mean annual runoff from 22 drainage basins in the U.S. to the total annual precipitation and the precipitation weighted temperature. It is well known that evaporation is not only a function of temperature, but also insolation, humidity, wind speed, surface characteristics, and advection effects. Large differences of insolation and humidity occur between areas in the United States, leading to evaporation differences between regions more than if only temperature were affecting the evaporation. Karl and Reibsame claim that temperature fluctuations alone are not as great a factor in runoff

changes as previously believed, because earlier studies have overstated the role of evaporation. Hence, they believe that future GCM modeling will have to do a better job at predicting regional precipitation if we are to assess impacts on individual basins.

In the latter half of the 1980s researchers (Dickinson et al., 1989) began to derive regional climate forecasts from GCMs by embedding a detailed mesoscale hydrology model with approximately 100 grid points for each grid point of the GCM. A grid with a resolution of 60 km was found useful for simulating mesoscale circulations in the western U.S., providing comprehensive and interactive descriptions of surface-water budgets, including precipitation, evaporation, snowmelt, runoff and soil-water movement . Not surprisingly, however, the studies showed that regional environmental stresses are influenced strongly by local topography and are not well reproduced or forecast accurately by models at this spatial scale.

The most comprehensive studies, recently commissioned by the EPA and DOE, have explored primary impacts in terms of crop growth, runoff, and forest succession models at a regional scale, and then applied these results as inputs for economic analyses and adjustment studies (Rosenberg et al., 1990; Smith and Tirpak, 1989).

To date, many impact assessments have been oriented toward individual resources, with available fresh water being a major concern. Coastal storms and sea level rise can increase the penetration of saline waters into coastal aquifers. Warmer winters in coastal mountain regions (bringing higher rain to snow ratios, decreased snowpack, and earlier spring melt) may reduce the water available for agriculture in late spring. Water supplies in regions that have small reservoir storage and large consumer demand relative to basin renewable supply are potentially more vulnerable (Gleick, 1989).

There have been some studies on the potential economic consequences of climate change on water for the Great Lakes Region in the U.S. and Canada. Data on potential economic impacts due to climate change were presented at the First North American Conference on Preparing for Climate Change (1987) and the First United States-Canada Symposium on the Impact of Climate Change on the Great Lakes Basin (Marchand, et al., 1988). These analyses suggest magnitudes of possible impacts, and could form the basis for more detailed explorations. Most of these studies used some version of the GISS (Goddard Institute for

Space Studies) model with effective doubling of atmospheric carbon dioxide concentrations from its pre-industrial level as the basis of predicted outcomes. The doubling is expected to occur by the year 2050. For the Canadian portion of the basin Cohen (1986) predicted:

- a 15% reduction in net basin water supplies,
- lake levels at their 1963-65 levels (the lowest this century),
- an annual loss of 2400-4200 GWh of hydro-energy on the Lake Ontario outflows (CAN\$34 to CAN\$65 million based upon 1979 data),
- a reduction in electricity demand due to climate warming equal to 6400-7600 GWh resulting in annual savings of CAN\$99 to CAN\$118 million,
- annual navigation economic loss of US\$27.8 million due to reduced lake levels,
- economic losses of CAN\$36.5 in recreation due to loss of snow cover in the area's ski resorts,
- an increase in the economic benefits of camping recreation of CAN\$14 million due to extension of the summer season,
- a 7% decline in Ontario's agricultural output due to moisture stress on crops (leading to economic losses of from CAN\$101 to CAN\$170 million per year),
- and a 2.6% increase in demand for municipal water supplies for lawn watering, etc.

Good data do not exist for navigation benefits but Raoul and Goodwin (1987) cite an additional US\$50 to US\$60 million per year as the value of increasing Lake Superior's navigating depth from 27 ft. to 28 ft. Marchand et al. (1988) studied the effect of climate on the economy of Great Lakes shipping. They applied GCM output for doubled carbon dioxide, a regional hydrological model and a regional Great Lakes economic model, and found that mean annual shipping costs could rise by as much as 30% under plausible scenarios. The analysis allowed testing the benefit/cost ratio of policy options for maintaining artificially higher water levels. No data were available for the environmental implications for water quality (see paper by Blumberg and DiToro (1988) which predicts losses of 1 to 2 mg/l of dissolved oxygen in Lake Erie due to temperature effects alone), wetlands and fisheries (a 20 cm lowering of Lake Huron-Michigan levels could dessicate 64% of all the U.S. Great Lakes wetlands), water supply and waste disposal for industry, commercial operations, recreation, and commercial fishing.

The most recent impact study for San Francisco Bay, by Gleick and Maurer (1990), concluded, *inter alia*, that costs to protect existing structures, restore wetlands and build drainage systems in the face of a one meter sea-level rise will approach \$2 billion, with yearly maintenance close to \$100 million, and that worsening impacts are likely to outpace the political consensus needed to take steps to adapt. Levees in the San Francisco South Bay have already substantially interrupted the functioning of the salt marsh ecosystem. Armentano et al. (1988) developed a model to analyze impacts of climate change on national wetlands. They found that most estuaries were too small to use the regional-scale methodologies effectively.

Thus far, the best methodology for integrated assessment of economic impacts of global warming has been developed for a non-coastal region, i.e., the states of Missouri, Iowa, Nebraska and Kansas, termed the MINK study from the first letter in the four states names (Rosenberg et al., 1990). The goal of this study was to assess impacts for a mid-continental, agricultural region, and a specific analytical framework was developed to cope with the abruptness of change, its temporal and spatial variability, the complexity of the regional economy, and the full range of available adaptations and adjustment technologies and management techniques.

Uncertainty in Water Resources Planning

It has long been recognized by water-resource planners that extreme events dictate detailed planning, design and operation of their systems. Dams and levees are constructed and operated in response to floods and droughts. For example, following the great northeast floods of 1955, when Hurricanes Connie and Diane ravaged the region twice within a week, a number of reservoirs were constructed to help control flood flows in the Connecticut, Delaware and other basins. Now, almost 40 years after the fact, and following a period with relatively few hurricanes, these structures stand largely unused, with little history of having protected anything against a major flood. Even though they were designed using standard procedures, they are a potential embarrassment unless they can be put to some use, perhaps to provide flood protection under changed climate conditions.

By their very nature and rarity, extremes (at both ends of the scale, floods and droughts alike) do not define a large enough sample to allow deterministic or statistical basis for design. Historically, planners have used critical periods of record, empirical corrections to observations, statistical procedures based on prescribed density functions, even synthetic events to help generate realistic design values. While many of these techniques are useful in the orderly world where the Central Limit Theorem governs, they have failed to capture the true (and dangerously large) departures from the mean that are characteristic of natural phenomena and that designs are based on. Indeed, in recent years a whole discipline, chaos theory, based on unstable fluctuations of typical records has been invented. To counter these unstable fluctuations, Fiering and Rogers (1991) tried a variety of statistical formulations; however, the density functions they used were typically too smooth and too well behaved to reproduce historical extremes reliably enough to serve as useful adjuncts to the planning process. For example, in the case of Hurricanes Connie and Diane, the statistical characteristics of either storm alone could be generated by a number of statistical tricks. However, their combined effect could not be produced without artificially and rather arbitrarily juxtaposing the two storm events; this is because apart from the one historical event formed by the two storms, nothing in the record even remotely suggested the possibility that such a catastrophe might occur.

Looking at actual hydrology can be quite misleading. For example, Figure 2 (Parry and Carter, 1986) shows what happens when the mean of a probability distribution of streamflows is decreased and the variability increased. Information of this type ought to be very useful to the water planner. However, consider how the information that the mean streamflow would decrease by 20% and that the standard deviation would increase by 10% over a period of 60 years would be viewed by a typical water manager². The manager would estimate the likely flows over the next 60 years using some sort of stochastic simulation model and obtain results similar to those shown in Figure 3 (plotted for only 5 of the many thousand simulations) based upon actual river flow data. Figure 3 shows how the stochastic variation masks the

²This is at the extreme levels of predicted outcomes from climate change in the U.S. For the Colorado, for example, Nash and Gleick (1990) reduced the earlier predictions by Revelle and Waggoner (1983) of declines in annual flow from over 40% to 14 to 23% for a 2-degree C temperature rise coupled with a 10% decrease in precipitation.

changes in the means and standard deviations. Even if we knew exactly the change in climate, at least for about the first 40 years of the new time series, management decisions would probably be no different than if the manager had not been presented the new information.

FIGURE 2

Changes in Probability Distributions for Changes in Parameters

FIGURE 3

Simulated 20% Decrease in Mean and 10% Increase in Standard Deviation

In order to predict the socioeconomic consequences of climate change we need to estimate the parameters of the future climate in terms of temperature, precipitation, etc. We also require estimates of their inherent variability. Unfortunately, this forces us to rely upon guesses or the output of the GCMs, and the sources of uncertainty when using GCM output are difficult to specify. Two recent reviews (Gleick, 1990; Rind et al., 1992) highlight the problem of GCM output being too coarse-scale for modeling hydrologic processes. In addition, soil moisture algorithms used in GCMs have been overly simplistic (Gleick, 1990). The same holds true for evapotranspiration (Rosenberg et al., 1990). An improved representation of terrestrial hydrological processes, for instance, in the GCM developed at the Geophysical Fluid Dynamics Laboratory (GFDL) has demonstrated that GCMs previously greatly overestimated the value of potential evaporation, so that modeled soil moisture was seriously underestimated in seasons of water shortage (CEES, 1992, p. 19).

The GCMs provide average precipitation and temperature values on temporal and spatial scales that are too large to make reliable designs of, and operating policies for, such reservoir systems. Apart from unavoidable and irreducible uncertainties in GCM output, there is a real need to translate that output onto a finer grid and to interpolate extreme values where the GCMs provide temporal and spatial averages. Climate stresses are generated at large scale and must be mapped into event sequences at basin scale so that regional

and local hydrological phenomena, and particularly hydrologic extremes, can be anticipated in a statistical setting; these smaller scale phenomena are the bases of regional planning and engineering design.

And those rare events that dictate hydrological design are drawn from distributions which are perhaps non-stationary and poorly defined at best. Their parent densities might be quite distinct from those which govern ordinary events. How should these be described? How do they enter the design process? And will they change as a function of global climate change?

Rind et al. (1992) in a review of hydrologic modeling in the context of climate change set forth a number of unresolved hydrological research questions which reflect hydrological uncertainty. These include:

1. Can runoff and infiltration be calculated accurately enough from basin models that have relatively coarse vertical and horizontal scales?
2. Does small-scale heterogeneity overwhelm averaged values of surface parameters?
3. How do we model sub-grid-scale soil moisture?
4. What are alternative formulations for potential evapotranspiration (PET)?
5. Can large horizontal gradients in soil moisture exist between a forested and agricultural landscape for long periods of time?
6. Is drainage through a permeable bottom layer necessary for accurate representation of surface hydrology?

Taking an entirely different approach, and not concerned with climate change, James, Bower, and Matalas (1969) analyzed the relative importance of different kinds of variables in water resources planning. They assessed the relative importance of four types of input variables covering four areas of disciplinary concern; hydrology, environmental response, choice of planning goals, and economics. Their paper is cautionary for water resources planners and managers of the 1990s as we struggle with what to do about potential or predicted climate change. Their definition of the concerns of water planners is:

Water resources planning in the context of investment decisions involves the determination of how much to spend for capital, operation, and maintenance costs over time for what structures and nonstructural measures, when, and where. The objective of such planning is to decide upon the size, type, location, and method of operation of facilities and the points in time that they will have to be in operation, in conjunction with the type, size, location, timing, and method of operation of related structures (James, Bower, and Matalas, 1969, p.1165).

If we now take into account the problems of making long-term projections of water demand, I believe that we have little chance to predict what will happen in the distant future. For example, Figure 4 (based upon the Congressional Research Service, 1980) shows some of the problems faced by managers and planners of water resources when making predictions over relatively short time periods -- and I stress that this is only for 25 years -- not 100 years as most climate change scenarios require. The figure plots projections made in 1975 for the year 2000 by four major studies of future water demands in the United States along with the best estimates that we have for actual withdrawals for 1980 and 1985. For the year 2000 projected demand ranges from a high of 1,510 bgd to a low of 330 bgd. The low figure was an almost threefold downward revision by the Water Resources Council of its own 1968 forecast. The 1990 usage was reported at 339 bgd which was an 11% decline from 1980, and well below the greatly reduced 1975 Water Resources Council forecast for 1990.

Figure 4

Projections of U.S. Water Withdrawals 1975-2000

Capacity Expansion: The Problem With Time Horizons

Many water resources planning problems encountered may be categorized as "capacity expansion" problems. Typically these problems are of the type where there is a demand for increasing additional water supplies over some time period. The goal is to meet this demand over time at least cost. This problem is common to many industries such as electric power. An analytic approach to single-purpose water projects was first formulated by Harold Thomas (1971). The problem of capacity expansion can be viewed as a series

of sequential decisions of how much excess capacity to build into the system to meet the future demands.

Figure 5 shows a typical view of a "staircase" of future investment in excess capacity.

Figure 5
Capacity Expansion in Water Systems

The simplest case which assumes linearly increasing demands and no shortages is still a difficult problem to solve analytically for the size of the next investment (and, hence, all succeeding ones since the staircase repeats itself *ad infinitum*). Based upon the second order conditions for optimality of the time series of investments required to meet the demand over an infinite time horizon, Thomas derived a solution in terms of the number of years of excess capacity to be built,

$$\tau = \frac{6}{r}(1 - b^{1/3}) \quad (1)$$

where r is the discount rate and b is the economies-of-scale parameter.

The details of the derivation are given in Muhich, (1966, Appendix D). The implications of this result for planning water resources can be quite startling. Equation (1) tells us that the optimal time horizon is independent of the rate of growth in demand and independent of magnitude of the capital costs. It depends solely upon the discount rate and the economies-of-scale parameter. The economies-of-scale parameter ranges from 0 to 1, where unity implies that there are no economies-of-scale and that there is no incentive to plan for more than one year at a time. From equation 1 the optimal excess capacity is 0 — do not build ahead of demand. A typical value of b for large engineering structures is in the range of .5 to .8. The smaller the value of b , the larger the economies-of-scale and the longer into the future one plans.

The functional form of equation (1) is a surprise³. Less surprisingly, when the discount rate is high, the optimal planning horizon should be short. Examples given by Thomas, based upon plausible costs and economies-of-scale parameters for water infrastructure, imply that when the discount rate is 3% we should plan for 41 years of growth in demand, and when the discount rate rises to 10%, we should plan for only 12.4 years into the future. This simple model explains why public water planners feel quite comfortable with the 40 years planning horizon but feel very uncomfortable with 12-year planning horizons and the private sector water planners feel exactly the opposite.

These results quoted above should be tempered, however, with some practical considerations of transaction costs which do not appear in the models. Even though no costs enter into equation 1, bureaucratic and political considerations may make the total cost of the project much more lumpy, hence, decreasing the economies-of-scale parameter and making larger size more attractive than the simple model would suggest.

The capacity expansion model, coupled with the levels of uncertainty shown in Figure 3 lead to some important implications for planning for water use under climate change. For most cost functions, demand forecasts, and discount rates, one should plan only for short periods into the future. So the future is not far away. Hence, forecasts of major changes happening over 40 to 50 years will have no impact upon the rational optimal choice now. The planner can upgrade his estimates of global climate change impacts upon water resources and continue to make improved relatively short-term decisions.

When uncertainty is introduced into the parameters of the capacity expansion model the optimal decision period will change. For example, a 25% underestimate of the discount rate gives an optimal design period moving from 41 down to 33 years, and similarly, a 25% overestimate makes the error move in the opposite direction to 55 years. How well can we determine the "correct" discount parameter? Errors of the same magnitude in estimating the scaling parameter as those reported above for the discount rate cause even

³For the case of geometric demand growth this is strictly not true, however, Muhich (1966) showed computationally that over the range of traditional discount rates the optimal time horizon was essentially independent of the rate of growth of demand and was mainly a function of the discount rate. Many other cases involving linear and geometric demand growth with various possibilities for shortage have since been considered in the literature. See Fallon (1986) for a useful review of this literature.

larger errors in the time scale for the project. However, given the state of engineering cost accounting there is no reason to think that the estimation errors for the scaling parameter will be anywhere as large as the estimates of the discount rate which involves complex social judgements.

The analysis of capacity expansion discussed above appears to be in conflict with actual practice in the U.S. with the long lead times and large projects mentioned earlier. However, it should be recalled that those are historical data. It is unlikely that many mega-projects will be built in the future; most effort will be in system expansion and maintenance rather than in entirely new projects.

Selected Cases Studies

For the purposes of this paper I have chosen three cases which span the United States from the humid east to the arid west. Although two of these are historical cases and have nothing to do with climate change per se, they do cover the range of issues likely to occur in analyzing the socioeconomic consequences of climate change. The cases deal with water supply and water quality along with irrigation and hydropower. One deals with a historical reassessment of a series of investments, another with the current operation and management of a large system under severe stress due to drought, and the third with an analysis of the socioeconomic impacts of potential climate change on a multi-state region in the Midwest. These three cases deal with most of the important aspects of water resources planning, particularly those issues most likely to be faced under a changed climate.

1. The Potomac River Basin

James, Bower, and Matalas (1969) considered the Potomac River Basin as a case study in 1969. In hindsight this was a particularly fortunate choice since over the intervening 24 years, a series of decisions and plans have actually been implemented in the Potomac Basin and can be used as a test of the conclusions of their paper. It was also the focus of one of the chapters in the 1977 National Research Council's study on climate change and water supply (Schwarz, 1977).

In 1963, the U.S. Corps of Engineers recommended that 16 major reservoirs costing \$400 million and 418 headwater reservoirs costing a further \$100 million be built in the Basin (U.S. Army Engineer District, 1963). Nine of the major reservoirs were recommended for immediate authorization in order to meet flow requirements and water quality improvements by 1985-1990.

The details of the actual implementation of the Potomac plan are given in Sheer (1984). The important point is that eventually only one small water supply reservoir was built. The water supply goals and the great improvement in water quality were achieved mainly by operating the existing separate systems more efficiently as one large system, and by implementing the federal Clean Water Act of 1972. This is a cautionary tale and should be borne in mind by those who would have us make important decisions before we have understood the full implications of the relative uncertainties in the system or the advantages of non-structural measures.

James, Bower, and Matalas used four-way analysis of variance on the output of a simulation model of the basin that was run under different sets of assumptions regarding the various types of input variables. The model, like many such river basin simulation models, dealt with hydrological uncertainty in great detail simulating 1000 years of monthly flow data for each of 30 sites around the basin. The environmental response was assessed using two models; one basically using 5-day Biochemical Oxygen Demand (BOD which measures the amount of oxygen consumed over a 5-day period by organic pollutants as they are oxidized by biological and chemical processes) as an indicator of environmental damage, and another using the ultimate oxygen demand with much more attention to impacts in the estuary. The economic inputs were limited to forecasts of waste load and water demand made by the Corps of Engineers and a version of it in which the total demands were scaled down by 25%. The political role was characterized by setting as goals two levels of dissolved oxygen in the river and estuary. The authors found that the economic followed by the political variables were the most important determinants of the total number of months failing to meet the dissolved oxygen target. Trailing far behind these variables was the environmental response; the system was least sensitive to variations in the hydrology.

One should be careful, however, to indicate that these results were based upon a particular set of simulation models with specific assumptions regarding the types and ranges of uncertainty for each of the major factors or variable types. Nevertheless, what actually happened between 1963 and 1992 seems to bear out the major conclusions of the James, Bower, and Matalas study. Because the reliability and variability of the water availability was swamped by uncertainties in the political and economic factors, the dire predictions of the original Corps of Engineers Report did not come to pass. The political will to interconnect and run the system as a whole was the most important possibility not considered in the original plans. Incidentally, the only set of variables that did not change significantly were those of the hydrology.

Schwarz (1977) created a simulation model to assess the potential impact of climate change on the Potomac Basin water supply⁴. He discovered that, although the scenarios for possible climate outcomes gave a range of hydrological outcomes with large extremes and wide ranges in the streamflows, when these flows were put into the water system model, the outcomes were greatly buffered. This is a point often overlooked in the discussion of climate change on water resources; it is not the change in flows that is important but the economic consequences associated with those flows. Schwarz's conclusion is worth repeating:

The result of this analysis was generally disappointing to those who believe that climate change should radically alter the water supply planning process....If, in addition, we add in the uncertainty of the timing of possible climate changes, then it becomes even more certain that current planning does not have to be concerned with climatic change (Schwarz, 1977, p.118).

In Climate Change and U.S. Water Resources (Waggoner, 1990), Schwarz returned to this theme (Schwarz and Dillard, 1990) with case studies of the perceptions of the managers of several large water utilities (Indianapolis, New Orleans, New York, Salt Lake City, Tucson, Washington, D.C., and Worcester (Mass)). In each case he found that the managers and planners questioned were taking a "wait and see" approach. Some, notably those in New York City, had already carried out some studies of the consequences of climate change on their systems. Apart from some concern with coastal flooding due to sea level rise, all

⁴Note that by 1977 water quality was no longer the major concern because of the implementation of the Clean Water Act of 1972.

the utilities believed that they could adapt easily and relatively cheaply to climate change when, and if, it came. All were waiting to see if a scientific consensus would emerge before they had to act.

Based upon his experience with the Potomac Basin, Sheer (1986) has since unearthed several other cases in which joint management of water supplies could lead to large increases in water availabilities. For example, Sheer estimates that conjunctive use of surface and groundwater in Houston, Texas could increase system yields by 20% even though both sources are already highly developed, and joint management of the water supplies on the Platte River could reduce water shortages by 30% even permitting additional water withdrawals. This type of management might be able to fully compensate for climate change impacts on the supply and demand for water in some instances.

So far, most of the adaptation discussed has been by improving management of the resource in the face of uncertainty. This could be characterized as supply-side management. As we have seen, large expansions of supply (at given levels of reliability) are possible quite inexpensively through improved management of existing facilities. The newer aspects of water management are on the demand-side. The following example illustrates the potential for large reductions in demand.

2. The California Drought

The recent 6-year drought in California provides us with some excellent material on how hard, or how easy, it is for large water using systems to respond to large and persistent changes in water availabilities. The drought provides us with a natural laboratory within which we can study potential climate change almost like a scientist would perform a controlled experiment. In the applied sciences and the applied social sciences (both critical for water planners), we rarely have the opportunity to follow such "experiments." One nice feature is that the drought is stimulating a whole new literature on water users' and water planners' responses to shortages.

As Director of California's Department of Water Resources, Kennedy (1991) was in charge of suggesting remedies for the crisis. 1987 through 1991 was the driest four-year period on record for much of the state. By the beginning of 1991, urban areas were facing as much as a 50% shortage of water. In early

February the State Water Project reduced urban water deliveries to 10% of normal supply (that is a 90% reduction) and eliminated all agricultural deliveries. At that time the state was two-thirds of the way through the rainfall season and 1991 was the driest year on record. There were calls in the media and from citizen's groups for the new governor, Pete Wilson, to declare a statewide emergency and reallocate all of the water regardless of ownership (under state law the governor has the authority to take property but has to provide compensation). Frightened by the prospect of multi-billion dollar litigation, the top officials decided instead to institute a Drought Water Bank. The Bank was instructed to purchase water from farmers and then resell it to those with the most pressing needs. There was to be no coercion; all purchases and sales were to be on a voluntary basis. After much discussion it was agreed to offer \$125 per acre-foot of water to the sellers with the hope of obtaining between 750,000 and 1,000,000 acre-feet of water and sell it at \$175 per acre-foot to whomever wanted it.

By the end of June 1991, the Drought Water Bank had purchased about 750,000 acre-feet of water through 340 separate water sales contracts: 400,000 from fallowed farmland, 210,000 from groundwater sources, and 140,000 from surface reservoirs. It was a surprise to many that such large quantities of water became available so quickly. There is talk of making this temporary Bank a permanent feature in California's water system. However, such a development would probably run into multi-year negotiations about the permanent transfer of water rights and the resolution of potential third-party impacts. Kennedy claims that because of the crisis situation his agency was able to move quickly and decisively. This, he believes, may not be the case in anything less than another full drought situation. The full implications of the marketing of the water at more than "give-away" rates can be appreciated by the fact that at the end of 1991 fully 25% of the water that was purchased by the State was still in reservoirs without any willing purchasers -- adieu to the Californian water crisis!

Becker et al. (1991) concentrated upon the effect of the drought on agriculture and natural resources and concluded that California agriculture had been able to cope well with the first 4 years of the drought due to its flexible system of delivery of alternate sources of water. However, increasing reliance on groundwater was causing rapid declines in the water tables in many areas and could not be sustained for many more

seasons. Fish, wildlife, and forests have been severely impacted by the drought. Gleick and Nash (1991) examined the environmental and societal costs of the drought and analyzed the indirect impacts of the drought. They claim that the greatest impacts have been on the environment, that many of the ecological effects may be irreversible (the delta smelt; *hypomesus transpacificus*), and that while the direct impact upon agriculture is likely to be only around 2% of the state's total agricultural income of \$18 billion, substantial economic costs (an additional \$3 billion over the 5 years of the drought) will be borne because of decreased hydroelectric potential and loss of tourism (during the 1990-1991 season ski resorts reportedly lost about \$85 million).

Peabody and his collaborators (1991) took a broader look at the problem of water shortages as a permanent feature of the Californian water planning scene. The drought is only incidental to their much wider exploration of water use. The subtitle to their report is " Water Resource Management in a Closing Water System." The concept of a "closing system" is of interest to us because instead of focusing on ways to expand water supply they focus upon exploring ways to make better use of the existing water supplies (demand management).

...in a closing system, all users become increasingly interdependent. Each use of water either reduces or increases the relative supply for someone downstream, by reducing the quantity or quality of the water that is discharged. Management of the interdependence becomes a public function. Ultimately, a closing water system requires much more management than an open system....The difficult part of managing a closing system is the development of mechanisms to get all users to acknowledge their interdependence and to engage them in a negotiation process that binds them to the agreements reached (Peabody 1991, p. 7).

In addition to the emergency Drought Water Bank, they also discussed four other approaches to making better use of the existing water supplies: conservation and rural/urban water transfers (the agreement between the Imperial Irrigation District and the Metropolitan Water District that promotes the transfer of water conserved in the Imperial Valley to the Los Angeles region); conservation via pricing (Broadview Water District's tiered pricing program); water storage and exchange (the Arvin-Edison/Metropolitan Water District's agreement to use a rural aquifer to store temporarily urban water supplies); and the expansion of dialogue among users from different sectors (the Three-Way Water Agreement Process between the Pardee

group and the Hetch Hetchy group). Gleick and Nash examined the proposition of "drought as analogue of climate change," and concluded that, while an imperfect analogue, it does demonstrate the vulnerability of the economy and the environment of California to variations in climate. Surprisingly, after describing the quite remarkable adaptations made by Californians to much graver situations than typically predicted by the climate models, they claim that the responses would not be adequate to cope with actual climate warming. On the contrary, Peabody and his colleagues are quite optimistic about the prospects for adaptations by the various water users in California in the face of a "closing water system."

The differences between the Peabody and the Gleick points of view stem largely from how much each group weighs the value of instream flows. The availability of additional instream flows was given a boost by the recent passage of the 1992 Omnibus Water Bill which arranged for 800,000 acre-ft of water to be diverted from federal irrigation projects to maintain instream flows in the rivers and the delta.

To a reader with an historical inclination, all of the Californian studies have a hollow ring. Each study, in its own way, indicates the remarkable adaptations that have occurred and are occurring in response to the 6-year drought of 1987-1992. What I worry about is how much adaptability the Californian water system has to the 100-year drought that could occur. From 1750 to 1830, the period prior to U.S. control of California, based upon tree ring data it appears that an 80-year drought occurred in California with each year well below the 1600 to 1960 average moisture (Bredehoeft, 1984). Ever since 1850 the state has been in an unusually wet period. This is the period of the intensive economic development of the region. How many more years into the future can California keep ahead of the supply limitation by demand management of the type recently practiced? One does not need the threat of exogenous climate change to be quite concerned about the water supply in California. California has survived the historic droughts because the anthropogenic stress on the system has been amenable to rapid, and relatively painless, reduction: with the population of 30 million still growing this may not be the case in the future.

3. The MINK Study

The MINK Study prepared for the U.S. Department of Energy (1991) by Resources for the Future (Rosenberg, et al., 1991) provides an innovative approach to assessing the economic consequences of climate change on a variety of economic sectors (agriculture, forestry, energy and water resources) in Missouri, Iowa, Nebraska, and Kansas. Realizing the problems with forecasting future climate from GCM's the authors chose to characterize future (2030) climatic conditions and water availabilities as similar to those that were experienced in the dust-bowl drought decade of 1931-1940. The streamflows during that period were on average only 72% of those of the 1951-1980 period. They also allowed for a CO₂ concentration ranging up to 450 ppm. This avoided having to choose between the conflicting GCM forecasts.

They used a simulation model, called EPIC, to determine the demand for irrigation water. Frederick's (1991) analysis of the water resources in the MINK study also considered a variety of industrial, municipal, recreational, hydropower, and instream flow demands. The region's water resource institutions and the implications of water shortages on alternative uses were examined to assess the impacts of a 1930s climate on the region and to evaluate policy responses. Under the analog climate, instream flows would be sharply reduced, irrigation in Iowa and Missouri would continue to grow despite the reduced availability of water because the warmer, drier climate would increase the economic value of irrigated relative to dryland agriculture, and lower groundwater recharge rates would contribute to a reduction in irrigation in the High Plains area. Yet, when the impacts of reduced production in agriculture and forestry are mapped into economic consequences, the impacts appear to be surprisingly small. The study claims that the major economy-wide impact would come from lost production of feedgrains on rainfed and irrigated lands. However, when adjustments are made for CO₂ enrichment effects on plant growth, the impacts on agricultural production are greatly reduced. Under the best case scenario, the effect of climate induced decline in agriculture would be to reduce overall regional product by between 0.3 and 1.4 percent. In the worst case scenario, which was viewed as unlikely by the authors, with a decline in crop production and no on-farm adaptation or CO₂ enrichment, total regional product might decline by more than 10 percent. It also appears that the water-based recreation would be significantly affected by reduced instream flows. The

authors also note that the environmental implications of reduced streamflows are not captured by standard economic measures.

What stands out in this carefully conducted study is that there are many built-in adaptation opportunities in human systems which tend to mitigate the effects of even large natural perturbations. Hence, the overall economic consequences due to climate change in the MINK region are surprisingly small for quite large reductions in available water resources. As the authors of the MINK study point out, however, climate warming may be greater than the effects of the 1931-1940 drought. In this case the effects could be larger.

Conclusions

There are many uncertainties to be faced by water managers and planners. These uncertainties become ever larger when future climate change is contemplated. It appears from the cases reported in this paper that hydrological changes may be among the least important. Nevertheless, water is, and will remain a critically important resource for maintaining ecosystems and economies. This may be paradoxical, but there is a remarkably wide range of substitutability in human water use -- the uses by nature may be far less substitutable and, hence, potentially more important under climate change. Moreover, uncertainty concerning water availability may be one of the most easily reducible of the inherent uncertainties. The Potomac River case shows that the hazards of making errors in forecasting the demand for water, even for periods as short as 25 years into the future, are largely due to errors in estimating the socioeconomic, not the hydrological, variables. Essentially, the Potomac case tells us to plan for flexibility and make best use of existing facilities.

Of the hydrologic parameters, it appears that the two most important that water managers need to get from climatologists are the potential magnitudes of future water availability and its variability. The Potomac case makes clear that, once economic and political uncertainties are resolved, managing the variability of the water supply is the most important aspect of planning. Therefore, if the climate experts were able to give us accurate estimates of the changes in the means, variances, skewness, and persistence of either the precipitation or the streamflows, then we could improve the accuracy of our plans for meeting future demands.

Given typical discount rates and the economies-of-scale of water projects, the optimal planning period is usually less than 20 years (Thomas, 1971). Schwarz's results for the Potomac indicate that, even with very strong assumptions about the variability of the parameters of climate change, the range of responses of the system are well within the range of uncertainty about the social and economic parameters, and within the range of fairly easy adaptation, if required.

The California case presented the best evidence of the adaptations available in modern U.S. circumstances. While the adaptations are by no means painless, the magnitudes of the seeming "shortfall" were far greater than expected to occur under all but the most extreme climate change scenarios. For California, it would appear that we should not be worrying excessively about climate change given the demonstrated ability of the socioeconomic system to adapt. The case studies, taken as a whole, indicate that even if we know the future hydrological parameters exactly, we probably would not change how we currently carry out water planning and management in the United States. The existing systems appear to be flexible and adaptive enough to withstand large changes in water availability and increased demand. This does not mean, however, that we should not concern ourselves with climate change. We should. What it does mean is that we should not be stampeded into taking inappropriate actions. There is a growing clamor for preemptive action even before we know the consequences "because the costs of being wrong" may be catastrophic. Obviously we should keep our eyes open for the occasional catastrophe -- one good catastrophe can ruin your whole day! How do we avoid the catastrophes? We do this by continuing to carry on research on the nexus of climate change, water resources, and socioeconomic adaptation; not solely on the hydrology but also upon other parts of the socioeconomic system and the aquatic ecosystem. The one area that stands out from the California case study as a potential catastrophe is the consequence of possible climate change upon stream biota and other ecosystems dependent upon water. These are largely being neglected by a science policy which misallocates the climate research monies to large scale climate modelling at the expense of these more valuable areas of knowledge.

I believe that this paper also demonstrates that while there appears to be little need for a new methodology to assess the socioeconomic consequences of climate change, there is the need for more

research on the mechanisms of adaptation of water resources systems to climate change. Research is needed on both supply-side and especially on demand-side adaptations (Frederick, 1993). This paper demonstrates that we are probably far from a crisis in U.S. water resources due to actual or potential climate change. It shows where the major uncertainties lie in making rational plans for water and it indicates the need for a shift in research emphasis with regard to climate change impact assessment.

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FIGURE 1: Socioeconomic Consequences of Climate Change

FIGURE 2: Changes in Probability Distributions for Shifts in Mean, Variance, or Both

Changes in probability distributions and stochastic outcomes for shifts in mean, variance, or both. (after Parry and Carter, 1986.)

FIGURE 3: 60-year Simulation with Decreased Mean and Increased Variance

Climate Change: Gota River Data
20% Decrease Mean 10% Increase SD

FIGURE 4: Projections of Water Withdrawals from Various Sources 1975-2000

FIGURE 5: Capacity Expansion in Water Systems

CONCLUSIONS, REMAINING ISSUES, AND NEXT STEPS

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The workshop focused on methodologies to assess the impacts of climate change on terrestrial and aquatic ecosystems and their socioeconomic consequences. It did not deal in any detail with the other components (i.e., models designed to estimate changes in atmospheric concentrations of greenhouse gases or in climatic factors) of an integrated assessment shown in Figure 2 of the introduction. This final chapter discusses some of the issues addressed during the San Diego workshop and highlights a few of the major findings of the papers. Issues discussed below include limitations of past modeling efforts and impediments to developing better models of the impacts of climate change on forest, grassland, and water resources; suggestions for future research both to develop better data and models and to employ existing data and modeling capabilities to improve the usefulness of climate impact assessments for policy purposes; and the need for developing a common assessment framework.

Limitations of past modeling efforts

The papers in this volume indicate the availability of a variety of sophisticated biophysical and socioeconomic models for forests, grasslands, and water resources. While

* The views expressed here are those of the authors and do not necessarily reflect those of their institutions or the other participants in the February 28 to March 3, 1993 workshop held in San Diego, California.

these models do a reasonable job of simulating those resources for the limited conditions for which they were developed, their ability to model climate change impacts decades from now is problematic. Obvious shortcomings are that the biophysical and socioeconomic models are generally not integrated within resource sectors and the various sectors have not been linked. Thus, feedback mechanisms, including automatic adaptations due to changes in technology, economics, value systems, and institutions are often overlooked. A notable exception to this was the modeling undertaken for the MINK study that is described below. Each of the biophysical and socioeconomic models discussed in this volume have a number of drawbacks for assessing the impacts of climate change on the various resource sectors and the resulting social and economic consequences.

Establishing a future baseline in the absence of climate change

The ability to model future biophysical, social, and economic baselines is very poor, even in the absence of climate change. As noted in the introduction to this volume, establishing credible baselines decades into the future in the absence of climate change is a critical step in the assessment process. Differences between these future baselines and the present situation may well be much greater than the impacts of climate change alone (Goklany, 1992 and IPCC, 1991). A major impediment to projecting future baselines with confidence is that the biophysical, social, and economic baselines are not independent. The biophysical baseline will depend upon future natural resource use and demand which will be determined by, among other things, future social and economic factors including per capita wealth; absolute population and population densities; and technologies for producing, using, conserving, and managing natural resources. The challenge of modeling the future baseline is further complicated because changes in technologies and social, economic, and environmental conditions would lead to automatic adaptations, i.e., normal efforts to reduce any negative effects and to increase any positive consequences. In turn,

these factors (per capita wealth, absolute population, population densities and technologies) will be determined by--as well as determine--social, economic, and legal institutions.

Forecasting future technologies and the evolution of social, economic, and legal institutions over the next 50 to 100 years is, at best, an uncertain task. Past forecasting efforts over much more modest time frames have generally fallen far short of subsequent reality (Goklany 1992, Rogers, this volume). One reason for the poor showing is that such analyses tend to overemphasize the relevance of past trends while making inadequate allowance for normal human responses to change. In addition, most social, economic, and legal institutions are often explicitly or implicitly assumed to be invariant, further precluding automatic adaptations. Failure to make adequate allowance for adaptations such as technological changes that go beyond those currently under development, future institutional changes, and individual and organized responses that could reasonably be expected to occur to cope with real or perceived stresses or take advantage of any favorable changes tends to overestimate the impacts of climate change. The assumption that the future will be much like the present may be virtually inevitable given the difficulties of modeling technological and institutional change.

Projections of land use and land cover are an important component of the future baseline. Likely impacts on terrestrial ecosystems include changes in the distribution and abundance of various species and in the sinks, sources, and reservoirs of carbon, methane, and other greenhouse gases affected by ecosystems. The differences between a land use/land cover baseline 50 to 100 years hence (absent climate change) and the current situation are likely to be significantly larger than those due to climate change alone. But our ability to model these changes is poor. A complicating consideration is that land use/land cover and ecosystem health and composition depend upon locality-specific factors including demographics, historical land use, management practices, geology, soils and

climate. Therefore, such baselines should be developed at relatively small geographic scales. But at these scales, uncertainties multiply for projections of virtually all the physical, biological, climatic, and socioeconomic factors that would determine future land use/land cover. Clearly, if one is interested in the future distribution and abundance of a particular species, the more limited the range of the species or the narrower its ecological niche, the greater the uncertainties attendant to the projections.

Modeling the implications of large future perturbations

It may be argued that the problems in modeling future baseline conditions may not be all that significant because modeling the impacts of climate change requires estimating the differences between two conditions: one with and the other without climate change. Thus, the argument goes, systematic errors would be diminished, if not eliminated. While this is a valid argument, it begs the question regarding the validity and accuracy of estimates of the impacts of climate change 50 to 100 years into the future. This question highlights another major shortcoming of current models. As is to be expected, existing models are based and validated, if at all, on present day conditions. The further the future baseline conditions from those existing currently, the greater the uncertainties associated with the model results. In fact, the applicability of some of these models may be in doubt if the changes in these conditions are more than a mere perturbation.

Because current biophysical models have been developed for current atmospheric and climatic conditions, they are less able to model impacts resulting from large changes in those conditions. In particular, biophysical models need to be able to model impacts on ecosystems resulting from simultaneous and relatively large changes in atmospheric carbon dioxide concentrations, temperature, and water availability. All these factors affect each species' productivity and distribution by modifying its photosynthetic rate, ability to cope with stresses (e.g., low moisture levels, atmospheric pollutants, and nutrient deficiencies),

and competitive advantage (and disadvantage) relative to other species. These effects, in turn, would further change the supply of and demand for water resources.

Incorporating the potential effects of CO₂ enrichment on biological processes presents major challenges to biophysical models of climate change. Controlled experiments strongly suggest that increased atmospheric carbon dioxide, independent of any climate effects, has important impacts on plant growth and evapotranspiration rates from agricultural lands and grasslands. Parton et al. (this volume) note that the direct impact of CO₂ on photosynthesis and water use in grasslands could be as large as those due to climate changes. Moreover, the direct CO₂ effect may reduce the nitrogen content and, thereby, the digestibility of the forage. Studies on crops and young trees suggest that rising levels of atmospheric carbon dioxide alter photosynthetic rates, stomatal apertures, and the response of vegetation to various stresses such as drought, atmospheric pollutants, and nutrient deficiencies. These changes may increase above and below ground biomass, altering the levels of carbon and nitrogen in the soil. The direct CO₂ effect could potentially produce fundamental changes in carbon and nitrogen cycles (National Academy of Sciences, 1992, Zak, et al., 1993). Much less is known about the potential effects of CO₂ on mature trees or an entire forest ecosystem because of the greater difficulty of undertaking controlled studies. Consequently, the ability to model the effects of CO₂ is poorer for mature trees and forest ecosystems than for grasslands.

Socioeconomic models are also based upon present day conditions. Thus, they too would do a much better job in estimating impacts if these conditions are perturbed slightly, than if there are substantial changes in social and economic conditions. Given the rate at which technologies, demographics, and institutions have changed during the twentieth century, it requires a substantial leap of faith to assume that current socioeconomic models will be valid for whatever conditions exist fifty to a hundred years in the future.

Other limitations of biophysical models

Biophysical models estimate potential, rather than expected, vegetation. Potential vegetation estimates do not consider the human demands placed on land and water resources to produce food, forest products, habitation, transportation, and industrial products. Over the centuries this demand has resulted, and will continue to result, in conscious manipulation of the landscape and the ecosystems they support by diverting land and water for human use. These conscious efforts are accompanied by inadvertent modifications due to factors such as the introduction of non-native species, deposition of airborne pollutants or nutrients, and the unintended consequences of agriculture and water management projects. For these reasons, the correspondence between potential and actual (or expected) vegetation is often slight. This lack of realism does not stem from any shortcoming in the biophysical models. However, more realistic models must be fully integrated across sectors and with socioeconomic models because the very presence and type of vegetation are increasingly determined by human needs and desires. Adding to these problems is the lack of standard land cover and land use data to describe the current situation.

Current biophysical models have not been developed to the point where they could simulate the evolution of one type of landscape such as a forest into another such as a grassland. Thus, while existing models can project changes in the mix of various species of trees in a forest ecosystem or grasses in a grassland ecosystem, they cannot project the mix that might exist during or after a transition from one type of ecosystem to another.

Climate change projections

The quality of estimates from impact assessments suffers from the unavailability of reliable projections of climate change at the spatial and temporal scales necessary to model impacts and policies at regional (or smaller geographic) scales. Convenience and the

absence of better alternatives have made general circulation models (GCMs) the primary source of the climate change information used in impact analysis. However, until GCMs can reasonably describe the current climate at regional and subregional scales, it is hard to put much faith in its ability to project the future climate under different atmospheric conditions. Furthermore, analyzing how climate change will affect a forest, grassland, and watershed--the levels at which most impact analysis is undertaken--requires climate data at a much finer resolution than the GCMs currently provide. For example, local information and characteristics are critical for determining if a species might go extinct as a result of climate change or for assessing the impacts of climatic variables on water supplies.

Valuing impacts on natural resource systems

Even if the natural and social scientists jointly were able to describe the with and without climate change futures with reasonable accuracy, the social scientists would be left with the challenge of placing values on these changes. Valuing the impacts on marketed goods such as agricultural crops and timber harvests is straight forward and non-controversial. For small changes, market prices can be used to value such goods. For impacts large enough to alter the market price, changes in consumer and producer surplus are used to estimate the net social impacts. However, as was noted in the introduction to this volume, standard economic measures do not capture the full extent of humankind's stake in the health of these natural resource systems. These systems often provide recreation benefits that are not marketed and public goods such as scenic amenities and wildlife habitat that are not marketable. They also provide nonuse outputs such as the existence values of preserving a scenic vista or an endangered species. These nonuse values are much harder to estimate. A further complication arises because nonuse values estimated for today's population may be invalid in the future due to changes in per capita wealth, population, value systems, and other factors.

Economists have developed several methods to estimate the value of nonmarketed goods and services that are not reflected in standard economic measures such as the national income accounts. The travel cost method assumes that the distance traveled to enjoy a natural asset such as a forest or stream is closely correlated with the cost of (and therefore the willingness to pay for) enjoying the resource. Hedonic pricing uses differences in property values among sites to estimate the marginal value of various attributes such as being located near a recreation or scenic location. By combining the travel cost and hedonic techniques, a willingness to pay for greater quality can be estimated from decisions to visit a particular location among several with varying attributes. These valuation techniques are not without their problems. But when carefully applied, they may provide reasonable estimates of the value of these nonmarketed benefits of resource systems (Smith, 1993).

The contingent valuation method (CVM) relies on surveys to estimate the values of public and other nonmarketed goods and services. CVM does not depend on observed behavior to estimate values. Consequently, this technique can be used for situations where travel cost and hedonic techniques are unavailable or inappropriate. Although CVM can be applied more broadly for estimating nonuse values of natural resource systems, the results are likely to be more uncertain and controversial. A contingent valuation survey presents people with the opportunity to buy goods such as cleaner air or the preservation of a natural ecosystem in a hypothetical market. The responses, which elicit a willingness to pay that is contingent upon the hypothetical market that is described to the survey respondent, are subject to several potential sources of bias. Strategic bias arises when a respondent wants to influence the outcome. Information bias occurs if respondents are asked to value unfamiliar or poorly defined attributes or goods. Starting point bias results when the predefined range of possible answers does not include the full range of respondents' willingness to pay. And hypothetical bias arises when respondents give ill-

considered or even flippant answers because they know they do not actually have to pay the value they attribute to the good.

Estimating the total value society places on a good or attribute of a resource also requires scaling up the survey results over the entire population pool that is viewed as valuing the good in question. Since the selection of the relevant population is critical to the final result and may involve as much art as science, it too is likely to be controversial. Proponents of CVM believe careful survey design and implementation can keep the distortions within an acceptable range (Smith, 1993 and Mitchell and Carson, 1989). Skeptics argue that contingent valuation answers are inconsistent with the basic axioms of consumer choice theory and do not provide an appropriate measure of economic value (Diamond, et al., undated).

Implications for future research

Workshop participants noted a number of areas where scientific advances would contribute importantly to overcoming some of the above mentioned shortcomings in our ability to assess the impacts of climate change on natural resource systems. High priority should be given to integrating biophysical and socioeconomic models, linking the various natural resource sectors, and understanding the dynamics of social and economic systems and their responses to changing demographic, economic, resource, and environmental pressures.

Improved biophysical models are needed to better simulate changes in productivity, water demand, and respiration under changed climatic and atmospheric conditions. This suggests a need for additional experiments on vegetation and ecosystems under increasing CO₂ concentrations for a variety of field conditions that can be expected to occur in the future. Such conditions would include less-than-ideal nutrient conditions, presence of pests and diseases, and changes in pollutant loadings, non-CO₂ greenhouse gas

concentrations, and climatic factors. Such experiments would provide the empirical basis for development and/or refinements of biophysical models. As noted above, this need is especially acute for mature trees and forest ecosystems.

Other suggested research priorities include: developing or modifying forest and grassland ecosystem models to allow the simulation of transitions from one type of ecosystem to another; developing a standard land use and land cover data base with a resolution sufficiently fine to allow meaningful analyses of the composition and health of terrestrial ecosystems; and analyzing the sensitivity of the values of nonuse activities to factors such as socioeconomic conditions, cultural and ethical value systems, and the status and trends of specific natural resources.

Better and more reliable estimates of climatic factors are needed at finer geographical resolution than are currently available from GCMs. More powerful and faster computer systems would increase the capacity of the GCMs to produce more credible and site-specific results; they would also increase the capacity to account for feedback linkages in integrated climate assessments. In the meantime, other measures can help overcome some of the problems associated with reliance on the results of the GCM models. Better ways of nesting models would facilitate the integration of models relying on data of differing geographic scales. And sensitivity analysis can be used to examine the implications of different and highly uncertain climate outcomes. However, without some idea as to the likelihood of a particular outcome, climate policy tends to be driven by fear of the unknown and the desire to reduce risk rather than an assessment of the expected net benefits of alternative policies.

McKenney and Rosenberg (1991) reviewed the vary scanty literature and interviewed practitioners of impact assessments to determine the types of information analysts and policy makers need from GCMs to better understand the impacts of climate change on natural resource systems. The analysts indicated general dissatisfaction with

the current spatial and temporal resolution of GCM outputs. They asked for improved estimates of climate variability and extreme events, better estimates of changes in precipitation and soil moisture, and more reliable simulation of the transient response of climate to increasing concentrations of greenhouse gases.

Extending existing methodologies and developing megamodels

There was a consensus among the participants that extending and evaluating previous efforts to do assessments should be a priority area for future climate change research. In particular, the broad methodology developed for the study, Processes for Identifying Regional Influences of and Responses to Increasing Atmospheric CO₂ and Climate Change - the MINK Project (Rosenberg, 1993 and Rosenberg and Crosson, 1991), was mentioned on several occasions as one that warrants expansion and refinement.

The MINK project developed a four stage methodology and applied it to study the implications of climate change for the four-state area of Missouri, Iowa, Nebraska, and Kansas. The climate change scenario assumed that the climate of the droughty 1930s with and without elevated concentrations of CO₂ becomes the norm. The first stage of the study (task A) described the region's current conditions for the climate sensitive sectors agriculture, water, forestry, and energy and for the whole economy. Task B imposed the climate change scenario on the current baseline, task C developed a future baseline for the year 2030 in the absence of climate change, and task D imposed the climate change scenario on the future baseline developed under task C. Institutional and technological adaptation possibilities were incorporated into the analysis of both the future baseline and the future climate change scenario. In contrast to the MINK approach, most published studies have assumed that the future baseline would be similar to the present. That is, they impose the assumed climate of tomorrow on the world of today.

The MINK study also provides a multi-sector analysis of the impacts of climate change on the study region as well as some linkages among resource sectors. For example, it considers the impacts of altered water supplies on irrigated agriculture and energy production and the impacts of atmospheric CO₂ enrichment on crop production. A subsequent extension of the study that examined the impacts of CO₂ and land cover on runoff and water availability in the Missouri River basin moved closer in providing an integrated assessment of the climate change impacts (Frederick et al., 1993).

Suggested expansions of the MINK methodology include applying it to a different region, introducing different climate scenarios, using different models to relate climate variables to agricultural and forest productivity and water availability, and introducing different tools to evaluate the economic implications of the ecosystem changes. These extensions could provide insights as to the applicability of the MINK methodology in areas where climate change presents different challenges to established socioeconomic activities, the sensitivity of the MINK region to climate variables, and the possible advantages of using alternative models for integrating ecological and economic impacts, or of employing different measures for estimating the overall impacts of climate change on the region.

The U.S. Geological Survey's study, *Sensitivity of Water Resources in the Delaware River Basin to Climate Variability and Change* (Ayers, et al., 1993) provides a detailed analysis of the impacts of climate variables on the hydrology of that basin but makes little attempt to understand the socioeconomic implications of these climatic and hydrologic changes. A joint project of the U.S. Geological Survey and the Bureau of Reclamation is examining the linkages between climate variables and the hydrology of the Gunnison River Basin and the implications of the hydrological changes for the operation of the Bureau of Reclamation's water management facilities on the river. Extending the socioeconomic analysis of this project might provide insights as to how management and

institutional changes could help an arid and semiarid region adapt to altered water supplies associated with climate change.

Extending regional studies that were undertaken with no intent to study climate change could provide an efficient means both of addressing policy issues relating to possible climate change impacts and of developing improved methods for undertaking integrated climate impact assessments. Federal agencies, notably the Corps of Engineers, have done a number of planning studies of water resource regions that could provide the baseline analysis for a climate impact assessment. Indeed, the Water Resources Institute of the Corps of Engineers has initiated climate impact assessments for the Great Lakes and the Potomac, Rio Grande, and Savannah river basins.

Spatial and temporal scales were often cited by the authors and other workshop participants as particularly important considerations for linking ecological and socioeconomic models to achieve more policy relevant studies of the implications of climate change. Binkley and Van Kooten (this volume) note several opportunities for making better use of the rich set of forest ecology models described by Dale and Rauscher (this volume) to address economic issues at different spatial scales. For example, the microscale models of the vegetation dynamics of individual tree stands could be used to assess how optimal economic management such as harvesting, thinning, and fertilization might differ at the enterprise level under alternative climate conditions. These stand-type models also could be run for a sample of inventory points and then aggregated up to assess how climate change might affect regional or national timber supplies or the non-timber outputs of forests. Alternatively, impacts on timber and other forest outputs can be studied with regional-scale ecosystem models that describe tree productivity under different climate regimes. Intra- and inter-annual changes are particularly important in analyzing the economic implications of the climate for grasslands (where seasonal changes in forage strongly influence animal productivity) and water (which is a fugitive resource).

Linking grassland ecology and animal performance models to evaluate the implications of climate change on livestock grazing requires better attention both to the temporal impacts of climatic or management induced disturbances and to the spatial characteristics of the land.

The spatial and temporal availability of water are key to the type of productivity of the ecosystem found on the land, a fact that is incorporated in the forest and grassland ecosystem models. The productivity of the forests and grasslands in turn affect water supplies by influencing runoff, evapotranspiration, and infiltration from these lands. Yet there have been few attempts to integrate hydrologic models with those relating climate variables to land cover. The extension of the MINK study noted above (Frederick et al., 1993) used the Erosion Productivity Impact Calculator (EPIC) model to estimate first the impacts of the 1931-1940 analog climate, with and without CO₂ enrichment, on agricultural and grazing lands and then the impacts of the resulting land cover on runoff and water supplies in the Missouri Basin. Binkley and van Kooten (this volume) suggest that integration of forest ecosystem and hydrologic models would be a useful area for further research.

A major focus of this project was on the difficulties of linking biological and socioeconomic models and on ways to overcome these difficulties. As the previous discussion indicates, much is yet to be done before successful seamless linkages will be made. Even more effort is needed to incorporate important feedbacks into the assessments. The potential importance of climate change for policy concerns such as economic development and the future demand and availability of energy, food security, and land use requires that analyses proceed with tools that are still imperfect. Accounting for the impacts of climate change on land use and land cover is an important step to move beyond analysis of the linkages between the ecosystem and socioeconomic factors toward truly integrated assessments that also account for the feedbacks among sectors of the

economy and among the four components of an integrated assessment (socioeconomic factors, ecosystems, atmospheric chemistry, and the climate) described in the introduction to this volume.

A number of 'megamodels' intended to describe and even quantify the broad suite of physical and socioeconomic issues related to climate change are now under development. Three groups in the United States -- Massachusetts Institute of Technology, Carnegie Mellon University, and Battelle's Pacific Northwest Laboratories -- are currently engaged in such model building exercises with the support of the Electric Power Research Institute and other sponsors. Similar efforts are underway elsewhere. These modeling efforts seek to link human activities to greenhouse (and other) gas emissions with their effects on atmospheric chemistry and climate change (see Figure 2 in the introduction). Improved understanding of the impacts of climate change on agriculture, forestry, unmanaged ecosystems, and water resources and the consequent changes in land use are important objectives of these efforts. To close the circle, the impacts of the resulting changes in land use on emissions of greenhouse gases and on human activities are to be incorporated into the models. Feedbacks among and between all of these factors and processes must be considered if they are to provide more credible answers to the 'what-if' questions asked by policy makers.

Development of a common assessment framework

It was suggested at the workshop that, in order to better serve national policy purposes, all assessments should conform to a common framework or approach. This framework should be general enough to allow for the use of different data, models, and procedures but sufficiently specific to enable the results of different regional and site specific studies undertaken by various researchers to be reasonably compared and/or aggregated. All such assessments would include key analytical and evaluation tasks

regardless of whether their focus is on the implications of climate change for forestry, range, water, or other resources. The common framework would make it possible to compare results of different studies undertaken by various researchers for a particular geographic area, or allow aggregation of the results of different studies at different locations to national and international levels. This could help policy analysts and policy makers sort through the numerous impact assessments, and, in theory, extend their information base. At the same time, a common framework should not be a straitjacket but it should encourage the development of a diversity of approaches to climate impact analysis.

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