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Progress and future directions in spatial modeling of forest landscapes

William L. Baker and David J. Mladenoff

Introduction

Today, we are confronted by new questions underlying natural resource disputes and forest management throughout the world. How will our future forest landscapes look? What products, services, and opportunities will they afford for people? How well will the biological diversity and functioning of forest ecosystems be perpetuated? Increasingly, these questions demand a long-term outlook on large land areas, and a spatially sophisticated framework.

Now, we are asked not just how much old growth forest will there be, but will old growth forest patches in 2050 AD be sufficiently connected to other patches to insure movement and viability of metapopulations of area-sensitive forest species? This kind of question is difficult to answer with chronosequences, experiments, stand-level plot studies, and other techniques that have been the basis of research fundamental to forest management in the past. There is little doubt that spatial models of forest landscapes will have to play an increasing role in addressing these questions.

Forest landscape ecological models (FLMs) have matured over the last decade from simple, checkerboard-scale, abstract, game-like models to complex models of large landscapes with feedbacks, spatial interactions, and linkages to other models. Here, the achievements and findings evident in the diversity of presentations in this book will be reviewed, present shortcomings will be outlined, and a little about future directions of research will be speculated.

Themes in forest ecology represented in models

The themes that are the subject of our modeling efforts are those that produce structure in forest landscapes from the scale of individual trees to that of entire landscapes and regions. Models with roots in the gap or individual-tree modeling traditions are rich with detail about tree-to-tree interactions and the resulting successional process (Caspersen *et al.*, Chapter 2; Liu *et al.*, Chapter 3; Urban *et al.*, Chapter 4). The LANDIS and VAFS/LANDSIM models use vital attributes or life history traits in modeling succession with natural disturbances (Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6). Natural disturbance itself is another significant theme, with most models focused on fires. The intricate details of spread of individual fires are modeled mechanistically in *FARSITE* (Finney, Chapter 8), while the longer-term behavior of fires and fire effects on landscapes are the foci of one version of DISPATCH (Baker, Chapter 11) and SAFE FORESTS (Sessions *et al.*, Chapter 9). The spectrum of approaches to fire modeling in landscapes is reviewed by Gardner *et al.* (Chapter 7). Perhaps, because of their central importance globally, timber harvesting and deforestation are a focus of models oriented toward human disturbances (Liu *et al.*, Chapter 3; ZELSTAGE of Urban *et al.*, Chapter 4; Dale and Pearson, Chapter 10; Baker, Chapter 11; Gustafson and Crow, Chapter 12).

Treatment of forest ecology in landscape models

What are the essential processes and structures in forest landscapes that must be modeled? The answer to this question is still evolving, in part from our modeling efforts. In a related area of expanding research, on metapopulations, it was a modeling study (Levins, 1970), rather than an empirical study, that stimulated much of the subsequent empirical and modeling research (e.g., McCullough, 1996; Hanski & Gilpin, 1997). The stimulus for FLMs, in contrast, has followed empirical research and natural resource controversies that have shifted the focus from the stand level to the landscape ecology of forests (e.g., Harris, 1984; Thomas *et al.*, 1990; Laurance and Bierregaard, 1997). Some of the major processes and structures that appear essential to model can perhaps now be identified, yet our image of the forest and our understanding of its complexity continue to change.

Processes and structures of at least four scales now appear to be of interest in FLMs (Table 13.1). At the patch level are the many well-known processes that generate spatial and vertical structure within a forest stand, based largely on the response of individuals. These processes have been the subject of much research and modeling effort (e.g., Botkin *et al.*, 1972; Oliver and Larson, 1990). Processes and structures at the landscape scale are less well studied, but well represented in our models. Regional and global processes may influence landscape dynamics as well, but these also have received less attention.

Patch processes in landscape models

A forest stand is a patch of forest that is internally relatively homogeneous. This somewhat arbitrary forest unit has been the subject of much previous empirical research. In FLMs a stand is represented as either a single pixel or as a group of pixels or a polygon. Indeed, in grid-based FLMs the concept of a forest stand may be unnecessary, and processes may center around individual pixels that represent repeating square units of fixed size within a forest.

Table 13.1. *Major processes and structures affecting tree populations in FLMs*

Scale	Processes	Structures
Patch	Within-patch dispersal	Within-patch mosaic of seed densities
	Regeneration	Within-patch mosaic of trees of different ages/sizes
	Growth	Variation in vertical/spatial array of tree sizes
	Mortality	Spatial and vertical mosaic of dead and downed wood
	Competition	Modifies the regeneration and growth processes
	Within-patch herbivory	Modifies the regeneration and growth processes
	Succession	Successional stages, communities
	Small natural disturbances	Within-patch mosaic of successional stages/tree groups
	Boundary/edge differentiation	Edge versus interior environments
Landscape	Patch-to-patch dispersal	Patch-to-patch mosaic of seed densities
	Metapopulation dynamics	Patch-to-patch mosaic of sub-populations
	Herbivore movements	Patch-to-patch variation in herbivory effects
	Large natural disturbances	Disturbance patches
Region	Fluctuation in regional species pool	Regional seed and pollen rain
	Herbivore migration	Spatial variation in herbivory effects
Global	Neotropical migrant declines	Decline in bird-disseminated seeds
	Climatic change	Variation in regeneration, growth, and mortality processes

Models differ in the within-stand tree-to-tree interactions and vertical forest structure that is simulated. In gap models and derivatives, the stand has vertical structure and interactions that control light and moisture regimes (Caspersen *et al.*, Chapter 2; Urban *et al.*, Chapter 4). In FACET, for example, the stand consists of a grid of cells potentially occupied by individual trees, in which shading by adjoining trees and overstory trees affects light availability monitored at 1 m vertical increments (Urban *et al.*, Chapter 4). Moreover, the soil has multiple layers in which soil water is maintained and in which roots grow. Overstory trees influence soil water through interception and modification of transpiration rates. Light, water, nutrients, and temperature influence tree establishment, growth, and mortality. Competition between trees thus arises from effects on light and moisture in the canopy and, potentially, below ground. In LANDIS and VAFS/LANDSIM, only tree species age classes are simulated, and individual trees, vertical layers in the canopy, and soil are not simulated. When cells or polygons approach tree size, then these models may track individual tree locations. Species are ranked by shade tolerance, and can reproduce in their own shade or the shade of less tolerant species, as an approximation of vertical shading interactions (Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6). In FORMOSAIC, the landscape is divided into grid-cells, but the location and birth, death, and growth of each tree within a grid-cell is tracked. Tree size and neighborhood pressure influence individual tree growth, using a demographic approach, so vertical canopy layers, shading, and moisture-driven functions are not used (Liu *et al.*, Chapter 3). In other FLMs, there is no vertical or horizontal structure within the stand or pixel, and within-stand processes operate only on aggregate variables. For example, the age of each forest pixel increases (MetaFor of Urban *et al.*, Chapter 4; Baker, Chapter 11; Gustafson and Crow, Chapter 12) or carbon accumulates (Dale and Pearson, Chapter 10).

Within-stand processes also affect natural disturbance in several models. Within-stand fire and fuel-buildup processes are reviewed in Gardner *et al.* (Chapter 7). A species-specific function adds leaf litter, branches, foliage, and whole stems to time-lag fuel moisture classes in relation to tree demography in FACET (Urban *et al.*, Chapter 4). More simply, rates of fuel accumulation and decomposition vary with land type and cell age in LANDIS (Mladenoff and He, Chapter 6) and VAFS/LANDSIM (Roberts and Betz, Chapter 5), while probability of fire is conditioned on soil moisture and time since fire in MetaFor (Urban *et al.*, Chapter 4). Fires initiate probabilistically, based on mean fire interval (Urban *et al.*, Chapter 4; Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6). Fire intensity depends upon fuel load only (Mladenoff and He, Chapter 6) or also includes moisture (Urban *et al.*, Chapter 4). In *FARSITE*, fire spread rate and intensity are calculated from the Rothermel equations, which use physical fuel properties, moisture content, wind speed, and slope (Finney, Chapter 8), and a simplified version of this approach is used in SAFE FORESTS (Sessions *et al.*, Chapter 9). Damage within a stand depends upon fire intensity and species ability to tolerate fire (Urban *et al.*, Chapter 4; Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6) or on crown scorch height (Finney, Chapter 8) and established fire effects models (Sessions *et al.*, Chapter 9). FORMOSAIC explicitly and spatially models the effects of pigs on sapling recruitment in tropical rainforest and the effects of windthrow as a mortality agent (Liu *et al.*, Chapter 3). Some models do not contain large-scale disturbance components at the present time (e.g., Caspersen *et al.*, Chapter 2), and some disturbances (e.g., disease outbreak) have not been modeled.

The within-stand conditions that lead to increased probability of disturbance by timber harvesting and tenant farmers are also modeled in LANDLOG, FORMOSAIC, and DELTA. In LANDLOG and HARVEST the within-stand contribution to the susceptibility of a stand to harvesting depends only upon stand age, which increases as the model runs (Baker, Chapter 11; Gustafson and Crow, Chapter 12). In FORMOSAIC trees must reach a certain diameter before they are eligible for harvesting, which then occurs as selective logging, with an associated, larger impact zone around the tree (Liu *et al.*, Chapter 3). In DELTA, the carbon content of the forest recovers linearly following cultivation (Dale and Pearson, Chapter 10). SAFE FORESTS uses an optimization approach to allocate harvest and other silvicultural activities to reach forest structure and harvest goals subject to watershed constraints (Sessions *et al.*, Chapter 9).

The environment of a stand plays a significant role in modifying within-stand tree growth, regeneration, and mortality, as well as the probability of natural and human disturbances. In FACET, temperature and incoming radiation, adjusted for elevation, slope, and aspect, alter within-stand rates of tree growth, regeneration, and mortality in part directly, but also through effects on soil water balance (Urban *et al.*, Chapter 4). In the present landscape implementation of SORTIE the focus is on the effects of spatial variation in soil moisture on probability of sapling mortality (Caspersen *et al.*, Chapter 2). In FORMOSAIC, growth functions for individual trees are in part a function of slope and elevation (Liu *et al.*, Chapter 3). In LANDIS and VAFS/LANDSIM individual pixels or polygons are classified into landtypes or habitat types, based on environment, and the types influence species regeneration, fire characteristics, and fuel accumulation within the stand (Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6). Fuel moisture is a function of terrain variables in *FARSITE* (Finney, Chapter 8), and custom fuel models are modified by terrain variables in SAFE FORESTS (Sessions *et al.*, Chapter 9). Soil suitability for agriculture and the carbon content of the original vegetation type influence colonists' choice of lots to clear in the DELTA model (Dale and Pearson, Chapter 10). In LANDLOG, the suitability of a particular pixel for timber harvesting is determined by a combination of elevation, soils, slope, and proximity to riparian areas (Baker, Chapter 11). In MetaFor, elevation, slope, and aspect influence temperature and moisture indices that constrain species-specific establishment probabilities (Urban *et al.*, Chapter 4). The environment is thus influential, but is limited to a static function of topography and is not spatially interactive in most models. For example, while the soil varies both vertically and spatially inside stands in FACET (Urban *et al.*, Chapter 4), there is not yet simulation of horizontal hydrologic interactions, such as runoff or subsurface flow, or spatial flows of organic matter or nutrients.

FLMs have seldom to date been used to address the effects of forest fragmentation, so it perhaps is unsurprising that they commonly do not directly model some patch-level phenomena that are a consequence of fragmentation. For example, the edge environment of a patch often contains a different micro-environment from the interior (Murcia 1995), leading to different rates of birth, growth, and death. This can be modeled using FACET (Urban *et al.*, Chapter 4), by preventing tree growth in the cells representing the opening, since the light regime is three-dimensional. The FORMOSAIC application presented here specifically addresses the effects of adjoining oil palm plantations on dynamics in rainforest fragments differing in size, but does not include micro-environmental edge effects (Liu *et al.*, Chapter 3). Other models also do not presently have this capability, perhaps largely because they have been developed for use in continuous forests. Other potential patch-level effects on tree populations include changes in pollinator abundance, changes in herbivory as exemplified in the effects of pigs on rainforest (Liu *et al.*, Chapter 3), and an altered disturbance regime inside the fragment. Application of FLMs to fragmented forest landscapes may require further development of patch-level phenomena.

Landscape-level influences and interactions

A primary process that links patches in most present tree-based FLMs is seed dispersal, which may be a distance function, a neighborhood function, or not be spatially determined. In the landscape implementation of SORTIE, seedling density is a function of the diameter of the source tree and is modeled as a radially symmetric cubic function of distance from the source tree (Caspersen *et al.*, Chapter 2). In LANDIS species can disperse with high probability a certain "effective distance", but dispersal declines exponentially beyond that distance (Mladenoff and He, Chapter 6). In VAFS/LANDSIM species can regenerate in a stand only if there are sexually mature individuals in the stand itself or in one of its immediately adjacent neighbors (Roberts and Betz, Chapter 5). In FACET, seedling establishment is not currently spatially linked, but is simply a function of the environment within the stand, while in MetaFor the abundance of neighboring cells occupied by a species also influences its probability of establishment (Urban *et al.*, Chapter 4). In FORMOSAIC, the oil palm plantations surrounding a rainforest patch do not, but a surrounding species-rich forest does, provide seeds into the rainforest patch (Liu *et al.*, Chapter 3).

In the DELTA model, the movement of tenant farmers among lots is somewhat analogous to seed dispersal in tree models. However, the probability of abandonment of a lot is a function of time on a lot, and the probability of choosing another lot is a function of lot size, soil quality, distance to market along roads, and current carbon storage, although other factors can be added (Dale *et al.*, 1993). In many ways this is a more complex movement component than is present in tree-based FLM models to date, but it is essential to the success of DELTA in replicating the spatial dynamics of deforestation (Dale and Pearson, Chapter 10).

In addition to the movement and dispersal of organisms, another spatial linkage in FLMs is the spread of natural disturbances, most commonly fire, and in two instances also wind (Liu *et al.*, Chapter 3; Mladenoff and He, Chapter 6). In LANDIS, fire spreads to susceptible neighbor pixels once ignited, but is more likely to spread in a wind direction determined at ignition; fire size is constrained by mean, maximum, and minimum sizes specified as inputs (Mladenoff and He, Chapter 6). In VAFS/LANDSIM, fire can spread to neighboring polygons based on their mean fire interval, but fire size is also constrained by inputs (Roberts and Betz, Chapter 5). Similarly, in SAFE FORESTS, fire spreads to neighboring polygons, with fire size constrained by inputs (Sessions *et al.*, Chapter 9). In MetaFor, fires spread probabilistically to neighbors based on their soil moisture status and time-since-fire, also constrained by a specified maximum fire size (Urban *et al.*, Chapter 4). In one version of DISPATCH, fires spread probabilistically to neighbors based only on time since the last fire (Baker, Chapter 11). In the most complex fire-spread model, *FARSITE*, fire-spread is modeled as a vector-process influenced by physical fuel properties, moisture conditions, wind speed, and topography (Finney, Chapter 8). Other models do not simulate fire spread.

Some models also spread human disturbances. In LANDLOG, once a timber harvesting operation is initiated in a pixel, it attempts to spread to produce an approximately rectangular harvest unit with some random shape modifications as spread completes, but spatial constraints and adjoining stands typically lead to irregularly-shaped units (Baker, Chapter 11). HARVEST uses a similar approach, and also includes clear cutting, shelterwood, and seed-tree, as well as group-selection silvicultural approaches (Gustafson and Crow, Chapter 12). Deforestation operates on individual lots in DELTA, rather than spreading in grid-cell space (Dale and Pearson, Chapter 10). ZELSTAGE includes the algorithms from CASCADE (Wallin *et al.*, 1994) that model dispersed-patch and aggregated timber harvesting strategies (Urban *et al.*, Chapter 4). ZELSTAGE can also do hierarchically nested management in which within-stand prescriptions, such as thinning, can be distributed spatially across the landscape. Harvesting has also been incorporated into the most recent version of LANDIS (Gustafson *et al.*, unpublished data).

Some FLMs approach having the structure of models of metapopulations, or a set of sub-populations weakly linked by dispersal (Hanski and Gilpin, 1997), yet the themes of metapopulation modeling (viability, extinction) have not been themes of FLMs. The essential features of metapopulation models are within-patch birth, growth, and death processes (including catastrophes), typically modified by environmental conditions in the patch, coupled with dispersal between patches. Perhaps the reason that FLMs have not been applied in a metapopulation sense is that the focus to date has been upon dominant trees that produce pattern on the landscape scale. These trees typically are not distributed in isolated sub-populations weakly linked by dispersal, as are, perhaps, some rarer trees or other plants in forests. As a consequence, FLMs have not had a focus upon the within-stand small population processes (e.g., demographic stochasticity, genetic deterioration) that may lead to sub-population extinction (Wilcove, 1986). The most demographically explicit models (SORTIE; Caspersen *et al.*, Chapter 2; FORMOSAIC; Liu *et al.*, Chapter 3) may be most suitable for this use in the future.

As mentioned earlier, FLMs have not commonly been used to address problems associated with forest fragmentation, and this may explain the absent or incipient attention to landscape-scale effects on population processes. Animal studies have emphasized the role of corridors, barriers to movement (e.g., roads), and the resistance of the matrix to movement as factors influencing small populations in patches (Forman, 1995). Some of these processes, as well as the within-patch fragmentation processes mentioned earlier, do also affect plant populations, and might in the future be useful additions to FLMs when applied to fragmentation problems. FORMOSAIC does use the movement of pigs and seeds to analyze adjacency, one significant aspect of forest fragmentation (Liu *et al.*, Chapter 3).

FLMs do not presently include spatially interactive land surface processes. Wind direction may be specified for the spread of an individual fire at the onset (Mladenoff and He, Chapter 6; Finney, Chapter 8), but wind direction modifications by topography are not presently tractable in FLMs. Runoff and subsurface flow processes that spatially redistribute precipitation in watersheds also are not included. However, these are comparatively subtle additions to models that already account for the primary topographic effects on the temperature and moisture regimes important to tree populations.

Regional and global influences in landscape models

Regional processes and structures can have effects on local dynamics, even at the patch level, through secondary effects. Regional declines in forest abundance may influence local bird populations (Askins *et al.*, 1987). In the case of bird-disseminated plant propagules, there may be subsequent changes in dispersal rates. Similar inter-scale interactions may also come from the global scale. For example, declines in Neotropical migratory birds due to forest loss in their wintering grounds may mean declines in these birds in temperate forest landscapes where they play roles in seed dispersal and in regulating insect abundance (Hagan and Johnston, 1992). It could perhaps be argued that these kinds of interactions from regional and global scales are less significant than are the basic environmental and disturbance processes that produce most of the pattern in our landscapes. Indeed, one of the difficulties of modeling these kinds of effects is that it may require decades or even centuries for their impact to become significant. However, 500 or 1000 years of forest dynamics are now routinely being simulated, and at this temporal scale the relevance of regional and global processes is potentially significant.

Along a similar vein, few of our models now have in place a mechanism for linkage to large-scale exogenous influences, such as global climate change, yet here the potential effects are well known. Gap models have been used to analyze the potential response of forests to global climate change (e.g., Solomon, 1986), but the ramifications for entire forested landscapes have not been effectively explored using FLMs. Simple scenarios for the response of disturbance landscapes to global change have been explored (Baker, 1995), but there remains considerable potential for using more complex models containing tree populations to explore the landscape implications of global change, perhaps through direct linkage to global climate models (GCMs).

Interactions among scales and world views in FLMs

Interactions between the patch, landscape, regional, and global scales (Table 13.1) are known, as mentioned above, from empirical research, yet our models reflect differing emphases about the relative importance of these scales. To a large extent, this reflects the development and genealogy of FLMs. Model development in landscape ecology has been done by individuals with training in various fields of ecology and forestry, but not landscape ecology explicitly, because it is such a new field (Mladenoff and Baker, Chapter 1). In part, this means the field is a diverse collection of researchers with experience at a range of spatial scales, with a similarly diverse set of attempts to develop FLMs. The field contains both new models built from the ground up to address larger scales, and approaches that use existing, fine-scale models as building blocks.

These differences in development and genealogy may also reflect differences in world views underlying our modeling approaches and emphases. Is the most significant source of pattern in landscapes individual trees or larger-scale forces, such as natural disturbance? Models that include individual trees or age/size-classes of trees emphasize the generation of pattern at the landscape scale from within-stand processes modified by landscape-scale environmental variation (Caspersen *et al.*, Chapter 2; Liu *et al.*, Chapter 3; Urban *et al.*, Chapter 4; Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6). The landscape version of SORTIE seeks to employ models to evaluate how large scale patterns of the distribution and abundance of species emerge from small scale processes (Caspersen *et al.*, Chapter 2). Proponents of this perspective may even suggest that the multiple scales that influence forest landscapes (Table 13.1) can all essentially emerge from models of individuals:

> Individual-based models link all of these separate levels in the ecological hierarchy. The responses of individuals to their local environment is based on physiological and behavioral responses. The aggregation of all individuals of a species produces the population dynamics of that species. The aggregation of all individuals of many species interacting with each other and with their environment produces community dynamics. Ecosystem dynamics result from the aggregation of individual-environment interactions into large-scale material and energy fluxes.
>
> (Huston *et al.*, 1988, p. 690)

While there is reason to be enthusiastic about the ability of individual-based models to capture landscape-scale patterns, other modelers may argue that there are important processes, such as large-scale disturbance, global change, and the behavior of the global economic system that impose considerable structure on the fate of individual trees in forests, and that do not primarily emerge from the behavior of individuals. For example, two-way interactions between pathogens and forest development or landscape patterning suggest that some within-patch population processes and structures are in part controlled by landscape-scale processes and structures (Castello *et al.*, 1995). Similarly, there is increasing evidence that local climate is in part a reflection of land surface structures and processes (e.g., Copeland *et al.*, 1996), so that the rates of tree natality, growth, and mortality in a landscape may in part be an indirect reflection of landscape structure or regional forest abundance. Certainly, large-scale economic and social forces are constraining the fate of patches of tropical rainforest (Dale and Pearson, Chapter 10) and individual high-value trees in temperate forest landscapes. However, it may be difficult

Table 13.2. *Analogies between world views and modeling frameworks*

World view	Models and authors
Behavioralist	SORTIE: Caspersen *et al.*, Chapter 2
	ZELIG version FACET: Urban *et al.*, Chapter 4
	DELTA: Dale and Pearson, Chapter 10
Structurationist	FORMOSAIC: Liu *et al.*, Chapter 3
	METAFOR: Urban *et al.*, Chapter 4
	ZELSTAGE: Urban *et al.*, Chapter 4
	VAFS/LANDSIM: Roberts and Betz, Chapter 5
	LANDIS: Mladenoff and He, Chapter 6
	FARSITE: Finney, Chapter 8
	SAFE FORESTS: Sessions *et al.*, Chapter 9
Structuralist	LANDLOG: Baker, Chapter 11
	HARVEST: Gustafson and Crow, Chapter 12

Models are placed where their primary emphasis is at the present time.

to determine whether individual trees are controlling landscape processes or landscape processes are controlling individual trees (Castello *et al.*, 1995), so an interactive view is also reasonable.

These differences in emphasis recall differences in world view that underlie how people explain the functioning of social systems, which can be broadly painted as behavioralist, structuralist, and structurationist (e.g., Zimmerer, 1991). Behavioralists attribute primacy to individuals (agency) and emphasize the power of the individual relative to structural constraints, which are often treated as simply context. Structuralists tend to emphasize that the behavior of individuals is so constrained by large-scale political and economic structures that there is little point in focusing on individuals as agents of change. Structurationists, in contrast, emphasize the mutual dependence of structure and agency. Giddens (quoted from Zimmerer, 1991), a chief proponent of structuration, suggests that "the structural properties of social systems are both the medium and the outcome of practices that constitute these systems" (Giddens, 1979, p. 69).

There is, then, an analogy between social theory and the theory or world views underlying our modeling emphases (Table 13.2). Individuals in human social systems are analogous to individual trees in a forest landscape. In our modeling approaches, there appears to be a convergence toward an inclusion of processes that represent both structure and agency and their interactions. Even in models that focus on large-scale disturbance (ostensibly a "structural" focus), such as *FARSITE*, there is considerable mechanistic influence at the stand level (local physical fuel properties), as well as influences on the local level from regional weather (e.g., influencing local fuel moisture and wind speeds). This structurationist world view, blending processes and structures at several scales and including their interactions, may be becoming the norm in forest landscape ecological models because of the recognition that landscape dynamics derive from the interaction of processes and structures at scales ranging from the individual tree to the patch, region, and even globe (Table 13.1).

Capabilities, limits, and needs in the forest landscape modeling process

Landscape size, resolution, and scaling

In the last decade computer capabilities have increased by more than an order of magnitude, and this is reflected in the scale and resolution of present models. Grid-based models now commonly work with extents close to, or greater than 1000 rows × 1000 columns (e.g., Baker, Chapter 11). Distributing a model over many workstations enables thousands of detailed gap-level plots to be simulated in a few hours (Urban *et al.*, Chapter 4). The individual-tree-based models of Caspersen *et al.* (Chapter 2) and Liu *et al.* (Chapter 3) can now be run effectively at the scale of hundreds of thousands of individual trees. Timber harvesting models are now feasible at the scale of entire National Forests (Baker, Chapter 11; Gustafson and Crow, Chapter 12). Complex polygon-based models with hundreds of polygons, ten species, and 30 habitat types can be run in minutes (Roberts and Betz, Chapter 5). DELTA can simulate 3000 lots on a 300 000 ha land area for 50 years in a few minutes (Dale *et al.* 1993). *FARSITE* can simulate a large landscape fire in complex topography in a few minutes (Finney, Chapter 8). Clearly, spatial modeling of forest landscapes has reached the level at which complex forest processes can be simulated in reasonable times on large land areas.

Model design, modularity, and modeling languages

There is potentially considerable advantage to creating forest landscape models or components of these models that are generic and modular in design (Reynolds & Acock, 1997; Sequeira *et al.*, 1997). For example, LANDIS (Mladenoff and He, Chapter 6), FORMOSAIC (Liu *et al.*, Chapter 3), and *FARSITE* (Finney, Chapter 8) use a relatively newer object-oriented programming design and the C++ language to compartmentalize or encapsulate the various program modules. In this way the internal duties of a module are separate from the internal dynamics of other modules, and the interaction of those modules (Mladenoff and He, Chapter 6). This approach can allow for easier program modification and additions, without broadly affecting other portions of the model code. Such a design may lead to a collection of modules or a toolbox approach, which can be selected from and joined, depending on need. Cross-platform compatibility (Windows or Unix) is also maintained as a part of this philosophy. However, an integrated modeling approach that addresses a range of scales and processes would be needed to facilitate this kind of generic development, and may be less likely to occur if it depends on individual investigator-driven research. More recent development in computer languages, such as Java, carry modularity and generic, cross-platform compatibility

Table 13.3. *Levels of coupling of GIS and FLMs during model runs*

No linkage to GIS	Liu *et al.*, Chapter 3;
GIS preprocessing of input data or GIS display of final output maps, but no use of GIS during model runs	Caspersen *et al.*, Chapter 2; Urban *et al.*, Chapter 4; Roberts and Betz, Chapter 5; Mladenoff and He, Chapter 6; Finney, Chapter 8; Sessions *et al.*, Chapter 9; Dale and Pearson, Chapter 10; Gustafson and Crow, Chapter 12
Files transferred from model to GIS during model runs; some GIS functions used during model runs	Baker, Chapter 11;
GIS and model share common files and memory and use a common interface	None
Model embedded in GIS as one system	None

further. Java was developed for Internet applications that need to operate on all computing platforms transparently. These developments in programming languages may further encourage a generic landscape modeling toolbox.

Use of GIS software, functions, and capabilities

Although geographical information systems (GIS), software packages for manipulating map data, contain programs potentially useful in FLMs, these models do not always use GIS. FLMs and GIS can be coupled at several levels of integration (Nyerges, 1993; Fedra, 1993), but present FLMs either do not use GIS or are only loosely coupled with GIS (Table 13.3). For some models there may be no particular value in linkage with GIS. Where use of GIS is advantageous, a loose coupling requires the least development, but as larger land areas with finer resolution are simulated, there may be significant time constraints from file transfer operations. For example, with LANDLOG (Baker, Chapter 11), the file transfer operations consume more than half of the processing time when simulating a 894 column × 1209 row area.

Most FLMs coupled with GIS currently use the GIS only for display or for a few data processing functions. Tighter integration with GIS may be advantageous if these models require more spatial sophistication, using more complex GIS functions, or require more frequent interaction with the GIS. For this integration to be possible, however, the GIS software itself must be reasonably open, so that embedded models can directly use GIS functions and data structures. For example, in the popular ARC/INFO GIS software (ESRI 1997) it was necessary to write model operations using a macro-language prior to Version 7.2, when an application-programming interface, that allows GIS functions to be directly called from standard programming languages, became available.

Validation of forest landscape models

Many of our landscape models are not yet validated for use as predictive models, simply reflecting their stage of development, or their intended purpose. However, validation is not a singular matter. Rykiel (1996) suggests that it is necessary to carefully state what the validation criteria will be based upon the purpose of the model, its desired performance, and the context for its use. He distinguishes (i) operational validation, where model output is tested relative to desired performance standards, (ii) conceptual validation, where theories or assumptions and model logic are evaluated, and (iii) data validation, where the quality of the input data are determined to meet a specified standard. Rykiel reviews Sargents' (1988) explanation of suitable validation testing procedures.

Testing approaches from previous ecosystem modeling research are useful starting points for landscape models, but may require further development in some instances. Sensitivity analysis and error analysis can lead to model refinement and effective data collection by identifying the needed precision of data collection and most important model parameters (Gardner *et al.*, 1981). Predictive spatial models may attempt to replicate cell-by-cell patterns or may only aim to predict aggregate measures of landscape structure. Turner *et al.*, (1989) and Costanza (1989) review model goodness-of-fit evaluation procedures for these two approaches. Loehle (1997) suggests that a hypothesis testing framework, rather than goodness-of-fit testing, will lead to better models. A neutral-model approach has been adapted for spatial modeling (Gardner *et al.*, 1987) and Henebry (1995) suggests an autocorrelation-based approach that can be used in a hypothesis-testing framework. Error analysis in a spatial framework may also require new approaches, such as an analysis of the contribution of interpolated input data to output model error (Phillips and Marks, 1996).

Applications of forest landscape dynamic models

Richard Hobbs has recently provided a strong challenge to landscape ecology:

> I suggest that the products of landscape ecology (i.e., theory, methodology etc.) are best assessed, not on their intrinsic interest or popularity in the scientific literature, but on the impact they have on the planning and management of real landscapes . . . I suggest that in its present condition, landscape ecology has surprisingly little to offer those wishing to plan and manage the landscapes of the future.
>
> (Hobbs, 1997, p. 6)

Can this challenge be met? Do our models offer something useful to those wishing to plan and manage future landscapes?

Our models appear to be almost universally firmly linked to the real world, and to have considerable value for planning and management, although some of the potential is just over the horizon at the present time. Dale and Pearson (Chapter 10) address a global problem, tropical deforestation, using a rich empirical database on the landscape and on human behavior, and with important model outputs (carbon output, forest loss). Baker (Chapter 11) and Gustafson and Crow (Chapter 12) use US government data to project the potential consequences of continuing present timber harvesting practices on a National Forest into the future, a forest planning need globally. ZELSTAGE is designed to analyze the effects of forest management and natural disturbance on landscapes in the Cascade and Coast ranges in Oregon (Urban *et al.*, Chapter 4). Liu *et al.* (Chapter 3) examine the impacts of exotic pigs and timber harvesting on a tropical rainforest fragment. The LANDIS model has been used to examine the long-term consequences of landscape recovery from a century of human use (Mladenoff and He, Chapter 6).

VAFS/LANDSIM has been used to analyze the long-term impacts of lengthening the fire return interval on vegetation and landscapes in Bryce Canyon National Park, Utah (Roberts and Betz, Chapter 5). The *FARSITE* model can be used for predicting the potential pattern of fire spread as a fire is burning, or can be used to examine potential fires that might burn given certain fuel management options, both of which are very useful for fire managers (Finney, Chapter 8). SAFE FORESTS (Sessions *et al.*, Chapter 9) is focused on the joint management of fire, late-successional forests, and timber harvesting in the Sierra Nevada Mountains. Caspersen *et al.* (Chapter 2) have, in the landscape version of SORTIE, established a strong empirical link to tree population dynamics and the physical landscape in their study area, and now are in a position to explore applied problems. ZELIG version FACET has the potential to address many problems, as evidenced by the application of gap models over the last two decades, but to do so now in a spatially informative manner.

Future directions

Where will forest landscape modeling be in the near future, and what are the potential directions of development that appear most fruitful? First, technological developments will surely lead to faster computers, making simulation of large, satellite-image-scaled areas and more complex models more feasible, even as the volume of satellite data leapfrogs this development by an order of magnitude. Second, some progress toward modular and generic models (e.g., Mladenoff and He, Chapter 6) may make it possible to reach the stage where development is through incremental improvements in process algorithms rather than new model construction. Third, further development of socioeconomic drivers for landscape models (e.g., Dale and Pearson, Chapter 10) will be needed to make our models more relevant to planning and management. Addition of meaningful output variables (e.g., fraction of old growth forest, volume of timber) will also increase the utility of our models (e.g., Sessions *et al.*, Chapter 9). Fourth, a pluralism of emphases, from individual-based to regional/global models will continue to be useful for addressing problems at multiple scales, with meta-modeling (Urban *et al.*, Chapter 4) used when linkage is needed. Fifth, models more deeply embedded in GIS will become more feasible and more desirable due to greater use of GIS functions. Sixth, increasing attention to development of spatial algorithms will be needed, particularly to overcome the constraints in both grid-based and vector-based approaches. Finney's (Chapter 8) creative integration of vector-algorithms and raster-data is an example. Diverse efforts to develop process concepts and efficient algorithms is healthy, as is a pluralism of emphases. Seventh, it would behoove us to move our models into a phase of testing and validation that will shore up current developments and lead to refinements in process concepts and algorithms. Along with new testing and validation techniques, the field is now maturing to a level where detailed model comparisons can be made. Such comparisons, on a single landscape or dataset, should be a priority for research. This would give us valuable information concerning the appropriate model and scale to be used for specific questions, as well as help in evaluating comparative model designs and algorithms.

Lastly, linkage of landscape models to global climate models, and other process models, may be achievable, with potential benefits to both modeling efforts. It would be useful to reach the level of development of global climate models, where alternative models and empirical data are each contributing to refinement of models and data that are capable of helping us choose the future that Hobbs (1997) suggests we are not yet helping to shape:

> Landscape ecologists must decide whether they wish to participate in the process of shaping future landscapes, or simply act as passive recorders of changes in landscape patterns.
>
> (Hobbs, 1997, p. 7)

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EDITED BY

DAVID J. MLADENOFF and WILLIAM L. BAKER
University of Wisconsin–Madison
University of Wyoming

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