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Exploring component-based approaches in forest landscape modeling

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Abstract

Forest management issues are increasingly required to be addressed in a spatial context, which has led to the development of spatially explicit forest landscape models. The numerous processes, complex spatial interactions, and diverse applications in spatial modeling make the development of forest landscape models difficult for any single research group. New developments in component-based modeling approaches provide a viable solution. Component-based modeling breaks a monolithic model into small, interchangeable, and binary components. They have these advantages compared to the traditional modeling work: 1) developing a component is a much smaller task than developing a whole model, 2) a component can be developed using most programming languages, since the interface format is binary, and 3) new components can replace the existing ones under the same model framework; this reduces the duplication and allows the modeling community to focus resources on the common products, and to compare results. In this paper, we explore the design of a spatially explicit forest landscape model in a component-based modeling framework, based on our work on object-oriented forest landscape modeling. We examine the representation of the major components and the interactions between them. Our goal is to facilitate the use of the component-based modeling approach at the early stage of spatially explicit landscape modeling. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Forest landscape model; Component-based modeling; Landscape component; Spatially explicit; COM

1. Introduction

Ecological processes occur across a wide range of spatial and temporal scales, and an equally wide variety of models can be developed to emulate these processes. No one model can address issues at all scales, and because of this, explicit and inexplicit assumptions must be made to build models to simulate ecological processes of interest. These scale-related assumptions result in ecological models ranging from those simulating physiological processes of single leaves, operating on the order of minutes (e.g., Reich et al., 1992), to those simulating biogeographical and biogeochemical processes of a continent, operating on the order of months or years (e.g., VEMAP Members, 1995; Haxeltine et al., 1996).

Ideally, model development and implementation should have general standards in 1) determining ecological processes to be incorporated, 2) representation of these processes, using a set of identified variables, and 3) representation of the interactions among these processes. These standards should not prevent modelers from making specific implementations such as selecting an algorithm to represent a process.

However, ecological modelers lacked model standards to follow in design and implementation of models (Jorgensen et al., 1995). In this "no standard" environment, individual research groups have developed models suited for their purposes without considering interoperability with other models or model components (Wood, 2001). No standards probably made model development easier and quicker than those with standards. This may have leaded to rapid advances in both theory and application in the early stage (before 90s) of ecological modeling (Costanza et al., 1993). On the other hand, no standards have made it difficult for new models

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to be built upon the existing ones and therefore, duplicated inventions are inevitable. For example, following the first generation of forest stand dynamic (gap) models (Botkin et al., 1972; Shugart, 1984), hundreds of gap models have been developed, essentially to model the same ecological processes, but with different conceptualization of how to represent these processes and their interactions. Many of these later models may have various improvements over the first gap models, but they are difficult to evaluate (Bugmann et al., 1996; Bolliger et al., 2000), since comparisons must be based on the same standards, which did not evolve from these models (e.g., Pastor and Post, 1985; Solomon, 1986; Martin, 1992; Urban and Shugart, 1993; Prentice et al., 1993; Fischlin et al., 1995; Bugmann, 1996).

The development of modeling standards requires a rigorous test and evaluation process that was lacking. The early, less sophisticated, programming technology may have compounded this issue of lacking modeling standards. Traditional programming widely used before the 1990s created models as a monolithic computer program, which lacks a modular structure. Therefore, they could not be understood as efficiently as later models developed using the object-oriented programming (OOP) approaches that emerged in the late 1980s (Rumbaugh et al., 1991). By using modular approaches, OOP simplified the complex problems of designing and maintaining the structured model source code. This progress made the model code easier to read by programmers and allowed new versions to be delivered more quickly than ever before. However, compared to the traditional models, OOP made little difference to the end users, since an OOP model may remain as one monolithic executable file, compiled and linked from the source code. Once compiled, it does not change until either the original developers recompiled and distributed the new version, or a different group learned to modify code of the model so that they could create a new version. In either case, if they occurred at all, model development would involve a lengthy process, and model evaluation and testing remained as difficult tasks. Such limitations have become obvious when the end users intend to incorporate their research ideas in the models and they need more access to the models (such as modifying some model components) than to simply use them. These problems are generic and not specific to ecological modeling (Box et al., 1999).

Recent developments of component-based approaches from software engineering are useful to ecological modeling. The component-based approaches break the monolithic executable program into separate pieces or components (Chappell, 1996; Orfali et al., 1997; Maloney, 1999; Tapadiya, 2001). A component in a model is like a mini-model; it comes packaged as a binary code that is compiled, linked, and ready to perform certain tasks for the entire model. Components connect with each other at run time to form a complete model. With a component-based model, it is possible to replace some components while maintaining the integrity of the model. The component-based modeling approaches have the following advantages: 1) developing/modifying a component is a much smaller task than tackling a whole model, 2) a component can be developed using most programming languages since the format is binary, and 3) new components can replace the existing ones under the same model framework; this reduces the duplication and allows the modeling community to focus resources on the common products and compare results. Since component-based models provide end users with possible access to the components (such as modify an existing component), more groups may participate in the same modeling work. Therefore, a component-based model can be more rigorously tested, evaluated, and modified than before, and these processes can be driven, not solely by original developers, but by the modeling community (Rogerson, 1997; Box, 1998; Box et al., 1999).

During the last decade increasing demands in addressing ecological problems in a spatial context have led to the development of spatially explicit landscape models (Mladenoff and Baker, 1999; Higgins et al., 2000; Curnutt et al., 2000). The numerous processes and complex spatial interactions involved in spatial modeling make the development of these models difficult for any single research group, especially when species-level information is required across a large spatial extent (He et al., 1999a). We believe that, at this early stage of landscape modeling, it is important to address the modeling issues such as sharing, interchangeability, and interoperability to facilitate the development of model standards and minimize duplications. Component-based modeling provides an important tool in addressing these needs. In 1998, the first International Conference on Modeling Complex System was held in New Orleans, Louisiana, USA, and a workshop was carried on to introduce component-based approaches in ecological modeling (Smith, 1998). However, we have not seen actual implementation using these approaches in ecological modeling, although applications of component-based programming approaches are commonly used in the software industry (Rubin et al., 1998; Maloney, 1999; Tapadiya, 2001). The recent developments in building modeling tools that minimize the programming efforts, show certain potentials (Maxwell and Costanza, 1997; Villa and Costanza, 2000; Fall and Fall, 2001). In this paper, we discuss the design of a spatially explicit forest landscape model in a component-based modeling framework based on our work on object-oriented forest landscape modeling. We examine the representation of the major components and the interactions between them. Our goal is to facilitate the use of the component-based

modeling approach at the early stage of spatially explicit landscape modeling.

1.1. The approach of component-based forest landscape modeling

Landscape modeling is a recent endeavor (Roberts, 1996; Roberts and Betz, 1999; Baker et al., 1991, 1999; Urban et al., 1999; Gardner et al., 1999; Mladenoff and He, 1999; Higgins et al., 2000; Curnutt et al., 2000). Among the existing models, there is no consensus on the spatial and non-spatial processes incorporated and the representations of these processes, although they may share many similar spatial operations (such as dimensioning and re-dimensioning a map, spatial query, representing spatially contiguous processes, spatial data classification, and etc.). This makes applying component approaches to landscape modeling important. During the past years, we have developed a spatially explicit and stochastic forest landscape model, the LANDIS model (Mladenoff et al., 1996; Mladenoff and He, 1999; He et al., 1999a; He and Mladenoff, 1999a). LANDIS appears to be advanced compared to other existing models in its simulation capacity. LANDIS simulates: 1) large (10^4–10^7 ha) and heterogeneous (both site environmental conditions and vegetation) landscapes, 2) interaction of dominant forest disturbance regimes, such as fire and windthrow, with species-level forest succession, 3) realistic forest management practices at tree species level, 4) at a range of possible scales and map input-data of varied resolutions, and 5) with spatially-explicit ecological interactions, and mechanistic realism, while having modest input parameter needs. It is logical that we explore the component modeling approaches using LANDIS, which is also an object-oriented model (He et al., 1999a). We believe that the focus of this paper should be on the concepts and ecological design of model components. Thus, we will present general idea and then specific examples using the LANDIS framework. The programming specifications that are associated with each component will not be presented.

1.2. Model components

Spatially explicit forest landscape models usually have certain basic components to simulate the spatial and non-spatial processes (Fig. 1), including 1) tracking individual sites and their locations (the SITES and SITE components), 2) keeping track of vegetation on each site (the SPECIES and AGELIST components), 3) keeping track of physical site characteristics such as landtypes or ecoregion (the ECOREGION component), 4) modeling non-spatial vegetation dynamics such as succession and establishment at each site (the SUCCESSION component), 5) modeling spatial processes such as dispersal (the SEEDING component), fire (the FIRE component), windthrow (the WIND component), and harvest (the HARVEST component), and 6) managing simulation scenarios and processing input and output data (the SCHEDULER component).

SITES divide the entire landscape into rows and columns comprising singular SITES. Each SITE contains unique information about SPECIES, which change via SUCCESSION through time. In a spatial context, SUCCESSION occurs on every SITE as long as a species exists, while landscape processes occur at multiple SITES or the landscape scale interacting with succession dynamic at each SITE (Fig. 1). In a temporal context, SUCCESSION and seed DISPERSAL occur constantly, FIRE and WINDTHROW disturbances occur at much longer temporal scales, and HARVEST falls in between. SITES and SITE link spatially and/or temporally constant components with spatially and/or temporally explicit components (Fig. 1). A heterogeneous landscape can be further stratified into ECOREGION with homogeneous physical characteristics. The ECOREGION component is a spatially explicit and temporally constant component that encapsulates environmental variables such as soil, topography, and climate.

For a component-based model to work, each component should have a set of binary interfaces. These interfaces are functions that perform certain tasks or interact with other components when called. The new version of a component may use a different approach to simulate a given process, such as an alternative fire ignition algorithm for the FIRE component, but the interfaces should remain the same, so that the updates can be placed into effects without requiring the changes of other components. When new interfaces must be implemented with our understanding advancing to incorporate new interactions between components, they need to be added to all involved components. In this case, the old interfaces can also be maintained for at least one version, so that the new components are still compatible with older versions.

Component-based software requires some type of binary architecture standards to regulate how components interact at run time. These standards have been developed such as Component Oriented Model (COM) for Windows' environments (Brochschmidt, 1995; Rogerson, 1997; Box, 1998), and Common Object Request Broker (CORBA) for Unix environments (Orfali et al., 1997). These binary standards are a set of technical specifications for coding requirements and do not interfere with the ecological design of each component. Choosing COM or CORBA depends upon the platform the component-based model will be run. For PC-based applications, model components can be built as executables such as dynamic linked libraries (DLL) or EXE based upon the COM specifications (Box, 1998). They are invoked through the landscape event scheduler (SCHEDULER), which assembles individual components involved based upon the input specification of a

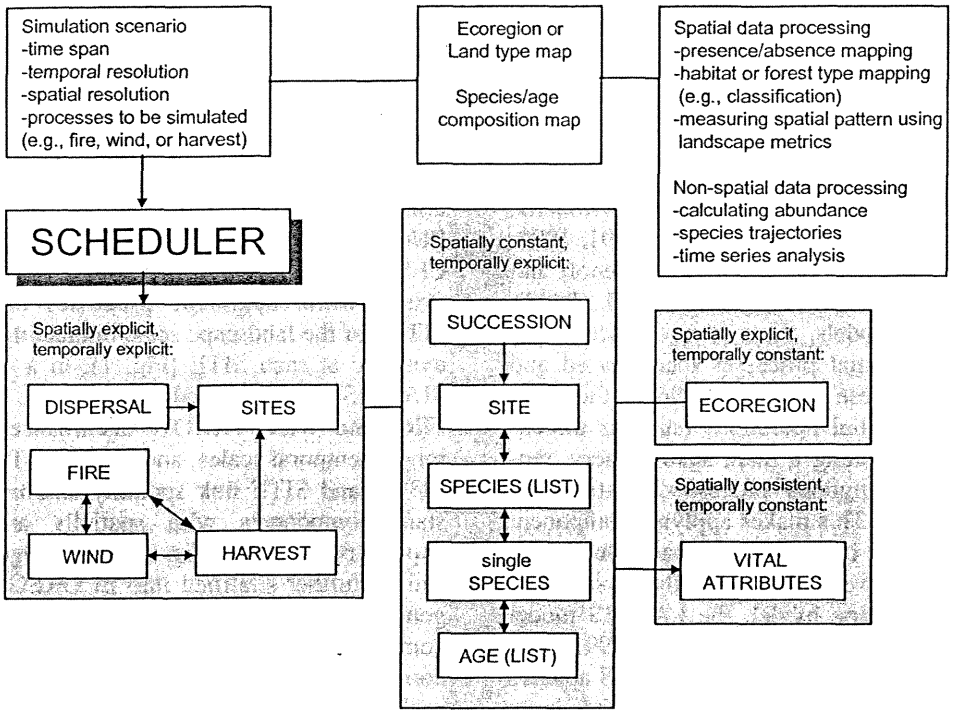

Fig. 1. Components (white blocks inside the gray boxes) in the paradigm of component-based forest landscape modeling, ranging from spatially and temporally constant to spatially and temporally explicit.

particular simulation (Fig. 1). One or more components can be invoked by SCHEDULER running locally or through networks with a server/client type of relationships (Rogerson, 1997; Box, 1998; Rubin et al., 1998; Box et al., 1999).

The SCHEDULER component must first read input files that contain all parameters of a particular simulation. It measures the dimension of the input map and initiates the SITES component that is the internal representation of the map (Fig. 1). SITES divides the simulation area into a grid of equal sized cells or pixels and each single pixel is represented by the SITE component, with pixel size determined from the input. FIRE, WIND, HARVEST, DISPERSAL, and SUCCESSION are components that simulate the corresponding tasks. They can be activated singularly or jointly. If jointly, the interactions of these components will also be simulated (Fig. 1). Once a component is invoked, it can refer to the memory blocks used by other components (the client) through the defined binary interfaces and/or allocate its own memory. In both cases, the invoked components can modify information stored in client memories (see the following discussions of each component).

1.3. Design and description of individual components

1.3.1. The SPECIES component

As stated previously, no models can simulate ecological processes at all scales. In forest landscape modeling, landscape processes such as seed dispersal, fire, windthrow, and harvesting are of primary interest. To simulate these spatial processes and their interactions with site or stand scale succession processes, landscape models must incorporate both (He and Mladenoff, 1999a; He et al., 1999a). However, the decisions made on the level of detail used in representing vegetation dictates the level of mechanism that site-scale succession can simulate, and how other components interact with such information. In LANDIS, it is assumed that, for landscape modeling, detailed, individual, tree information and within-stand processes can be simplified, while large scale questions such as spatial pattern, species distribution, and disturbances, can be adequately addressed. Therefore, in the SPECIES component we propose to represent only species age-cohort, not individual trees. Age-cohorts have been found equally adequate in addressing species composition and spatial distributions (Bugmann, 1996; Mladenoff and He, 1999; Franklin et al., 2001).

The representation of a species age cohort can be done with a sorted linked list, an abstracted data type (Fig. 2). A sorted linked list manages the data in a sequential order (e.g, sorted by value or name). One of its advantages is its reliance upon dynamic allocation of computer memory. Only species and age cohorts present are stored and no space is held for species and age cohorts that are absent. An example of such a data structure shows that the vertical list constitutes a species name list, while horizontal lists comprise the corresponding age cohorts of the species (Fig. 2a). Another advantage of using a

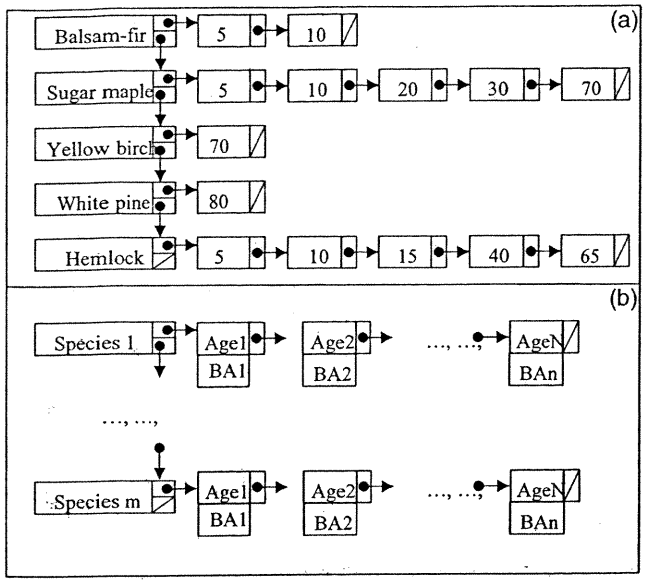

Fig. 2. a) Sorted linked list representation of species and age-cohort at 5-year interval for a site where balsam fir occurs as 5 and 10, sugar maple 5, 10, 20, 30, and 70 years old, yellow birch 70, white pine, 80, and hemlock as 5, 10, 15, 30, and 65 years old. b) Sorted linked list representation of species, age-cohorts and basal areas. Neither the number of species, nor the number of age cohorts is the limiting factors of such a representation. If there is no adequate data to parameterize detailed basal area and age cohort, as it often is in a real application, reasonable assumptions can be made either by reducing temporal resolution or the classes of basal areas.

linked list data structure is that the datum of each node can be any integer. In other words, the structure can be applied to any model time-steps such as one year or three years. Furthermore, with such a representation, the data member of basal area can be easily added at each node, and this provides the possibility for the model not only to represent but also to quantify each age cohort recorded (Fig. 2b).

1.3.2. The ECOREGION component

The ECOREGION component is an encapsulation of environmental data that stratifies the landscape. Ecoregion classes are typically processed from other GIS layers such as climate, soil, or digital elevation models (DEM), using standard GIS operations (He et al., 1996). Often however, landscape-modeling projects are confined by the availability of input data. Ecoregion therefore, should be scaleable, and can be as small as a land type unit, in accordance with the research scale. Two assumptions are made to the ECOREGION component, similar to those in LANDIS. First, within an ecoregion, similar fire characteristics, fuel accumulation rate, and individual species responses are assumed. These assumptions are largely validated by numerous empirical studies. For example, fires are more frequent and have a shorter mean return interval on xeric ecoregions than mesic ecoregions (e.g., Kauffman et al., 1988); fuel decomposition rate is lower on a xeric ecoregion than that on a mesic ecoregion (Brown et al., 1982). Second, species establishment ability may vary among ecoregions. In other words, certain ecoregions favor certain species over others. Therefore, when a seed travels from one ecoregion to another, it may or may not establish, depending on its establishment ability on the latter type of ecoregion.

1.3.3. The SITES component

SITES component is an internal representation of the simulated landscape. It creates an internal map before simulation by dimensioning the landscape to the desired cell size, setting coordinates, and allocating computer memory. The cell size of SITE can be varied depending on the input data to accommodate studies at various resolutions. Besides map parameters, the internal data of SITES is a matrix of reference pointers to individual SITE components. Therefore, the SITES component can retrieve information stored at individual SITEs and allow a spatial process operating on SITES to interact with individual SITEs through the interface of a single SITE (Fig. 3). SITES supports general spatial operations such as boundary checking, whether certain SITEs are active (e.g. excluding non-simulation area such as water body or urban center), or querying X and Y coordinates for a given SITE. These operations are defined as binary interfaces and called by other components (Fig. 3). SITES has an interface for ECOREGION so that environmental variations encapsulated by ECOREGION can be referenced by each SITE (see below).

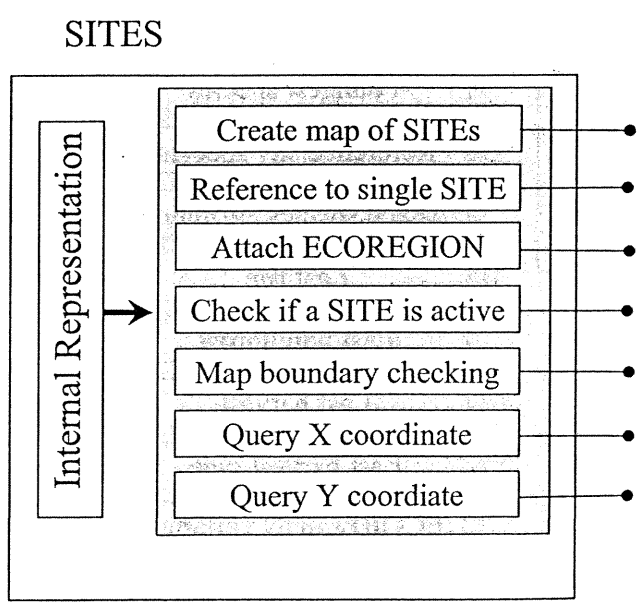

Fig. 3. The interfaces of the SITES component. SITES is an internal representation of the simulated landscape. The interfaces support common map operation requests and reference to environmental data and single cell (SITE).

1.3.4. The SITE component

SITE component represents a basic modeling unit (cell). It interacts with all other components, because for spatially explicit modeling, succession dynamics, spatial processes, and environmental variations all interact at each SITE (Fig. 4). It also tracks the disturbance and harvest history and has an interface for SPECIES (Fig. 2).

The SUCCESSION component queries the SITE component for the information related to species lists, age cohorts, and species *attributes* including age of maturity, longevity, shade tolerance, vegetative reproduction probability, and species establishment capability on the SITE. Therefore, to communicate with SUCCESSION, the SITE component has interfaces to support species list operation, such as loop through all species (first, next, and current) to find what species occur on a SITE. SITE supports query of species age (e.g. oldest and youngest) and the effective seeding and maximum seeding distance to facilitate requests of the DISPERSAL component to determine whether mature trees exist.

The FIRE and WINDTHROW components query SITE for the time since last disturbance, current fuel accumulation regime, and the mean return interval of the site (encapsulated by ECOREGION), to calculate disturbance probabilities, severity, and species susceptibility (see the section of the FIRE/WIND Components). The HARVEST component queries SITE to determine when and what type of the last harvest was performed on a SITE, and if the stand age meets the minimum age criteria (Fig. 4).

1.3.5. The SUCCESSION component

SUCCESSION simulates competitive processes driven by species vital attributes including longevity, shade tolerance, fire tolerance, vegetative reproduction capability, seeding distances. In the SUCCESSION component, a species establishment and survival mainly depends on species vital attribute and the environmental suitability (e.g. Roberts, 1996; Roberts and Betz, 1999; Mladenoff et al., 1996).

SUCCESSION has an interface with SPECIES and succession is performed on each species, based upon its attributes and site conditions. At each iteration of model, species birth, death, and growth are simulated. "Birth" simulates vegetative reproduction or successful seedling establishment (Fig. 5). "Death" typically simulates species reaching their maximum longevity. It applies only to the particular age cohort that reaches species longevity. "Growth" simulates species aging during each model iteration. "Remove" simulates the removal of one or more age cohorts of a species from the site due to vari-

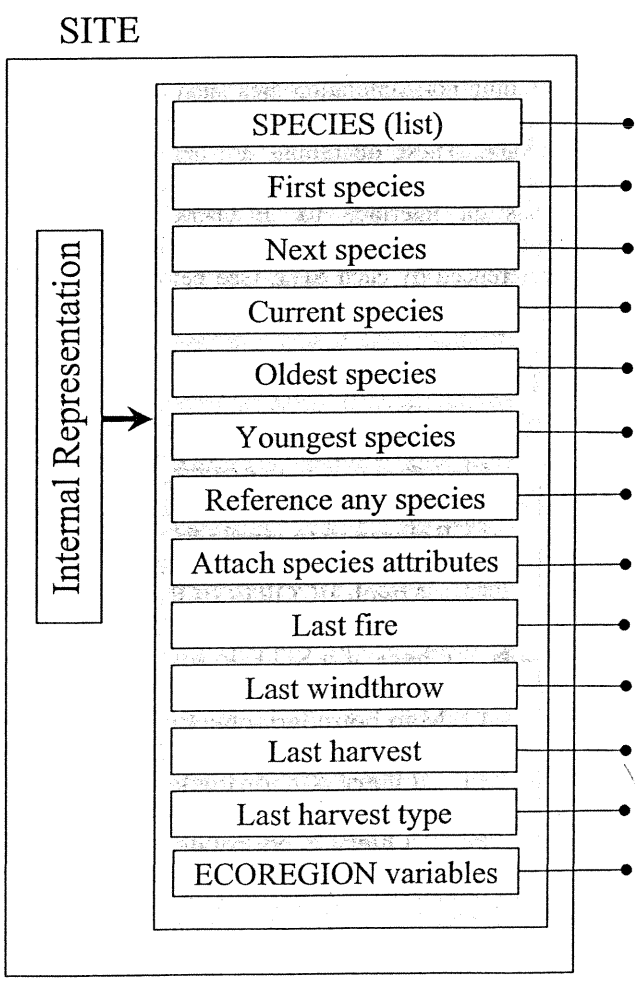

Fig. 4. The SITE component represents a basic modeling unit (cell). It has interfaces with all other components, because succession, disturbance, and environmental variations all interact at each site.

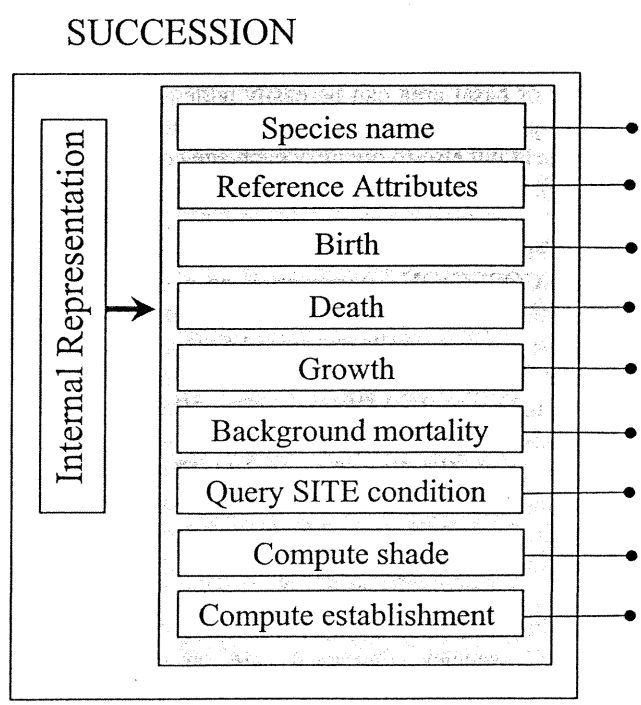

Fig. 5. At each model iteration, the SUCCESSION component simulates species birth (new establishment), death (reaching longevity or removal by a disturbance), and growth (age increment).

ous causes (Fig. 5). Disturbances and harvest can all result in removal of certain species age cohorts. For example, wind disturbance tends to remove older age cohorts, while fire disturbance tends to remove younger age cohorts. "Clear" simulates the removal of the species (entire age cohorts) on the site, which usually accompanies severe fire disturbances or clear-cut harvest (Fig. 5). When seed successfully arrives at a site, the "shade" checking interface determines whether seedlings are allowed to establish based on the shade tolerance rank of the seeding species relative to the species already occurring on the site. For example, quaking aspen is a shade intolerant species that cannot seed into a site on which shade tolerant sugar maple is already established. When light conditions are favorable to a species, the "establishment" interface determines if the species can establish (Mladenoff and He, 1999). The environmental conditions of a site, such as soil nutrient and water availability, may favor certain species over others. The species establishment coefficient, a number from 0–1, encapsulated in ECOREGION is an order quantifying how environmental conditions favors various species (He et al., 1999b). These factors are not mechanistically simulated. Rather, they are assigned probabilities that can be derived empirically from field data or from the simulation results of a gap model (He et al., 1999b).

1.3.6. The DISPERSAL component

Seed dispersal is a spatially explicit process (Fig. 6). It performs the function of dispersing seeds from one SITE to other SITEs. When seeds arrive at a SITE, SUCCESSION component will simulate the steps of establishment. DISPERSAL component searches for mature age cohorts of each species through "check maturity" interface and references to the species attributes for species effective seeding distance and maximum seeding distance (Fig. 6). Various seeding methods can be implemented using these seeding distances. The implementation of a particular seeding method will affect the behavior of seed dispersal, but not the interfaces of DISPERSAL. For example "effective seeding" method emphasizes effective seeding distances. Effective seed dispersal distance is the distance within which seed has the highest probability (e.g. $P>0.95$) of reaching. The maximum seed dispersal distance is the distance beyond which a seed has near zero probability (e.g. $P<0.001$) of reaching. Seed dispersal probability (P) between the effective (ED) and maximum seeding distance (MD) follows a negative exponential distribution:

$$P = e^{-b\cdot\left(\frac{x}{MD}\right)}$$

where x is a given distance from the seed source ($MD>x>ED$), m is the maximum seeding distance, and b is an adjustable coefficient ($b>0$), which can change the shape of the exponential curve corresponding to various seed dispersal patterns when information is available (Fig. 7) (He and Mladenoff, 1999b).

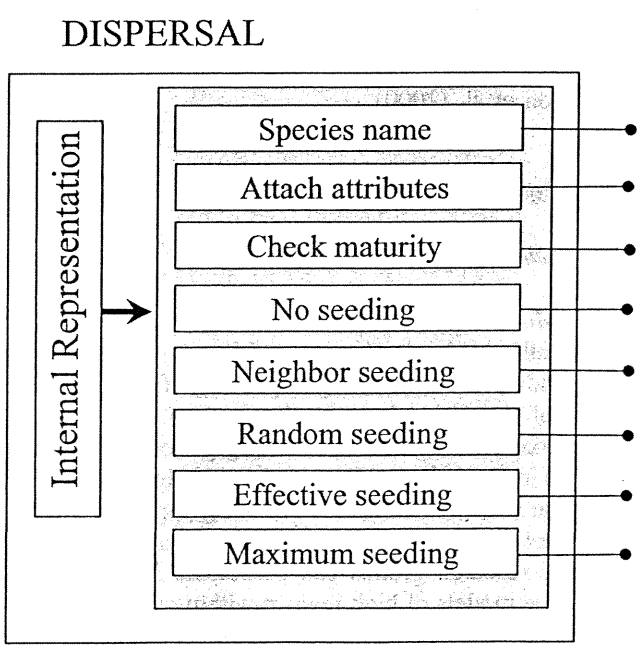

Fig. 6. The DISPERSAL component performs the function of dispersing seeds of mature species from one SITE to other SITEs using provided seeding methods.

1.3.7. The FIRE and WIND components

Fire disturbance is a spatially explicit process interacting with SUCCESSION and other landscape components. They appear to be stochastic for a single site, but have repeated patterns in terms of ignition, location, size, and shape at landscape scales. It has long been noted that some areas are more fire-prone than others are. The differences are often characterized by ECOREGION. Using the interfaces defined (Fig. 8), the FIRE component will activate ECOREGION, calculate fire probability, perform "ignition", generate "fire size", determine fire severity based on fuel regimes, and execute spreading (Fig. 8). Each of the above operations are associated with a mathematical representation based on

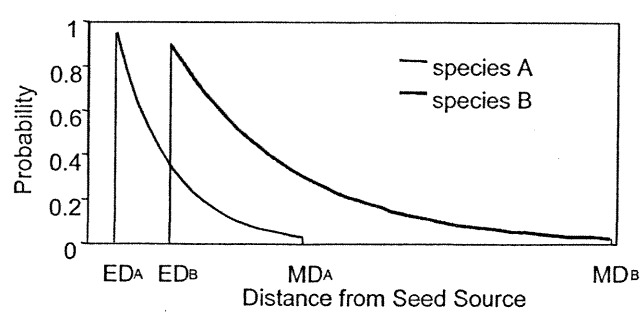

Fig. 7. The negative exponential distribution of tree species seeding probability in relation to distance from available seed sources. ED-species effective seeding distance, MD-species maximum seeding distance. Other functions can also be used.

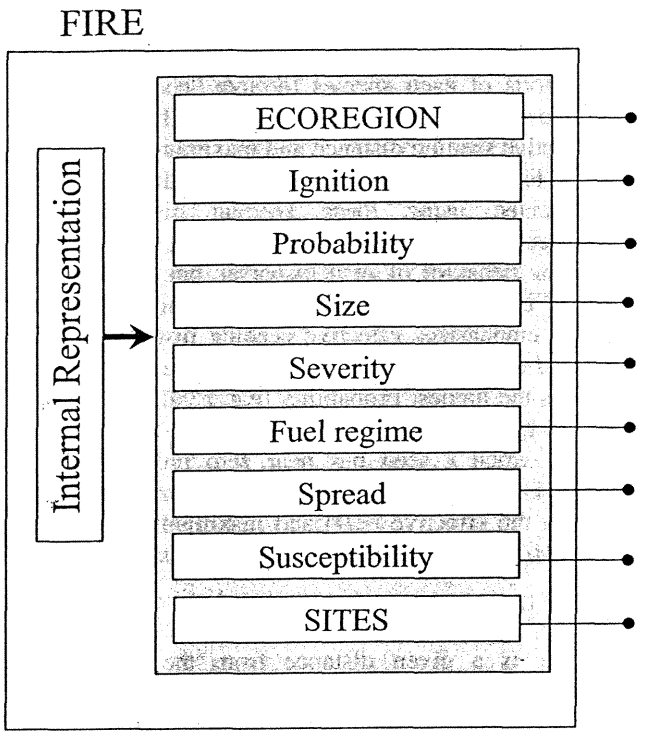

Fig. 8. The FIRE component has interfaces of ECOREGION to derive ignition probability, fire probability, and fire severity (depending on fuel loads accumulation). It also has an interface with SITES so that a fire spread interacts with species information at site level.

existing studies, e.g, Pickett and White (1985), Pickett et al. (1989), Johnson (1992), Johnson et al. (1990), Baker et al. (1991). For the FIRE component, the mean fire return interval is used to calculate fire probability:

$$P = b \cdot lf \cdot MI^{-(e+2)}$$

where P is the fire probability of a cell, MI is the mean fire return interval of a given ecoregion on which the cell resides, b is a constant and lf is the number of years since last fire on that cell. With the above distribution, P varies among ecoregions with MIs, and it can be further altered by lf recorded for each single cell. For example, if fire burns a given cell in a given time step, lf of the cell is reset to 0, and P for that cell is calculated as 0 during that time step.

Furthermore, fire size can be defined from the following equation integrating random factors and the mean fire size:

$$S = a \cdot (10.0)^r \cdot MS$$

where S is the fire size,$MS$is the mean fire size, a is a constant, and r is a normalized random number (He and Mladenoff, 1999a). Such a distribution simulates frequent small fires and infrequent large catastrophic fires (Fig. 9).

Each ecoregion may have a unique combination of MI and MS, which is the first assumption in the ECOREGION component. Fire intensity is determined by the quantity of fuel, which is derived from the time since last fire was recorded for each cell. The FIRE component interacts with individual species and age cohorts on SITE involved. Fire is a bottom-up disturbance, and fires of increasing intensity affect younger age classes first. The interactions of fire with species fire tolerance and age susceptibility can be explicitly defined (e.g., He and Mladenoff, 1999a).

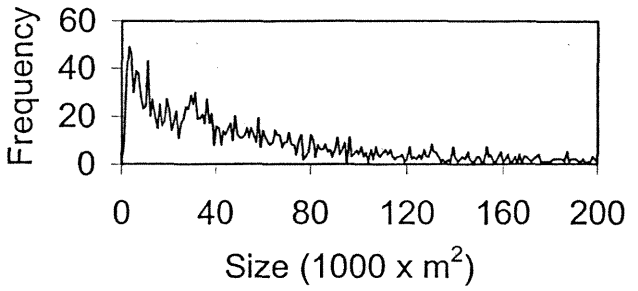

Fig. 9. Fire size follows log-normal distribution with small fire occurring more frequently than large fires.

WIND uses an approach similar to FIRE to simulate windthrow, except that species susceptibility to windthrow increases with age and size (Mladenoff and He, 1999). Windthrow increases fuel loads, and the time since a windthrow event can also influence the potential fire intensity class, depending on decomposition dynamics of the particular ecoregion. Interactions between these two disturbances can be interesting and complex. Generally, windthrow becomes more important on ecoregions with long-lived species and where fire frequency is low. We will not discuss the HARVEST component that requires significant text due to the complexity. The ecological aspects of this component are presented in Gustafson et al. (2000).

2. Discussion

2.1. Modeling approach implications

2.1.1. Model reuse

Spatially explicit landscape modeling is a recent endeavor. Individual research groups often face the challenges of simulating large landscapes and complex spatial interactions with limited funding periods. This often leads to relatively simple models, with broad assumptions that may prevent them from being applied to practical issues. With component-based modeling approaches, multiple research groups can participate in developing landscape models of high realism within various ecosystems. For example, assessments of forest ecosystem response to various fire risks are important in planning a long-term management scenario, and such assessments are often assisted with models (Li et al., 1993). Instead

of developing a new model from scratch, the assessment team often selects one from many existing models. While a perfect match seldom occurs, they are more likely to find that the model selected generally works well, but certain behaviors need to be modified. This is the place where component-based approaches have advantages. For example, the fire component properly simulates large, infrequent, and high intensity fire regimes (e.g., fires in northern hardwoods), but the small, frequent, and low intensity fire regimes (e.g., fires in central hardwoods) are not correctly simulated. Instead of contacting the original developers for modification requests, this group may choose to develop their own fire component. Since a component uses a binary interface and can be compiled using any language, they are not confined by issues such as acquiring the source code, or limited to the original programming language. Thus, the probabilities of developing a new fire component in the component-modeling framework increase. As long as the new component incorporates the same interfaces as the original one, such as those discussed in previous sections, it can simply replace the old component and improve the model behavior of simulating fire disturbance, without affecting other model components. Presumably, while more groups participate in such efforts, a model would evolve over time driven not solely by original developers, but by the modeling community (Rogerson, 1997; Smith, 1998).

2.1.2. Model standards and model integration

The model components can be distributed and accessed on the networks using Distributed Component Model (DCOM) techniques (Rubin et al., 1998). The access in general facilitates model sharing, which in turn promotes a rigorous process of model evaluation. In the past, sharing on ecological modeling generally meant making an executable or program source code available. Such sharing has proven difficult, because the users have to either use the shared model, accepting all assumptions made to the model, or work with the source code to modify the model so that it suits their needs. Being able to modify another's computer source code is not only constrained by the programming languages, but also programming styles. Moreover, it often requires expertise to be both modeler and programmer to thoroughly understand the original model implementation. Such limitations make shared monolithic simulation models less likely to be fully used, than models implemented using the new component-based approaches. In addition, components can be combined to form numerous simulation scenarios, and therefore, they can be tested, replaced, and compared. Thus, the process of evaluation with component-based models can be more rigorous than traditional models. Such an evaluation process facilitates the emergence of model standards, which could evolve from the commonly accepted components. These components and standards, once established, can evolve within the modeling community, leading to a healthy software development process through model reuse.

The beneficiaries of component-based modeling can go beyond landscape modeling and extend the practice to other types of models and model integration. Model integration is an important and little explored issue. Most practical needs in ecosystem management can be better addressed through models integrated at different scales (Smith, 1998; He et al., 1999b). For example, succession dynamics in forest landscape modeling is often simplified, since landscape processes and spatial patterns across broad scales become the focus (Baker et al., 1991, 1999; Gardner et al., 1996, 1999). However, some situations may require greater detail about species dynamics. In these cases, the simple succession component could be replaced entirely by a more detailed gap model. However, this will require the gap model also to have a standard binary interface. True and seamless model integration can be achieved using expandable components that operate at multiple spatial and temporal scales. Moving ecological modeling towards a mature discipline will require standards evolving from all types of models. This can lead to true and seamless model integration, and will allow cross-scale environmental assessments involving multiple models.

3. Applications

The applications using component-based approaches should not differ from those of existing landscape models. However, the strength of component-based models is its potential to develop new applications that may not be easily developed using existing models. These applications have been demonstrated in various pilot projects through the LANDIS model base on which the components are designed.

To understand disturbance and recovery of forest landscapes, we used the model to examine how disturbance regimes and species dynamics interact across a large (500, 000 ha), heterogeneous landscape in northern Wisconsin, US, with multiple ecoregions having different species establishment environments and fire disturbance regimes. We found that there are feedbacks over time between species, disturbance, and environment, resulting in the re-emergence of patterns that characterized the landscape before extensive human alteration. However, such a recovery process would take one to several hundred years depending on ecoregion and the extent to which the initial spatial patterns and species age-cohort distributions were altered by previous disturbances (He and Mladenoff, 1999a, 1999b).

We examined the interactions of fire and windthrow disturbances in temperate and boreal forest landscape. The results suggest that fire disturbance is potentially

more dominant than windthrow in shaping forest landscapes, but windthrow becomes important with forest aging, since older trees are more vulnerable to windthrow (Mladenoff and He, 1999). There are also feedbacks between fire and windthrow disturbances. The time since a windthrow event can influence the fire severity class, depending on decomposition dynamics of the particular ecoregion, and the wind disturbance interval (Mladenoff and He, 1999).

In simulating forest species response to potential climate warming, we developed a protocol of linking an ecosystem process model to LANDIS. Using ecosystem models that integrate soil moisture and nutrient dynamics, and climate data, individual species response to climate warming can be more realistically derived than using landscape models alone. These individual species responses were then used to parameterize LANDIS, which integrates large-scale landscape processes (He et al., 1999b). The responses of northern temperate hardwood species vary among ecoregions depending on soil nutrient and water regimes. Simulation results indicate that boreal species disappear from the landscape in 200–300 years and approximately the same amount of time for a southern species to become common. Warming can accelerate the re-colonization process for current species, such as found for eastern hemlock, where moisture does not become limiting. However, the re-colonization is strongly affected by available seed source, which must be explicitly described on the landscape. These phenomena cannot be simulated with most gap models, which assume a random seed rain.

In examining the consequences of forest harvesting and increased fire regimes due to climate warming, we found that increased fire frequency can accelerate the decline of shade-tolerant species such as balsam fir and sugar maple and accelerate the northward migration of southern species (He et al., 2002). Forest harvesting accelerated the decline of northern hardwood and boreal tree species. Forest managers may instead consider a conservative cutting plan or protective management scenarios with limited forest harvesting. This could prolong the transformation of the barrens into prairie from one-half to one tree life cycle.

We believe that with component-based modeling, future applications would expand to examine practical problems including cause–effects and scenario–consequence types of analyses, through the combinations of various components and especially integrating models of different scales.

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