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LANDIS:

A Spatial Model of Forest Landscape Disturbance, Succession, and Management

David J. Mladenoff, George E. Host, Joel Boeder, and Thomas R. Crow

LANDIS is a stochastic, spatially explicit model of forest landscape disturbance and succession. It is designed to simulate the forests of the northern lakes states. LANDIS is raster-based and programmed in C++ with both imperative code and hierarchical, object-oriented data structures. LANDIS simulates succession semiquantitatively as tree species age classes. This approach allows concentration of model complexity on algorithms that simulate landscape-scale spatial interactions such as seed dispersal on a matrix of land types with differing disturbance regimes. LANDIS contains interacting windthrow and fire disturbance regimes, that we believe have not previously been modeled. The model links dynamically with GIS by operating in an ERDAS raster file format and is implemented for both MS-DOS and UNIX operating systems. The model includes a graphical interface and its own routines for spatial analysis and calculation of various indices of landscape pattern, and graphical and map output. The model has been developed to analyze changes in landscape structure in response to fire and windthrow disturbance regime combinations and forest harvest levels and patterns.

INTRODUCTION

Objective

We are conducting research to understand landscape-scale forest ecosystem dynamics in the northern lakes states region (Mladenoff et al. 1993, 1994). This region is dominated by highly altered and extensive second-growth forests that followed destructive logging in the past. In this context, our goal has been to develop a model of forest disturbance and succession for research into landscape-scale processes and applications in the northern lakes states. Traditional research methods that incorporate experimental methods and replication are seldom possible at landscape scales. Simulation models provide a tool to conduct experiments and examine results over large spatial and temporal domains. Similarly, landscape models provide a tool for managers and policy makers to test and evaluate management applications.

Background

Ecological landscape models, including forest and landscape disturbance models, have recently been reviewed and classified (Baker 1989; Sklar and Costanza 1991; Turner and Dale 1991). Here, we are interested particularly in spatially explicit forest landscape models that include dynamic processes of disturbance (including management) and succession and that also have a functional link with geographic information systems (GIS).

Forest ecosystem models that simulate single-plot species interactions, "gap" models of the JABOWA/FORET type, have been in use for some time in simulating forest change (Botkin et al. 1972; Shugart 1984). Such approaches are valuable for understanding ecosystem dynamics at within-stand scales, but even a single-stand level simulation (10s–100s ha) using such a method would challenge state-of-the-art computer capabilities. The challenge in forest landscape models, as in others, is to balance resolution, detail, and practical functionality. This means that no model is likely to meet all needs. We need to assure that the perceived need in model resolution is real for the anticipated tasks and not an artifact of our inability to adjust our traditional conception of informational needs from a fine-grained, site-specific scale to the landscape as a whole.

A few spatial models of forest fire disturbance exist (Kessell et al. 1984) and can simulate the spread of a single disturbance based on landscape characteristics, but they do not have the ability to simulate multiple, repeated dynamic changes (Baker et al. 1991).These models have a recovery or successional component that is strictly deterministic and lacks spatial interaction. A spatial model of fire disturbance that incorporates climatic driving variables has been developed for the Boundary Waters Canoe Area (BWCA), a wilderness area in northeastern Minnesota (Baker 1992). The model simulates recovery of patch age classes and therefore landscape structure as influenced by climate change and fire suppression effects on fuel and disturbance susceptibility. However, the model does not include an explicit forest-succession routine.

Roberts (1994a, 1994b) combined fire disturbance and forest succession in a spatial model of landscape dynamics in the southwestern United States. His model (VAFS/LANDSIM) is polygon based and operates on species life history characteristics or vital attributes (Noble and Slatyer 1980), fire susceptibility and response, and site characteristics. The model balances the need for computational efficiency while including dynamic processes between disturbance and recovery. Its limitations are the fixed polygons and spatial processes that are driven by the order of polygon neighborhoods rather than actual distances. Although LANDSIM contains some highly generalized processes, the model realistically simulates the forest landscape dynamics of the southwestern United States. Roberts (1994a) also examined the behavior of the model algorithm using sensitivity analysis based on varying the main ecological parameters.

MODEL DESCRIPTION

General Characteristics

Our model of landscape disturbance and succession (LANDIS) is an elaboration of the approach of Roberts (1994a, 1994b). It is similar in concept, temporal resolution (ten-year time step), and basic model algorithm. The basic conceptual structure of LANDIS is also similar to the forest gap models, where succession is based on interactions between species life history characteristics (Table 32-1), site conditions, and disturbance regime or management. With LANDIS, we have attempted to retain more of the ecological dynamics of gap models with the capability to spatially model larger areas. LANDIS simulates forest change semiquantitatively by modeling tree species as ten-year age classes, not as individual stems as in gap models. Succession and disturbance contain stochastic, spatially dynamic elements.

Table 32-1. List of species life history parameters that drive the model.

Long	Species longevity (years)
Mature	Age of sexual maturity (years)
Shade	Shade tolerance class (1–5)
Fire	Fire tolerance class (1–5)
Wind	Windthrow tolerance class (1–5)
Effseed	Effective seed dispersal distance
Maxseed	Maximum seed dispersal distance
Vegprob	Vegetative reproduction probability
Sprout	Maximum sprouting
Estab	Species establishment coefficient (by land type)

However, LANDIS differs in several ways from the approach of Roberts (1994b):

1. Our model operates in raster mode, which allows complex dynamics to be more easily modeled than in vector format, such as dissolution and aggregation of patches.
2. Spatial interactions such as seed dispersal and disturbance spread are based on distances instead of polygon neighborhoods.
3. Model algorithms are programmed to allow operation at different scales of resolution by modifying cell size.
4. The model is programmed in C++ using hierarchical, object-oriented data structures (Figure 32-1) (Boeder et al., *Spatially*, 1993). Although LANDIS is more detailed than LANDSIM, the object-oriented structure and raster format maintain computational efficiency.
5. The model has a user interface and a free-standing spatial analysis package (APACK) that allows rapid calculation of landscape summaries and indices without exporting to a GIS or statistical package (Boeder et al., *Spatially*, 1993; *Spatial Analysis*, 1993).
6. LANDIS reads and writes ERDAS raster files, making GIS links rapid. Real-time operation and linkage with GIS to interact with other data layers can be done with appropriate hardware and software. Map output also can be easily converted to other formats such as ARC/INFO and Postscript.
7. Development of the model for the northern lakes states required designing both windthrow and fire disturbance routines and interaction between them. We are not aware of other models that incorporate such disturbance dynamics.

Successional Dynamics

The model successional algorithm is based on that of Roberts (1994a, 1994b), with several additions. Succession is a competitive process driven by species life history parameters (Table 13-2). Pattern of seed dispersal, species establishment, and shade tolerance, along with disturbance (fire and windthrow) susceptibility and response, determine vegetation change on different kinds of sites (Figures 32-2 and 32-3). The values for life history parameters are derived from published literature (Curtis 1959; Burns and Honkala 1990; Loehle 1988). Our approach differs most from Roberts (1994a) in the disturbance and seeding algorithms. The large number of tree species in the region exhibit a great variety of seed longevity and dispersal modes (Pastor and Mladenoff 1992). Seed dispersal is parameterized as actual dispersal distance curves, rather than by polygon neighborhood as in Roberts (1994a). This allows for more complex dispersal and establishment dynamics to be modeled. Using actual dispersal distances also allows the model to be used at variable scales or cell sizes.

The seeding algorithm is the slowest component of the model. The seeding algorithm can be switched to simpler modes in the model if desired, including no dispersal and uniform dispersal.

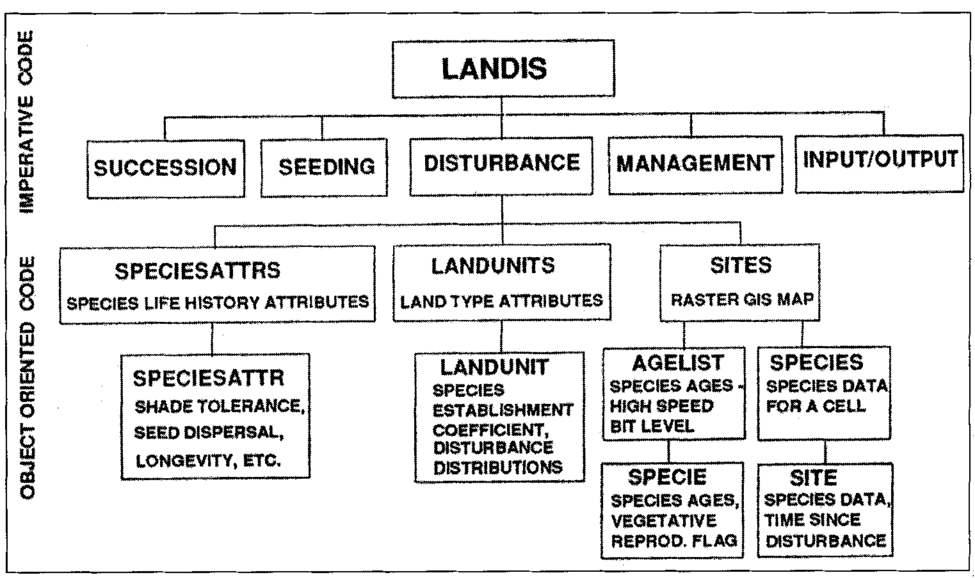

Figure 32-1. General structure of LANDIS model code. The model contains both more traditional imperative code and object-oriented structures.

Table 32-2. Analysis methods and indices currently calculated in APACK module. Algorithms and sources are in Boeder et al. (1993b).

Fractal dimension	Edge ajacency
Perimeter: area ratio	Electivity index
Patch area statistics	Connectivity (distance)
Patch perimeter (edge) statistics	Percolation ratio
Landscape diversity/dominance	Angular second moment

However, we feel that these spatial seeding dynamics are some of the most important characteristics of the model. These stochastic processes allow simulation of local species recolonization following disturbance, more realistic successional change over time on large landscapes, and the potential for modeling species migration in response to major large-scale events such as global climate change.

Site Factors

Site characteristics are input to the model as a map layer consisting of ecologically defined land types. Ecological land units can be identified at multiple scales by dominant controlling factors (Barnes et al. 1982; Host et al. 1987). Land units in this landscape are defined in terms of major landscape geomorphic features. Ecologically, in terms of a soil moisture/nutrient gradient, these correspond roughly to mesic, dry mesic, and xeric (Curtis 1959). Any practical number of such classes are possible at a selected resolution.

For each species an establishment coefficient summarizes the probability of that species establishing on each land type, without competition (Roberts 1994a). These values are estimates based on data in Curtis (1959) and Burns and Honkala (1990). The establishment parameters encapsulate what is known about environmental constraints on each species in the region, primarily moisture and nutrient requirements as expressed by site conditions. These land type differences are important because they affect species establishment and relative success. Site characteristics also influence fuel accumulation and persistence (productivity and decomposition), which is important in the interaction of the fire and windthrow disturbance regimes and variation in disturbance susceptibility with stand age (Clark 1991; Frelich and Lorimer 1991a).

Disturbance

Modeling succession over large landscapes in the northern lakes states requires an integration of windthrow and fire disturbances (Mladenoff and Pastor 1993). Xeric sites in the region usually support vegetation that is both more fire prone and requires fire for reestablishment. Such interactions on real landscapes are complicated by human changes, such as fire suppression, which modify natural disturbance regimes, succession, and fuel loads (Clark 1988; Baker 1992). Fire disturbance is implemented in the model similar to Roberts (1994a), where fires are categorized within five severity classes according to time since last fire. Fuel accumulation also varies according to site characteristics. As a result of these factors, fuel accumulation and decomposition curves are mediated by land type in the model. These curves are estimates based on examples and patterns in the literature for different forest and site types (Bormann and Likens 1979; Gore and Patterson 1985). These factors interact with the fire tolerance parameter of the tree species. The combination of fire severity class and species fire tolerance determines which species age classes are killed (Figure 32-2).

Windthrow is a top-down disturbance, and susceptibility increases primarily with tree size (age class). Windthrow is implemented in the model within five severity classes, based on percent of canopy removal. This differs from fire, which is a bottom-up disturbance, where smaller (younger) age classes are killed first, according to disturbance severity and species susceptibility. Both types of disturbance are important in the northern lakes states, with windthrow important in all types of forest (Canham and Loucks 1984; Mladenoff 1987). Fire is more important on drier sites, typically with pine (Heinselman 1973). Besides the differing modes of these two disturbances, their temporal interactions produce complex combinations and patterns of forest ecosystems on the landscape (Figure 32-2). For example, fire following a windthrow disturbance will have fuel loads different from a fire in the same landscape without a preceding disturbance.

Both fire and windthrow disturbances are generated in the model by selecting randomly from the appropriate disturbance-size distributions. These are estimated negative exponential distributions based on the published literature for the region (Frelich and Lorimer 1991a, 1991b; Canham and Loucks 1984; Baker 1991, 1992). The disturbance frequency and rotation period for the landscape (by land type) are estimates based on Canham and Loucks (1984) and Frelich and Lorimer (1991a). For a given disturbance event, a potential disturbance size is selected from the distribution, but realized size or ultimate spread is based on local susceptibility. The realized disturbance-patch spread must be contiguous for fire, but for windthrow it need not be.

Model Output

The model produces maps based on landscape composition at specified time steps (Plate 32-1). The maps can be produced as cover types or age classes. Several forest classification algorithms may be selected (Boeder et al., *Spatially*, 1993), based on order of dominants, successional stage, or fuzzy community membership (Roberts

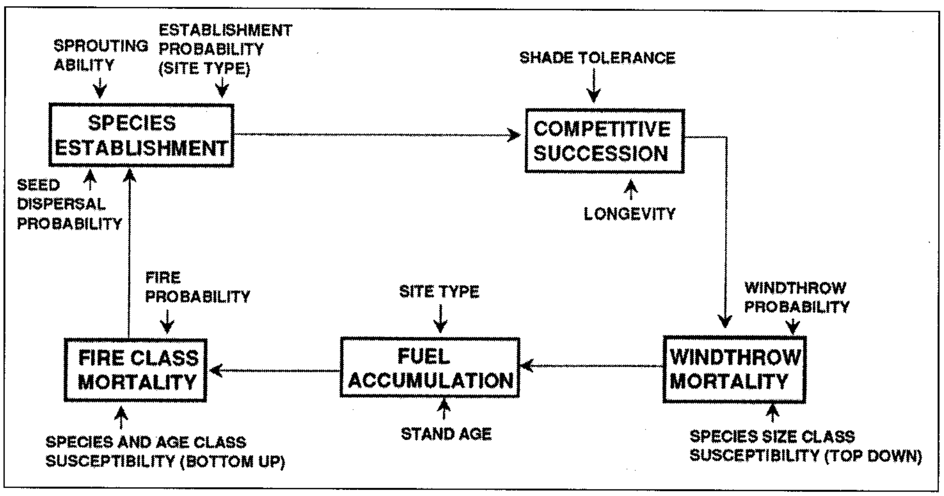

Figure 32-2. Succession (upper half) and disturbance (lower half) dynamics of the LANDIS model. Disturbances (windthrow and fire) can occur in any order, or singly on the landscape, with future disturbances susceptibilities modified accordingly for a given site.

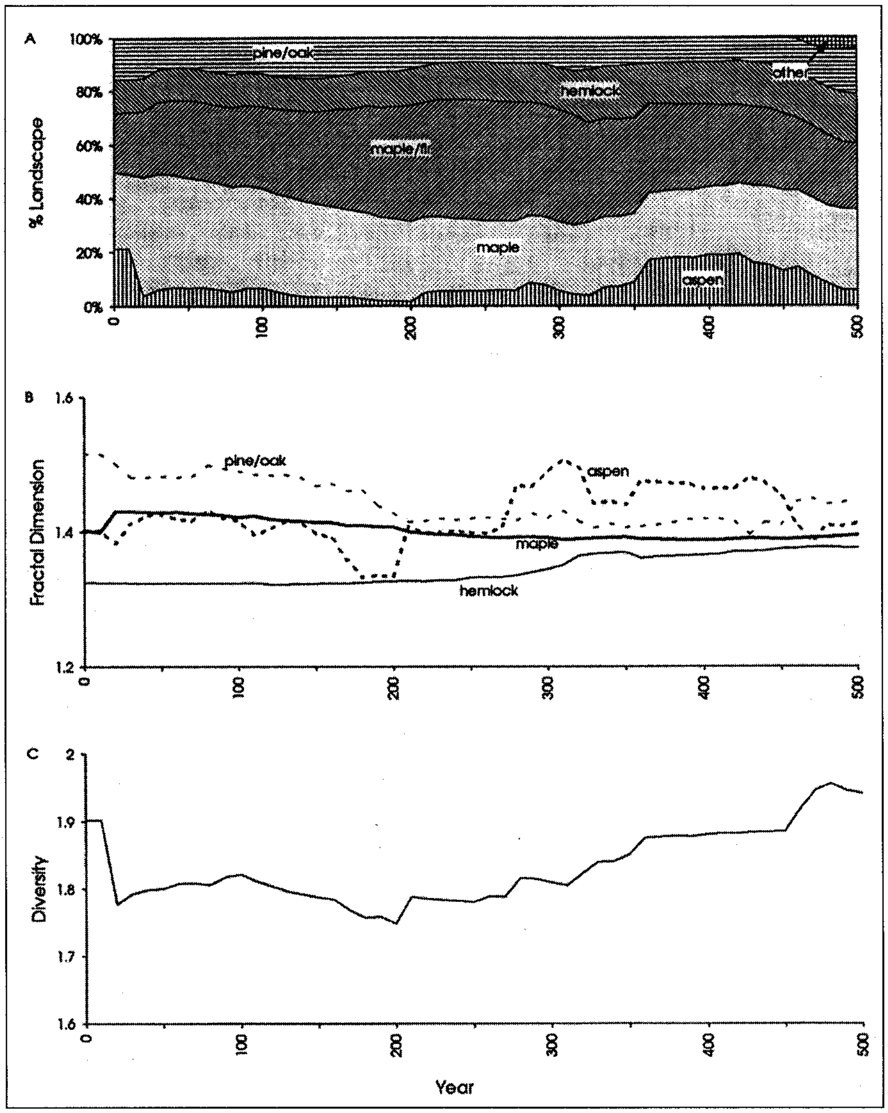

Figure 32-3. Example of selected analytical and landscape index output from APACK plotted through the 500-year simulation: (a) landscape composition by dominant species, (b) fractal dimension of patch types by dominant species, (c) landscape diversity.

1994a). Disturbance and age class maps are also produced at desired time steps, as well as a cumulative disturbance map at the end of a simulation. Spatial analyses and indices are produced as specified in the appropriate output format (table, graph, or chart).

Sample Results

In the example simulation (Plate 32-1), a landscape of approximately 10,000 ha is simulated for 500 years at 60-m resolution (approximately 37,500 cells). Landscape succession responds to disturbances occurring at different rates on the three land types. The starting map (1980s) is dominated by early successional forest following widespread logging and fire before the middle of the century (White and Mladenoff 1994). Gradual inward spread of late successional species like maple (*Acer saccharum*) and balsam fir (*Abies balsamea*) accelerate from recolonization nodes that establish by longer distance seed dispersal.

Landscape pattern indices describe change over the simulation period. Fractal dimension is more variable among the early successional patch types dependent upon higher-intensity disturbances.

Landscape diversity decreases over time as the landscape becomes more dominated by late successional types but increases as the disturbance susceptibility and realized disturbances again increase the area of successional types, such as aspen (*Populus tremuloides*). Codominant or age class maps provide additional insights. Running the same simulation as shown without the natural disturbance rates results in maple dominance 150 years sooner. Once maple is dominant, windthrow changes the age class of patches, but without fire, most areas remain dominated by maple (Plate 32-1).

CONCLUSION

The spatially dynamic disturbance and dispersal algorithms are the core of LANDIS model behavior and allow it to reasonably simulate the dynamics and composition of the northern lakes states' forests for various land types. The model shows promise in examining forest landscape dynamics in relation to disturbance and management (cutting) and in analyzing changing landscape pattern. The interaction of disturbance regimes (windthrow and fire) in the model is a novel implementation which we have only begun to explore.

Routines are being implemented that incorporate landscape structure effects on disturbance spread and succession, such as edge effects on windthrow susceptibility and probabilistic selection of windthrow directionality. The object-oriented structure of LANDIS (Figure 32-1) (Boeder et al., *Spatially*, 1993) is intended as the base for development of other rule-based management applications of the model, such as forest management and habitat utilization (Mladenoff and Host 1994).

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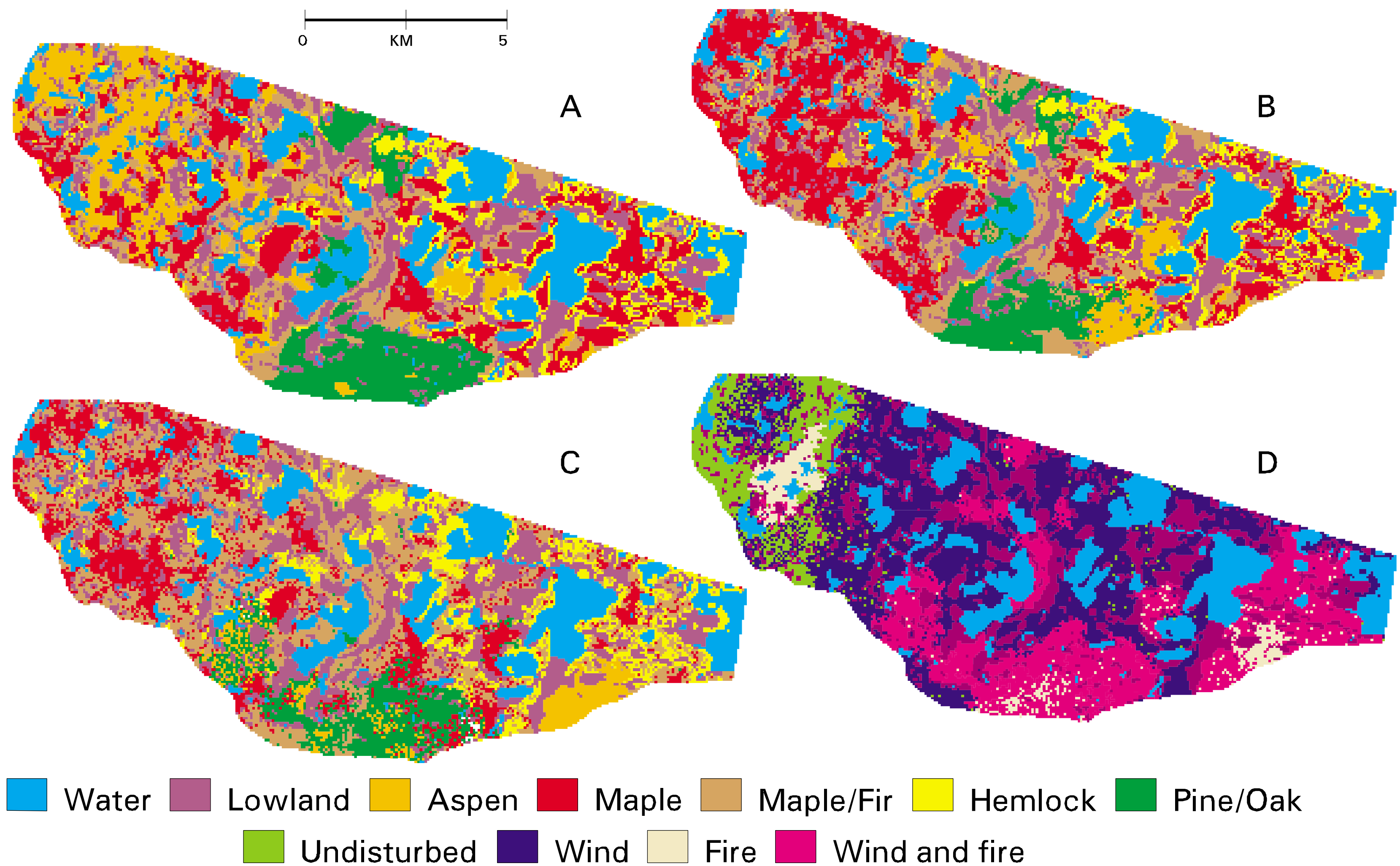

Plate 32-1. Map output at selected time steps from a 500 year LANDIS simulation of a 10000 ha landscape at 60 m cell size (approximately 37500 cells): a) initial state, b) 50 years, c) 300 years, d) cumulative disturbance over the 500 year model run.

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