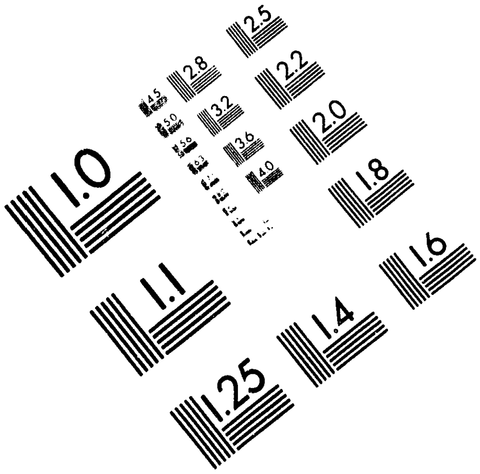

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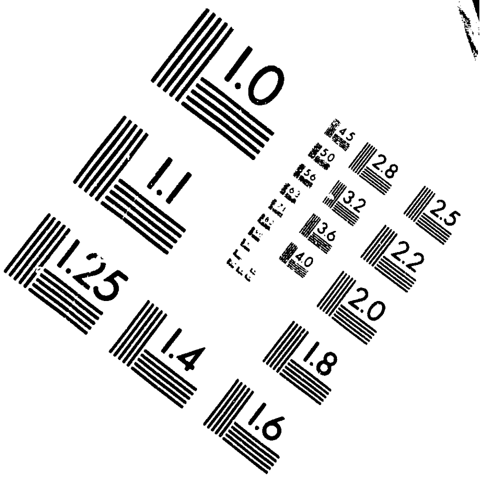

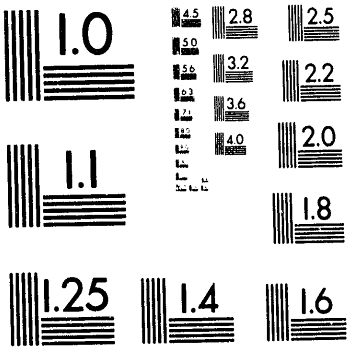

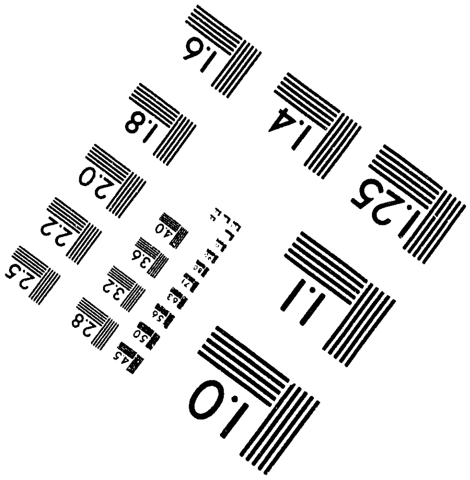

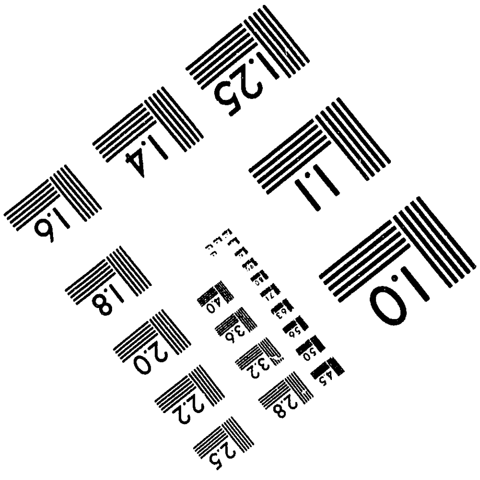

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Assessing Impacts of Climate Change on Forests:
the State of Biological Modeling

Virginia H. Dale

Environmental Sciences Division
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37831-6038

and

H. Michael Rauscher

North Central Forest Experiment Station
U.S. Department of Agriculture Forest Service
Grand Rapids, Minnesota 55744

Submitted to

Climate Change

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Abstract. Models that address the impacts to forests of climate change are reviewed by four levels of biological organization: global, regional or landscape, community, and tree. The models are compared as to their ability to assess changes in greenhouse gas flux, land use, maps 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 consider the largest number of impacts. Developing 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 development 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

Increased atmospheric concentrations of greenhouse gases are expected to result in global climate change. For temperate ecosystems, temperatures may increase by 2 - 4° C, and precipitation patterns may vary from current conditions. For example, winter precipitation in central North America is predicted to increase by 15% and summer precipitation to decrease by 5 - 10% (Houghton et al. 1990).

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. For example, if global warming causes a reduction of forest biomass on a worldwide scale, then less carbon is retained in forest vegetation.

If this carbon is released to the atmosphere, the greenhouse effect may be enhanced. Currently, 90% of terrestrial carbon is stored in forests.

At the biome level, species respond to climate change by evolving, migrating, becoming extinct, or adapting to new disturbance regimes. Compositional effects include changes in the distribution and abundance of sensitive species (those at the edge of their climate range) or less desirable species. The introduction of species from more southern climates may constitute one type of exotic invasion.

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. For example, decreased soil moisture and a warmer climate may increase fire intensity (by affecting forest fuel levels) and the chance of fire initiation. The resulting change in frequency and area of burned land may set the stage for repopulation by species that find the altered climate more beneficial. Also, the probability of insect outbreaks may change as a result of an altered density of predators or parasites (which react to both changes in climate and availability of host species). One example of landscapes responding via nutrient cycles is projections of species shifts on different soil types (Pastor and Post 1988). On loamy soils, the warmer temperatures may allow greater decomposition rates and establishment of a new set of species (with higher rates of litter decomposition). In contrast, on sandy soils, the increased soil moisture problems can result in a shift to species with lower growth rates, less biomass, and poor litter quality. The existing mosaic of soil conditions will result in a new distribution of forest communities (Huston et al. 1988). The new landscape pattern will affect the plants and animals dependent upon those forest systems.

The response of individual trees to climate change occurs through phenology, reproduction, or physiological processes on time scales (ranging from minutes to decades) and spatial scales (ranging from cells to that of a large tree). Climate change effects on these processes are largely mediated by temperature effects on metabolic reactions. Extreme cold can kill many tree species. Woody plants of temperate regions generally require a chilling period of temperatures below 5° C for rapid budburst. All trees require a period with sufficient warmth for growth. Moisture requirements are specific to each species and are influenced by the amount and periodicity of precipitation, soil conditions, and prevailing temperatures. Small trees respond to increased concentrations of atmospheric CO_2 by increased biomass accumulation (especially in roots) even when water or nitrogen are limiting, decreased concentration of nitrogen in green leaves, and increased water use efficiency (Eamus 1991, Eamus and Jarvis 1989, Mousseau and Saugier 1992, Wullschleger et al. 1993). It is not clear what implications these results have for increased atmospheric concentrations of CO_2 effects on mature trees or decomposition rates.

Human activities must be considered in evaluating effects of climate change on forest systems (Table I). At the most basic level, human use of fossil fuels and forest clearing are responsible for the rapid global climate changes projected for the next century. Thus, reduction of fossil-fuel burning and land clearing would decelerate the rate of climate change. Also, climate change impacts may be exacerbated by human activities. For example, forest cutting, road development, and urban expansion create land cover patterns that may be barriers to successful seed dispersal and plant establishment. On the other hand, human activities may mitigate effects of climate change on forests. For example, species unable to migrate to more northerly areas that will have appropriate habitats under predicted warming trends may be planted as part of forest management schemes.

Historical and paleoecological evidence shows that climate change effects on forests have been significant. Interpreting past climate change effects requires knowledge of the regional complexity because weather is influenced by topography and large water masses. Past climate changes have been complex as have the species responses to those changes. For example, with climate warming, intact forest systems have not moved northward; instead, species have responded individualistically (Davis

1989). Furthermore, biological responses have occurred with time lags. Multiple impacts produce species assemblages different from any that we see today (possibly resulting from a combination of changes in climate and atmospheric chemistry). Therefore, paleoecological evidence argues for 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 response to past conditions, the 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 largely determined by human activities. Secondly, global temperatures are predicted to increase at an unprecedented rate. Gaining an understanding of how current forests will respond to the transient in global temperatures and precipitation patterns requires reliance on computer models that can deal with some of the complexities of the forest and climate systems. Because human activities are such an integral part 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 should capture many features of modern forest systems.

This paper reviews 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 are a necessary aspect for consideration. Existing interfaces between socioeconomic and ecological models of forest resources are therefore discussed. A review of research needs focuses on developing 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.

A CONCEPTUAL FRAMEWORK FOR ASSESSING CLIMATE CHANGE IMPACTS TO FORESTS

It is useful to have a conceptual framework of climate change impacts on forests. This framework should facilitate the exchange of information among researchers studying different levels of biological organization and among researchers and policy analysts. This framework should also provide general guidance to program managers, individual researchers, and data management groups, so that information needs at different biological scales are generally known and can be considered when designing research studies. We do not suggest that one large, centralized modeling effort or data base be attempted. Rather, modeling research should be conducted independently at various 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 includes models that operate at different scales (Fig. 1). Global models provide the climate conditions for the region and smaller scales. Regional models provide the natural and policy constraints for the landscape. The landscape biological interactions result in changes in reflectance, evapotranspiration, land cover, and vegetation distribution for the region. Landscape properties determine migration patterns, climate and water constraints, natural disturbance regimes, and management effects that have direct impacts on forest communities. Species composition, size and age distribution, biomass, and numbers of trees are derived from community processes and do affect landscape dynamics. Community properties that influence individual trees include costs (e.g., from predator activities), constraints (e.g., light) and benefits (e.g., symbiotic activities). Individual tree models provide carbon and nitrogen fluxes, leaf area information, and information on 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 inclusion of the major perturbations involved in global change. Perturbations relevant to global change can be grouped into four categories: climate change, land use/land management, natural disturbance regimes, and anthropogenic pollution. Climate change incorporates both natural variations in climate and anthropogenic effects such as global changes induced by increasing concentrations of greenhouse gases and regional climate changes brought about by desertification. Furthermore, there are possible interactions between the perturbation categories. For example, climate change affects the dispersal and scavenging of atmospheric pollutants.

Each of these perturbations can occur at a variety of temporal and spatial scales (Delcourt and Delcourt 1988) and can have a range of effects upon the system. The relevant characteristics of the perturbation are partially determined by the level of organization being considered and the questions being asked. For example, critical global change factors to examine when considering vegetation and soil interactions include cloudiness, precipitation (amount, temporal and spatial distribution, storminess, frontal locations), temperature (mean, diurnal, and seasonality), humidity, and atmospheric deposition. The impacts of these changes are constrained by prevailing nutrient status, moisture, temperature, 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. We discuss climate models (from a forest perspective) as well as forest models that assess climate impacts because the initial conditions or scenarios are determined by the output from climate models.

A. Global-scale models

We have identified four classes or groupings of global-scale models: (1) general circulation models (GCMs), (2) biosphere-atmosphere transfer models, (3) carbon balance models, and (4) vegetation dynamics models (Table II). GCMs provide broad-scale projections of climate changes under increasing atmospheric concentrations of greenhouse gases. They use the laws of physics to model climate and climate change with horizontal resolutions of 200 - 400 km and vertical resolutions of 10 - 20 layers of atmosphere. The concentration of such greenhouse gases is set at the beginning of each model run, and the impact of changes in concentration of these gases on global temperature and precipitation is analyzed (Houghton et al. 1992). GCMs do not model the transient dynamics of carbon or nitrogen. There are at least 19 GCMs in use worldwide (Cess et al. 1990).

The biosphere-atmosphere transfer schemes such as BATS (Dickinson 1986) and the Simple Biosphere Model (SiB, Sellers 1986) are advanced land-surface parameterizations for atmospheric GCMs (Table II). The purpose of these models is to realistically parameterize the exchanges of water and energy fluxes between the land surface and the atmosphere. These models are intended to be used as the land process modules within GCMs and are not run separately. Models like BATS and SiB explicitly treat vegetation as a factor that controls water and energy fluxes, interception, and other land surface processes. These land-surface process models are undergoing testing and evaluation for both GCMs and mesoscale meteorological models. A future goal within this coupled systems modeling concept is for these biosphere-atmospheric transfer schemes to provide feedbacks in land-atmosphere interactions based on changes in land-atmosphere characteristics resulting from climate change-induced shifts in ecosystem composition, structure, and function.

The purpose of global carbon-balance models is to simulate the carbon dynamics between atmosphere, ocean, and biosphere and predict future atmospheric CO_2 levels (Table II). Most of these models are highly aggregated compartment models with as few as 3 to 20 or more compartments. Harvey (1989) has shown that the degree of aggregation has a significant effect on some of the results obtained. The more recent approaches (e.g., Esser 1991) use relatively comprehensive models parameterized separately for each distinctive biome. Models of Moore et al. (1981), Houghton et al. (1983, 1985, 1987), Detwiler and Hall (1988), and Bogdonoff et al. (1985) are based on information at the biome level, predict carbon fluxes over large regions or the globe, and account for lags in carbon release or uptake. These lags result from the slow decay of dead plant material, soils, and wood products or the accumulation of carbon in regrowing forests following shifting cultivation and logging. The major problem with global carbon-balance models is their inconsistency with observations. These models lack realistic land-surface characteristics, such as those characteristics provided by land-cover and land-use data. Further, the models do not provide confidence bands around the estimated flows and pools. For example, Johnson (1992) estimates the uptake of carbon by terrestrial vegetation as 102 Gt C/year while the evolution of carbon from the terrestrial biosphere to the atmosphere is given as 100 Gt C/year. On a the global scale, it is difficult to believe that we can estimate the flow rates to within a 2% error bound. The conclusion must be drawn that we really don't know whether the terrestrial biosphere is a net source or sink of carbon.

Global vegetation dynamics models attempt to predict the kinds and rates of global vegetation formation changes in response to climate change. This information can be used to assess global impacts 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 two ways. One approach uses empirical models of climate and vegetation in a spatial context and superimposes scenarios of climate change by using the Holdridge life zone classification system (Emanuel et al. 1985). A second 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 third approach is to scale up the vegetation dynamics 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. This class of models needs further development and testing.

B. Landscape and regional models

Landscape and regional scale models can be classified into six groups: (1) climate change scenario models, (2) mesoscale climate models, (3) regional hydrology models, (4) regional vegetation and land-use models, (5) geographic information systems models, and (6) landscape transition models (Table III). In order to assess climate change impacts at the landscape and regional level, climate change scenarios are needed at those scales. The horizontal resolution in current GCMs is too coarse to provide useful regional-scale climate information. One approach is to nest a mesoscale meteorological model in a GCM and run the mesoscale model to provide time series data for climate scenarios and input to ecological and hydrological models. To develop useful regional climate change scenarios, it is possible to use limited area models with boundary conditions from GCM output or empirically derived relationships between regional climate and GCM output data (Houghton et al. 1992). Landscape scale hydrology models are needed to account for water dynamics, but few have been developed.

Regional vegetation and land-use models focus explicitly on how changes in the regional patterns of forests affect the carbon budget or forest properties. Global carbon budget "bookkeeping" models run at the regional scale form one class of such models (Bogdonoff et al. 1985). A key element in effective landscape-scale vegetation and land-use dynamics models is to accurately estimate the rate of change of land-use classes. Data that documents change from forest to agriculture or other land uses can be obtained either from historical information (Flint and Richards 1991) or remote sensing data (Dale 1990). Land-use changes frequently contribute more to overall estimation errors than do those associated with the available information on carbon dynamics within a single land-type unit. Since deforestation is largely a process of land-use change, some landscape and regional models have complex socioeconomic components. In Grainger's national scale approach (Grainger 1990), 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 on disturbances and animals to the extent that vegetation pattern affects susceptibility to disturbances and animals movements.

Geographic information systems (GIS) models project patterns of vegetation types given the spatial distribution of soils topography, and climate. Applying the GIS modeling approach to the topographically diverse landscape of Switzerland, Brzeziecki et al. (1993) use 12 data layers to predict vegetation patterns for over one million pixels of size 250 m^2. Neilson (1993) has developed a global

GIS model that predicts vegetation patterns under particular hydrologic scenarios. Iverson et al. (1993) use Weck's climatic index (Weck 1970) in combination with topography and soils data to model potential vegetation biomass of South and Southeast Asia. The advantage of using a climate index is that it is an empirical relationship between readily available climate data and potential biomass density that can be applied world-wide.

Landscape transition models estimate patterns of forest and other land uses in the face of climate change. These models use a cellular automata approach to explore effects of changes in the location, size, shape, and composition of forest boundaries. 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 presence of suitable habitat such as that might which occur with climate change (Fig. 2). 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) uses two dispersal models within the cellular automata design to predict a failure of many north 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 animals and disturbance movements 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 by five groups: (1) vegetation dynamics, (2) forest growth, (3) forest biomass, (4) organic matter decomposition, and (5) water balance (Table IV). 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. Such a gap size may not be adequate for the effective regeneration of some species. 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). Community dynamics models have only indirectly examined anthropogenic air pollution effects on forests by assuming that air quality affects tree growth rate (Dale and Gardner 1987). These 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), as opposed to spatial pattern.

Forest growth models are used to assess the yield of managed forests under prescribed conditions and usually require large calibration data sets (Table IV). These models are generally derived from extensive growth records using regression analysis. The equations may replicate the data and have statistical significance without having any biological basis. Such growth functions usually predict the expected tree diameter increment under given site and stand conditions. The forest models are included in this review because they do project the data needed for economic timber yield models and are well documented. Based on our experience with the federal agencies that endorse models for assessing impacts of forests to air pollutants, we want to clarify that these models are not appropriate for assessing climate change impacts. Forest growth models are designed to be used under climate conditions identical to those under which the model parameters were derived (Dale et al. 1985).

The forest biomass, organic matter decomposition, and water balance models are all mass-balance models (Table IV). Their respective functions are to estimate aboveground and belowground productivity, 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. A synthesis and comparison among these models against standard data sets would be a useful and timely exercise in order to evaluate their usefulness for studies of climate change impacts. 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 empirically examine effects of climate change. Procedures are being developed to link these physiologically based models to vegetation dynamic models (Luxmoore 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 address regional questions of climate change impacts.

D. Individual tree models

There are two groups of models that operate at the scale of whole plants— whole tree and soil microcosm models (Table V). The objective of these models is 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. Models at this scale are most readily related to the direct measurement of parameter values. Effective 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 for assessment should consider forests features at risk as a result of climate change. The major categories of information needed from research on global climate change impacts to forests are summarized below.

1. **Development of future environmental scenarios.** What is the expected range of climate variability for different forest ecosystems? How might weather and growing conditions change? How might these changes impact transport and deposition of air pollutants?
2. **Estimated flux of greenhouse gases from terrestrial systems to the atmosphere.** How does the changing climate affect the flux?
3. **Predictions of expected changes in land use.** How changes in population and nonforest land uses affect land remaining in forest cover under global change?
4. **Compilations of maps of forest type distribution.** Where and when will forest type distributions be altered in response to climate change?

5. **Compilations of maps of species composition changes.** What changes are expected in maps of species distribution that reflect changes in the relative abundance of species?

6. **Estimates of changes in forest resource productivity.** Within broad forest ecosystems, what changes are expected in timber and biomass production and in water quality and quantity?

7. **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?

8. **Estimates of potential effect on biological diversity.** How are genetic, species, ecosystem, and land-use diversity expected to change?

9. **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?

Comparison of these research needs with the forest models (Table VI) shows that no one model meets all the needs although many climate change impacts to 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 the 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 largest number of research needs. Nevertheless, an understanding of the processes at other scales is frequently necessary for landscape or regional interpretation.

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 VII). 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 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 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).

Factors other than credibility also influence 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 forest 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 incorporate age or species structure. In other words, the most sensitive features of the forest projections could not be translated to the economic projections. Thus, 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 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 that should be measured or estimated with the greatest care (Dale et al. 1988).

Models provide a means to assess the implications of information gaps. These gaps can be dealt with by (1) assuming there is no effect, (2) hypothesizing a relationship 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 CO_2 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.

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 can also incorporate 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 (TAMM) 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 for linking socioeconomic and ecological models has been proposed (Lee et al. 1993, Fosberg et al. 1992), but examples are needed. The next step beyond models that have a one-way link is truly integrated 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 of critical features of the process at a coarser scale (Fig. 1). Examples of such nested models include mesoscale climate models to GCMs (Giorgi and Mearns 1991) and hydrologic models to 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.

An example may best illustrate "nested models" (Fig. 3). The example pertains to effects of climate on tree-feeding insects. A Leslie matrix model that simulates changes in the number of individuals by age classes is used (Leslie 1945, 1948; Usher 1966). Leslie matrix models of Balsam-woolly-aphid (BWA) and fraser fir are 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 (Dale et al. 1991). The BWA model operates as a 2-day time step and tracks the number of insects in five age classes. The fraser fir model operates on an annual basis and predicts the number of trees in five age classes. Once a year, the effects of adult aphid density on fir survival are 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 to forest may come from either empirical or modeling studies. Climate, land-surface characteristics, and land-use information need to be obtained at the appropriate resolution for impact analysis. 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 need to be obtained 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 the greatest uncertainty. The 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 on the responses of diameter growth responds to experimental conditions are needed when these models are used.

The frequency, intensity, and duration of natural disturbances can be affected by climate change (Franklin et al. 1991). The first step of the research program would be to evaluate the potential effects of various disturbances on forests and the certainty with which these effects can be predicted. This information can be used to determine which perturbations are most important to study when assessing climate change impacts to forests.

D. Research needs for forest models

Research should focus on having model input and output relevant to biological models at different scales. For example, community models require information on carbon and nitrogen distribution, leaf area, and phenology from 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 so that transfer of information can more readily occur. For example, landscape transition models can be developed at various taxonomic or functional levels, and 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 the causes and patterns of land use, forest management, and anthropogenic pollution for forest research, and 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 be manifest in the time frame or spatial resolution of typical 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 (Table VI). 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. Such a spatially explicit model 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, the new 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 forest effects from climate change are poorly linked. No integrated models yet 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 CO_2 change.

Level of organization	Spatial scale	Temporal scale	Major processes	Human activities
Biosphere	Globe	Years to millennia	Energy, carbon, water fluxes	Deforestation, fossil fuel burning
Biome	Subcontinental	Centuries 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 CO_2 and Climate Change Affect Forests', BioScience 40, 575-587.

Table II. Global-scale models

Model class	Time step	Objective	Examples*
General circulation models (GCM)	Minutes - hourly	Predictive understanding of atmospheric physical dynamics	Lacis and Hansen 1975, Wetherald 1988, Randall et al. 1989, Mitchell 1989
Biosphere-atmosphere transfer models	Hourly - daily	Provide a terrestrial biosphere submodel for GCMs	Dickinson et al. 1986, Sellers et al. 1986
Carbon balance models	Annual	Estimate the rate of atmospheric CO_2 increase	Siegenthaler 1983, Oeschger et al. 1975, Enting and Pearman 1987, Houghton et al. 1983, Esser 1991, Berner and Lasaga 1989
Global vegetation dynamics models	Annual	Assess the rate and direction of changes of the global vegetation formations or biomes	Emanuel et al. 1985, Esser 1989, Overpeck et al. 1991, Prentice et al. 1989, 1992

*Complete citations can be found in the references.

Table III. Landscape- or regional-scale models

Model class	Time step	Objective	Examples[*]
Climate change scenarios	Steady state	Static mesoscale models that translate GCM scale output to the landscape scale to provide climate input for other models and assessments	McCorcle and Heilman 1992
Mesoscale climate models	Hourly	Predict regional climate	Giorgi and Mearns 1991
Regional hydrology models	Daily	Balance the water budget	Al-Khashab 1958 Haan 1972
Regional vegetation & land use models	Yearly	Balance the carbon budget, examine effects of land use change on forests	Rotmans and Swart 1991 Kurz et al. 1992 McGuire et al. 1992 Southworth et al. 1991 Bogdonoff et al. 1985 Grainger 1990
Geographic information systems models	Steady state	Project spatial patterns of vegetation based on given climate, topography and soils	Brzeziecki et al. 1993 Neilson 1993
Landscape transition models	Variable	Estimate landscape patterns and their effects	Turner et al. 1991 Schwartz 1992 Gardner et al. 1993

[*] Complete citations can be found in the references.

Table IV. Community scale models

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

*Complete citations can be found in the references.

Table V. 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 et al. 1990 Weinstein et al. 1991 Ford and Kiester 1990 Schaefer et al. 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 VI. Forest models address specific research needs for assessing impacts of climate change

	Global		Landscape or region			Community		Tree
	Carbon-balance models	Global vegetation dynamics models	Regional vegetation and land-use models	Geographic information systems models	Landscape transition models	Community vegetation dynamics models	Forest biomass models	Tree models
Flux of greenhouse gases	X	X						
Changes in land use			X		X			
Maps of forest types	X	X	X	X	X			
Maps of species compostion 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		

Table VII. 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.

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 proportion of a newly available habitat that is successfully colonized as a function of the rate of habitat movement with climate change and the probability of dispersal, i, for communities with low probability of extinction (e=0.1) and high probability of extinction (e=0.5). When t=1, habitat movement is rapid, and when t=10, habitat movement is slow. The maximum possible colonization is 0.8.
Source: Turner, M. G., Gardner, R. H., and O'Neill, R.V.: 1991, 'Potential responses of landscape Boundaries to Global Climate Change', pp. 52-75 in M. M. Holland, P. G. Risser, and R. J. Naiman, (eds.), Ecotones: The Role of landscape Boundaries in the Management and Restoration of Changing Environments, New York: Chapman & Hall.

Fig. 3. 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.

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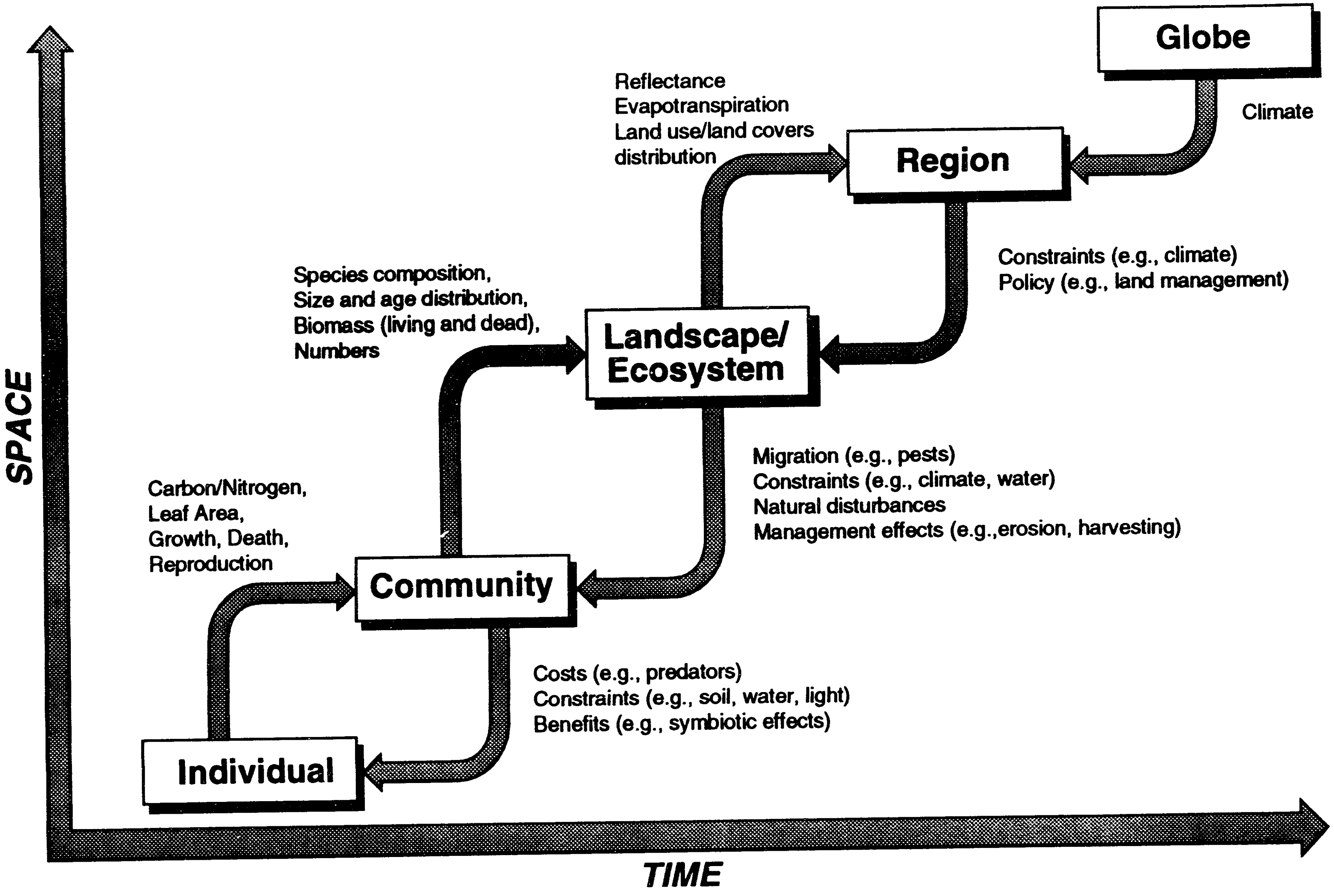

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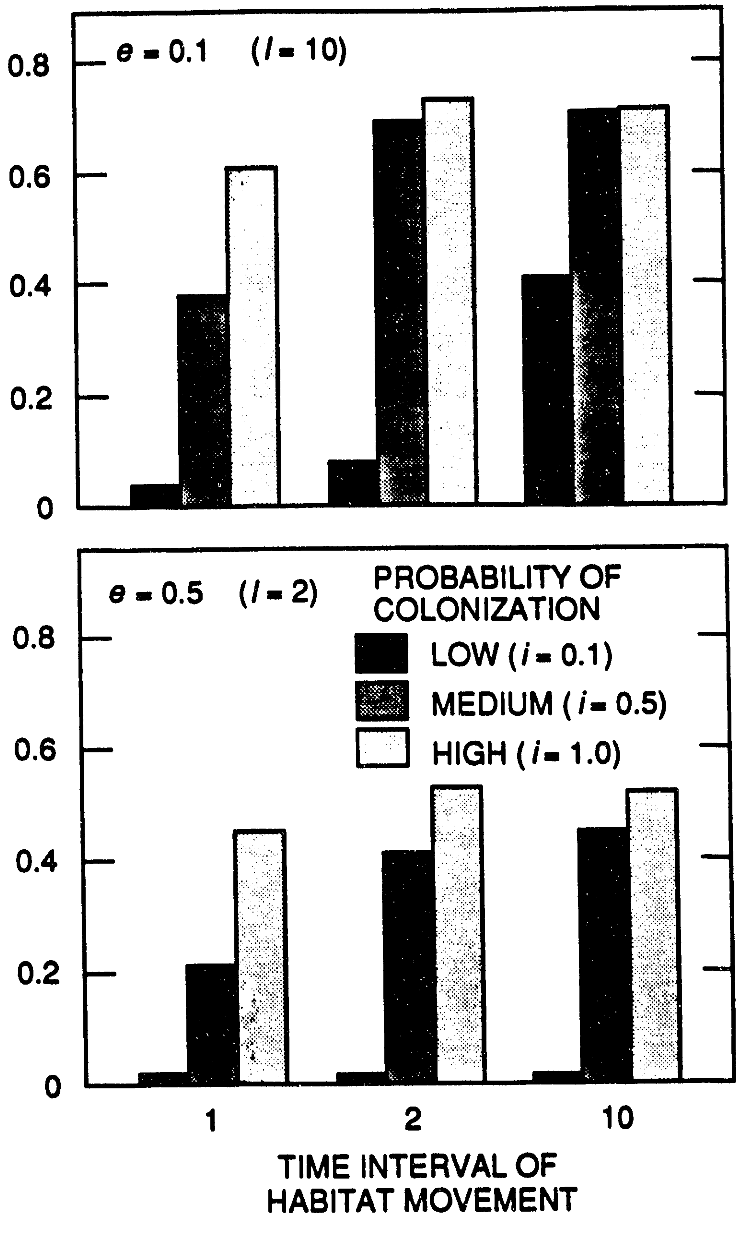
PROPORTION OF NEW HABITAT COLONIZED



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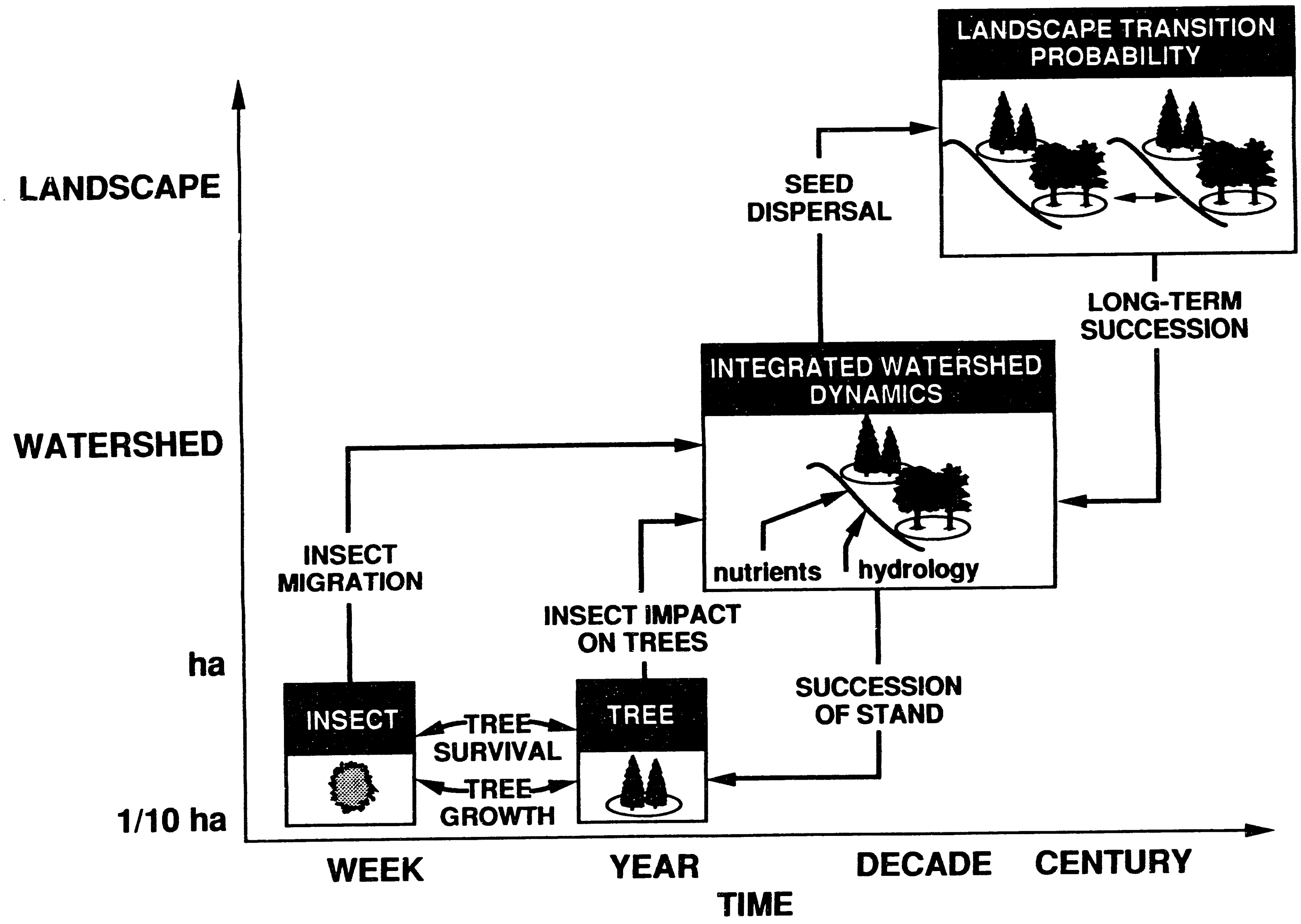

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