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Improving Environmental Simulation Models to Assess Climate Change Impacts

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ABSTRACT

Increased levels of atmospheric carbon dioxide and other by-products of human civilization are expected to disrupt the global energy budget and induce climatic change, which will alter the distribution of plant species and the composition of plant communities. In spite of the importance of these projected effects, our understanding of the processes leading to such changes needs to be strengthened. This paper addresses the need to improve models that are used to assess spatial aspects of the response of vegetation to anthropogenic climate change. Several modifications are suggested, each of which relates to changes in forest community composition that occur during periods of climate change: spatial structure is an important determinant of community composition, and therefore, forest fragmentation, and spatial dispersal functions should be explicitly modeled. Other factors to be examined are the interactions of environmental change and competition and the effect of modeling scale on results. The described methodology uses a geographic information system to link interdependent forest plots in a computer simulation model of forest dynamics. Dispersal functions of species, forest fragmentation, and rates of climate change would be varied among runs of the simulation model, and projections would be analyzed for sensitivity using detrended correspondence analysis, variance analysis, and semivariogram techniques. The combination of physically-based dynamic models in a spatially-distributed multi-cell framework requires considerably more computational power than have prior studies. Approaches to computational intensity and efficiency are discussed.
1.0. INTRODUCTION

Several research teams have concluded that during the next century, the global climate will warm approximately 3 degrees centigrade, in large part because of human activities (NRC 1983, MacCracken 1985). This anthropogenic climate change will have far reaching outcomes that we are now only beginning to understand. One particularly important impact of climate change is its effect on the distribution of plant species (Malanson ed. 1989, Peters and Lovejoy eds. 1990).

Analyses of the spatial dynamics of plant communities during periods of climate change must be conducted to improve understanding of the processes through which distributions are altered in a landscape, the effects of spatial processes on competition, and the effects on those processes of the spatial configuration of forest vegetation types. We argue that fragmentation, corridors, and barriers affect the potential distribution of forest tree species and the structure and diversity of forest vegetation because spatial structure affects the dynamic response of vegetation to exogenous forces. In addition we suggest that computer simulation models of the dynamic processes of establishment, growth, and death of forest trees, should be coupled to a geographic information system (GIS). A GIS can be used to organize the data used as input to simulation models, including accepted scenarios of global climate change, and to analyze and display the results. We also describe new ways for analyzing the results of environmental simulation models using detrended correspondence analysis and semivariograms. These methods are computationally intensive, and we discuss methods for overcoming computational intractability.

1.1. Significance

Landscape ecology is a rapidly developing research area (Turner 1989). Based on the seminal work of MacArthur and Wilson (1967), researchers are now cognizant of the theoretical importance of the spatial configuration of landscape elements on ecological
processes (cf. Forman & Godron 1986). Yet, a substantial gap remains in knowledge about how the spatial configuration of landscapes controls their reproduction and interactions among species competing for space. Spatial details have been considered in models only recently (e.g. Sebens 1987, Nagylaki 1988), and few studies of vegetation have dealt directly with the effects of configuration (e.g. Forman 1983). While various paradigms in ecology (e.g. inertia and resilience, species strategies, the continuum concept) provide insights into relevant vegetation processes, they do not fully incorporate the relative locations or spatial processes of populations or individuals. Our primary theoretical concern is to investigate the role of these factors in forests. A specific objective of this paper is to demonstrate the need to consider the effects of:

- fragmentation,
- barriers, and
- corridors

on the distribution of forest tree species, forest community structure, and forest diversity.

A secondary theoretical concern that must be examined is the role of competition in structuring communities. Two specific aspects of competition are important:

1) The difference in the importance of scramble and interference competition under conditions of varying fragmentation and spatial pattern on a landscape.

2) The response of community structure to environmental changes when old competitors disappear and new ones arrive.

Although these two foci do not address all aspects of competition, they are likely to be important at regional and continental scales of study. We recognize that computer simulation modeling does not account for every aspect of forest dynamics, nor provide a guide to process and pattern at specific individual sites. This approach has proven
successful, however, in studies of many forest types and elucidates generally important processes, and thus can indicate possible futures in a generalized or hypothetical environment (cf. Shugart 1984).

1.2. Biodiversity

The problem of biological impoverishment also is being addressed by many researchers. In 1988 the World Wildlife Fund, in cooperation with several federal agencies, sponsored a conference on "Consequences of the Greenhouse Effect for Biological Diversity", and co-PI Malanson organized a smaller symposium on "Natural Areas Facing Climate Change." Several papers presented at these conferences highlight the need for the research proposed here. Several authors, most notably Harris (1990), cited the importance of spatial configuration to the creation and maintenance of biological diversity. Woodward (1990) and Davis (1990) raised questions about competition and dispersal that need to be addressed in the context of climate change. Graumlich (1989), Shugart (1990) and Botkin and Nisbet (1990) found modeling efforts and projections of biological diversity to be a promising approach to this problem. Although Hanson et al. (1990) demonstrated a methodological and conceptual basis for revising environmental simulation models, a more thorough geographical perspective on this problem is needed.

Peters and Darling (1985) and Hanson et al. (1989) illustrated that organisms living in isolated habitats could face local extinction as climate changes. For example, species living on mountain-tops could be squeezed out of existence by an advance of organisms from lower elevations. Hanson et al. (1989) noted for tundra, higher elevations in the mountains and higher latitudes in the arctic than now occupied do not have the soil to support plant growth, and a forest advance may be more rapid than the potential development and colonization of new areas. Thus, for a species with a defined climatic range, the problem can be defined by comparing the rate of climate change across the
landscape with the rate species can move across the landscape in the same direction. Although the most likely direction now is northward, as it was at the end of the Pleistocene, migration may be redirected by topography or where moisture is more important than temperature. This problem may be increased where the direct effects of climate change are compounded by indirect effects, such as altered fire regimes (Clark 1988, Harte and Torn 1989, Westman and Malanson 1990). Interaction with other species will also be affected: species may depend on the concurrent migration of symbionts or may face new pests, predators, or competitors. As is the case for naturally occurring isolates such as mountain-tops and islands, the rate at which species can migrate will be slowed where the landscape is fragmented by human occupation.

If we are to understand the potential effects of future global climate change on vegetation fragmented by human activities, we need to incorporate, in models and theory, lessons learned about the Holocene dynamics of naturally fragmented communities. Two questions arise. First, will inertia play a role in determining the ecological response of vegetation in the current environment or will species adjust their ranges quickly and so maintain a degree of equilibrium with the climate? At past rates of change species seemed to maintain equilibrium (Webb 1986, 1990), but the degree of stability depends on the scale of analysis (Prentice 1986). In particular, where the landscape was fragmented nonequilibrium conditions may have existed. Davis et al. (1986) documented the probable effect of Lake Michigan as a barrier to the migration of beech (Fagus) for 1000 yr. Cole (1985) reported a nonequilibrium response for the vegetation of topographic benches in the Grand Canyon. Because these sites are isolated, when climate changed, and some species became locally extinct, those species that remained were not immediately faced with new competitors from the south because the sites were not spatially contiguous with southerly vegetation and thus were less accessible. These remaining species continued to live in climate conditions outside their current range. Cole (1985) referred to this phenomenon as inertia. The second relevant question is the nature of the response of
plant communities to climate change: do species migrate across continents as an ensemble, or do species respond individualistically so that communities keep changing? Evidence suggests that the latter is true (Wright 1984). During the Quaternary, species lived in a variety of assemblages no longer extant, although the component species exist. The extent to which these questions can be addressed in regard to future climate change depends on the structure of relevant computer simulation models of vegetation dynamics.

2.0. EXISTING MODELS

Two models have been widely used to examine the dynamic processes which affect the composition of forest stands. They are the JABOWA simulation developed for the Hubbard Brook, NH experimental watershed (Botkin et al. 1972a,b), and its modification for southeastern forests, FORET (Shugart & West 1977). Although the models have been extensively examined and tested, and are based on a functional relationship between tree growth and climate, seedlings are established in the models using a random generator, and rates of establishment are modified only by site conditions. In spite of this limitation, workers have adapted the JABOWA and FORET models for other forests. All modifications concern species response to environmental stress. Growth, based on growing-degree-days, is now modified by shading in all versions, and by drought, fire, moisture, or temperature in some. In all of these models specific spatial effects are averaged for stands, however, and do not approach the tree-by-tree detail of some models (e.g. Ek & Monserud 1974). Green (1989) modeled spatial dynamics explicitly, but, instead of growth parameters, used species life history characteristics, which do not allow the calculation of the relative abundance of species within cells.

Both FORET and JABOWA have been used to examine forest response to past (Solomon et al. 1981, Davis & Botkin 1985, Solomon & Webb 1985) and future climate change. Solomon (1986) adapted FORET to project vegetation changes given CO2-induced climatic change in eastern North America, but he did not consider any spatial problems,
such as barriers, for species migrations nor effects of recurrent disturbances. Pastor and Post (1988) adapted FORET to include the effects that climate change might have on soil water and nitrogen availability. These uses of simulation models have been favorably reviewed (Shugart et al. 1986, Solomon & West 1987), and several other authors have applied models to similar questions (Dexter et al. 1987, Malanson & Westman 1989, Michaels & Hayden 1987).

The major shortcoming of the JABOWA and FORET models is that they have oversimplified two key points that did not affect their original intended use, but which do affect their use for modeling other aspects of climate change: dispersal abilities and growth-climate relationships. First, each model incorporates an assumption of ubiquitous dispersal: the seedling of any species in the array of species modeled can arrive on any site at any time, and can establish as a seedling if other environmental conditions are met. To state an extreme case, if the climate of northern Canada warms drastically, tupelo can establish there immediately. This aspect of these models is clearly untenable because dispersal ability has been shown to affect the presence of species (e.g. Malanson & Kay 1980) and their response to climate change (Davis et al. 1986).

![Growing Degree Days](image)

**Figure 1.** Parabolic functions of growth in terms of growing degree days are used in FORET; also shown is the proposed Gaussian modification giving an asymmetrical hybrid function.
Second, the growth - climate relationships of the species are defined as parabolas with their end points at the present-day limits of the species in growing-degree-days (e.g. species C in Fig. 1). Davis and Botkin (1985) noted that fundamental assumptions underlying the use of this parabolic function are that the current vegetation is in a steady state with the climatic average, that the climate is optimal at the midpoint and least favorable at the extremes, and that the relationship does not change through time. In addition, this relationship embodies the realized niche of each species in the presence of all other species. It does not consider, however, that the ranges of species might be limited by competition with others, or that species might be able to expand their range in the absence of other species. With this assumption the model has not been appropriate for testing ideas about competition or the community vs. individualistic response of vegetation during periods of change. Although, some might argue that species will always be faced with competitors and so the use of the realized niche in a model is sufficient, observations of species presence and absence during the early Holocene indicate that individualistic changes in range may leave species without major competitors, especially in isolated sites (cf. Cole 1985, Davis et al. 1986).

3.0. NEW METHODS AND PROCEDURES FOR ENVIRONMENTAL SIMULATION MODELING

Environmental simulation models can be used to elucidate differences in community responses to assumptions about species adaptations and environmental changes. Several factors affect forest dynamics and structure. Among the most important are: species adaptations, climate change, and spatial structure (Table 1). The sensitivity of the model to changes in each factor can be examined separately using statistical techniques and the display capabilities of a GIS, and ranges of the factors then can be chosen for the simulation of interactions.
Table 1: Adaptations and environmental changes to be modeled

Adaptations:  
- Dispersal functions  
- Changes in the climatic range

Climate change:  
- GISS transient modeling predictions

Spatial structure:  
- Fragmentation in varying degrees  
- Corridors and barriers of varying width  
- Different overall grid size and scale

3.1. Enhancements to Existing Models

Modifications of the JABOWA-FORET simulation model are suitable as the principle vehicles for conducting new simulation runs. The model has been well studied in a variety of relevant situations. The standard inputs for tree species adaptations can continue to be used. The length of time for which each simulation is run is 1000 yr. This time is sufficient for the detection of changes of the type we are interested in examining.

3.1.1. Adaptations, dispersal functions

In a spatial model, dispersal can be treated as absent, unlimited, or with spatially varying function values. Perhaps because plant dispersal ability is difficult to document (van der Pijl 1972), in many past models it has either been assumed to be unlimited (e.g. Solomon 1986) or has been ignored. In spite of the difficulty involved, however, dispersal can be modeled in a general way. Johnson et al. (1981) provided a useful formalization of this process and we have modified FORET to account for dispersal (Hanson et al. 1989, 1990). This modification gives a spatial character to the model and differences between diversity and composition were found for different assumptions about dispersal in limited simulation trials. Because of uncertainty about actual dispersal abilities over many years for most tree species, it will be necessary to examine a range of possible dispersal abilities.
that can be reasonably proposed. The simulation of changing forest composition over a plane with variable pathways of dispersal can test whether spatial configuration plays a major role in forest dynamics.

At each annual iteration of the model each stand references surrounding stands for information on the availability and probability of propagules arriving onto the stand. We suggest that sixty-eight of the dominant tree species of eastern North America be included in each simulation. Dispersal functions for 15 common tree species of eastern North America have already been identified (Hanson et al. 1989, 1990), and functions for other species can be derived from the literature. These functions are not exact, because research on the actual dispersal of seeds is accurate for only a few species. General characteristics of propagule morphology, however, allow a useful classification of dispersability to be developed. In contrast, Green (1989) used a single inverse square function to represent unidentified species or vegetation types. Our model will then determine the seed rain based on the presence, distance to, and dispersability of trees on surrounding plots.

3.1.2. Adaptations, climatic range

In existing models the growth - climate relationships of the species are defined as parabolas with their end points at the present-day limits of the species in growing-degree-days (e.g. species C in Fig. 1). The present definition of climatic range in the model represents the realized niche of each tree species as a parabolic graph of relative growth over growing-degree-days.

The basic growth equation:

\[
\frac{dD}{dt} = \frac{GD(1-(DH)/(D_{max}+H_{max}))}{274+3b_2D-4b_3D^2}
\]

becomes:

\[
\frac{dD_3}{dc} = \frac{dD_\alpha}{dc} \cdot \frac{4(DEGD-DEGDmin)+(DEGD_{max}-DEGD)}{(DEGD_{max}-DEGDmin)^2}
\]
where DEGD is the number of growing-degree-days (cf. Botkin et al. 1972a). Allen Solomon (see Solomon 1986) has provided data on the range of growing degree days and other parameters for sixty eight dominant species of eastern North American forests. These species range from *Picea rubens* (minimum 600, maximum 3700) to *Diospyros virginiana* (minimum 5526, maximum 13395).

Forest tree species clearly are observed outside of their natural range when competition is reduced. But because of the synergistic effects of pests and disease, it is likely that climate will have a greater effect on forest trees than would be indicated by these conspecifics in protected locations (cf. Allison et al. 1986). Nevertheless, the parabolic shape should be modified and expanded. Because the model successfully reproduces the present distribution of species, much of each growth curve parabola is acceptable. The midpoint in growing-degree-days should be kept as the optimum growth point, assuming that optimum growth conditions are at the center of the present range; the points where the parabola for a species intersects with others also should be kept as points indicating competitive relationships. The midpoint and the points of intersection are fit with a Gaussian curve using an algorithm that defines the parameters of the Gaussian function and provides statistical information on its goodness-of-fit (Gauch et al. 1974). For a set of data points \((x,y)\) this method uses a least squares procedure to find the three parameters \(Y_0\) (maximum), \(\mu\) (mean), and \(\sigma\) (standard deviation) of the Gaussian equation:

\[
y = Y_0 e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

Thus, the parabolic shape is retained on the colder (fewer growing-degree-days) side of the midpoint, while the Gaussian curve will be applied on the warmer side (e.g. species B in Fig. 1). We consider this asymmetrical function to be more realistic. We have derived this function for the sixty-eight dominant species.

The advantage of using the Gaussian function is that the tails are extended into climatic realms beyond their present limits of existence and potential growth in present
versions of the model. With all species present, competitive effects reduce the influence of these tails substantially, but when species are without competition the tails on the modified functions allow continued existence in climatic conditions not now experienced. Thus, species are excluded from some climatic realms when competitors are present, but, without competitors, a small chance of growth and survival exists. This format expands the model from the limits of representing the realized niche in the presence of other species, but, without years of experimental work, it can only be said to move in the direction of the fundamental niche.

3.1.3. Incorporating climate change

Current predictions from a general circulation model (GCM) about the effects of increased radiative trace gases can be used as the basis for changing climate in environmental simulation models (e.g., Botkin and Nisbet 1990). Cess and Potter (1988) noted that the GISS GCM (Hansen et al. 1988) retained its relatively cool \(1 \times \text{CO}_2\) condition while incorporating horizontal ocean transport of heat, and they recommended that the GISS procedure for controlling sea surface temperatures be generally utilized. Current predictions for eastern North America from the GISS GCM can be used as the basis for altering climate in the environmental simulation model. The GISS model, like the NCAR and GFDL models, projects a climate change midway between the extreme projections of the UKMO and OSU models (Cess and Potter 1988) of CO\(_2\)-induced climate change.

Indirect effects and feedbacks may also be considered. Although Strain (1990) summarized information on the direct effects of CO\(_2\) enrichment on vegetation responses, Botkin and Nisbet (1990) stated that not enough information is known about this process to incorporate it into a stand model; Sedjo and Solomon (1989) also concluded that the long term effects of CO\(_2\) fertilization were likely to be minor, rejecting an earlier assumption used in simulations by Solomon and West (1986). Also, it is neither possible,
or desirable, to include the feedbacks of vegetation change in the projections of climate change. First, we are examining forest dynamics in eastern North America, and the changes in these forests are not likely to have a major impact on global climate: we expect changes in species composition, for which climate feedbacks are unknown but are likely to be small, rather than large changes in biomass. Sedjo and Solomon (1989) calculated that temperate and boreal forests worldwide would release 63 Gt (billion metric tons) of carbon to the atmosphere (present stock of 720 x 10^{15} Gt; annual anthropogenic input 5.3 Gt yr^{-1}) under a 2 x CO\textsubscript{2} climate. Most of this miniscule release is attributable to Asian boreal forests, and much would be balanced by sinks in other vegetation types. Therefore, we conclude that global changes in CO\textsubscript{2} due to regional shifts in forest types in eastern North America will be minor. Second, understanding the nature of changes in the energy and water budgets of these forests that might occur as climate and species change would require a major research undertaking in itself. Furthermore, because we are not interested in calculating feedbacks from vegetation change into a climate model, the numerical problem of interfacing processes at different time scales does not arise.

Although these climate and biological feedbacks need not be incorporated, climate type and rate of change must be varied over the landscape to introduce a higher degree of accuracy into the environmental simulation models. We can simply use projected changes in annual climate as input into the annual calculations of growth and reproduction in the simulation of forest dynamics. The effects of climate warming on forest composition and dynamics should be tested using transient conditions. The GISS model is advanced in its projection of transient climate change into the near future, and these transient projections can be used to simulate initial climate changes. Schneider (1989) emphasized the importance and realism of studying transient conditions as opposed to the equilibrium climate response (stepped) to a doubling of CO\textsubscript{2}. Because the transient projections do not go far into the future, a hypothetical approach to the current equilibrium projections of the GISS model may be appropriate for our use. We suggest that gradual approaches to
these equilibrium values over the next one-hundred years be used to test both linear and logistic transient climatic change (Fig. 2), and that the initial changes be modified using the transient projections of the GISS model for the next 20 years (the GISS model is the only one for which such transient results have yet been published, to the best of our knowledge). Beginning with present distributions of species representing present conditions in eastern North America, the models should be run with the new conditions of growing degree days and moisture defined by these projections.

![Figure 2: Transient climate change: linear and logistic approaches to the 2 x CO₂ equilibrium projection.](image)

3.1.4. Geographic Information Systems

The JABOWA and FORET models simplify the nature of forest dynamics in relation to the environment. Slope, aspect, and microtopography, for example, do not vary in the models. Pearlstine et al. (1985) and Pastor and Post (1988) have included differences in soil type among cells, but in a static manner. Studies in forest dynamics, however, have found these models to be accurate, useful, and enlightening. A GIS can be used to organize the spatial data needed in models with varying spatial configurations.

In the models discussed, GISs have been used to manage and display data in a few instances (e.g., Pearlstine et al. 1985, Pastor and Post 1988). The GISs were not, however,
used to manage spatial processes distributed among cells. Casey and Jameson (1988), for example, discuss the use of a GIS, but they apparently confused a GIS with a matrix of cellular observations. This pattern is common in the application of GIS: they typically are not used in a dynamic interaction with temporal simulation models. This pattern need not be the case, as has been demonstrated, at least in concept, for the interaction of vegetation and fire (Kessell 1979). Many current studies of GIS and environmental questions focus on software development or on demonstration projects (Iverson & Risser 1987, Johnson et al. 1988, Mead et al. 1988, Shaw 1988). The potential exists to link dynamic simulations and geographic information systems in an interactive model (cf. Pastor et al. 1988). One area of deficiency in GIS development is the assessment and treatment of change in spatial data. Armstrong (1988) and Langran (1989) have outlined the concepts and directions needed to progress in this field.

A GIS is an ideal tool to apply to environmental simulation models because GIS software is often made to handle grid cell databases, and such data drives most spatial environmental simulation models. Thus, the GIS can be used to organize data in proper formats, to store results, to generate graphical map displays of projected results so as to facilitate detection and analysis of change, and to prepare data for statistical analyses. This approach allows a variety of spatially referenced factors to be easily defined and manipulated. Therefore, a GIS can be used to evaluate the range of changes that will occur in computer simulations.

An especially important aspect of current GIS capabilities to our work is the integration of spatial modeling capabilities with display technology. The fusion of these components allows us to explore various aspects of spatial problems by enabling us to evaluate visually the results of modeling efforts and to then revise the model to incorporate information gained in previous iterations. This type of problem solving involves the use of heuristic information and, with geostatistics, forms the basis for a
rapidly growing branch of GIS research involving the design of decision support systems (Armstrong et al. 1986, Armstrong and Densham 1990).

3.2. Application of enhanced models

3.2.1. Spatial structure, forest fragmentation

The importance of space can be assessed by incorporating configuration information in the spatial referencing framework of a GIS. Normally, a square grid is used. The basic configuration has all cells available for forest, and from this basis conditions of progressive forest fragmentation are simulated. The degree of fragmentation can be increased in a series of uniform steps by increasing the number of randomly selected grid cells defined as non-forested. The rate of increase can be approximated using data on forests from eastern North America (e.g. Curtis 1956). At each step, the configuration, as well as the total number of forested cells, can be varied. First, the sample size (n of plots) and their spacing is specified, then random spatial configurations are generated and evaluated with respect to their fragmentation by the use of an index of spatial autocorrelation:

\[ I = \sum_{i<j} w_{ij} z_i z_j / 2A \sum z_i^2 \] (Cliff & Ord 1981)

This index approaches -1 when complete fragmentation is encountered, and approaches +1 when complete clustering occurs (Griffith 1987), and it can be used to systematically increment the amount of fragmentation in the model environments. For example, a step size of 0.1 would be appropriate in the range of -1.0 to +1.0. The possible effects of spatial autocorrelation on the community structure of vegetation has been discussed by Malanson (1986), and simulations would address some of the issues raised. An alternative approach would be to simulate changing shapes with altered interior-to-edge ratios, presence of holes within patches, and fractal-based shape indices (cf. Rex and Malanson 1990).
3.2. Spatial structure, corridors and barriers

A second approach focuses on the effects of corridors, where strings of grid cells, running north-south, remain forested while surrounding cells of the matrix become non-forested. Next, barriers can be introduced in which strings of grid cells, running east-west, are defined as non-forested. These corridors and barriers can be used to approximate known features such as the Appalachian Mountains, the Mississippi River valley, the Great Lakes, and other conditions at random locations. Various sizes and shapes of barriers should be modeled, and systematically increased to determine thresholds of impenetrable barriers.

3.2.3. Spatial structure, scale

The importance of scale in environmental simulation modeling also should be investigated. First, the effects of changing the size of individual grid cells while holding the overall grid size constant, and thus changing the distance from cell to cell and averaging conditions over increasingly wider areas, should be considered (Figure 3a). This test emphasizes the problems of aggregating spatial data. Second, the sizes of the cells and the distances between their centers can be changed together (Figure 3b). This range of distances between stands will test the effect of changing definitions of species dispersal functions and will enable the examination of differences in spatial data handling that arise between large and small scale studies. Because of the computational requirements when the total number of trees is increased, it may be preferable to retain the small stand size, and to separate them spatially while assuming that they represent larger areas.
Figure 3. Schematic representation of the configurations that will be used to assess the effects of spatial scale.

The original models represent a single stand of trees of c. 1/12 ha. This size limit, however, is only a technical constraint, and we can use the 1/12 ha stands as representative of a surrounding area of forest. For this research 250,000 stands can be defined in a 500 x 500 grid. The grid would represent an area 5000 x 5000 km. Over this surface we would begin with an initial north-south gradient of growing degree days and an east-west gradient of moisture.

3.2.4. Interaction

While it is possible to run all possible combinations of the above factors, this effort would waste computer and human resources. Instead, indicator functions of dispersal and species' climatic ranges can be chosen from runs in which single factors are varied. Then interaction among factors of climate change and spatial configuration could be examined by running the model in several combinations of these factors. If the total range of change modeled for each factor is divided into fourths so that five points covering this range are used in simulations, then there are 25 runs for any combination of two factors.
This approach would enable a set of economically viable projections to evolve systematically as information on species responses and interactions accumulates through additional simulation runs and field studies.

3.3. Analysis of projections

In order to test the effects of adaptations and spatial configuration on forest response to climate change the sensitivity of a quantitative indicator of forest community composition to the variations in input described above can be analyzed. The forest dynamics model projects several measures of abundance for the tree species. Calculated output for each species includes absolute and relative density, basal areas, and frequency, and a composite importance value, all of which can be subdivided among classes of basal diameter. While these measures allow one to examine how species are changing and draw conclusions relating forest dynamics and the traits of the species, they do not provide a single measure representing the stand that allows comparison with other stands. In addition, current evaluation methods fail to examine explicitly the spatial characteristics of simulation results.

3.3.1. Detrended Correspondence Analysis

In order to analyze the differences among projections of the model, statistical methods of vegetation science can be applied. The first step would be to ordinate the communities projected by the simulations. Ordinations allow a useful visualization of the similarity of stands as they change through time, and they produce a few dimensions that represent the vegetation of each stand at a point in time. Ordination uses the information in a stand-by-species matrix to create a stand space, defined by axes for each stand and the abundance score (importance value) of each species on those axes, and a species space, defined by axes for each species and the score of each stand on those axes. This information is reduced to a few axes using one of a variety of methods. The most
commonly used method, Detrended Correspondence Analysis (DCA; Hill & Gauch 1980) uses reciprocal averaging (Benzecri 1973) of the species and stand spaces to produce four dimensions (each dimension is represented by an axis produced by an eigenvector). Often, much of the interpretable information is on the first and second axes, and the score of each stand on these axes can be used to represent it relative to other stands. For visual analysis of a landscape consisting of such stands, we think that a two dimensional color scale (e.g., as in a two-variable choropleth map) could be proportional to the first two axes. The landscape is mapped by these color variations for each year, and changes projected over time are represented by change in the color of the landscape. Such analyses are well supported by existing GIS technology.

Gauch (1982) noted that because the relationships summarized by an ordination of real sample data result from the interaction of many nonlinear variables, statistical techniques such as analysis of variance and regression do not always prove useful (i.e., nonlinear, interacting independent variables produce multicollinearity and skewed distributions which are not easy to interpret and which violate assumptions underlying the use of such models). Most community ecologists and biogeographers feel that ordinations of extensive field data sets can only be used to generate hypotheses, and not to test them, and that the application of ANOVA to ordination scores is to be eschewed (regression analyses are considered acceptable as exploratory ventures). We contend, however, that ordination scores for data from direct experimental manipulation of vegetation or of computer simulation experiments, where the processes differentiating the control and treatment cases are clearly identified, may be used in tests of hypotheses. In these cases the causal processes leading to the ordination scores are limited in number and in variation, and interactions are known. For example, Malanson & Trabaud (1987) applied ANOVA to measures made on the plane of the first two axes of DCA applied to data recorded in an experiment. A single hillside was divided into plots which were then burned at different seasons and intervals. Significant differences were found for the
trajectories of the plots on the ordination plane among treatments. A study in which many random plots in an area subject to different fire regimes were sampled would not be appropriate for ANOVA in a parallel fashion. A study in which the species-by-stand matrix was produced by a computer simulation model of the response of vegetation to fire regime would, however, be appropriate for ANOVA because the variation in the environment can be controlled in the same way that burning small plots on a hillside controls the variation. We are not aware of any studies in which ordination has been applied to the projections of a computer simulation model, nor are we aware of the application of ANOVA or a similar test to the scores.

If the total basal areas for each species is used as a surrogate for abundance in the ordination, then these basal values can be made proportional to the highest total abundance of all species on any stand at any time. These measures of abundance can be recorded, for example, at 50 yr intervals over the 1000 yr of the simulation. Each stand at each point in time must be considered as a separate site for entry into the ordination. The ordination gives scores for each species and each site on four orthogonal axes and reports eigenvalues for each axis. Usually the first two are sufficient to elucidate ecological relationships, and the location of the sites on the plane defined by the two axes can be graphed.

The trajectory of each stand across this plane through the years of the simulation also can be plotted, and several measures can be taken from this plot:

1) location of the stand in ordination space at any time;
2) direct distance from origin to endpoint in the temporal trajectory;
3) actual distance traveled in ordination space; and
4) the ratio of direct to actual distance.

Differences in these measures can be analyzed among different forest stands within the same simulation run and among various simulation runs for the same stand. Differences in any of these measures among various stands within the same simulation, provide
information on separation within the statistical (DCA) space. The ecological or floristic
differentiation, is displayed in reference to fragmentation, corridors, barriers, edges, and
the starting conditions. The actual location of a stand (in grid units) on the model plane
can also be analyzed because climate changes differentially across the plane. The GIS
provides the capability to visualize changes in the magnitude and distribution of these
measures.

The difference in any of the measures of individual species or of community
structure among projections of various simulations of the same stand provides information
on the differentiation of forest communities in respect to different conditions of climate
change and different spatial configurations. The values for the same stand among
simulations of different conditions will be used as a variable in hypothesis tests using
ANOVA and Tukey's studentized range test; stands within the same simulation will not be
compared in this way because they are not independent. These analyses provide an
interpretable measure of the significance of changes in forest communities through time
and at given points in time, and, for comparisons of individual species, test the effects of
spatial structure on the relative importance of scramble and interference competition.
These analyses of variance are, in effect, tests of the significance of the sensitivity of the
simulation to the variations in input of species dispersal abilities, climate change, and
spatial structure of the landscape.

3.3.2. Semivariogram Analyses

In addition to variance analysis tests we intend to explore the application of
semivariogram analyses (Burgess & Webster 1980, Burrough 1986) to elucidate spatial
structural processes operating in the simulation runs. Semivariogram analysis is based on
the measurement of spatial variance of observations as distances among them increase.
This method has been developed and widely tested in soil science and geological
applications (Burgess and Webster 1980, Burrough 1986). Given a plot of variance
estimates among observations against distance, a function is fit to the observations, and this function can be evaluated to determine the scale at which significant interactions take place. When the interaction effects reach zero, or when they reach a threshold that is theoretically justifiable, the range of the semivariogram is established. A nugget effect is also frequently observed. This nugget represents a non-zero intercept -- there is a variance at distance = 0.0 -- and is normally considered to be the result of measurement error, or to have arisen from exogenous causation. To our knowledge, no spatial analyses of the landscape pattern of vegetation, as represented by the ordination scores, has ever been done. Turner et al. (1989) reviewed a variety of methods used to analyze spatial simulations. Their analysis, however, only addressed discrete distributions on the plane, such as classes of land use or habitat, and are not equally applicable to the analysis of continuous data, such as species importance values or ordination scores.

Individual species values, ordination scores, and diversity will be subjected to semivariogram analysis. The analyses of the semivariograms should prove useful in several respects. First, semivariogram analysis of a landscape of ordination scores will be new in vegetation science and the possibility of elucidating scales of pattern among vegetation types should be of interest. Second, semivariogram analysis can consider directional variation, and the combined effects of east-west moisture gradients and north-south temperature gradients may be of interest. Third, the effects of barriers or corridors on spatial pattern and its direction may be revealed by this analysis. We expect that as fragmentation increases, the range of the semivariogram will decrease because autocorrelation will decline as patches become increasingly isolated (cf. Malanson 1986).

Another method which may prove useful in this regard is multiscale ordination (Ver Hoef and Glenn-Lewin 1989). This method is uses two-term local covariance to derive eigenvectors and eigenvalues for increasing block sizes in vegetation. The interpretation of eigenvectors is similar to other ordination methods. Species loading, and the loading of block sizes, on the eigenvectors indicate important scales of pattern, and
the loading for individual species may also be interpreted as spatial pattern. This method, however, does not apply to the problem of temporal trends in a multi-cell landscape that we have described.

3.4. Computations

Environmental simulation models often require substantial amounts of computing time for each run. This computational intensity occurs because the models are iterative, operate over long time horizons, and require many numerical computations at each iteration. For these reasons, supercomputers should be applied to ecological simulation modeling.

Because of the great expense of model development in supercomputing environments, however, a layered approach can be adopted in which initial tests of models are conducted on a microcomputer-based workstation. Many workstations use an operating environment (Unix) and programming languages that facilitate interchange of data and programs to the supercomputing environment. In addition to their compatibility with supercomputers, workstations are well adapted to GIS software use and development because their performance and high resolution displays are ideally suited for generating cartographic output.

3.4.1. Parallel Processing in Environmental Simulation Modeling

Traditional approaches to environmental simulation modeling have used a linear, sequential model of processing. In fact some supercomputers operate by speeding up what is mostly a sequential process (e.g. through pipelining). While such a computational approach is defensible, it sometimes carries a substantial performance penalty. Existing models can be adapted to parallel computing environments which will greatly improve the speed at which large scale spatial simulation can be performed because several model
elements can be processed concurrently. Thus, with concurrency, improvements in performance can be made at any given level of processing technology and speed.

Casey & Jameson (1988) have described the application of parallel processing to environmental simulation modeling applications. In most applications of environmental simulation models each element or cell in the model is evaluated sequentially. These models are implemented on computer systems that have a single data stream that is operated on by a processor that operates by executing a single instruction (SISD). This traditional architecture is inefficient for processing large spatial problems because of its aspatial restrictiveness. When each cell is evaluated using a SISD approach, it is treated as an isolated problem to be solved.

Large spatial problems can be decomposed into many sub-problems, and therefore, they can be processed concurrently. Two main tasks must be accomplished before concurrent processing can take place: domain partitioning and update ordering. In most instances, the first task determines the way in which the second is performed. Domain decomposition proceeds by evaluating whether the problem is homogeneous, wherein each member of the domain requires identical amounts of computation, or inhomogeneous. Inhomogeneous problems require additional work to achieve balance among processor workloads. Domains also can be classified as regular if the geometry of the problem is simple (e.g. a rectangular mesh). Note, however, that problems are rarely found which satisfy each dichotomy exactly; most exist along a continuum of homogeneity and regularity. Simple rectangular domains, which are largely homogeneous however, are typical for spatial environmental simulations models. Finally, domains may have atomistic elements beyond which further decomposition cannot take place.

Fox et al. (1988) describe an additional principle of domain decomposition. They coin the term "loosely synchronous" to describe those problems that contain a parameter which can be used to synchronize the different grains of the decomposed computation. Synchronization, therefore, refers to a property of the problem or the algorithm rather
than the characteristic of the computer environment. A simple example is the series of
time steps that occur in environmental simulations models. Time steps enable the problem
to be divided into cycles and different compute nodes can be synchronized at the end of
each cycle (update).

When specifying a domain decomposition, there are two objectives that should be
accomplished. The first is to balance the workload among processors in so much as it is
possible, and the second is to minimize communication overhead. Communication must
occur along interprocessor boundaries when the domain is broken into discrete grains for
processing, and thus the subgoal is to minimize the perimeters of the subdomain
boundaries. For a grid, therefore, it is best to take the rectangular domain and to break
it into congruent square or rectangular subdomains (Fox et al. 1988). In Figure 4 a series
of grid cells is divided into a set of subdomains in which there is local data access for
each element in the interior of each subdomain. In the shaded regions along the
subdomain boundaries, interprocessor communication must take place. For simple edges,
communication with one other processor must take place, but for corner elements, two
processors must be addressed.

Figure 4. Illustration of interprocessor communication in a rectangular domain.
Given this domain partitioning, an update scheme that works well is a checkerboard ordering in which each subregion is subdivided further into four regions of two kinds: red and black (Fox et al. 1988). In such a configuration, for a rooks move topology (4-connected), no tile is adjacent to a block of the same color, and thus updating can take place first for one color, and then the next. The color cycle is repeated as often as updating is required by the algorithm being executed.

The major restriction to a concurrent approach to processing environmental simulation models is data dependency which occurs if the calculation of a value for a cell is dependent upon the results of calculations from another cell. Cell-based simulation models, however, can be constructed to eliminate such dependencies by using temporary blocks of storage for surrounding cells, and writing the results to a separate matrix for each iteration of the model.

Although parallel computing can be performed in several modes, the most common are single instruction - multiple data (SIMD) and multiple instruction - multiple data (MIMD). In SIMD approaches a single instruction (e.g. a right shift) is executed concurrently on each processor, but each processor operates on a separate data element. In a MIMD architecture, the set of instructions is normally greater than one; the size of the set of instructions is known as the granularity of parallelism. Once the problem is decomposed to a level of granularity appropriate for the architecture of the machine on which the processing will take place, an adaptation of a sequential algorithm can be applied to the problem. On a MIMD computer the program, therefore, can be broken into numerous discrete "chunks" which in this case can correspond to the set of processes operating on each cell. Thus, in theory, each cell could be allocated to a separate processor, and speed-ups would be large. In practice, however, a separate machine may not be available for each cell, and communication, and other forms of overhead will ultimately reduce efficiency.
4.0. CONCLUSION

This paper describes a series of improvements to existing environmental simulation modeling practices that would enable an evaluation of the importance of spatial structure and processes in determining the dynamics of forest community ecology. In our models projections of anthropogenic climate change are used as the driving force chosen to create dynamic alterations to environmental conditions. The key responses of forest ecology to such shifts are competitive interactions for resources. Such interactions are mediated spatially. We consider the effects of spatial structure in the models by fragmenting a continuous plane of forest into islands, barriers, and corridors. We examine the effects of spatial process by including dispersal in the models. The simulation models produce projections of species abundance values at chosen time steps for each stand or cell. In order to evaluate this information we argue that ordination scores for each stand on the plane can be analyzed for differences among simulation runs using ANOVA and semivariograms in addition to visual interpretation of GIS displays. This methodology requires intensive computational resources, and we discuss approaches to make the best use of current technology.

When fully implemented, the proposed modifications will contribute to basic knowledge and the advancement of research in three areas:

1. Environmental modeling - by including spatial processes in a spatially differentiated multi-cell simulation model, and adapting existing model structures for parallel processing on a supercomputer;

2. GIS - by linking spatial databases to environmental simulation models for dynamic visualization, spatial analysis, and simulation model data management;

3. Ecological impact of climate change - by assessing the importance of
spatial structure of the landscape (e.g., fragmentation) in the maintenance or loss of biological diversity.

This information, and the models developed, may be of direct use in planning for forest management given the projections for global climate warming. These contributions are founded on a tenet of physical geography: the assumed importance of space in mediating the interaction of physical and biological process-response systems.
5.0. REFERENCES


