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Forecasting landscape-scale, cumulative effects of forest management on vegetation and wildlife habitat: A case study of issues, limitations, and opportunities

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Abstract

Forest landscape disturbance and succession models have become practical tools for large-scale, long-term analyses of the cumulative effects of forest management on real landscapes. They can provide essential information in a spatial context to address management and policy issues related to forest planning, wildlife habitat quality, timber harvesting, fire effects, and land use change. Widespread application of landscape disturbance and succession models is hampered by the difficulty of mapping the initial landscape layers needed for model implementation and by the complexity of calibrating forest landscape models for new geographic regions. Applications are complicated by issues of scale related to the size of the landscape of interest (bigger is better), the resolution at which the landscape is modeled and analyzed (finer is better), and the cost or complexity of applying a landscape model (cheaper and easier is better). These issues spill over to associated analyses that build on model outputs or become integrated as auxiliary model capabilities. Continued development and application of forest landscape disturbance and simulation models can be facilitated by (1) cooperative efforts to initialize more and larger landscapes for model applications, (2) partnerships of practitioners and scientists to address current management issues, (3) developing permanent mechanisms for user support, (4) adding new capabilities to models, either directly or as compatible auxiliary models, (5) increasing efforts to evaluate model performance and compare multiple models running on the same landscape, and (6) developing methods to choose among complex, multi-resource alternatives with outputs that vary over space and time.

Keywords: Forest landscape model; LANDIS; HARVEST; LANDSUM; SIMPPLE; VDDT; Validation; Multi-resource evaluation; Succession; Disturbance

1. Introduction

Over the past 15 years, forest landscape disturbance and succession models have matured into practical tools for large-scale analysis and planning. Prior to the 1990s it was relatively easy to conceive of the components necessary for a landscape model that could forecast the spatial and temporal outcomes of forest management, but implementation was hampered by available software and computing capacity. Today, bolstered by vast improvements in computing capacity and geographic information system (GIS) software, a number of forest landscape models and decision support systems have evolved into applied tools for evaluating effects of forest disturbance, including management practices, at the landscape scale. This evolution has been propelled by the needs of forest mangers to account for large-scale cumulative effects of proposed management alternatives.

Many of the available forest landscape change models and decision support systems have been summarized in key documents and databases including Barrett (2001), Mladenoff and Baker (1999), Mowrer et al. (1997) and Gordon et al. (2004) http://ncseonline.org/NCSSF/DSS/Documents/index.htm. The subset of forest landscape disturbance and succession models generally fall in to three broad groups:

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(1) Polygon-based systems that model changes through time for somewhat homogenous vegetation units (e.g., forest stands >1 ha in extent) represented as mapped polygons. For each polygon, forest change over time due to succession or disturbance is modeled with a finite set of forest conditions (states) and pathways (deterministic or probabilistic transitions among states). Cumulative landscape change is defined by the collective spatial and temporal changes for the polygons. Examples of polygon-based models include LANDSUM (Keane et al., 1997, 2002), SIMPPLE (Chew, 1995; Chew et al., in press) and VDDT/TELSA (Beukema and Kurz, 1998).
(2) Raster-based models that uniformly divide the landscape into a mosaic of square sites (i.e., rasters or pixels). The area of a site is user defined but typically falls within the range 0.01 ha to 1 km^2. Modeled spatial processes such as seed dispersal, tree establishment, harvest or fire affect individual sites. Cumulative changes across the entire landscape or any subset are represented as the cumulative change (and variation) for the included sites. Examples of raster-based models include LANDIS (He et al., 1999, 2005; Mladenoff and He, 1999; Mladenoff, 2004) and HARVEST (Gustafson and Crow, 1999; Gustafson and Rasmussen, 2005).
(3) Tree-based growth and yield modeling systems with spatial modeling capability. These are an extension of individual-tree-based models that predict changes (growth, mortality, harvest, and ingrowth) for a statistically representative sample of trees from a forest stand. Predicted changes to the individual sampled trees can be aggregated to estimate stand-level change. Over the past two decades improvements in spatial analysis tools and computing capacity have provided options to model stand dynamics within multiple stands simultaneously while also modeling spatially explicit process that move among stands and/or depend on the pattern of stand adjacencies (e.g., harvest, insect dispersal, or fire). Cumulative landscape impacts are represented by the combined changes and patterns in individual trees and stands over time. Examples of this class of models include FVS (Dixon, 2007) and LMS (e.g., McCarter, 1997; McCarter et al., 1998). This confluence of technologies has blurred the distinction between traditional growth and yield models and landscape disturbance and succession models.The order (1–3) represents a *general* pattern of increasing detail in (a) initial data requirements, (b) model complexity, (c) computation load, and (d) options for mapping or summarizing results. It is important to match management information needs with model capabilities, complexity, and data requirements. In theory, the simplest model that can provide the required information is preferable; in practice the model that has the fewest *perceived* barriers to implementation, regardless of complexity, is often the one applied.

For more than a decade, we have applied the LANDIS model of forest landscape disturbance and succession in the Midwestern United States and concurrently applied GIS-based wildlife habitat suitability index models (Larson et al., 2004). As LANDIS development continues and the mechanics of model implementation become less onerous, we face an emerging set of issues common to application of many landscape disturbance and succession models: (a) matching appropriate models to the tasks at hand, (b) overcoming complexity of calibration for new geographic regions, (c) defining initial conditions for a large landscape, (d) testing or validating results at the landscape scale, (e) understanding each model's strengths and weaknesses, (f) securing computing resources for large landscapes and/or multi-resource evaluations, (g) finding user support, and (f) quantitatively comparing anticipated cumulative effects of complex management alternatives. In this paper we discuss our experience with LANDIS and our observations relative to these issues. Where possible we relate the issues to the broader set of forest landscape disturbance and succession models.

2. LANDIS applications in the midwest

2.1. The LANDIS model

The LANDIS landscape disturbance and succession model is thoroughly described in numerous sources (e.g., He et al., 1999, 2005; Mladenoff and He, 1999; Mladenoff, 2004), and LANDIS web sites provide additional background, reference material and access to software (http://web.missouri.edu/~umcsnrlandis/, http://landis.forest.wisc.edu/documentation). LANDIS was initially developed and applied in Wisconsin (USA) (e.g., He et al., 1998; He and Mladenoff, 1999; Scheller and Mladenoff, 2005; Sturtevant et al., 2004b; Zollner et al., 2005; Radeloff et al., 2006), with subsequent applications elsewhere in the United States (Larson et al., 2004; Syphard and Franklin, 2004; Wimberly, 2004; Franklin et al., 2005; Shifley et al., 2006), Canada (Van Damme et al., 2003), China (He et al., 2002; Wang et al., 2006), and Europe (Pennanen and Kuuluvainen, 2002; Schumacher et al., 2004).

Briefly, LANDIS estimates at 1- or 10-year intervals the presence or absence of tree species or species groups by age class for each site (i.e., raster). Tree species succession is governed by a set of stochastic rules based on species' vital attributes (e.g., longevity, age at initiation of seed production, seed dispersal distance, fire tolerance, shade tolerance, and sprouting probability). Species and age class dynamics are affected by stochastically modeled disturbances due to harvest, fire, or wind (weather); disturbance frequency and size distribution are user-defined and vary by ecological land type.

2.2. Application on National Forests

Our applications of LANDIS have been in the Ozark Highlands of southeastern Missouri and in south-central Indiana (Shifley et al., 1997, 2000, 2006; Larson et al., 2004). Those landscapes range from steeply dissected, rocky Missouri Ozark plateaus dominated by black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), white oak (*Quercus alba* L.), post-oak (*Quercus stellata* Wangenh.) and shortleaf pine (*Pinus echinata* Mill.) to mesic, rolling, fertile hills in Indiana with complex mixtures of the trees in the red oak and white oak groups, sugar maple (*Acer saccharum* Marsh.), yellow-poplar (*Liriodendron tulipifera* L.) and numerous species of lesser abundance.

LANDIS applications in Missouri have primarily been on contiguous portions of the Mark Twain National Forest ranging from a few thousand (Shifley et al., 2000) to more than 70,000 ha in extent (Shifley et al., 2006). On the Mark Twain we have examined the long-term effects of alternative management regimes on forest structure and tree species composition and on wildlife habitat suitability (Larson et al., 2003, 2004; Shifley et al., 2006). In Indiana our applications have been directed at forecasting, as realistically as possible, the outcomes of the alternatives proposed in the Forest Plan (United States Department of Agriculture Forest Service, 2006) for the 80,000 ha Hoosier National Forest. That analysis included the development and application of 10 landscape-level habitat suitability models (Rittenhouse et al., 2007) that utilized LANDIS output to forecast changes in wildlife habitat suitability.

National Forests are partitioned into discrete purchase units (proclamation boundaries) within which the National Forest ownership is concentrated but which also include intermixed private lands. While working with the Hoosier National Forest we also made provisional forecasts of expected changes on adjacent private lands within each purchase unit.

2.3. LANDIS initialization

As the LANDIS model has evolved the documentation and user interface have improved to the point where application of LANDIS software is within the grasp of any determined analyst with a modern computer. The contemporary barriers to application are more often related to finding suitable data to define initial landscape conditions and to calibrating the relationships that govern forest dynamics (e.g., seed dispersal, species establishment, windthrow, and wildfire).

Maps of landforms or ecological landtypes are user-defined in LANDIS and required for differentiating spatial processes and event probabilities that are expected to differ among landtypes (He et al., 2005). Although, ecological classification systems are widely available, in our applications ecological landtypes and landforms were not fully mapped across our study areas. Consequently, mapping ecological landtypes across our study region, personally or via contractors, was an initial requirement. Elevation changes across our study areas are generally less than 200 m and a reduced set of ecological landtypes representing northeast (cool) slopes, southwest (warm, dry) slopes, wide ridges, narrow ridges, small drainages, and mesic riparian areas proved sufficient and could be derived from a digital elevation model. Mapping ecological landtypes can be time consuming, but there are numerous examples of methods and/or algorithms for doing so from spatial data (e.g., Franklin, 2003; Shao et al., 2004; Syphard et al., 2007a,b).

Some investigators have used remotely sensed data and ecological landtypes to coarsely define dominant forest cover and age class (e.g., for sites >1 ha in size), the two essential vegetation characteristics needed to describe initial vegetation conditions (He et al., 2007) In our applications we needed a smaller site (raster size) to more realistically model selection harvests, windthrow, and landscape elements (e.g., length of edge habitat) relevant to wildlife species of interest. Consequently, we used site sizes of 0.01 or 0.09 ha and based initial estimates of dominant forest cover and age on stand-level inventories maintained on the Hoosier and Mark Twain National Forests.

Mapping initial forest age and dominant cover type on privately owned lands was more problematic; private ownerships in our study area typically range from 10 to 500 acres and have no site-specific forest inventory data. Existing GIS coverages are available to (1) distinguish private lands from public lands, (2) distinguish forest land from nonforest, and (3) in some cases to distinguish conifer cover from hardwoods. We used those data layers to map the location of private forest ownerships and then used state-level data on the frequency distribution of ownership sizes (Birch, 1996) to create and overlay a hypothetical, ownership grid with approximately the same frequency distribution of parcel sizes. We used the intersection of ownership boundaries and mapped ecological landtypes to define locations for private land management units (i.e., a substitute for stand boundaries). We then summarized Forest Inventory and Analysis (FIA) field data (United States Department of Agriculture Forest Service, 2007) for private ownerships in the region and used the frequency distribution of forest area by dominant cover type, age class, and ecological landtype to populate initial forest conditions for each privately owned management unit. Thus, we knew that the univariate frequency distributions of forest area by age class and by dominant species generally matched that for private forest lands as a whole, but the spatial patterning of those units was only spatially representative, not spatially exact. The process for deriving initial map layers differs with available data sources; other published methodologies include species distribution modeling (Franklin, 1998) and hierarchical Bayesian techniques (He et al., 2007).

2.4. LANDIS calibration

Tree species establishment coefficients in LANDIS differ by landtype to characterize differential rates of species recruitment among landtypes. We used FIA and other inventory data to guide initial estimates of species establishment coefficients and then used long-term projections of species change to estimate trends, discuss trends with local experts, and refine coefficients. We found derivation of the species establishment coefficients the most difficult part of the calibration process because they do not correspond to any readily measurable inventory characteristic. Nevertheless LANDIS has proved amenable to calibration for more than a dozen different ecosystems by users in North America, Europe and Asia (Mladenoff, 2004).

Calibration of algorithms for exogenous disturbances caused by fire, windthrow, and harvest add additional layers of complexity to LANDIS. Federal and state agencies generally have good historical records of wildfires that can be used to estimate frequency and size of fire events. The heterogeneous spatial patterns of wildfire events are increasingly being described in mathematical and mapped formats (Haight et al., 2004; Yang et al., 2007; Shang et al., 2007; Guyette et al., 2002).

Historical estimates of weather damage to forests are not as common. For our study regions we were limited to a few sources for small-scale windthrow (Rebertus and Meier, 2001), tornadoes (National Oceanic and Atmospheric Administration, 2007), and ice damage (Rebertus et al., 1997). LANDIS currently has no mechanism for simulating the intense, linear impacts of tornado events which are infrequent, but not inconsequential in their impacts on forest structure over a century of change.

Harvest disturbance is typically user defined and supported by well documented historical records or well defined future plans. Consequently, simulated harvest events are generally easier to model that wind or fire events (Gustafson et al., 2000).

2.5. Linking habitat suitability models

Forecasting changes in wildlife habitat quality or population size is often an objective of landscape simulation, and we developed and applied GIS-based wildlife habitat suitability models in conjunction with the LANDIS for this purpose. Habitat suitability index (HSI) models estimate habitat suitability on a scale of 0 (not suitable) to 1 (highly suitable) based on an assessment of resource attributes considered important to a species' abundance, survival, or reproduction (U.S. Fish and Wildlife Service, 1980, 1981). Individual habitat attributes are modeled as suitability indices (SIs) represented as mathematical or graphical relationships. Overall habitat suitability, or the HSI, is calculated as a mathematical combination of the individual SIs. The HSI is typically calculated as the geometric mean of the individual SIs, although more complex formulas can be used depending on how the SIs are thought to interact.

Recent developments in habitat suitability index modeling have resulted in models that can be applied to large landscapes through the utilization of GIS (Duncan et al., 1991; Gustafson et al., 2001; Larson et al., 2003, 2004; Rittenhouse et al., 2007). Landscape-scale, GIS-based HSI models can address ecological and landscape effects on wildlife such as area sensitivity, edge effects, interspersion, landscape composition, and juxtaposition of resources (Larson et al., 2003, 2004; Rittenhouse et al., 2007). These models rely on data layers derived from remote sensing and other existing spatial databases or from large-scale inventories and can include data layers produced by LANDIS or other simulation models that represent future forest conditions. With GIS-based models, SI and HSI values are calculated for each pixel in the landscape and the distribution of HSI values for all the pixels in a landscape can be summarized with maps or descriptive statistics, or used as inputs to other models (e.g., Larson et al., 2004; Shifley et al., 2006) (Fig. 1). The models we applied in these projects are available in a stand-alone software package, Landscape HIS models (http://www.nrs.fs.fed.us/hsi; Dijak et al., 2007), that can be applied to data from a wide range of sources.

3. Discussion

3.1. Model scale and detail

In our work we faced some obvious and some non-obvious issues of scale. Our use of a 0.01 ha or 0.09 ha site (raster size) for LANDIS and HSI model implementation in the Midwest was due to our desire to assess the impacts to wildlife habitat of the harvest or death of single trees or small groups of trees. The 0.01 ha raster size had an intuitive appeal—one raster cell was roughly equivalent to the crown area of a mature tree and allowed realistic spatial representation of the uneven-aged, individual-tree selection silviculture that is commonly practiced in Indiana. The 0.09 ha raster sized was approximately the size of a regeneration opening used with group selection silviculture in Missouri. Disturbance events smaller than the selected model resolution (e.g., small windthrow events) cannot be explicitly modeled, and the spatial arrangement of vegetation within a site (raster) is considered to be (a) homogenous, (b) indeterminate, or (c) inconsequential. Raster cell size is a critical decision for wildlife HSI modeling as well as for vegetation modeling. GIS-based HSI models frequently include suitability functions that assess habitat interspersion, patch size, and distance to edge; these metrics differ depending on how patches and edges are defined.

We were aware that a decrease in raster cell size results in an exponential increase in the number of raster cells and creates at least an exponential increase in data processing time. Nevertheless, for landscapes about 7 million raster cells in size LANDIS could process a century of landscape change in about 6 h using a high-end computer workstation. For the 80,000 ha Hoosier National Forest which we processed in five geographically discrete sections using a 0.01 ha raster cell size, we could model five different management alternatives for 150 years in about 1 week of computer time.

Our experience has been that we run every project at least three times. This is usually due to unanticipated issues with data processing or to errors in the design of a model scenario. Corrections generally mean rerunning the entire scenario. In our work, a larger concern than running LANDIS to model future tree species age structure and species composition is the effort required for post-processing LANDIS outputs via GIS or custom spatial analysis programs to summarize landscape statistics and habitat suitability. For example, to use Landscape HSImodels (Dijak et al., 2007) to calculate habitat suitability for nine species on the Hoosier National Forest, at three time steps (10, 50, and 150 years of elapsed time), for five management alternatives required 980 h of computer processing time. As we acquire the ability to work with larger landscapes and derive more characteristics of interest from modeled scenarios, post processing considerations will become even more influential in defining the scope of tractable projects. To some extent, buying more computing capacity can mitigate issues of project size and processing time, but it is surprisingly easy to design a project that imposes unreasonable computing demands.

The available forest landscape succession and disturbance models and decision support systems vary in complexity and

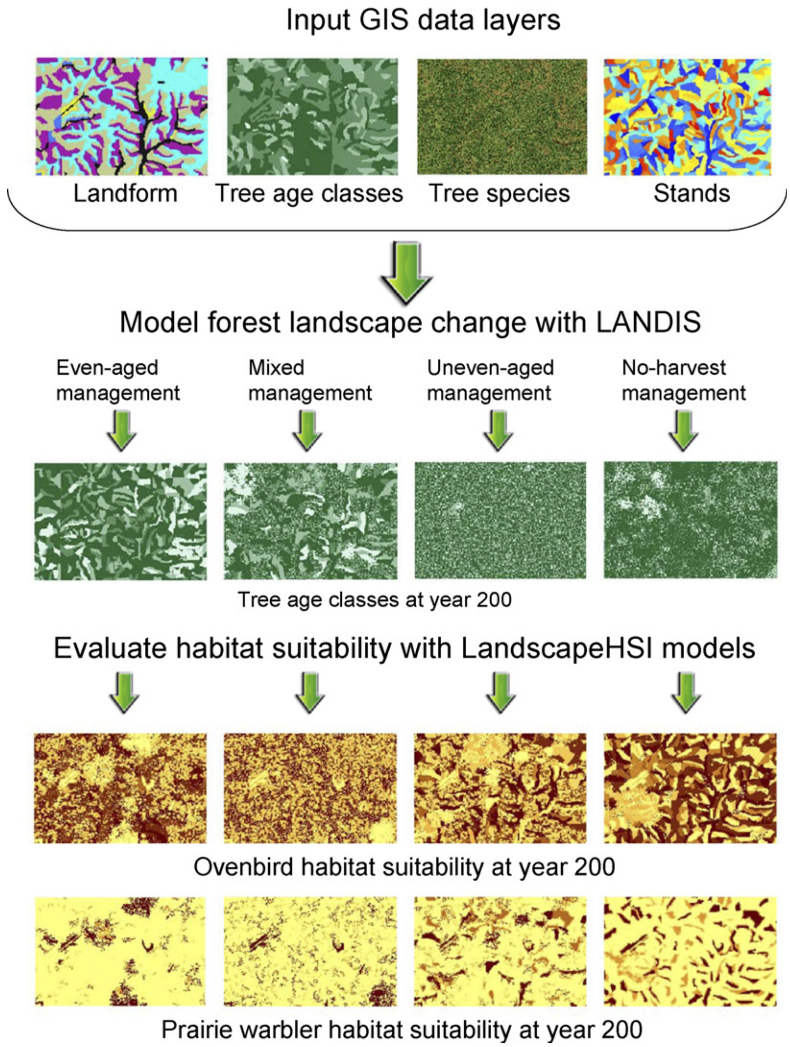

Fig. 1. Starting from initial GIS layers mapping landforms, tree age classes, tree species composition, and management units (stands) for the Mark Twain National Forest, we used LANDIS to analyze and communicate expected outcomes of alternative management strategies over time and space. We could forecast forest age structure spatially over for four alternatives (shown for the final year of a 200 years projection; darker sites have older trees). From the modeled scenarios it is possible to derive habitat suitability for numerous wildlife species (two shown, darker is better habitat), and a wide variety of other derived values. Similar maps and values can be estimated for each year or each decade of the modeled scenarios. This figure highlighting 2835 ha within the 71,142 ha modeled landscape illustrates some of the many types of information that can be generated, how that information can be communicated to professionals or the public, and the complexity of choosing a preferred alternative in a spatially explicit, multi-resource modeling environment.

capability. Thus, when addressing complex forest landscape modeling problems it is important to match the model to the question at hand and then continue to revaluate options and required outcomes. For example, for applications where harvest effects are the primary agent of forest change and detailed information about species succession is not required, a model such as HARVEST (Gustafson and Crow, 1999; Gustafson and Rasmussen, 2005) may be more appropriate than LANDIS. HARVEST carries less detail about each site but is easier to initialize and can manipulate large landscapes that are impractical to investigate using LANDIS (or can run equivalent landscapes significantly faster). Similarly, if the management questions can be addressed using the aggregate information for larger sections of forest (e.g., based on forest stands that are roughly 2–20 ha in extent) then models such as VDDT/TELSA (Beukema and Kurz, 1998), SIMMPPLE (Chew et al., in press) or LANDSUM (Keane et al., 1997, 2002) may be fully adequate yet easier to calibrate and require less computational processing.

Despite the tradeoffs among scale, detail, conceptual complexity, and computational complexity, the effort and expense of implementing any landscape disturbance and succession model are so demanding that we are unaware of any side-by-side comparisons of different landscape models applied to address the same scenarios on the same large landscape. There are, however, some useful publications and web-based tools to compare model features and capabilities (Barrett, 2001; Mowrer et al., 1997; Gordon et al., 2004; http://ncseonline.org/NCSSF/DSS/Documents/index.htm). The high overhead associated with initializing and applying any landscape disturbance and succession model creates a high incentive to continue with the simulation model that one starts with, limitations notwithstanding. Thus, model selection should also consider adaptability of the model to address the range of other landscape-scale management issues that are likely to arise after a model has been successfully implemented in given region.

3.2. Organizational issues

Applying a landscape model to address practical or policy-relevant problems requires a team approach. Maps of initial landscape conditions (e.g., land types, forest cover, and forest age) rely on shared data from multiple sources. Information about disturbance patterns from fire, wind, and harvest often come from specialists with local experience. It is not difficult for scientists to conjure up theoretical scenarios for application of a landscape disturbance and succession model, and those exercises can be enormously instructive in understanding cumulative effects of management decisions (e.g., Shifley et al., 2006). However, some of the most challenging problems are those faced by public land managers with specific management issues where they must define objectives and alternatives, quantify expected outcomes, interpret the implications, select a course of action, communicate decisions to the public, implement the practice, and live with the consequences of either an accurate or an erroneous prognostication. Strong partnerships among practitioners, scientists, and technical experts are necessary to allow landscape simulation science to continue the transition from theory to practice.

In our experience, the individuals with the greatest expertise for interpreting the ecological, social, and policy implications of model results are generally not those with the specialized skills for running the landscape model. For example, staff specialists with forest management agencies are often the local experts on the ecological and social implications of present and future forest conditions. However, they often lack the time or motivation to learn how to calibrate and apply a landscape succession and disturbance model. This tendency is exacerbated by the fact that forest planning efforts are usually periodic rather than continuous, and planning involves periods of intense modeling and data analysis followed by years of plan implementation. Thus, there are potential efficiencies in creating a Service Center approach—maintaining a core group of landscape modeling experts who are available to serve multiple clients with planning or other issues suitable for model applications.

We have observed that when a forest landscape succession and disturbance model has been initialized and demonstrated, new model applications for that landscape usually follow. For example, the ability to apply LANDIS on National Forests in Missouri and Indiana has generated new lines of research on fuel management and fire risk, additional habitat analyses for wildlife species of conservation concern, and implications for public land management priorities when evaluated within a surrounding matrix of private land managed with different management practices.

3.3. Missing pieces

Landscape disturbance and succession models or related decision support systems, despite their substantial capabilities, are ripe for further research and development. There are significant factors affecting landscape change that are not addressed in contemporary models. Perhaps the most obvious is land use change (e.g., the movement of land among categories of forest, agriculture, urban, and suburban). Although the total area of forest land in the United States has decreased by only about 1 percent in the last 50 years, the total proportion of affected acres is vastly greater because over time acres that shift out of forest cover are offset by tracts elsewhere that move back to forest cover (Alig et al., 2003). Urbanization tends to permanently erode forest area whereas shifts between forest and agricultural lands are cyclical. Although we lack the ability to forecast many types of land use change in a spatially explicit manner within forest landscape disturbance and succession models, the ability to link external landscape change models with forest landscape disturbance and succession models has been demonstrated for a large landscape in California (Syphard et al., 2007a,b), and that capability will undoubtedly continue to improve. In fact, the feasibility of incorporating complex spread processes in raster-based landscape disturbance and succession models has already been demonstrated through the incorporation of routines that forecast how insects and fire differentially move across a landscape in response to resource availability, topography, and/or weather (e.g., Sturtevant et al., 2004a; Yang et al., 2007).

3.4. Wildlife population change and viability

HSI models assess habitat quality—the potential for a pixel, patch, or landscape to support a species. However, actual wildlife population sizes or population growth rates can be limited by factors other than habitat availability (e.g., survival, fecundity, dispersal, age structure, spatial population structure). One approach to addressing population viability or growth is to link spatially explicit wildlife species viability models to landscape disturbance and succession models (Liu et al., 1995; Larson et al., 2004; Akcakaya et al., 2004, 2005). We used RAMAS GIS software (Applied Biomathematics, Setauket, NY, http://www.ramas.com/software.htm) to model population growth for individual wildlife species in conjunction with LANDIS projections and to assess population viability and growth in a changing landscape (Larson et al., 2004). The process of simultaneously applying landscape change and wildlife population growth models is becoming easier; the RAMAS software now offers a version that is integrated with LANDIS (http://www.ramas.com/landsc.htm) and it has been used to predict wildlife viability under different fire and tree harvest scenarios (Akcakaya et al., 2004, 2005).

4. Recommendations

Several steps can be taken to improve the utility and applicability of forest landscape disturbance and succession models, and they are important to the continued evolution of the technology.

4.1. Initialize large landscapes for application

The biggest barriers to implementing LANDIS and similar landscape disturbance and succession models are (a) mapping initial landscape conditions (e.g., land cover, ecological land type, forest composition, age structure) for large landscapes with mixed ownership, (b) calibrating the tree species successional dynamics, and (c) calibrating the disturbance and management events (e.g., wind, fire, harvest, fuel treatment, biological agents). A rough estimate is that about 70% of our effort went into landscape initialization and model calibration, 10% to running scenarios, and 20% to post-processing and summarizing results. Although the calibration and initialization tasks can be time consuming, they are certainly not overwhelming and have been completed in the course of landscape model applications in a wide array of settings (Mladenoff, 2004; Barrett, 2001; Mowrer et al., 1997; Gordon et al., 2004). After a model is initialized for a given landscape, it can usually support a wide range of analyses that address many different issues. Often the process of initializing a model for a large landscape is only marginally more difficult and time consuming than doing if for a smaller landscape. Thus, it is efficient and benevolent to initialize forest conditions across large landscapes and to share the maps and data among cooperators interested a wide array of landscape issues. That way more effort can be directed toward model application and analyses than toward landscape initialization.

4.2. Provide continuing software support

As landscape models move from research tools to application tools for forest planning, continuing technical support is increasingly important. This can occur through agency and institutional support or through software commercialization. To date, support for landscape models has primarily been from model developers who themselves are scientists. An example of software support that has worked for other forestry computer applications is the National Service Center (http://www.fs.fed.us/fmsc/) approach used for the Forest Vegetation Simulator (FVS) (Dixon, 2007 http://www.fs.fed.us/fmsc/fvs/index.shtml) and other forest growth and yield software. As growth and yield modeling capacity became integral to public land management, the U.S. Forest Service established a work group that provides user support, develops standardized user interfaces, adds new features, calibrates models for new ecoregions, conducts validation tests, and integrates the models with silvicultural and planning operations. One difference between forest growth and yield models and forest landscape models is that the latter have fewer individual users working on projects that are much larger in scale and scope.

It took more than 10 years for that on-going support system to evolve for FVS, and once established it has continued for more than 15 years. Landscape disturbance and succession models are now more than 10 years into development and consideration of a similar system of ongoing support is timely. Presumably such an approach would provide support for multiple modeling systems and assist users in public and private sectors. This approach could result in faster model implementation, creation of auxiliary software to interface with agency databases, and development of specialized reporting formats.

4.3. Validate models

Validation of landscape disturbance and succession models or wildlife HSI models is challenging. Statistical comparisons of observed and predicted patterns of landscape change or habitat suitability are limited by (a) lack of long-term or large-scale temporal and spatial data for forest landscapes and wildlife, and by (b) the stochastic nature of most landscape models in which disturbance events at a particular location are the result of random draws from a probability distribution for that event. Most often validation efforts are brief affairs where a structured series of simulation runs are used to compare patterns of change with expert opinion. Over time, experience with model predictions under a wide range of forest landscape conditions and disturbance scenarios affords increased understanding of the range of conditions where the model behavior is reasonable and useful. Greater attention to evaluation and validation of landscape disturbance and succession models and wildlife habitat or population models is warranted, and there is substantial guidance in the literature (e.g., Morrison et al., 1992; Rykiel, 1996; Vanclay and Skovsgaard, 1997; Pontius et al., 2004; Burgman, 2005). We are currently validating some of the HSI models described in this paper with independent data sets on abundance and reproductive success.

4.4. Develop methods to rank the multidimensional outcomes of management alternatives

The ability to analyze multiple scenarios and simultaneously consider the interactions and cumulative effects of decisions is essential to making informed management choices. Landscape disturbance and succession models are valuable because they provide a framework for simultaneously assessing and mapping effects of management alternatives not only for landscape pattern, vegetation composition, and vegetation age structure, but also for timber resources, wildlife habitat, water resources, and aesthetics. The emerging challenge is to develop techniques to simultaneously display, analyze, and understand the levels, interactions and trade-offs among all these factors (Fig. 1). Although quantitative methods previously have been applied to similar kinds of natural resource decision making problems (e.g., Haight et al., 2005), the field is relatively new and small efforts to merge decision making techniques with landscape disturbance and succession models could yield significant accomplishments. Applied landscape modeling projects are so complex that they may never be amenable to traditional optimization techniques, but there certainly are quantitative tools that could be used in a more rigorous approach to selecting among management alternatives.

5. Conclusions

Landscape disturbance and succession models have demonstrated utility in estimation of large-scale, long-term cumulative effects of forest management. They can be used for traditional forest planning and to address emerging scientific and policy issues related to forests and wildlife. Barriers to application are the (1) technical skills need to run the models and analyze the findings, (2) lack of sufficiently detailed information about initial landscape conditions, (3) effort needed for model calibration for new regions, (4) limited number of suitable links to other factors of interest (e.g., wildlife habitat, fuels, forest amenities), (5) limited user support, and (6) difficulty selecting among complex management alternatives with multi-resource interactions that vary over space and time.

Several scientific and administrative actions can help landscape disturbance and succession models continue their evolution as tools for policy-relevant analyses. First, continue to initialize more and larger landscapes so they are ready for model applications. Second, foster ongoing collaborative model applications for forest planning and related analyses in cooperation with forest managers. Third, provide support for continuing software improvement. Fourth, add new capabilities to the models, either directly or as compatible auxiliary models and software. These capabilities may include forecasts of land use change, impact of insects and disease agents, wildlife population viability estimators, or models for catastrophic weather events such as hurricanes and tornadoes. Fifth, more formally evaluate model performance; identify and quantify conditions where the models perform well and where they do not. Sixth, provide support for multiple modeling methodologies and multiple spatial scales. Landscape models differ in their strengths and limitations. The ability to apply multiple models to the same problem provides greater insight to the individual models and to the range of potential outcomes. Seventh, explore quantitative methods that can guide evaluation and comparison of management alternatives with complex, multi-resource tradeoffs that vary over space and time.

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References

Akcakaya, H.R., Radeloff, V.C., Mlandenoff, D.J., He, H.S., 2004. Integrating landscape and metapopulation modeling approaches: Viability of the sharp-tailed grouse in a dynamic landscape. Conserv. Biol. 18, 526–537.

Akcakaya, H.R., Franklin, J., Syphard, A.D., Stephenson, J.R., 2005. Viability of Bell's Sage Sparrow (*Amphispiza belli* ssp. belli) under altered fire regimes. Ecol. Appl. 15, 521–531.

Alig, R.J., Plantinga, A.J., Ahn, S.E., Kline, J.D., 2003. Land use changes involving forestry in the United States: 1952–1997, with projections to 2050. General Technical Report PNW-587. U.S. Department of Agriculture, Forest Service. 92 pp.

Barrett, T.M., 2001. Models of vegetation change for landscape planning: a comparison of FETM, LANDSUM, SIMPPLLE, and VDDT. General Technical Report RMRS-76-WWW. U.S. Department of Agriculture, Forest Service. 14 pp.

Beukema, S.J., Kurz, W.A., 1998. Vegetation dynamics development tool: user's guide (v. 3.0). Available from: ESSA Technologies Ltd., #300-1765 West 8th Avenue, Vancouver, BC V6J 5C6. 104 pp. Published on line. http://www.essa.com/downloads/telsa/ http://www.essa.com/downloads/vddt/index.htm.

Birch, T.W., 1996. Private forest-land owners of the northern United States, 1994. Resource Bulletin NE-136. U.S. Department of Agriculture, Forest Service. 293 pp.

Burgman, M.A., 2005. Risks and Decisions for Conservation and Environmental Management. Cambridge University Press, Cambridge, 488 pp.

Chew, J.D., 1995. Development of a system for simulating vegetative patterns and processes at landscape scales. Ph.D. Dissertation. University of Montana, Missoula. 182 pp.

Chew J.D., Stalling, C., Moeller K., Bella, E., Schreiner, R., Ahl, R., Jones, T., in press. User guide for SIMPPLLE, Version 2.5 (Draft). General Technical Report RMRS-xxx. U.S. Department of Agriculture, Forest Service. 338 pp. Published on line. http://www.fs.fed.us/rm/missoula/4151/SIMPPLLE/files/publications/SIMPPLLE-MANUAL-2-5.pdf.

Dijak, W.D., Rittenhouse, C.D., Larson, M.A., Thompson III, F.R., Millspaugh, J.J., 2007. Landscape habitat suitability index software. J. Wildl. Manage. 71 (2), 668–670.

Dixon, G.E. (Comp.), 2007. Essential FVS: A User's Guide to the Forest Vegetation Simulator. Internal Report. U.S. Department of Agriculture, Forest Service, Forest Management Service Center, Fort Collins, CO. 208 pp. Published on line. http://www.fs.fed.us/fmsc/fvs/description/index.shtml.

Duncan, B.W., Breininger, D.R., Schmalzer, P.A., Larson, V.L., 1991. Validating a Florida scrub jay habitat suitability model using demographic data on Kennedy Space Center. Photogramm. Eng. Remote Sens. 61, 1361–1370.

Franklin, J., 1998. Predicting the distribution of shrub species in southern California from climate and terrain-derived variables. J. Veg. Sci. 9, 733–748.

Franklin, J., 2003. Clustering versus regression trees for determining ecological land units in the southern California mountains and foothills. For. Sci. 49, 354–368.

Franklin, J., Syphard, A.D., He, H.S., Mladenoff, D.J., 2005. Altered fire regimes affect landscape patterns of plant succession in the foothills and mountains of southern California. Ecosystems 8, 885–898.

Gordon, S.N., Johnson K.N., Reynolds, K.M., Crist, P., Brown, N., 2004., Decision support systems for forest biodiversity: evaluation of current systems and future needs. Final Report Project A10. National Commission on Science and Sustainable Forestry. Published on line. http://WWW.NCSSF.ORG.

Gustafson, E.J., Crow, T.R., 1999. HARVEST: linking timber harvesting strategies to landscape patterns. In: Mladenoff, D.J., Baker, W.L. (Eds.), Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK, pp. 309–332.

Gustafson, E.J., Rasmussen, L.V., 2005. HARVEST for Windows v6.1: User's Guide. U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN. Published on line. http://www.ncrs.fs.fed.us/4153/harvest/v61/documentation/default.asp.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Can. J. For. Res. 30, 32–43.

Gustafson, E.J., Murphy, N.L., Crow, T.R., 2001. Using a GIS model to assess terrestrial salamander response to alternative forest management plans. J. Environ. Manage. 63, 281–292.

Guyette, R.P., Muzika, R.M., Dey, D.C., 2002. Dynamics of an anthropogenic fire regime. Ecosystems 5, 472–486.

Haight, R.G., Cleland, D.T., Hammer, R.B., Radeloff, V.C., Rupp, T.S., 2004. Assessing fire risk in the wildland–urban interface. J. Forest. 102 (7), 41–48.

Haight, R.G., Snyder, S.A., Revelle, C.S., 2005. Metropolitan open-space protection with uncertain site availability. Conserv. Biol. 19, 327–337.

He, H.S., Mladenoff, D.J., 1999. Spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. Ecology 80, 81–99.

He, H.S., Mladenoff, D.J., Radeloff, V.C., Crow, T.R., 1998. Integration of GIS data and classified satellite imagery for regional forest assessment. Ecol. Appl. 8, 1072–1083.

He, H.S., Mladenoff, D.J., Boeder, J., 1999. An object-oriented forest landscape model and its representation of tree species. Ecol. Model. 119, 1–19.

He, H.S., Hao, Z., Larsen, D.R., Dai, L., Hu, Y.M., Chang, Y., 2002. A simulation study of landscape scale forest succession in northeastern China. Ecol. Model. 156, 153–166.

He, H.S., Li, W., Sturtevant, B.R., Yang, J., Shang, Z.B., Gustafson, E.J., Mladenoff, D. J., 2005. LANDIS, a spatially explicit model of forest landscape disturbance, management, and succession: LANDIS 4.0 User's Guide. General Technical Report NC-263. U.S. Department of Agriculture, Forest Service. 93 pp.

He, H.S., Dey, D.C., Fan, X., Hooten, M.B., Kabrick, J.M., Wikle, C.K., Fan, Z., 2007. Mapping pre-European settlement vegetation at fine resolutions using a hierarchical Bayesian model and GIS. Plant Ecol. 191 (1), 85–94.

Keane, R.E., Long, D., Basford, D., Levesque, B.A., 1997. Simulating vegetation dynamics across multiple scales to assess alternative management strategies. In: Conference Proceedings – GIS 97, 11th Annual symposium on Geographic Information Systems – Integrating Spatial Information Technologies for Tomorrow, GIS World, Inc., Vancouver, British Columbia, Canada, pp. 310–315.

Keane, R.E., Parsons, R., Hessburg, P., 2002. Estimating historical range and variation of landscape patch dynamics: limitations of the simulation approach. Ecol. Model. 151, 29–49.

Larson, M.A., Dijak, W.D., Thompson III, F.R., Millspaugh, J.J., 2003. General Technical Report NC-233. U.S. Department of Agriculture, Forest Service. 51 pp.

Larson, M.A., Thompson III, F.R., Millspaugh, J.J., Dijak, W.D., Shifley, S.R., 2004. Linking population viability, habitat suitability, and landscape simulation models for conservation planning. Ecol. Model. 180, 103–118.

Liu, J., Duning Jr., J.B., Pulliam, H.R., 1995. Potential effects of a forest management plan on Bachman's sparrows *(Aimophila aestivalis*): linking a spatially explicit model with GIS. Conserv. Biol. 9 (1), 62–75.

McCarter, J.B., 1997. Integrating forest inventory, growth and yield, and computer visualization into a landscape management system. In: Teck, R., Moeur, M., Adams, J. (Comps.), Proceedings of the Forest Vegetation Simulator Conference. General Technical Report INT-GTR-373. Ogden, UT. USDA Forest Service, Intermountain Research Station. pp. 159–167.

McCarter, J.B., Wilson, J.S., Baker, P.J., Moffett, J.L., Oliver, C.D., 1998. Landscape management through integration of existing tools and emerging technologies. J. Forest. 96, 17–23.

Mladenoff, D.J., 2004. LANDIS and forest landscape models. Ecol. Model. 180, 7–19.

Mladenoff, D.J., Baker, W.L. (Eds.), 1999. Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK, 352 pp.

Mladenoff, D.J., He, H.S., 1999. Design and behavior of LANDIS, an object-oriented model of forest landscape disturbance and succession. In: Mladenoff, D.J., Baker, W.L. (Eds.), Advances in Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK, pp. 163–185.

Morrison, M.L., Marcot, B.G., Mannan, R.W., 1992. Wildlife-habitat Relationships: Concepts and Applications. The University of Wisconsin Press, Madison, 341 pp.

Mowrer, H.T. (Technical Compiler), Barber, K., Campbell, J., Crookston, N., Dahms, C., Day, J., Laacke, J., Merzenich, J., Mighton, S., Rauscher, M., Sojda, R., Thompson, J., Trenchi, P., Twery, M., 1997. Decision Support Systems for Ecosystem Management: An Evaluation of Existing Systems. General Technical Report RM-296. U.S. Department of Agriculture, Forest Service. 154 pp.

National Oceanic and Atmospheric Administration, 2007. Tornado Climatology. National Oceanic and Atmospheric Administration. Published on line. http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html.

Pennanen, J., Kuuluvainen, T., 2002. A spatial simulation approach to natural forest landscape dynamics in boreal Fennoscandia. For. Ecol. Manage. 164, 157–175.

Pontius Jr., R.G., Huffaker, D., Denman, K., 2004. Useful techniques of validation for spatially explicit land-change models. Ecol. Model. 179 (4), 445–461.

Radeloff, V.C., Mladenoff, D.J., Gustafson, E.J., Scheller, R.M., He, H.S., Zollner, P.A., Akçakaya, R., 2006. Modeling forest harvesting effects on landscape pattern in the Northwest Wisconsin Pine Barrens. For. Ecol. Manage. 236, 113–126.

Rebertus, A.J., Meier, A.J., 2001. Blowdown dynamics in oak-hickory forests of the Missouri Ozarks. J. Torrey Bot. Soc. 128 (4), 362–369.

Rebertus, A.J., Shifley, S.R., Richards, R.H., Roovers, L.M., 1997. Ice storm damage to an old-growth oak-hickory forest in Missouri. Am. Midl. Nat. 137, 48–61.

Rittenhouse, C.D., Dijak, W.D., Thompson III, F.R., Millspaugh, J.J., 2007. Development of Landscape-level Habitat Suitability Models for 10 Wildlife Species in the Central Hardwoods Region. General Technical Report NRS-4. U.S. Department of Agriculture, Forest Service. 47 pp.

Rykiel Jr., E.J., 1996. Testing ecological models: the meaning of validation. Ecol. Model. 90 (3), 229–244.

Scheller, R.M., Mladenoff, D.J., 2005. A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. Glob. Change Biol. 11, 307–321.

Schumacher, S., Bugmann, H., Mladenoff, D.J., 2004. Improving the formulation of tree growth and succession in a spatially explicit landscape model. Ecol. Model. 180, 175–194.

Shang, Z., He, H.S., Lytle, D.E., Shifley, S.R., Crow, T.C., 2007. Long-term effects of fire suppression on Central Hardwood Forests in Missouri Ozarks, USA. For. Ecol. Manage. 42, 776–790.

Shao, G., Parker, G.R., Zhalnin, A.V., Merchant, P., Albright, D., 2004. GIS protocols in mapping ecological landtypes for the Hoosier National Forest. North. J. Appl. For. 21, 180–186.

Shifley, S.R., Thompson III, F.R., Larsen, D.R., Mladenoff, D.J., 1997. Modeling forest landscape changes in the Ozarks: guiding principles and preliminary implementation. General Technical Report NC-188. U.S. Department of Agriculture, Forest Service, pp.231–241.

Shifley, S.R., Thompson III, F.R., Larsen, D.R., Dijak, W.D., 2000. Modeling forest landscape change in the Missouri Ozarks under alternative management practices. Comput. Electron. Agric. 27, 7–27.

Shifley, S.R., Thomson III, F.R., Dijak, W.D., Larson, M.A., Millspaugh, J.J., 2006. Simulated effects of forest management alternatives on landscape structures and habitat suitability in the Midwestern United States. For. Ecol. Manage. 229, 361–377.

Sturtevant, B.R., Gustafson, E.J., Li, W., He, H., 2004a. Modeling biological disturbances in LANDIS: a module description and demonstration using spruce budworm. Ecol. Model. 180, 153–174.

Sturtevant, B.R., Zollner, P.A., Gustafson, E.J., Cleland, D.T., 2004b. Human influence on the abundance and connectivity of high-risk fuels in mixed forests of northern Wisconsin, USA. Landscape Ecol. 19 (3), 235–253.

Syphard, A.D., Franklin, J., 2004. Spatial aggregation effects on the simulation of landscape pattern and ecological processes in southern California plant communities. Ecol. Model. 180, 21–40.

Syphard, A.D., Clarke, K., Franklin, C.J., 2007a. Simulating fire frequency and urban growth in southern California coastal shrublands, USA. Landscape Ecol. 22, 431–445.

Syphard, A.D., Yang, J., Franklin, J., He, H.S., Keeley, J.E., 2007b. Calibrating a forest landscape model to simulate high fire frequency in Mediterranean-type shrublands. Environ. Model. Softw. 22 (11), 1641–1653.

United States Fish and Wildlife Service, 1980. Habitat Evaluation Procedures (HEP). Division of Ecological Services Manual 102, Washington, DC.

United States Fish and Wildlife Service, 1981. Standards for the Development of Habitat Suitability Index Models for Use in the Habitat

Evaluation Procedure. Division of Ecological Services Manual 103, Washington, DC.

United States Department of Agriculture Forest Service, 2006. Land and Resource Management Plan, Hoosier National Forest. U.S. Department of Agriculture, Forest Service. Published on line. http://www.fs.fed.us/r9/hoosier/planningdocs/final_docs/2006_documents.htm.

United States Department of Agriculture Forest Service, 2007. The Forest Inventory and Analysis Database: Database Description and Users Guide Version 3.0. U.S. Department of Agriculture, Forest Service. 230 pp. Published on line at http://fia.fs.fed.us/tools-data/.

Van Damme, L., Russell, J.S., Doyon, F., Duinker, P.N., Gooding, T., Hirsch, K., Rothwell, R., Rudy, A., 2003. The development and application of a decision support system for sustainable forest management on the Boreal plain. J. Environ. Eng. Sci. 2, S23–S34.

Vanclay, J.K., Skovsgaard, J.P., 1997. Evaluating forest growth models. Ecol. Model. 98 (1), 1–12.

Wang, X., He, H.S., Li, X., Chang, Y., Hu, Y., Xu, C., Bu, R., Xie, F., 2006. Simulating the effects of reforestation on a large catastrophic fire landscape in Northeastern China. For. Ecol. Manage. 225, 82–93.

Wimberly, M.C., 2004. Fire and forest landscapes in the Georgia Piedmont: an assessment of spatial modeling assumptions. Ecol. Model. 180, 41–56.

Yang, J., He, H.S., Shifley, S.R., Gustafson, E.J., 2007. Spatial patterns of modern period human-caused fire occurrence in the Missouri Ozark Highlands. For. Sci. 53, 1–15.

Zollner, P.A., Gustafson, E.J., He, H.S., Radeloff, V.C., Mladenoff, D.J., 2005. Modeling the influence of dynamic zoning of forest harvesting on a northern Wisconsin landscape. Environ. Manage. 35, 410–425.