



ELSEVIER

Ecological Modelling 119 (1999) 1–19

**ECOLOGICAL
MODELLING**

An object-oriented forest landscape model and its representation of tree species

Hong S. He ^{a,*}, David J. Mladenoff ^a, Joel Boeder ^b

^a Department of Forest Ecology and Management, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706-1598, USA

^b Technical Center, Vista Information Solutions, Edina, MN 55435, USA

Received 24 January 1998; accepted 5 January 1999

Abstract

LANDIS is a forest landscape model that simulates the interaction of large landscape processes and forest successional dynamics at tree species level. We discuss how object-oriented design (OOD) approaches such as modularity, abstraction and encapsulation are integrated into the design of LANDIS. We show that using OOD approaches, model decisions (often as model assumptions) can be made at three levels parallel to our understanding of ecological processes. These decisions can be updated with relative efficiency because OOD components are less interdependent than those designed with traditional approaches. To further examine object design, we examined how forest species objects, AGELIST (tree age-classes), SPECIE (single species) and SPECIES (species list), are designed, linked and functioned. We also discuss in detail the data structure of AGELIST and show that different data structures can significantly affect model performance and model application scopes. Following the discussion of forest species objects, we apply the model to a real forest landscape in northern Wisconsin. We demonstrate the model's capability of tracking species age cohorts in a spatially explicit manner at each time step. The use of these models at large spatial and temporal scales reveals important information that is essential for the management of forested ecosystem. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Landscape model; LANDIS; Object-oriented design (OOD); Spatially explicit; Tree species; Age class

1. Introduction

Forest ecological research and management are increasingly being required to answer questions at larger, spatial and temporal scales (Mladenoff and

Pastor, 1993; Turner et al., 1993; Pickett and Cadenasso, 1995). These questions must be addressed by simulation models that incorporate spatially explicit dynamics (Mladenoff and Baker, 1999). Landscape modelers face the problem that ecological processes such as seed dispersal, seedling establishment, succession, wind and fire disturbance, insect defoliation, forest diseases and harvesting operate at various spatial and temporal

* Corresponding author. Tel.: +1-608-2656321; fax: +1-608-2629922.

E-mail address: hshe@facstaff.wisc.edu (H.S. He)

scales. Interactions among these processes are complex and not fully understood. This complexity has resulted in relatively simple landscape models focusing on a few ecological processes (Baker and Mladenoff, 1999). To design a landscape model that balances the integration of ecological processes across different spatial and temporal scales, the ability to simulate large areas over long time spans and current computational capability, is challenging.

No model can address issues at all scales. Explicit and implicit assumptions must be made during the design stage of model development. Decisions are typically made at three levels: (1) what ecological processes should be incorporated; (2) how do these processes interact; and (3) how are they represented. These decisions will affect the scopes of the model application as well as the model reusability. To be reusable, model updating is necessary to incorporate increasing understanding of landscape processes. Often, updating a landscape model involves modifications of built-in model assumptions, which can be difficult and time consuming for models designed with traditional approaches (Rumbaugh et al., 1991).

Model development involves a lengthy and interactive process of specification, design, verification, coding, testing, refining, production and maintenance (Carrano, 1995). Approximately 60% of development cost lie in the maintenance (Varhol, 1992). Therefore, more effective programming approaches such as object-oriented programming (OOP) are important for optimal software reusability and interchangeability. Programming tools, however, do not guarantee model reusability, as model design plays a major role especially when simulating large complex systems. Coupled with OOP, object-oriented design (OOD) has emerged as a tool to help build models that are maintainable and upgradable. The essence of OOD includes modularity, abstraction and encapsulation (Rumbaugh et al., 1991; Yourdon and Argilar, 1996). These techniques can be coupled with model decision making process at these corresponding levels: (1) to specify what objects to be included (modularity); (2) to define how objects interact (abstraction); and (3) to decide how objects are represented (encapsula-

tion). Models using the OOD approach contain individual modules that are less interdependent on each other, allowing model assumptions to be updated with greater flexibility than those designed with traditional modeling approaches.

Applications of OOD to the modeling of biological systems are increasing (Sequeira et al., 1997). Various applications are found in the design of crop or plant models (Sequeira et al., 1991; Acock and Reddy, 1997; Acock and Reynolds, 1997; Chen and Reynolds, 1997; Lemmon and Chuk, 1997; Luo et al., 1997), ecosystem modeling (Silvert, 1993; Reynolds and Acock, 1997), population and forage/energetics dynamics (Moen et al., 1996; Congleton et al. 1997) and species migration (Maley and Caswell, 1993; Downing and Reed, 1996). Forest landscape modeling is a recent endeavor (e.g., Keane et al., 1996; Roberts, 1996; Gardner et al., 1999; Mladenoff and He, 1999; Urban et al., 1999) often assisted by the development of spatial information capture and processing using remote sensing techniques and geographic information system (GIS). The majority of existing landscape models focus on one landscape process, typically fire, assuming that this process overwrites fine-scale dynamics (e.g., Green, 1989; Baker et al., 1991; Turner et al., 1994; Wu and Levin, 1994; Gardner et al., 1996; Li et al., 1997). In these models, vegetations are generalized as fire susceptibility classes (Turner et al., 1994) or as homogeneous stands or patches with ages represented indirectly by the time since last disturbance (Baker et al., 1991; Gustafson and Crow, 1994; Gardner et al., 1996; Li et al., 1997). While disturbance-affected landscape patterns can be successfully investigated over time, the feedbacks and interactions within the disturbed ecosystems, such as seed dispersal that can accelerate ecosystem restoration after disturbances (He and Mladenoff, 1998), cannot be simulated. These feedbacks reveal important information when measuring the rates and magnitudes of landscape changes (He et al., 1998a). Vegetation data, with which landscape processes interact, is not incorporated and therefore interactions of multiple landscape processes are difficult to examine using these models.

We have developed LANDIS, a spatially explicit and stochastic landscape model (Mladenoff et al., 1996; Mladenoff and He, 1999). LANDIS simulates large-scale landscape processes as well as fine-scale, species-level vegetation dynamics. The design of LANDIS is based on the OOD approach, differing from other forest landscape models. In this paper, we will discuss how OOD approach is integrated into LANDIS model design. Specifically, we present the methodology of how species-level vegetation information, such as a list of species present and their age class, in a spatially explicit context. We further discuss the data structure of AGELIST and show that different data structures can significantly affect model performance and model application scopes. To demonstrate the model capability of tracking these species and age-cohort dynamics explicitly and over long time spans, we analyze the results derived for a real landscape in northern Wisconsin.

It is impossible to present all components of LANDIS in this paper. Further information on specific elements of LANDIS, such as the overall ecological dynamics and model behavior (Mladenoff et al., 1996; Mladenoff and He, 1999), fire object (He and Mladenoff, 1999), seed dispersal (He and Mladenoff, 1998) and model parameterization (He et al., 1996; He et al. 1998a,b), can be found elsewhere.

2. Overall LANDIS design: an OOD perspective

2.1. Specification of model purpose and scope

The ecological design of LANDIS is similar to LANDSIM (Roberts, 1996) in successional dynamics, seed dispersal and fire disturbance, but its design is object-oriented and it is a raster-based model, optimized for greater spatial complexity. Specification involves the statement of purpose and model capability in terms of input and output. The following requirements were identified when building LANDIS:

- use satellite imagery as input, which should be in a format compatible with most GIS software.

- operate on large heterogeneous landscapes at various spatial resolutions (10–500 m).
- simulate forest succession dynamics at 10-year time-steps and over long time periods.
- simulate forest landscape change at the individual species level.
- simulate wind, fire and harvest disturbances.
- simulate the interaction between succession and disturbances simultaneously.
- simulate seed dispersal in a spatially explicit manner.

From the model's perspective, a landscape is a grid of equal-sized cells or sites, each having unique coordinates. Thus, site (i, j) is the place on the ground at column i and row j in the grid (Fig. 1). The cell size can be varied to accommodate studies at different scales. At each site, one or multiple species is present, similar to observations in the field. Furthermore, existing species may have single or multiple age-cohorts, which are divided into 10-year intervals from age 10 to the average longevity of that species (Fig. 1). The species list at one site may differ from those at adjacent sites and even if the species list is identical, the age-classes, may differ. The initial distribution of the dominant species can be derived from a classified satellite image (e.g. Wolter et al., 1995), or from existing vegetation maps. The associated species and species age-class data can be derived from available GIS and forest survey data (e.g. He et al., 1998b). However, use of the model does not have to be strictly subject to the availability of these detailed data sets, since assumptions of species distribution and age can be always made for a particular area based on the modeling purposes. For example, randomly distributed, even aged stands are assumed in examining forest succession dynamics in the Missouri Ozarks (Franklin et al., 1997; Shifley et al., 1997).

Satellite imagery, usually with fine spatial resolution such as 30×30 m for Landsat TM, can be re-sampled to a different resolution reflecting the scale required for a particular research object. It is worth noting that since only the presence or absence of species age cohorts are tracked, not individual trees, varying the cell size has less effect on the way that species information is recorded than when tracking individuals (Mladenoff and He, 1999).

The environmental condition of each site is defined by ecoregions or landtypes stratifying the landscape (Fig. 1). Landtype classes are typically processed from other GIS layers such as climate zones, soil maps, or digital elevation models (DEM), using standard GIS operations (He et al., 1996). This data layer can also be derived with a quantitative ecosystem classification that combines several environmental factors (e.g. Host et al., 1996). Landtype coverage is scaleable since proper GIS data layers can be processed according to the research scale. Often however, a research scale is confined by the availability of input data. The flexibility of using input data at various

scales in LANDIS allows model application to a wide range of conditions. Assumptions are applied to the landtype layer in the model design. Within a landtype unit, homogeneous fire characteristics, fuel accumulation rate and individual species response are assumed (Fig. 1). These assumptions are largely validated by numerous studies and expert experiences. For example, fires are more frequent and have shorter mean return interval on xeric landtypes than mesic landtypes (e.g. Kauffman et al., 1988); fuel decomposition rate is lower on a xeric landtype than that on mesic landtypes (Brown et al., 1982); and species establishment ability may vary among landtypes.

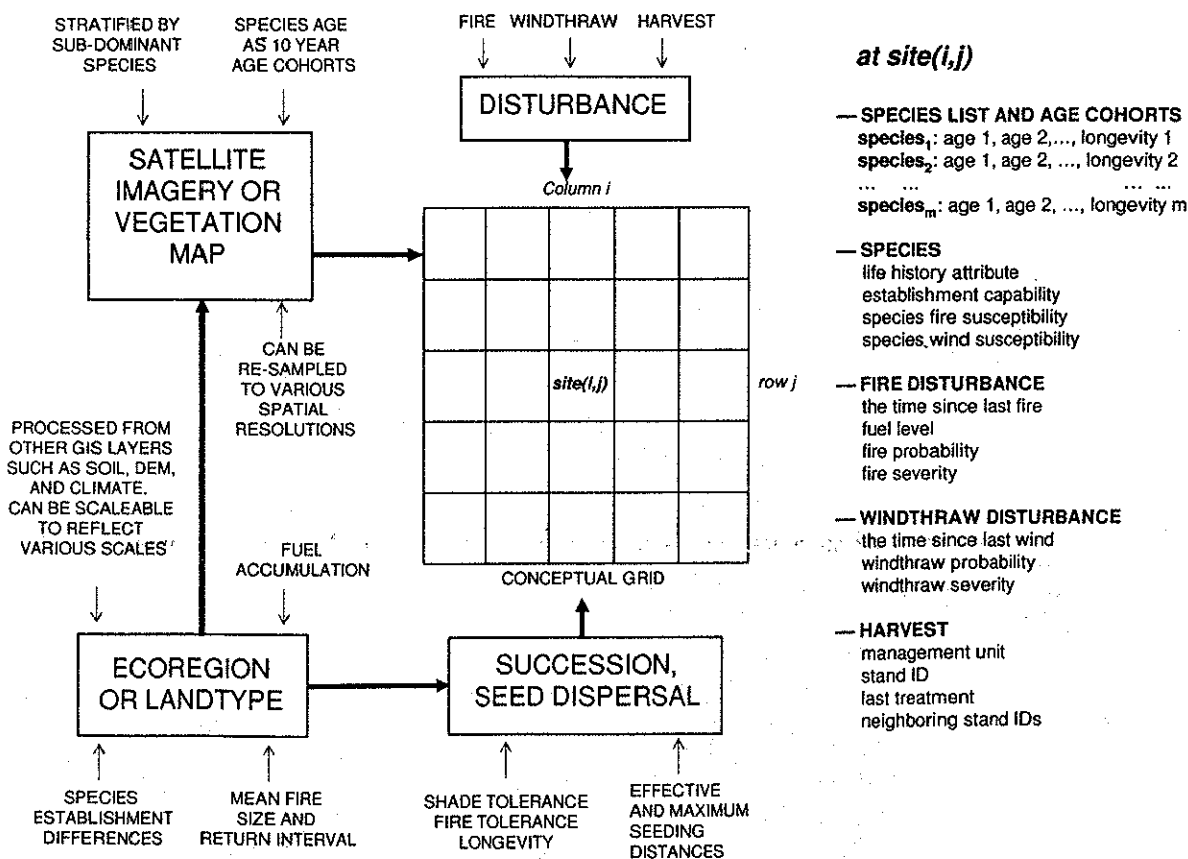


Fig. 1. Specifications in LANDIS model design. A landscape can be conceptualized as a grid of equal-sized individual cells or sites, e.g. site (*i,j*) and is stratified into environmentally homogeneous units as landtypes or ecoregions. Each site (*i,j*) on a certain landtype, records a unique species list and age cohorts of species. These species data change via establishment, succession and seed dispersal and interact with disturbances. The initial species and age cohort information can be derived from a species-level satellite classification or other existing vegetation map.

In other words, certain landtypes favor certain species over others. Therefore when a seed travels from site (m, n) to site (x, y) , it may or may not establish there depending on its establishment ability on the landtype where site (x, y) is located.

Succession at each site is a competitive process driven by species life history attributes. In contrast to most gap models which track each individual tree, succession (if included) is simplified in landscape models (e.g. Mladenoff et al., 1996; Roberts, 1996). Species competitive ability is mainly the combination of shade tolerance, longevity, vegetative reproduction capability, seeding capability and landtype suitability (Fig. 1). Seed dispersal is directly related to species effective and maximum seeding distances and it is also strongly affected by the existing seed source, which in turn can be highly altered by human and natural disturbances (He and Mladenoff, 1998). Spatially explicit seed dispersal needs to be designed to reflect this reality (Mladenoff et al., 1996).

Simulation of disturbance is combined with simulating succession. Any simulated disturbance is a result of spatially explicit interaction of environmental variables, vegetation information and the nature of disturbance itself. Fire and windthrow disturbances may occur at various locations on the landscape, with each event varying in time and form of occurrence. Neither the time when a disturbance occurs nor the pattern and shape of the disturbance is deterministic. They appear to be stochastic for a single site. Over a heterogeneous landscape however, they are not purely stochastic events since some landtypes and sites may be more prone to disturbance than others.

Fire is a bottom-up disturbance, since fires of increasing severity affect younger age-classes first. Fire severity is determined by fuel availability, which is based on time since the last fire and landtype characteristics that influence fuel production and decomposition (He and Mladenoff, 1999). Windthrow is a top-down disturbance and the probability increases with tree age and size. The time since a windthrow event can also influence the potential fire severity class, depending on

decomposition dynamics of the particular landtype. Interactions between these two disturbances can be interesting and complex. Generally, windthrow becomes more important on landtypes with long-lived species and where fire frequency is low. Mean disturbance return intervals and mean disturbance sizes can be derived from information in the literature on the region of interest (e.g. Heinzelman, 1973, 1981; Canham and Loucks, 1984; Frelich and Lorimer, 1991).

2.2. Modularity and abstraction

The essence of OOD is modularity, to where a complex problem is broken into multiple small and simple modules. In our case, the modules are the various ecological processes identified during model specification. Ecological processes differ in terms of the spatial and temporal scales at which they operate. For example, species life history attributes are static, independent of both spatial and temporal scales. Landtype, which may vary with spatial scales, is independent of temporal scale. Processes such as succession are constantly occurring on every site as long as a species exists. Seeding or seed dispersal also occurs constantly but operates at spatial extents larger than a single site. Other ecological processes such as fire, wind and harvest occur at landscape scales with strong temporal variations. Therefore in abstraction, ecological processes can be described as modules or objects from the spatially and temporally constant to the spatially and temporally explicit (Fig. 2). For spatially explicit landscape modeling, it is also necessary to identify the geographic objects where ecological processes occur. SITES and SITE occur as geographical objects on the landscape where various processes interact. SITES divide the entire landscape into rows and columns comprising singular SITES (Fig. 1). SITES and SITE link spatially and/or temporally constant modules with spatially and/or temporally explicit modules (Fig. 2). Each SITE contains unique information regarding SPECIES and their AGELISTS, which change via SUCCESSION through time. Information on LANDTYPE, a spatially explicit and temporally constant object, can be referenced from each

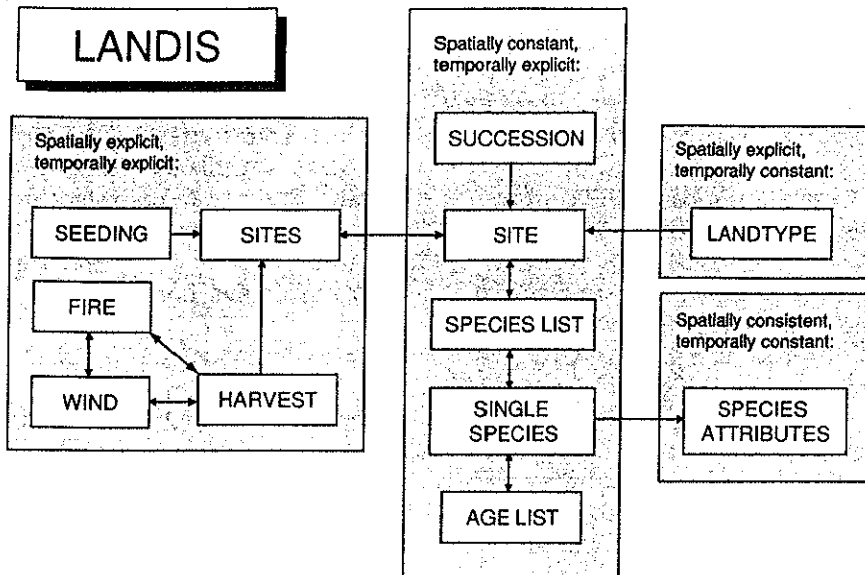


Fig. 2. LANDIS Modules. The modules correspond to the real world objects from spatially and temporally constant to spatially and temporally explicit.

SITE, SEEDING, WIND, FIRE and HARVEST, all spatially and temporally explicit processes, require spatial extents larger than a single SITE and operate on SITES. Interactions among FIRE, WIND and HARVEST exist since windthrows can potentially increase fire severity by adding fuels load due to blown-down trees and harvesting also affects fire probability and severity by changing the fuel regimes (Fig. 2).

Modularity and abstraction are often closely tied with model assumptions made during the design stage based on the purpose of the model. For example, wind, fire, or other disturbances can be integrated into one module, DISTURBANCE, or separated into individual modules. New spatially and temporally explicit modules such as forest DISEASE or INSECT defoliation can be added to the model. LANDTYPE can be further stratified into LANDFORM and SOIL. In all cases, assumptions built into the model define the scope of model application to disturbance. With OOD approaches these updates have little impact on the overall model structure.

2.3. Encapsulation

If modularity and abstraction involve high-level model decisions related to multiple objects, encapsulation involves low-level decisions that are object-specific, linking the high level model design (modularity and abstraction) to low level implementing. Encapsulation emphasizes the design of each object, including its internal (private member functions) and external (public member function) interfaces and data structure (data member).

2.3.1. Interface

An internal interface contains the internal functions or operations that can be only initiated within an object (e.g. Fig. 4). The idea of an internal interface originated with the information hiding approach (Pohl, 1993). The basic approach is that certain operations on the internal data structure should only be accessed from the object when inheritance and polymorphism are involved in the model design (Carrano, 1995). The technique is widely used in commercial software since accessibility involves highly sensitive security is-

sues (Booch, 1994). Internal functions can be omitted while external interfaces communicate with other objects and operate on the internal data members. It is generally true for ecological modeling that little effort is made on information hiding (e.g. Sequeira et al., 1997). For LANDIS objects, several internal operations are implemented, including the ability to 'read', 'write', 'copy' and 'dump' the internal data structure (e.g. Fig. 4). These are designed for input, output and debugging purposes. These operations are standard for all LANDIS objects.

The external interface of an object includes a set of public operations defined for the object (e.g. Fig. 4). It defines how a given object communicates with other objects. In most cases model updates involve re-defining, refining, replacing, or adding new functions to the external interface of certain objects. Under an OOD approach, changing an interface does not necessarily affect other object components. For example, changes made to the external interface of an object may have no impact on the internal interface and the data structure of that object. This makes the model updates and software reuse easier than those designed with the traditional approaches.

2.3.2. Data structure

The selection of data structures for the internal implementation of an object is an important process in model design. Data structures for different objects can vary significantly, such as those for fire (He and Mladenoff, 1999) and for species age cohorts, each designed to effectively accommodate the corresponding functions. The data structure implemented can substantially affect the performance in terms of running time of an application or simulation size limit. The rationale for employing a particular data structure is often not fully explained in descriptions of models that simulate biological systems (e.g. Chen and Reynolds, 1997; Sequeira et al., 1997). Since increasing model updates involve the replacement of old data structures, a comparison of various alternatives becomes important.

3. Example of object design: forest species objects

In the following sections, we further discuss the design of forest species objects, AGELIST, SPECIE and SPECIES, particularly their data structures, linkages and functions.

3.1. Age class (AGELIST object)

AGELIST is an object designed to store species age class information. It is generic and once designed, it can be populated with any forest species. AGELISTs are objects processing the greatest computer memory requirements in LANDIS model. Factors to consider when choosing a data structure include the efficiency (of common operations on the data), the memory overhead and implementation complexity. To illustrate these, we use an example to compare several typical data structures that can be employed in AGELIST. Assuming that we are simulating a landscape with only ten species, species and their age cohort data for a particular SITE are listed in Table 1.

3.1.1. Array based data structure

Arrays are the most popular data structures. A single species can be represented as an array with size corresponding to the longevity of the species. To record all the possible age cohorts of the above species, ten arrays with various sizes are needed: Balsam-fir [15], Aspen [9], Sugar-maple [30], Yellow-birch [20], Paper-birch [12], White-pine [40], Red-pine [25], Red-oak [25], White-cedar [25] and hemlock [45]. Arrays are designed for efficient access. Some common succession operations such as insertion (insert an age cohort, e.g. germination or new seed establishment) and deletion (remove an age cohort, e.g. species death) are very efficient. Retrieval (e.g. locate certain age cohort) is very efficient too. These operations are used by SUCCESSION and HARVEST for removal of certain species which have reached their longevity, or for planting certain species at age 10. However, existence querying (e.g. search age cohort to determine if a species exists) is inefficient with arrays. In the worst case, every data member has to be visited before the program knows that

Table 1
Typical array representation of species age cohorts

Species	Age-cohorts (years)	Longevity (years)	Arrays
Balsam fir	10, 80	150	Balsam-fir [1–15]
Quaking aspen	not present	90	Aspen [1–9]
Sugar maple	40, 90, 190, 270, 290	300	Sugar-maple [1–30]
Yellow birch	200	300	Yellow-birch [1–30]
Paper birch	not present	120	Paper-birch [1–12]
White pine	250	400	White-pine [1–40]
Red pine	not present	250	Red-pine [1–25]
Red oak	not present	250	Red-oak [1–25]
White cedar	not present	250	White-cedar [1–25]
Hemlock	10, 20, 100, 150, 200	450	Hemlock [1–45]

aspen is not present at the above sample SITE. This may suggest a significant drawback in speed, since existence querying is one of the most common and time-consuming operations in AGELIST.

If age presence or absence is represented as an integer (each array element holding one integer), there is a total of 256 integers needed for the SITE, the sum of all array elements. On a 32-bit computer, with each integer taking 4 bytes of memory, this equals 1024 bytes (Table 1). Since the same set of arrays is needed for every single SITE, assuming the simulated landscape contains 300 (rows) $\times$ 300 (columns) SITES, the total amount of memory used for species information is 300 $\times$ 300 $\times$ 1024 bytes, or about 90 MB. For a simulation of the same landscape containing 30 species assuming the longevity of average species is 150 years, the minimum memory required for species information alone is about 154 MB. Even if we replace the integer representation with characters (one character requires 2 bytes), reducing the memory requirement to about 77 MB, an array-based implementation is impractical as demonstrated. If employed it can significantly limit model application to small areas.

3.1.2. Bit-wise based data structure

In bit-wise representation, the species age list is represented as an array of binary data with each element containing 0 or 1: 0, denotes the species age cohort absent; and 1, denotes present. Thus for the example SITE, species age cohort informa-

tion is contained in an array, say, BitArray [10] (Table 2).

Since each digit represents a bit, on a 32-bit machine, 64 digits can represent species longevity up to 640 years, which satisfies all common tree species found in the Eastern US (Burns and Han-kala, 1990). For the example SITE, the bit-wise representation of an array of size 10 takes only 40 bytes to represent all age cohorts in the SITE (Table 2). For a landscape containing 300 $\times$ 300 SITES, total memory required for storing species age information is less than 4 MB. If simulating

Table 2
Bit-wise array representation of species age-cohorts

Species	Age-cohorts	Array
Balsam fir	0100000010000000	Bit-array [1]
Aspen	0000000000	Bit-array [2]
Sugar maple	000010000100000000010 0000001010	Bit-array [3]
Yellow birch	000000000000000000001 0000000000	Bit-array [4]
Paper birch	000000000000	Bit-array [5]
White pine	000000000000000000000 000010000000000000000	Bit-array [6]
Red pine	000000000000000000000 00000	Bit-array [7]
Red oak	000000000000000000000 00000	Bit-array [8]
White cedar	000000000000000000000 00000	Bit-array [9]
Hemlock	011000000010000010000 010000000000000000000 0000	Bit-array [10]

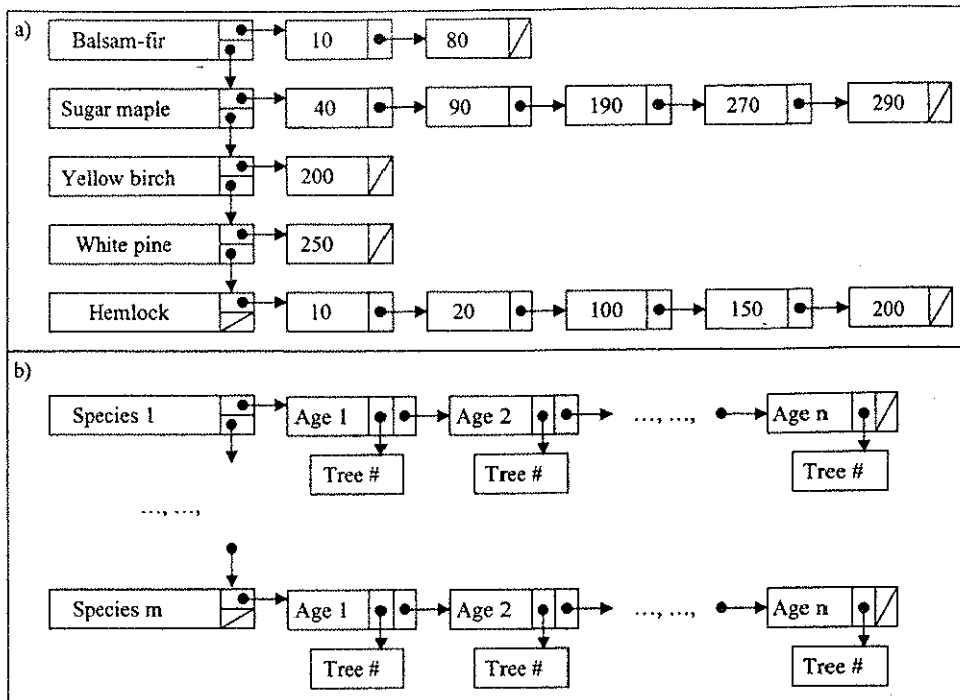


Fig. 3. Sorted linked list representation for: (a) species age-cohorts; (b) species age-cohorts and number of individual trees or density.

the same landscape with 30 species, total memory requirement for storing species age cohorts is less than 11 MB. Because the bit-wise array is so space efficient, it allows the model to be applied to large landscapes. Operations such as insertion at the youngest end and deletion at the oldest end of age cohorts are very efficient in bit-wise operation, involving bit shifting. Inserting a particular age cohort (such as planting), or deleting a certain age cohort in the middle (due to cutting or disturbance) is no less efficient than insertion or deletion at the ends. Similar to the array based data structure, query operation is inefficient. For the worst case, every bit has to be visited to decide that aspen does not exist on this SITE.

A significant deficiency that exists for both the array and the bit-wise data structure exists with the fixed 10-year age cohort representation (although it was a specification of design). It is impossible to apply this data structure to simulations of a time step other than 10 years. Holding of empty spaces (e.g. when species or age cohorts

are not present) is another inefficiency. It not only wastes memory, but more importantly, can significantly increase the run time by lengthening the time of existence queries.

3.1.3. Sorted linked list

A linked list is an abstract data type with each data element (node) referring to the next element with a pointer. A sorted linked list manages the data in a sequential order (e.g. sorted by value or name). One of the advantages of a linked list is its reliance upon dynamic allocation of computer memory. Only species and age cohorts present are stored. The species and their age cohort information from the example SITE can be represented with multiple sorted linked lists (Fig. 3a).

Among these lists, the vertical list constitutes a species name list, while horizontal lists comprise the corresponding age cohorts of the species (Fig. 3a). For this particular SITE, if ages are presented as integers, it takes 128 bytes (each pointer takes 4 bytes). For a landscape containing 300×300

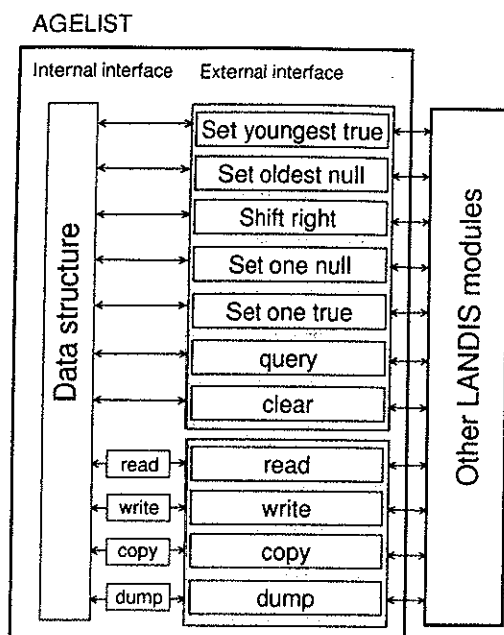


Fig. 4. LANDIS object—AGELIST, containing information for species age cohorts on a given site (cell).

SITES, assuming other SITES contains the similar species information, total memory required for storing species age information is only approximately 12 MB. When expanded to 30 species, the amount of memory increase, if any, will not be significant compared to the other two data structures described above. It should be pointed out that with dynamic memory allocation, the actual amount of memory required to represent species information varies. When the majority of SITES on the landscape contain most species and multiple ages, memory requirements can be large. However, forest landscapes are more often composed of many fewer species and age cohorts than the theoretical maximums due to competition. Therefore, the sorted linked list can be a memory-efficient method for storing species age information. Common operations of this data structure such as insertion and deletion are as efficient as a bit-wise data structure. Additionally, existence querying is much more efficient than the other two data structures since only species and age cohorts present are recorded in lists that are sorted.

A significant advantage of using a linked list data structure is that the datum of each node can be any integer. In other words, the model can be potentially applied to various model time-steps such as 1 or 3 years. Also, each node can theoretically have another attribute to keep track either individual tree species or forest density (Fig. 3b), providing greater potential of model application. Disadvantages to using a sorted linked list or other advanced abstract data types such as various tree data structures (Carrano, 1995) include that they are more difficult to code than the other two. Implementation can be much longer than the other two and the resulting programs can be difficult to debug.

3.1.4. Interface of AGELIST

All external operations defined for AGELIST are species related (Fig. 4). 'Set youngest true' simulates birth of a species, when a new age cohort is set present at 10 years old. 'Set last null' simulates death, when the last age cohort of a species is set to null. 'Shift right' simulates growth, when all age cohorts increase 10 years by moving rightward in the bit-level data structure. 'Set one null' simulates removal of a certain species age cohort. 'Set one true' sets a given age cohort (not necessarily the first), a method used for initialization of age information. 'Clear' simulates the removal of an entire age cohort of a species. 'Query age cohort' allows other objects to query for certain age classes, a method frequently requested by SUCCESSION, DISPERSAL, FIRE, WIND and HARVEST.

3.2. Single species (SPECIE object)

SPECIE is an object designed for a single forest species. Each SPECIE has its own AGELIST and species-specific functions.

3.2.1. Data structure of SPECIE

SPECIE inherits data members and interfaces from AGELIST. Inheritance, an important feature of OOD, is the mechanism by which some objects are specified as the decedents of others (Booch, 1994; Carrano, 1995). In this case, SPECIE, a single species object, has whatever data

structure AGELIST implements, whether it is an array of integers, a bit-wise array, or horizontal sorted linked list.

3.2.2. Interface of SPECIE

Operations defined for SPECIE includes the 'name', 'attribute', 'birth', 'death', 'growth', 'remove', 'clear' and 'query' (Fig. 5). 'Name' and 'attribute' are used to reference species name and attributes. 'Birth', 'death', 'growth', 'remove' and 'clear' mirror those in AGELIST. 'Birth' simulates a new species seeding in from another site, or on-site species regeneration. The latter usually applies to high shade tolerance species. For some species 'birth' simulates vegetative reproduction. 'Death' typically simulates species reaching their maximum longevity. It applies only to the particular age cohort that reaches species longevity. 'Growth' simulates species age-class increment during each model iteration. 'Remove' simulates the removal of one or more age cohorts of a species from the site due to various causes. Disturbances, harvest and background mortality 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. 'Remove' differs from 'death' in that it can remove any age cohort of the species. 'Clear' simulates the removal of the species (entire age cohorts) on the site, which usually accompanies severe fire disturbances or clear-cut harvest. For example, when SPECIE interacts with a fire object with severity class of four, all age cohorts are cleared if the species' fire tolerance class is of one (He and Mladenoff, 1999).

3.3. Species list (SPECIES)

SPECIES is a list of one or more species present on a given site. It is implemented with some generic operations for a list.

3.3.1. Data structure of SPECIES

SPECIES is an object that maintains a list of species present on each SITE. Since it does not deal with the features of any particular species, data members of AGELIST are not available to a SPECIES object. However, since a species list such as the vertical list in the sorted linked list already exists for any given SITE, there is no need to define new data structures or allocate separate memory locations to duplicate the same information. Rather, a pointer to AGELIST is a data member of SPECIES. This allows a SPECIES object to reference an individual SPECIE object. Other data members of SPECIES include integers tracking the current species (ID) and the total number of species on the SITE and a pointer to reference species attributes.

3.3.2. Interface of SPECIES

For the most part, the external interface of SPECIES includes utility functions to manage the species list (Fig. 6). 'First' sets an internal iterator to point at the first species in the list. 'Current' returns a reference to the species currently pointed to by the internal iterator. 'Next' moves the internal iterator to the next species in the list. 'Attributes' returns a reference to the attribute object of a given species. 'Number' returns the total number of species on the SITE. SPECIES is in-

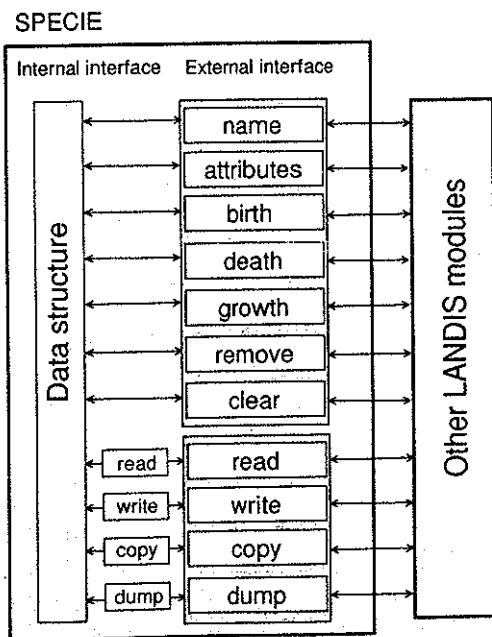


Fig. 5. LANDIS object—SPECIE, containing information for single species on a given site (cell).

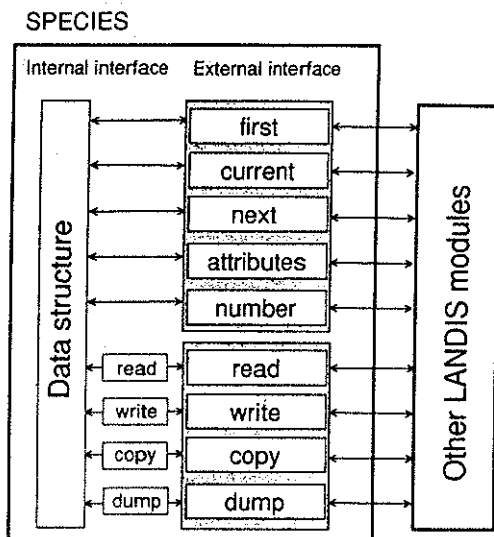


Fig. 6. LANDIS object—SPECIES, containing information of species list on a given site.

herited by SITE. The request of query for the oldest or the youngest species on the SITE is a common operation.

4. Model application

To demonstrate the capability of tracking age cohorts of individual species by the forest species objects, we chose a real landscape in northern Wisconsin, where simulations have been conducted to examine fire disturbance and successional dynamics at forest type level (He and Mladenoff, 1999). In this paper, we further analyze dynamics of forest species at age-classes level, illustrating the previous description of forest species objects.

4.1. Study area

The study landscape, comprising nearly 500 000 ha, is located in northwestern Wisconsin (46°91' to 47°92'). It is in a transitional zone between the boreal forest of Canada and the central deciduous forests to the south (Curtis, 1959). The area has been glaciated and there is little topographic relief. In the 19th century the region was largely

dominated by pine (*Pinus Strobus*, *P. resinosa*), eastern hemlock (*Tsuga canadensis*) and sugar maple (*Acer saccharum*). Yellow birch (*Betula alleghaniensis*), paper birch (*B. papyrifera*), spruce (*Picea glauca*) and balsam-fir (*Abies balsamea*) were also common. Today the region is largely covered by second and third growth forests following extensive logging and fire in the late 19th and early 20th centuries (Pastor and Mladenoff, 1992; Mladenoff and Pastor, 1993).

4.2. Model input

The model input map was derived from a classification of multi-temporal Landsat TM/MSS satellite imagery, representing spatial distributions of dominant canopy species or forest types at species and genus levels (Wolter et al., 1995). Secondary associated species and age-class information were derived by integrating the TM classification with forest inventory plot data (Hansen et al., 1992), stratified by landtypes (He et al., 1998b). A total of 23 species and 134 unique species-age cohort combinations resulted on the input map. To reflect the relative growth capability of each tree species under the environmental conditions of different landtypes, individual species establishment coefficients (0–1) were calculated based on species relative performance on different landtypes. These coefficients can be assigned directly by interpreting the available literature or derived from an ecosystem process model (He et al., 1998a). All life history attributes of species were derived from the literature as reported elsewhere (Mladenoff et al., 1996; Mladenoff and He, 1999). Historical fire data (mean disturbance size and mean fire return intervals) were interpreted from empirical studies in the region (Heinselman, 1973, 1981; Frelich and Lorimer, 1991). Mean fire size was set to 3200 ha, about 3% of the total area, with a maximum fire size of 16 000 ha, about 15% of the landscape. Mean fire return intervals vary among landtypes from 200 years on dry and sandy soil, to 500 years (well-drained loam), to 800 years (moderate to well-drained silt) and 1000 years (moderate drained silt and clay). Landtype boundaries were derived from an existing quantitative ecosystem

classification. The landscape was processed into 121 362 SITES (358×339 cells) with a 200×200 m cell size.

4.3. Results and analysis

We examined four tree species hemlock, sugar maple, white pine and quaking aspen, to analyze their age-class dynamics in a spatially explicit manner. The four species differ significantly in successional stage and current spatial distribution. Hemlock and sugar maple, with 450 and 400 years longevity, respectively, are shade tolerant, late successional species. They allow us to examine the multiple age-classes that may occur within stands. White pine is also long-lived (400 years longevity), but medium in shade tolerance. Quaking aspen is an early successional species with 90 years longevity. Maps of age cohorts at 10-year intervals were generated for each species. When multiple age cohorts occurred at a SITE, the oldest was plotted at that site. The frequencies of each age-class were then tallied across the landscape from these maps. The number of SITES at which a given age cohort occurred was represented as the percentages of the landscape, e.g. (number of SITES where age cohort n occurred)/(total number of SITES) $\times 100\%$. This was done for all the four species at each time step from year 0 to year 200. To summarize age-class dynamics, the age-class tally was then divided into five classes using natural breaks that identified breakpoints between classes so that each class has minimum variance (ESRI, 1996, Fig. 7a–d).

Hemlock, in general, is not abundant due to the historical logging of the past 100 years (Mladenoff and Stearns, 1993). At year 0, the largest group of hemlock is 60 years old, occupying only 0.9–1.3% of the landscape (Fig. 7a). The oldest age-class is 80 years old, covering 0.3–0.9% of the landscape. Hemlock regeneration, represented as ≤ 10 years old seedlings, occurs on 0.3–0.9% of the landscape (Fig. 7a). At year 10, all the previous age-classes of hemlock are increased by 10 years. The continuing increments create diagonal patterns depicting the percentage of species occurring on the landscape in relation to the simulation years and species age-classes. Hemlock regenera-

tion increased at year 10 with mature 60, 70 and 80 year hemlock present (0.9–1.3% of the landscape). Due to its competitive ability and low initial population, the increase of hemlock seedlings continues for about 100 years. However, after year 100, hemlock seedlings begin to decline. The decrease of hemlock seedlings before year 200 is due to the fire simulated for that period (He and Mladenoff, 1999), since young trees are more susceptible to fires than the old trees. At year 200, hemlock has substantially increased compared to its starting level. In general, the increasing trend will continue as indicated by the abundant seed sources of age-classes from 80 to 180.

Sugar maple is the dominant species in the study area. At year 0, both regeneration of 10 years old age-class and other age-classes are abundant, with 2.2–4.2% of the landscape containing sugar maple seedlings and 50, 60, 70 and 150 years old sugar maple occurring on 4.2–8.7% of the landscape (Fig. 7b). The older maple at various age-classes provide the potential seed sources. However, since sugar maple is the most fire intolerant species, its youngest seedlings are most susceptible to fire. The simulation results indicate that maple seedlings, largely at 0.4–1.2% of the landscape, did not re-attain their initial highs of years 0–20. The age-classes of sugar maple are uniformly distributed (Fig. 7b). This presents great potential for seedling increase when fire-breaks occur. At year 200, no significant increase of sugar maple is simulated (Fig. 7b).

White pine, another native dominant species, has very low abundance due to historical cutting (Fig. 7c), with the largest age class covering only 0.4–0.5% of the landscape. It is interesting to note that there is a 110 year age-class of white pine, then seedlings, occurring at 0.2–0.4% of the landscape (Fig. 7c). Combined with other age-classes existing at year 0, white pine regeneration is strong at year 0. White pine is not negatively affected by fire as are hemlock and sugar maple, but is less shade tolerant. Its seedlings need open space to establish. A repeated seedling pattern is simulated reflecting the periodicity of fire disturbance. Increases in white pine seedlings from year 160–200 where fires are frequent were observed (Fig. 7c). At year 200, white pine is significantly increased compared to year 0.

Quaking aspen is abundant at year 0 as a result of historical cutting and fires that favored its regeneration. While simulating the realism of the historical fire regime, the percentage of aspen seedlings on the landscape shows a similar pattern as found for white pine (Fig. 7d). Aspen generally decreases with the year of simulation but responds positively when fires are frequent (years 160–200).

All aspen age cohorts are within the 90 years range of its longevity (Fig. 7d).

Species age-class information can be examined in a spatially explicit manner. To show this, we took a snapshot of hemlock and sugar maple at year 0, 100 and 200 (Fig. 8a–f). At year 0, most hemlock is rare and young (<60 years). A few scattered pixels of hemlock old growth (about 120

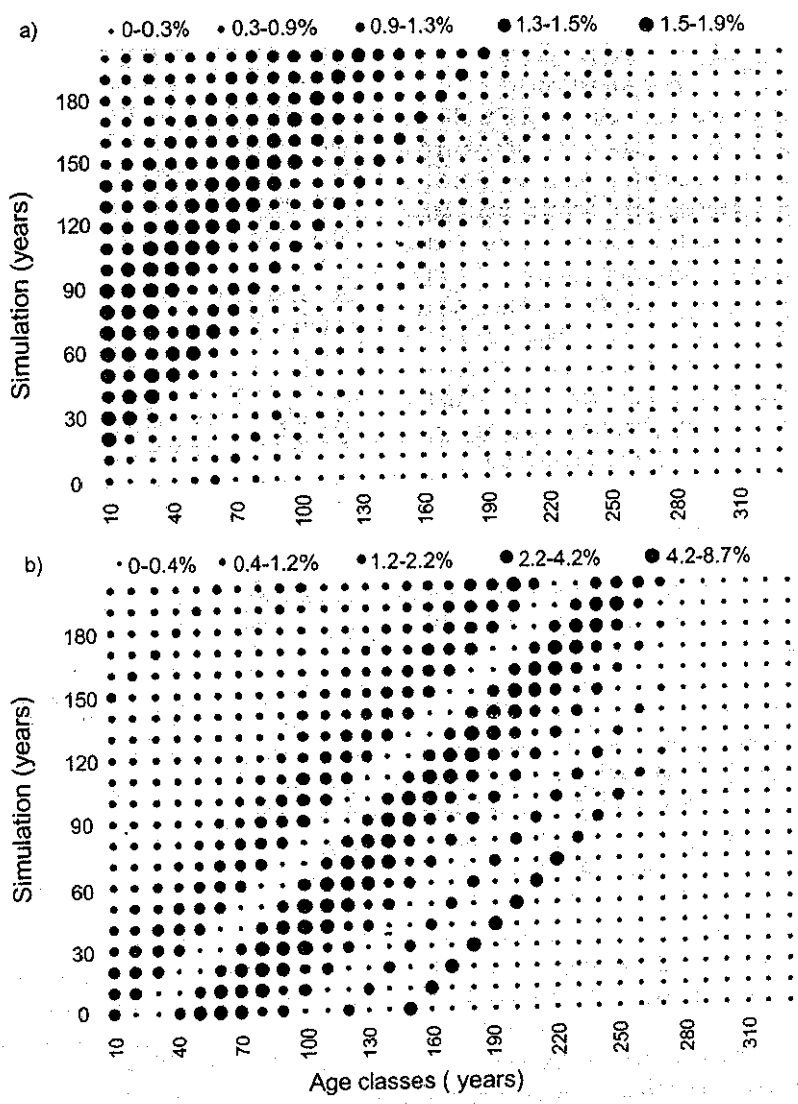


Fig. 7. The percentage ratings in response to age-class and simulation year for: (a) hemlock; (b) sugar maple; (c) white pine; and (d) quaking aspen.

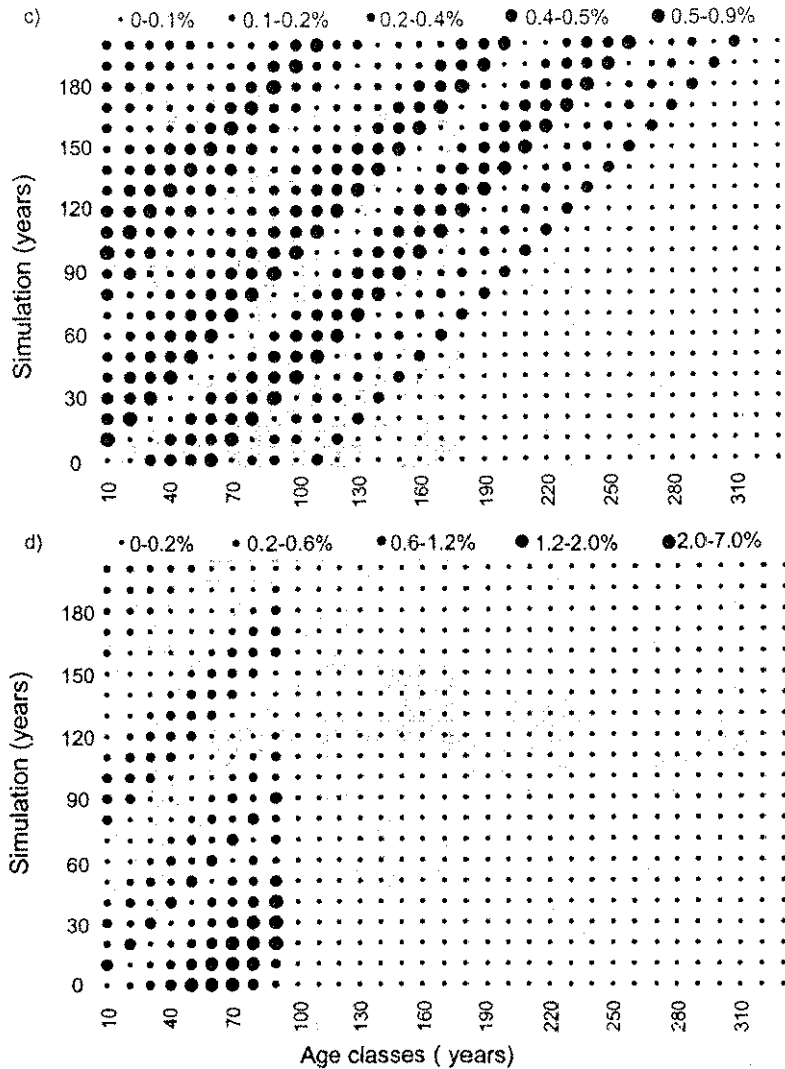


Fig. 7. (Continued)

years) which are not apparent in Fig. 7a are visible in Fig. 8a. At year 100, older hemlock age-classes (> 120 years) emerge while the majority remains young (< 60 years). Although some hemlock has been removed by fire disturbance, its abundance is significantly increased at this point (Fig. 8c). At year 200, hemlock patches are more consolidated and their age-classes more all-aged (Fig. 8e), as previously summarized (Fig. 7a). Sugar maple at year 0 is dominant on the land-

scape with age classes mostly < 60 years. Sugar maple old growth (age classes 120 and 150 years, Fig. 7b) is visible on some parts of the landscape (Fig. 8b). At year 100, sugar maple age-classes have diversified, with the majority reaching 150–180 years old (Fig. 8d). The pattern of fire patches is reflected in the distribution of sugar maple age classes across the landscape because sugar maple is the most fire intolerant species (Fig. 8d). At year 200, sugar maple remains dominant through-

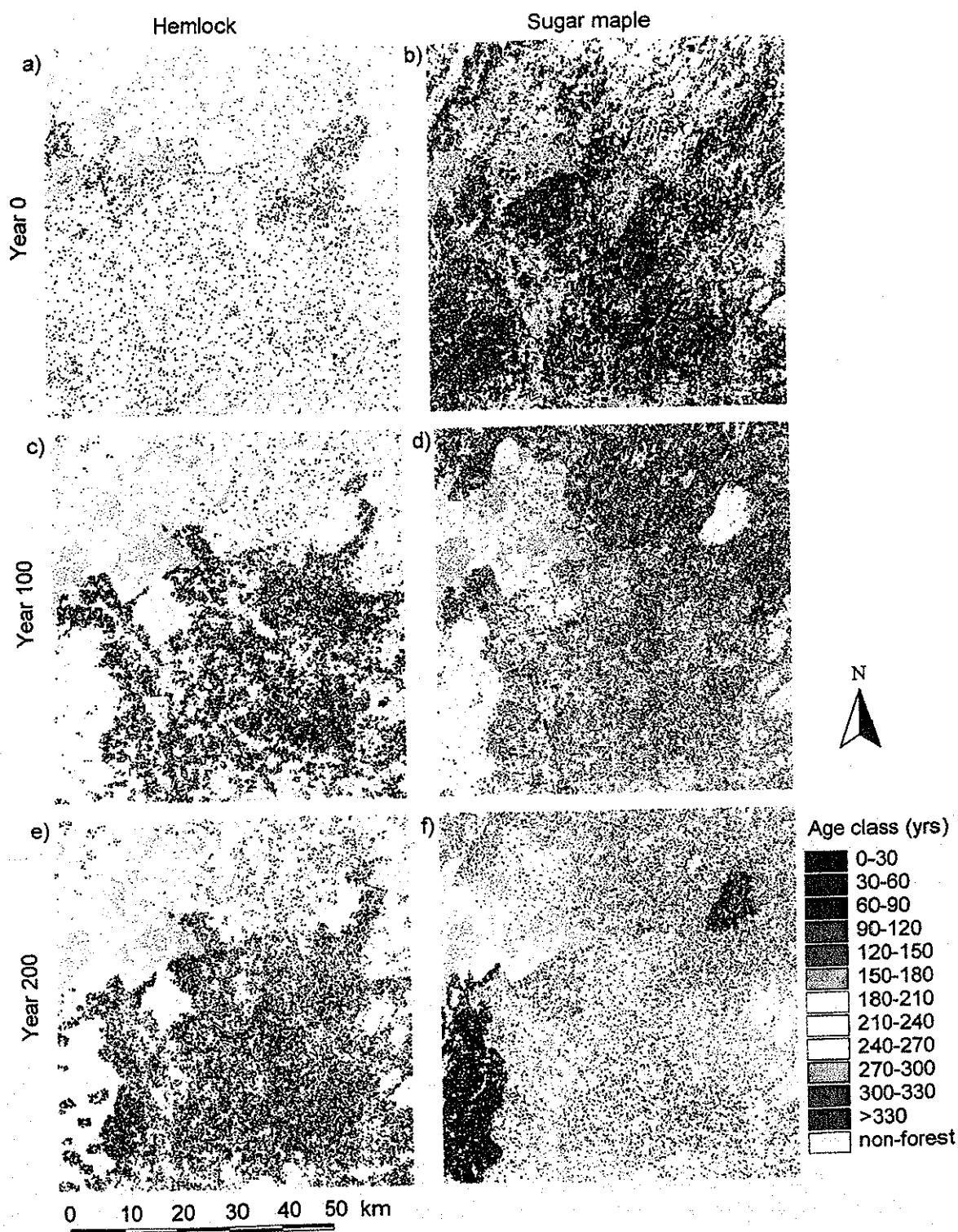


Fig. 8. Age-class distribution for hemlock (a, c, e) and sugar maple (b, d, f) for years 0, 100 and 200, respectively.

out (Fig. 7b) and the spaces opened by fires are gradually re-colonized with younger maples (< 90 years, Fig. 8f). As shown here, we are able to capture spatially explicit dynamics at the species age-class level with forest species object design in LANDIS.

5. Conclusion

The OOD approach is used in LANDIS to integrate various ecological processes for simulating forest landscape change at the species level over large spatial and time domains. The independence of LANDIS objects allows us to examine the consequence of landscape change under different sets of simulation conditions. For instance, the simulation described in this paper has fire as the only active disturbance. Simulations involving no disturbance, both wind and fire disturbances, or forest cutting can also be carried out (Mladenoff et al., 1996; He and Mladenoff, 1999; Gustafson et al., submitted). The ability to track each species as a 10-year age cohort from seedling to death for all sites can reveal new and important ecological information. The spatially explicit results are essential to issues such as species regeneration, harvest, planning and forest management decision-making. The capability of spatially explicit simulation of forest species in combination with various disturbances makes LANDIS, using the OOD approach, a useful tool for investigating issues such as forest landscape response to potential climate warming, landscape succession under different disturbance regimes and the impact on species composition of different harvesting regimes.

Programming methodology, either OOD or a traditional approach, does not change the essence of modeling. Modeling defines complex processes and their interactions logically and mathematically to deduce results that otherwise cannot be investigated. As described however, techniques of OOD are beneficial to the design of complicated models such as LANDIS. OOD is complementary to our understanding of ecological processes since often, when analyzing landscape dynamics, what ecological processes are involved, how they inter-

act and how to represent them, are research questions of interest and are also the assumptions that need to be made at modularity, abstraction and encapsulation levels. With OOD approach, these assumptions can be updated as our understanding of landscape processes increase. In general, model updates involve modifying model assumptions by adding/removing new objects, redefining external interfaces of the objects to support new operations and replacing the internal object representations with the ones that better utilize new hardware resources. Since the interface of an object is independent to the data structure employed, varying data structure should not affect the interface and varying interface should not affect the data structure. With OOD, various components of objects are less interdependent than the traditional programs and updates of OOD models can be done more efficiently than that for monolithic models.

Acknowledgements

We appreciate suggestions from Ted Sickley, Barry DeZonia, Volker Radeloff and Gary Wockner. This work was funded in part through a cooperative agreement with the USDA Forest Service Northern Global Change Program.

References

- Acock, B., Reynolds, J.F., 1997. Introduction: modularity in plant models. *Ecol. Model.* 94, 1–6.
- Acock, B., Reddy, V.R., 1997. Designing an object-oriented structure for crop models. *Ecol. Model.* 94, 33–44.
- Baker, W.L., Egbert, S.L., Frazier, G.F., 1991. A spatial model for studying the effects of climatic change on the structure of landscapes subject to large disturbances. *Ecol. Model.* 56, 109–125.
- Baker, W.L., Mladenoff, D.J., 1999. Progress on spatial modeling of forest landscapes. In: Mladenoff, D.J., Baker, W.L. (Eds.), *Advances in spatial modeling of forest landscape change: approaches and applications*. Cambridge University Press, Cambridge, UK.
- Booch, G., 1994. *Object-oriented analysis and design with applications*. Benjamin/Cummings, Redwood, CA.
- Brown, J.K., Oberheu, R.D., Johnson, C.M., 1982. *Handbook for inventory surface fuel and biomass in the interior forest*. USDA Forest Service Technical Report INT 129.

- Burns, R.M., Hankala, B.H. (tech. coords.), 1990. Silvics of North America Volume 1. Conifers and Volume 2. Hardwoods. USDA Forest Service Agriculture Handbook 654.
- Canham, C.D., Loucks, O.L., 1984. Catastrophic windthrow in the presettlement forests of Wisconsin. *Ecology* 65, 803–809.
- Carrano, F.M., 1995. Data Abstraction and Problem Solving with C++—Walls and Mirrors. Benjamin/Cummings, Redwood City, CA.
- Chen, J., Reynolds, J.F., 1997. GePSi: A generic plant simulator based on object-oriented principles. *Ecol. Model.* 94, 53–66.
- Congleton, W.R., Pearce, B.R., Beal, B.F., 1997. A C++ implementation of an individual/landscape model. *Ecol. Model.* 94, 1–17.
- Curtis, J.T., 1959. The vegetation of Wisconsin: an ordination of plant communities. University of Wisconsin Press, Madison, WI.
- Downing, K., Reed, M., 1996. Object-oriented migration modeling for biological impact assessment. *Ecol. Modell.* 93, 203–219.
- ESRI, 1996. Arcview 3.0. ESRI Inc. Redlands, CA.
- Franklin, J., Martin, R., Miller, J., Mladenoff, D.J., He, H.S., 1997. Parameterizing and calibrating the LANDIS model of disturbance and succession to examine the effects of altered fire regimes on vegetation patterns in southern California. International Society for Mediterranean Ecosystems MEDECOS VIII: Conference on Mediterranean Type Ecosystems (Abstract). San Diego, CA.
- Frelich, L.E., Lorimer, C.G., 1991. Natural disturbance regimes in hemlock hardwood forests of the upper Great Lakes region. *Ecol. Monogr.* 61, 145–164.
- Gardner, R.H., Hargrove, W.W., Turner, M.G., Romme, W.H., 1996. Climate change, disturbances, and landscape dynamics. In: Walker, B.H., Steffen, W.L. (Eds.), IGBP Book Series, No. 2. Cambridge University Press, UK.
- Gardner, R.H., Romme, W.H., Turner, M.G., 1999. Effects of scale-dependent processes on predicting patterns of forest fires. In: Mladenoff, D.J., Baker, W.L. (Eds.), *Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications*. Cambridge University Press, Cambridge, UK.
- Green, D.G., 1989. Simulated effects of fire, dispersal and spatial pattern on competition within forest mosaics. *Vegetatio* 82, 139–153.
- Gustafson, E.J., Crow, T.R., 1994. Modeling the effects of forest harvesting on landscape structure and the spatial distribution of cowbird brood parasitism. *Landscape Eco.* 9, 237–248.
- Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S. Spatial simulation of forest succession and harvesting using LANDIS. *Can. J. For. Res.* (submitted).
- Hansen, M.H., Frieswyk, T., Glover, J.F., Kelly, J.F., 1992. The eastwide forest inventory data base: user's manual. USDA Forest Service General Technical Report, NC 151.
- He, H.S., Mladenoff, D.J., 1999. Spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. *Ecology* 80.
- He, H.S., Mladenoff, D.J., 1998. Spatially explicit simulation of seed dispersal using a forest landscape model. In: *Proceeding of Modeling of Complex System Conference and COM Workshop*. June, New Orleans, LA.
- He, H.S., Mladenoff, D.J., Boeder, J., 1996. LANDIS, a spatially explicit model of forest landscape disturbance, management and succession—LANDIS 2.0 users' guide. Department of Forest Ecology and Management, University of Wisconsin-Madison, Madison, WI.
- He, H.S., Mladenoff, D.J., Crow, T.R., 1998a. Linking an ecosystem model and a landscape model to study forest species response to climate warming. *Ecol. Model.* 112, 213–233.
- He, H.S., Mladenoff, D.J., Radeloff, V.C., Crow, T.R., 1998b. Integration of GIS data and classified satellite imagery for regional forest assessment. *Ecol. Appl.* 8, 1072–1083.
- Heinselman, M.L., 1973. Fire in the virgin forests of the boundary waters canoe area, Minnesota. *Quat. Res.* 3, 329–382.
- Heinselman, M.L., 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.C. (Eds.), *Fire regimes and ecosystem properties*. USDA Forest Service General Technical Report WO-26.
- Host, G.E., Polzer, P.L., Mladenoff, D.J., Crow, T.R., 1996. A quantitative approach to developing regional ecosystem classifications. *Ecol. Appl.* 6, 608–618.
- Kauffman, J.B., Uhl, C., Cummings, D.L., 1988. Fire in the Venezuelan Amazon 1: fuel biomass and tree chemistry in the evergreen rainforest of Venezuela. *Oikos* 53, 167–175.
- Keane, R.E., Morgan, P., Running, S.W., 1996. Fire-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. USDA Forest Service Research Paper INT-RP-484.
- Lemmon, H., Chuk, N., 1997. Object-oriented design of a cotton crop model. *Ecol. Model.* 94, 45–51.
- Li, C., Ter-Mikaelian, M., Perera, A., 1997. Temporal fire disturbance patterns on a forest landscape. *Ecol. Model.* 99, 137–150.
- Luo, Y., Field, C.B., Monney, H.A., 1997. Adapting GePSi (Generic Plant Simulator) for modeling studies in the Jasper Ridge CO₂ project. *Ecol. Model.* 94, 81–88.
- Maley, C.C., Caswell, H., 1993. Implementing i-state configuration models for population dynamics: an object-oriented approach. *Ecol. Model.* 68, 75–89.
- Mladenoff, D.J., Host, G.E., Boeder, J., Crow, T.R., 1996. LANDIS: a spatial model of forest landscape disturbance, succession and management. In: Goodchild, M.F., Steyaert, L.T., Parks, B.O. (Eds.), *GIS and Environmental Modeling: Progress and Research Issues*. GIS World Books, Fort Collins, CO.
- Mladenoff, D.J., Baker, W.L., 1999. Development of forest modeling approaches. In: Mladenoff, D.J., Baker, W.L. (Eds.), *Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications*. Cambridge University Press, Cambridge, UK.

- Mladenoff, D.J., He, H.S., 1999. Design and behavior of LANDIS, an object-oriented model of forest landscape disturbance and succession. In: Mladenoff, D.J., Baker, W.L. (Eds.), *Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications*. Cambridge University Press, Cambridge, UK.
- Mladenoff, D.J., Pastor, J., 1993. Sustainable forest ecosystems in the northern hardwood and conifer forest region: concepts and management. In: Aplet, G.H., Johnson, N., Olson, J.T., Sample, V.A. (Eds.), *Defining Sustainable Forestry*. Island Press, Washington DC.
- Mladenoff, D.J., Stearns, F., 1993. Eastern hemlock regeneration and deer browsing in the Northern Great Lakes region—a re-examination and model simulation. *Conserv. Biol.* 7, 889–900.
- Moen, R., Pastor, J., Cohen, Y., 1996. A spatially explicit model of moose foraging and energetics. *Ecology* 77, 505–521.
- Pastor, J., Mladenoff, D.J., 1992. The southern boreal-northern hardwood forest border. In: Shugart, R.L., Bonan, G.B. (Eds.), *A Systems Analysis of the Global Boreal Forest*. Cambridge University Press, Cambridge, UK.
- Pickett, S.T.A., Cadenasso, M.L., 1995. Landscape ecology: spatial heterogeneity in ecological systems. *Science* 26, 331–334.
- Pohl, I., 1993. Object-oriented programming using C++ . Benjamin/Cummings, Redwood, CA.
- Reynolds, J.F., Acock, B., 1997. Modularity and genericness in plant and ecosystem models. *Ecol. Modell.* 94, 7–16.
- Roberts, D.W., 1996. Modeling forest dynamics with vital attributes and fuzzy systems theory. *Ecol. Model.* 90, 161–173.
- Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., Lorensen, W., 1991. *Object-orientated modeling and design*. Prentice-Hall, New York.
- Sequeira, R.A., Olson, R.L., McKinion, J.M., 1997. Implementing generic, object-oriented models in biology. *Ecol. Model.* 94, 17–31.
- Sequeira, R.A., Sharpe, P.J.H., Stone, N.D., El-Zik, K.M., Makela, M.E., 1991. Object-oriented simulation: plant growth and discrete organ to organ interactions. *Ecol. Model.* 67, 285–306.
- Shifley, S.R., Thompson, F.R., Larsen, D.R., Mladenoff, D.J., 1997. Modeling forest landscape change in the Ozarks: guiding principles and preliminary implementation. USDA Forest Service General Technical Report NC-188.
- Silvert, W., 1993. Object-oriented ecosystem modelling. *Ecol. Model.* 68, 91–118.
- Turner, M.G., Romme, W.H., Gardner, R.H., 1994. Landscape disturbance models and the long-term dynamics of natural areas. *Natural Areas J.* 14, 3–11.
- Turner, M.G., Romme, W.H., Gardner, R.H., O'Neill, R.V., Kratz, T.K., 1993. A revised concept of landscape equilibrium: disturbance and stability on scaled landscapes. *Landscape Ecol.* 8, 213–227.
- Urban, D.L., Acevedo, M.F., Garman, S.L., 1999. Scaling fine-scale processes to large scale patterns using models derived from models: meta-models. In: Mladenoff, D.J., Baker, W.L. (Eds.), *Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications*. Cambridge University Press, Cambridge, UK.
- Varhol, P.D., 1992. Object-oriented programming—the software development revolution. Computer Technology Research Corporation, Charleston, SC.
- Wolter, P.T., Mladenoff, D.J., Host, G.E., Crow, T.R., 1995. Improved forest classification in the Northern Lake States using multi-temporal Landsat imagery. *Photogr. Eng. Remote Sens.* 61, 1129–1143.
- Wu, J., Levin, S.A., 1994. A spatial patch dynamic modeling approach to pattern and processing in an annual grassland. *Ecol. Monogr.* 64, 447–464.
- Yourdon, E., Argilar, C., 1996. *Case studies in object oriented analysis and design*. Yourdon Press, Upper Saddle River, NJ.