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LANDIS and forest landscape models

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Abstract

This paper provides contextual documentation of the LANDIS model development to provide a framework for the other papers in this special issue. The LANDIS model of forest landscape disturbance and succession was developed since the early 1990s as a research and management tool that optimizes the possible landscape extent (100 s ha to 1000 s km^2), while providing mechanistic detail adequate for a broad range of potential problems. LANDIS is a raster model, and operates on landscapes mapped as cells, containing tree species age classes. Spatial processes, such as seed dispersal, and disturbances such as fire, wind, and harvesting can occur. LANDIS development benefited from the modelling and research progress of the 1960s to the1980s, including the growth of landscape ecology during the 1980s. In the past decade the model has been used by colleagues across North America, as well as in Europe and China. This has been useful to those not able to undertake the cost and effort of developing their own model, and it has provided a growing diverse set of test landscapes for the model. These areas include temperate, southern, and boreal forests of eastern North America, to montane and boreal western forests, coastal California forest and shrub systems, boreal Finnish forests, and montane forests in Switzerland and northeastern China. The LANDIS model continues to be refined and developed. Papers in this special issue document recent work. Future goals include integration within a larger land use change model, and applications to landscape and regional global change projection based on newly incorporated biomass and carbon dynamics.

Keywords: LANDIS; Forest landscape; Spatial models; Landscape ecology; Disturbance; Succession; Management

1. Introduction

Models that simulate change on forest landscapes have largely evolved over the last 15 years, building on both technology (computer power) and conceptual scientific growth in forest and landscape ecology (Mladenoff, in press). Additionally, ecological research work extending back to the 1960s has been key to this evolution (Mladenoff and Baker, 1999). My purpose here is to provide documentation, broadly defined, of the LANDIS (Forest Landscape Disturbance and Succession) model (Mladenoff et al., 1996). This will include a brief review of the model's historical context,

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purpose, original design and rationale; its subsequent (and on-going) evolution, an overview of key papers that trace the model evolution, and a brief review of past applications and current users. Some current model design additions and applications then follow in this special issue.

2. Forest ecology and forest management models

Research on forest disturbance and succession has been subject to many excellent reviews over recent decades and will not be repeated here (e.g., Glenn-Lewin et al., 1992; Pickett and White, 1985; McIntosh, 1985; West et al., 1981; Connell and Slatyer, 1977; Drury and Nisbet, 1973). Readers should consult the primary literature referenced in these reviews. Many of the concepts developed over the past century in ecology have a long and contentious history (McIntosh, 1985). These include concepts of climax and successional seres, equilibrium and non-equilibrium systems, community composition along steep versus moderate gradients, the importance of disturbance in natural systems, and long-term effects of human alterations to ecosystems. These concepts and principles are now commonplace in ecology, and they underlie the mechanisms and parameters used in forest change models of all scales, from single trees to regions, and whether the models are mechanistically simple or complex.

Models of forest change began as purely narrative, theoretical, or conceptual formulations, leading to applications of simple mathematical change transitions (e.g., Markov models (Feller, 1968; Stephens and Waggoner, 1970)). Later, more complex computer simulators followed, based on various mathematical formulations, or rule-based models. Early computer models of forest change in the late 1960s and early 1970s developed at the time that computer models were first being applied in ecology under the US International Biological Program (IBP) in a series of US regional forest change models. The IBP also funded attempts to develop complex models of ecosystem processes and trophic level dynamics. At about the same time, the first of what became called forest 'gap' models appeared (JABOWA; Botkin et al., 1972), and the first true, individual tree model of a forest stand (FOREST; Ek and Monserud, 1974). FOREST was a very innovative model that tracked spatial locations of tree stems in a stand; as such it was ahead of its time in terms of pushing then current computer capabilities.

JABOWA proved to be a more parsimonious approach and was more successful, spawning a host of variants and descendants. A fascinating genealogical chart of JABOWA descendants by D. Mailly is found in Kimmins (1997) (p. 488). The JABOWA family simulates trees on gap-sized forest plots, which have varied in different model derivations from 0.01 to 0.1 ha. Often called individual-based models, they do not really track the spatial location of individual stems, as did the FOREST model and the more recent SORTIE model (Pacala et al., 1993). SORTIE can be thought of as a more mechanistic gap model that is truly spatial. Its costs however, are the need for very detailed field data for parameterization, and a limitation of being able to simulate only 10 s of ha with this detail, and a 3-year instead of annual time-step. All of these individual-to-stand level models have focused on succession more than disturbance, in part because of design limitations, the physical extent of the area over which they could be applied, computational capability, and ecological knowledge. Where such models have included disturbances, such as fire, flooding, etc., they have been limited until recently by their non-spatial nature and again, limited extent.

Beside the more strictly ecological models, forestry growth and yield models also evolved during the 1970s and 1980s for a distinctive set of uses. These have also been broadly reviewed (Parks and Alig, 1988; Loucks et al., 1981; Munro, 1974). Related to these were the first forest planning models, linear programming models that usually included a growth and yield component (Iverson and Alston, 1986). Attempts were made in the late 1980s and the 1990s, especially within the US Forest Service, to address management and planning questions that became more complex, acknowledged to be broader in scale and required addressing more diverse sets of ecological concerns than in the past. These were generally tasks that severely stretched the capabilities and design intent of the growth and yield models and planning models (Johnson, 1992a). This was one of the forces that encouraged the development of LANDIS and related models, along with ecological advances and enhanced computer capability.

3. Early disturbance models

Early models of disturbance began as attempts to simulate the details of forest fire spread for suppression purposes (Rothermel, 1972) and were later integrated into a non-spatial forest planning framework (Kessell, 1976). Significant empirical ecological work on disturbance, largely fire (e.g., Heinselman, 1973; Johnson, 1992b) but also wind and to some degree insects and disease were required before disturbance became a main component of forest change models. Models in this area did not develop to any degree until landscape modelling approaches became more feasible, because of the inherent spatial nature of disturbances.

4. Landscape ecology and early landscape models

Landscape models of forest change have their origins both within and outside of forest models themselves. The gradient model of Kessell (1976) was perhaps the earliest forest model that was spatial, and included both biotic disturbance and fire. Major development of forest landscape models really occurred in the latter half of the 1980s. Several growing forces combined at this time to provide major impetus. Landscape ecology as an explicit field of study in North America grew dramatically beginning in the 1980s (Turner, 1989; Forman and Godron, 1981). This contributed by emphasizing the importance of the explicit inclusion of scale (with an emphasis on broad-scale) in ecological research and management. Computer power, and in particular access to desktop computers, began to grow exponentially. Finally, as alluded to in the section on forest models, environmental concerns and the increasing sophistication of land management problems and demands created a large demand for new modelling tools (Mladenoff, in press; Sklar and Costanza, 1990). There was a growing need for models that better integrated the more ecological approaches with tangible information that could be used by managers and planners to examine more complex, spatial scientific questions. In a sense, this was a push showing that the bifurcation of forest modelling approaches in the 1970s into ecological versus forestry models failed to meet the newly emerging demands.

Landscape ecology as a science very explicitly links research and management. Although the name implies a broad, human-scaled context and spatial study extent, this need not be so. Indeed, the conceptual approach has been applied at a range of scales and across systems as diverse as a few square meters of beetle habitat (Wiens and Milne, 1989), to all broader terrestrial scales, and even the oceans (Steele, 1989). Nevertheless, the foundations of landscape ecology are rooted in human-scaled and human-dominated landscapes (Forman and Godron, 1981, 1986). This link of an environmental science and management has never been so explicit as it is with landscape ecology. The very principles of the science—that explicit consideration of space is essential in understanding ecological processes, that interactions occur at and across a range of scales, and that these processes vary in both rate as well as time—make confronting the real, human-dominated landscape inescapable. The movement of species, energy and matter, if considered (for forests) beyond a single stand (10–100 s ha), means that a very large context must be considered. Important variables may occur in adjacent stands, or even much further away. Especially where most landscapes are divided up in terms of ownership, management authority, land uses and history, both management and science must confront the effects of this division. Researchers and managers have found they need to work together more closely than even before (Mladenoff, in press).

Researchers in landscape ecology quickly found that there are limits to what can be learned empirically, either through descriptive, correlative studies, or field experiments. The broad extent of spatial and temporal scales that often must be addressed means that many of the traditional methods of experimental science cannot be used in landscape ecology. There are limits of both cost, and of what is feasible on landscapes where many activities must take place, that will constrain landscape ecological research. In the same vein, problems of experimental replication are even more insurmountable at broad scales, and for many systems. Thus, spatial models become a necessity. We can, in effect, use stochastic, spatial models to conduct experiments by simulating replicated, factorial experimental designs where we can control and vary important parameters and variables according to our needs. There is really no other way we can assess how many multi-scale processes interact, or understand the very long-term dynamics of many systems. Also, using these models in this way gives us a method to assess the variability in simulation outcomes. While this is a typical approach in testing models, such as in sensitivity analysis (Gardner and Urban, 2004), we are also interested in the range of possible outcomes of the system interaction in general. In other words, what is the range of confidence we have in the scenario outcomes that our models give?

Related to this is a more typical use of these models in ecology. Ideally models and empirical studies are used together, iteratively, where data inform model design and algorithms, and then modelling feeds back to guide further empirical research and 'traditional' experiments. In landscape ecology, this approach may not work as simply as in other areas of ecology. It is often difficult to create and carry out such broad-scale empirical work. Nevertheless, the process still can work. The needed data may still be difficult to gain, but the models can help to clarify what those data needs are. There are still many imperfectly understood processes at many scales, many amenable to research.

A significant problem to all of this kind of research, is that often landscape studies, and building and using landscape models, require even greater amounts of time and money that much other ecological research. While models can help in assessing extremely long-term system behavior, in a relative sense this research demands very long-term support.

5. Trade-offs in landscape modelling

A driving need of the growth in landscape models has been the realization that ecological science and management questions have gotten more complex. For example, traditional stand level management, simple sustained yield and multiple use concepts, non-spatial estimates of growth and yield, and the unquestioned application of fire suppression, have all been applied too optimistically and uniformly across our forests, creating a caricature of well-functioning landscapes. They represent a failed conceptual model that for too long avoided acknowledging spatial interactions at a range of scales, and over longer time scales.

Landscape models can be categorized in many ways (Gardner et al., 1999; Baker and Mladenoff, 1999; Baker, 1989). My focus here is on models that simulate change over some range of time steps. For my purposes here I distinguish among models that are *empirical* and analytical, such as statistical models that often have a single solution. There are contrasted with *stochastic* models that include algorithms based on random choices. These are typically simulators. Models can also be *spatial*, in that they simulate entities such as individuals or cells that have explicit coordinates in two- or three-dimensional space. But not all spatial models are *spatially dynamic*. A spatially dynamic model includes not only explicit locations of entities, but includes processes that incorporate interactions among entities in space that in part drive change in the focal entity over time. Such models do not have a single solution, and are usually run in multiple replicates to generate a mean trajectory of system change. This can be thought of as the simulated version of the 'natural range of variability', a concept that is becoming more common in ecology and ecosystem management.

The problems inherent in designing and building any model are multiplied with stochastic, spatial landscape models, and therefore present even larger pitfalls. Beside the usual problem of data availability mentioned above, spatial landscape models require spatial input data, usually in map form suitable for digital processing within the model itself or linked with a geographic information system. At the same time, confronting the design of a spatial model quickly reveals that our increased ecological knowledge and geometric growth in computer speed are not panaceas. We still have technical limitations so that no spatial model can include interactions at all scales. There are similar technical limitations as well, in that the output of complex models quickly reaches a point where it is not possible to analyze or absorb the results. Both of these limitations support an assumption inherent to successful spatial models, that to understand the outcome of a spatial process at a given scale, complete knowledge of underlying mechanisms is not necessary, and likely is not possible. We need to resist the seduction, so irresistible to many scientists, that adding greater mechanistic complexity produces a better model. The real problem is determining how much knowledge is needed, at what scales and resolution, for the questions and applications planned for the model.

There are trade-offs to consider that are both technical and conceptual. Spatial forest landscape models and landscape models in general can operate on a number of different focal entities. The entities may be trees

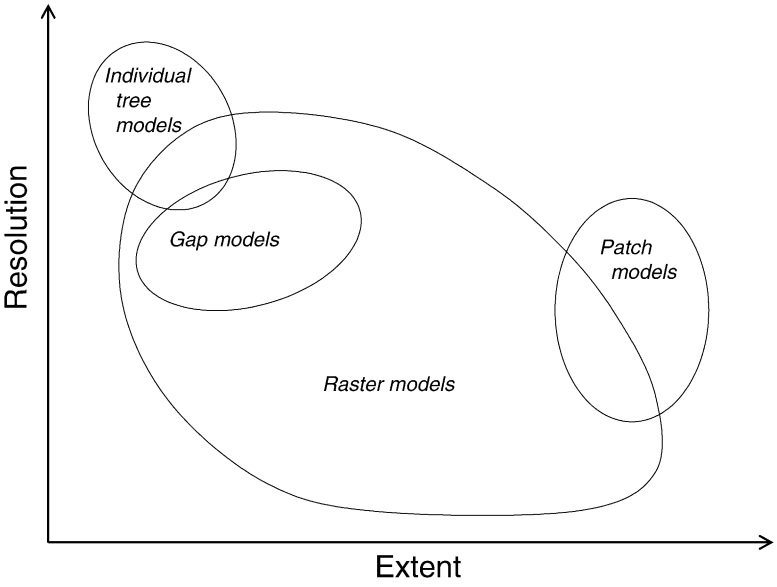

Fig. 1. Computational trade-off between technical limits—increasing spatial resolution (smaller cell size or minimum entity) and increasing extent (total landscape area)—in model design.

with actual *x*,*y* coordinates, gaps that may be occupied by multiple stems without explicit locations, cells or pixels on a rasterized landscape map, or delineated stands or patches (polygons). The last imply a GIS data format that is vector mode, where entities are part of maps with patches. Raster mode is the second format, where a map is gridded into a contiguous lattice of cells (Bolstad, 2002; Burrough and McDonnell, 1998).

The important technical and conceptual trade-offs are therefore the spatial resolution at which the model runs, i.e., cell size or minimum spatial entity such as patch size, the maximum landscape extent that can be simulated by the model, and the degree to which a model incorporates mechanistic detail and spatial dynamics. Whatever the prevailing computer capabilities or model detail, there will always be a computational trade-off between spatial resolution and extent—higher resolution (smaller cell size) or increasing extent both result in more cells to simulate. Different forest landscape model designs optimize these constraints in different ways (Fig. 1). In general, the highest resolution in these models would be carried by a model that simulates individual trees, or cell sizes small enough to represent such entities (e.g., individual based models to gap models). Patch or vector stand models can optimize extent, but will sacrifice resolution. Models (or GIS) operating in vector mode also have much greater computational costs in general for other technical reasons (Burrough and McDonnell, 1998). I believe that raster models have several advantages, both being the faster computational mode in general and, if incorporated into the design, being capable of representing the greatest range of the resolution/extent space (Fig. 1, Mladenoff et al., 1996).

At the same time raster-based models, because of their computational efficiency can also best represent the largest portion of the spatial dynamism/mechanistic detail space (Fig. 2). Therefore raster models have been shown to be most efficient and flexible to use over a range of scales. However, specialized uses can argue for one of the other approaches; the raster approach does not cover the entire space represented in each graph (Figs. 1 and 2).

6. LANDIS model purpose and design

The LANDIS model design came about with these issues in mind. The goals were to simulate forest landscapes (100 s ha–1000 s km^2), initially including succession and wind and fire disturbance that operate spatially (Fig. 3, Mladenoff et al., 1996). Initial work on

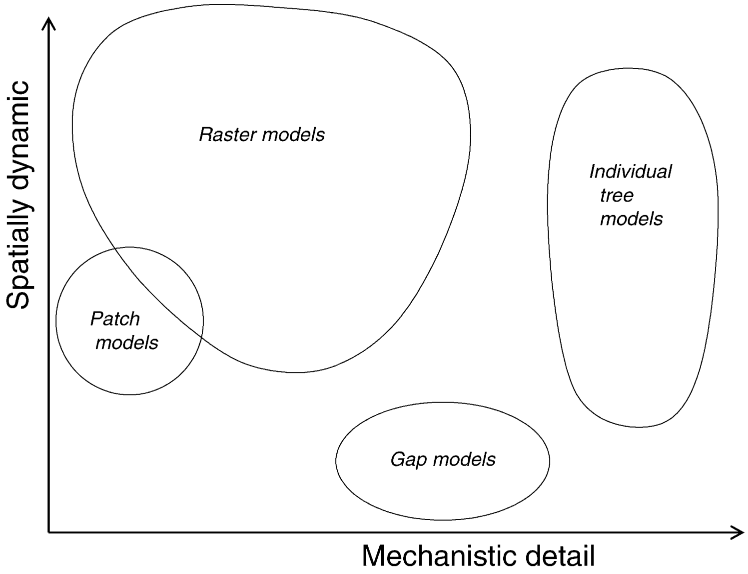

Fig. 2. Computational trade-off between conceptual model design factors—degree of spatial dynamics vs. increasing mechanistic detail.

the model began in 1991, and a prototype was first used and results presented in 1993 (Mladenoff et al., 1993). The design purpose was to optimize flexibility. This meant incorporating the ability to use a range of cell sizes (∼10 m–1 km) to allow a relatively broad range of questions to be addressed. At the same time we concluded, based on earlier attempts, that the model should have relatively few, simple parameters so that it could be transportable and used in different locations. This is one of the strengths of the gap models of the

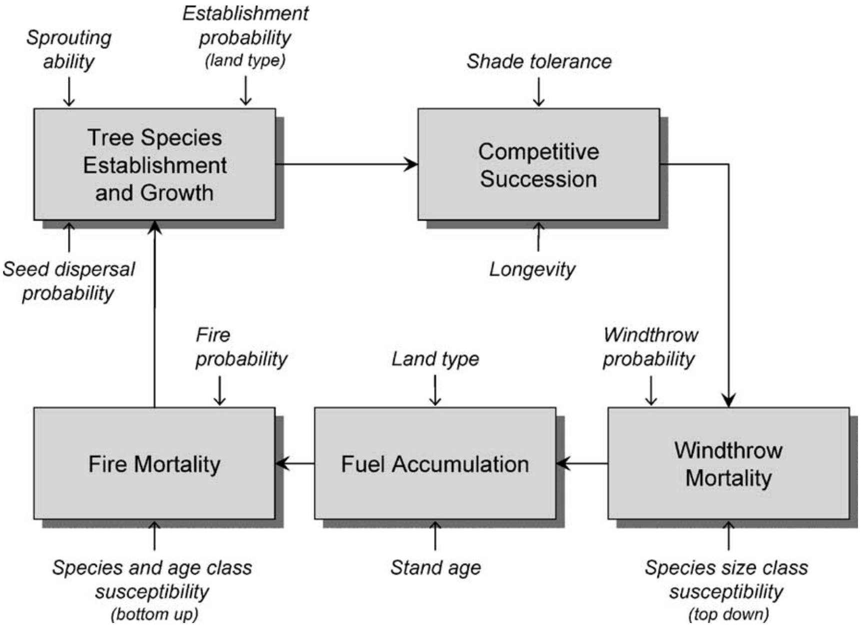

Fig. 3. Original conceptual diagram of LANDIS operation (based on Mladenoff et al., 1996, 1993).

Table 1
LANDIS model goals and purposes, and corresponding model design characteristics for LANDIS 1×

Purpose or goal	Model general design characteristic
Reasonable landscape realism in results	
Spatial dynamics	Spatial, stochastic, context-dependent cell change
	Species-specific seed dispersal distances
	Disturbance spread
Patch dissolution and aggregation	Raster (cell-based) mode
Computational efficiency	
	Raster (cell-based) mode, 10-year time step
	Free-standing program, outside GIS, GIS file format link
	Some parameters, inputs semi-quantitative, categorical
	Tree species represented as presence/absence of 10-year cohorts in a cell, not individuals
Easily modifiable code	Object-oriented design, hierarchical, C++ language
Usability for diverse users, locations, purposes	
	Graphical user interface
Flexibility of scales	Variable resolution (cell size 10 m–1 km), and map extent
Portability to different regions, forest types	Moderate, flexible input parameter needs
	Flexibility in required input data
Successional dynamics	
	Individual species, 10-year age classes
Spatial influences on succession	Seed dispersal distance functions by tree species
Disturbance dynamics	
	Fire, windthrow, code structured to add others (e.g., insects)
	Landscape spread, interaction of disturbances
Management consequences	Flexible forest harvest routine; spatial controls
Landscape environmental heterogeneity	
	Variable land types

The general model purpose was to examine fundamental questions about ecological dynamics, as well as questions of forest management consequences.

JABOWA/FORET lineage, though they are mechanistically more complex than LANDIS and cannot operate typically on entire landscapes (Shugart, 1984; but see adaptations by Urban et al., 1999). The lesson of the need for mechanistic simplicity was learned from attempts at extending the more complex gap models to spatial dynamics and across entire landscapes (Sarkar et al., 1996; Smith and Urban, 1988). A positive example of the power of mechanistic simplicity in forest modelling was learned from Dave Roberts' work in the very early 1990s which provided a patch-based landscape model of simple and elegant design (Roberts, 1992, personal communication; though not published until the mid-1990s (Roberts, 1996)). However, Roberts' model was particularly important in showing that individual tree species age classes could economically be simulated on landscapes if a raster approach was used with a 10-year model time-step, and only presence/absence of age classes tracked for each species, not actual stems (Roberts, 1996). At this point, the DISPATCH model (Baker et al., 1991; Baker, 1994) was also a significant step in formulating a model that simulated disturbance and regeneration of forest patches on very large landscapes. DISPATCH combined a patch-based disturbance algorithm with forest age-based regeneration in the patches, but not tree species.

Ultimately, we decided on a conceptual design similar to that of Roberts for LANDIS, but with somewhat greater mechanistic detail. Thus the need for more computational speed and the desire for greater flexibility brought us to the LANDIS design (Table 1, Mladenoff et al., 1996; Mladenoff and He, 1999). Priorities were to (i) provide a desired level of landscape dynamics and realism, (ii) maintain practical computational efficiency, (iii) emphasize non-equilibrium successional dynamics, (iv) include major disturbance types and their interactions, (v) represent environmental heterogeneity, and (vi) maximize usability, flexibility, and portability (Table 1). Greater narrative detail on the design rationale and process originally used to develop LANDIS is found in Mladenoff (in press).

The LANDIS model can be represented conceptually as a repeating cycle of processes that operate on the initial input map and subsequent time steps (Fig. 4). Tree species are filtered for their ability to exist on a particular cell based on propagule availability (seed or sprouting ability) in relation to the *land type*, a spatial landscape input that may correspond to soils, slope, or other physical characteristics (Fig. 4a). Land type can be an input data layer that can be scaled according to data availability and user needs. The species establishment coefficient (SEC) is derived by using the LINKAGES gap model (Pastor and Post, 1986), a model that incorporates ecosystem processes, and an algorithm to rank tree species response to site (He et al., 1999a; modified in Scheller and Mladenoff, in press). The SEC encapsulates a static, relative ranking of a species in relation to site type, characterized by moisture and nutrient dynamics as implemented in LINKAGES. Next, succession occurs within a cell based on species life history traits (Fig. 4b), such as shade tolerance and longevity. Simplified fuel dynamics and species and age-specific mortality caused by different disturbances constitute the third conceptual component of LANDIS (Fig. 4c). Because the diagram is a conceptual representation, the arrows linking disturbances imply possible pathways, not necessarily a fixed sequence of operations. In other words, any of the disturbances—fire, harvest, or wind—may occur at a cell or group of cells, depending on the various algorithms.

Interactions within LANDIS can be complex due to species and age-specific responses to spatially-explicit disturbances that vary in their relative intensity. Fire is a bottom up disturbance, where younger age classes are relatively more susceptible to fire than older age classes, and higher intensity fires will kill progressively older age classes. These age-dependent fire susceptibility thresholds decrease with increasing fire tolerance of individual species. Conversely, windthrow is a top down disturbance, most affecting older age classes first. Higher intensity events kill progressively smaller individuals (younger age classes) in a cell. Overall, disturbance-caused mortality then drives sub-

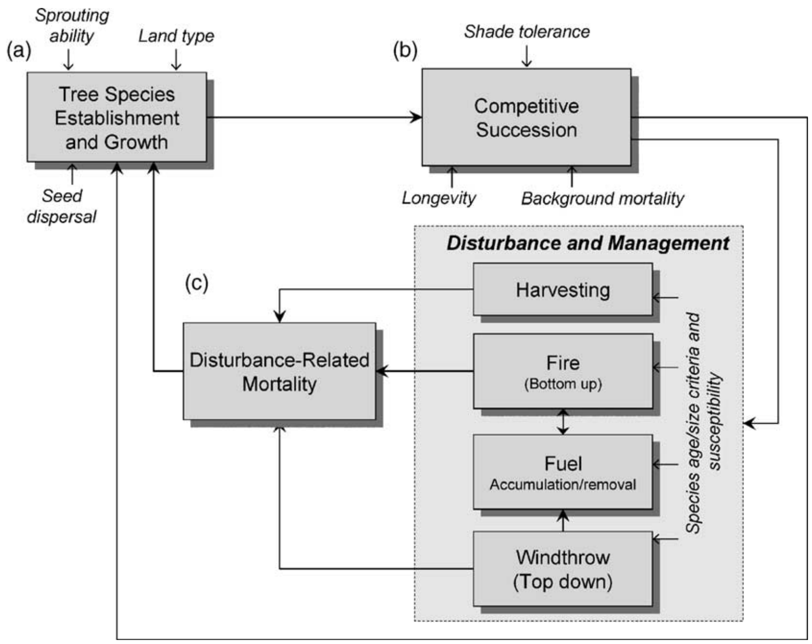

Fig. 4. Major LANDIS 1.0-3.7 model dynamics, including (a) species-site quality interactions, (b) successional dynamics, and (c) disturbance. An insect and disease module Sturtevant et al. (2004) and revised fuel and fire modules (He et al., and Shang et al., in press) are being incorporated into LANDIS 4.0. Biomass is incorporated in Scheller and Mladenoff (2004); and will be released in LANDIS-II.

sequent species establishment (Fig. 4a). The harvesting module was developed later, in the mid-late 1990s, and benefited from previous development of separate raster-based harvest simulators, Wallin et al., 1994; Li et al., 1993), and particularly the HARVEST model (Gustafson and Crow, 1994). Harvesting, depending on the particular mode implemented, can affect cells in either top down or bottom up fashion, depending on age classes removed and frequency. The harvesting module in LANDIS can be used to implement complex cutting regimes, with species, spatial, and temporal controls, as well as several harvesting methods (Gustafson et al., 2000).

Operationally, the model operates on a raster GIS format, but is a free-standing program (Fig. 5). Many inputs can be thought of as represented by maps of climate, soil, and topography (that may define *land types*). Implemented processes such as harvest and natural disturbance can also be thought of as 2-D map representations, all of which relate to the raster map of the landscape at a given time-step. Outputs similarly can be thought of as various mapped or table representations of the data (Fig. 5). Similarly, under current modifications, biomass is also now a spatial output (Scheller and Mladenoff, in press-b).

Table 2
Tree species life history parameters that drive the model

Parameter	Representation
Species longevity	Years
Age of sexual maturity	Years
Shade tolerance	Categorical (classes 1–5)
Fire tolerance	Categorical (classes 1–5)
Effective seed dispersal distance	Meters
Maximum seed dispersal distance	Meters
Probability of vegetative propagation	Binary (Y/N)
Maximum sprouting age	Years
Species site response	Species establishment coefficient (derived probability)

Tree species life history parameters drive the species dynamics of the model (Table 2). This approach is in part similar to the gap models, but here some parameters are simplified to categorical representation. This is part of the trade-off of maintaining more spatial dy-

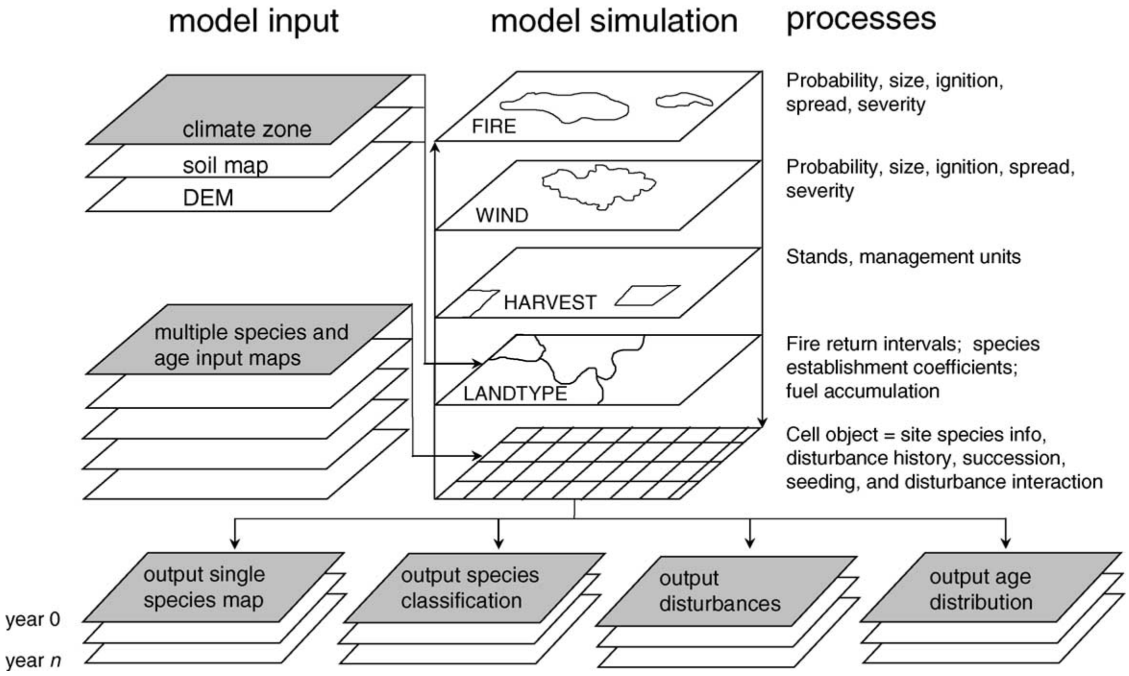

Fig. 5. Computer operational design of LANDIS.

namics and broader usability of the model (modest data input and parameter information needs), against more fine-scale mechanistic detail (Table 1). More specific details on the model design and algorithms are published in several papers. Model structure, behavior and testing are in Mladenoff and He (1999). Specific modules are described in detail in several papers: model object oriented design and tree species representation (He et al., 1999b), seed dispersal effects on tree species spread across the landscape (He and Mladenoff, 1999a), fire module and long-term landscape dynamics (He and Mladenoff, 1999b), and the harvesting module (Gustafson et al., 2000).

This special issue contains papers on the design and modification of the original basic LANDIS design (1.0–3.7), and some initial applications of these modifications. The original development region for the model was northern Wisconsin (USA), a region of mixed deciduous and coniferous forests (Fig. 6, Mladenoff et al., 1996). This was used as the landscape for continued model development, as well as projects of management and applied uses of the model, and examining ecological concepts and theory of spatial disturbance and long-term change on a landscape (He and Mladenoff, 1999b). Up to this point, the model has benefited from colleagues willing to adapt and test the model in various landscapes and forest ecosystems in North America and several other locations (Fig. 6). This is not an attempt at model imperialism and hegemony, but rather meeting two needs—that of other researchers to avoid the long path of model development, and our own desire to see the model tested in different systems. For example, the model was adapted to the oak forest landscapes of Missouri, to simulate change in a topographically more fine-grained and fire dominated landscape (Shifley et al., 2000). The model is also being used to examine ecological theory and effects of modified fire regimes in a southern California (USA) Mediterranean-type shrub and forest landscape (Franklin et al., 2001). In the eastern Finland boreal forest, Pennanen and Kuuluvainen (2002) added information on tree density and a more detailed, mechanistic fire module (FIN-LANDIS)

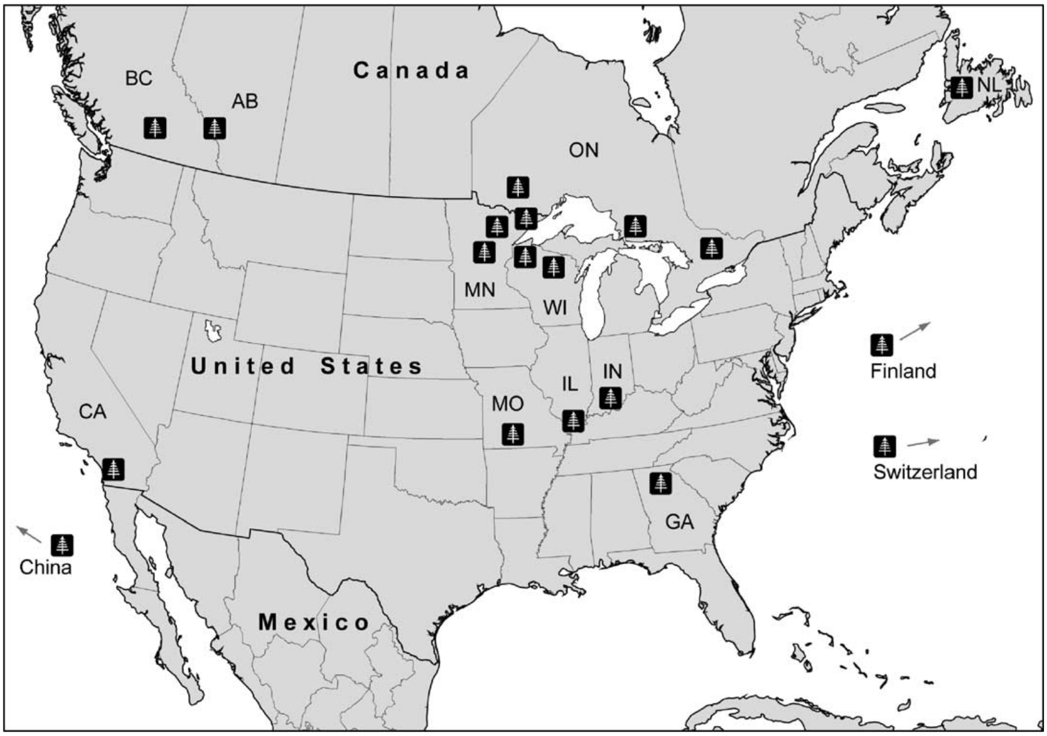

Fig. 6. Known locations where the LANDIS model has been or is being used, beyond the development region of the US northern Great Lakes region. Since the model is freely available, other users likely exist.

to simulate change. In northeast China the model was used to examine long-term dynamics under a natural disturbance regime (He et al., 2002).

We have also developed a system within a single interface that combines the LANDIS model with the spatial species metapopulation model, RAMAS GIS (Akçakaya, 2002). This system provides the first attempt at linking detailed, spatial landscape habitat change with a species metapopulation model (Akçakaya et al., 2004). Since the LANDIS model itself is freely available, other work is in progress at a number of labs, some of which we are aware of (Fig. 6), but many others have not interacted with us after downloading the program.

7. Future model use and evolution

The LANDIS model, as a research tool, and increasingly as a management tool, will continue to evolve. This is what the original design sought to facilitate. In part this is shown by many of the papers in this volume that highlight current development work and new applications in diverse locations. The need to remain conscious of the trade-off between mechanistic detail and model scope remains. LANDIS 4.0 capitalizes on the existing age-list and ordinal ranking structure of the original model, but adds new capability that includes more explicit fuel dynamics (He et al., in press; Shang et al., in press), fuel-fire interactions, and biological disturbances (Sturtevant et al., 2004). LANDIS-II adds mechanistic detail to the succession and disturbance interactions by changing the model 'currency' from the age-list to biomass (Scheller and Mladenoff, 2004), and will allow greater flexibility in time step length. Other modifications are occurring independently by others. These changes will allow simulation of a greater variety of disturbance and recovery dynamics, and carbon dynamics.

High priorities for the near-term future also reflect the nature of both ecological research as well as growing management needs. In the near future we plan links with an economic model, and embedding LANDIS within a larger land use change model. The model will continue to evolve, and continually increasing computer capability and growing knowledge will allow some growth in model detail and complexity. Trade-offs will always remain part of the equation. The basic successful formula will remain the same: keeping model complexity within the bounds of research needs and practical usability.

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