

Landscape Modeling for Forest Restoration Planning and Assessment: Lessons from the Southern Appalachian Mountains

Weimin Xi, Robert N. Coulson, John D. Waldron, Maria D. Tchakerian, Charles W. Lafon, David M. Cairns, Andrew G. Birt, and Kier D. Klepzig

ABSTRACT

Restoration planning, evaluation, and implementation are important in areas where abiotic disturbances (e.g., wildfires, hurricanes, and ice storms), biotic disturbances (e.g., outbreaks of native and exotic invasive pests and diseases), and anthropogenic disturbances (e.g., harvesting, planting, and fire exclusion) have altered forest landscapes. However, the effects of restoration practices are difficult to measure, and restoration goals often are unclear. Landscape modeling provides a tool for evaluating outcomes of various management scenarios and restoration strategies. In this article, we provide a framework for using landscape models for forest restoration. Specifically, we present a case study using LANDIS, a landscape simulation model of forest disturbance and succession, to explore the effects of restoration strategies for forests damaged by southern pine beetle in the southern Appalachians. Our research suggests that landscape models are valuable tools in the forest restoration decisionmaking process. Future work on landscape models for forest restoration and other related issues is discussed.

Keywords: landscape modeling, forest restoration, southern pine beetle, LANDIS model, desired future forest conditions, southern Appalachian Mountains

Restoration planning, evaluation, and implementation are important in forested areas of the United States and in many other regions of the world (Stan-

turf and Madsen 2005). In the United States, forest restoration has been identified as important for forest health and sustainable development (National Association of State Foresters

2001). The US Forest Service program dedicated to restoring public and private forests damaged by the southern pine beetle (SPB) *Dendroctonus frontalis* (Zimm.) serves as an excellent example of these efforts (USDA Forest Health Protection 2005).

Forest restoration is generally accepted as the reestablishment of natural ecological processes that produce certain dynamic ecosystem properties of structure and function (Stanturf and Madsen 2005). It also has been defined as the process of restoring a forest to its original state before degradation (Food and Agriculture Organization 2002). We broadly define forest restoration as the reestablishment of natural ecological processes that promote specific, historically relevant properties of forest structure and function, after and/or despite the effects of deleterious anthropogenic influences.

Received April 28, 2007; accepted March 24, 2008.

Weimin Xi (xi@tamu.edu) is postdoctoral research scientist, Knowledge Engineering Laboratory, Texas A&M University, Department of Entomology, Heep Center, TAMU 2475, College Station, TX 77843. Robert N. Coulson (r-coulson@tamu.edu) is professor and director, Knowledge Engineering Laboratory, Texas A&M University, College Station, TX 77843. John D. Waldron (jwaldron@uwf.edu) is assistant professor, Department of Environmental Studies, University of West Florida, Ft. Walton Beach, FL 32547. Maria D. Tchakerian (mtchakerian@tamu.edu) is assistant research scientist, Knowledge Engineering Laboratory, Texas A&M University, College Station, TX 77843. Charles W. Lafon (clafon@tamu.edu) is associate professor, and David M. Cairns (cairns@tamu.edu) is associate professor, Department of Geography, Texas A&M University, College Station, TX 77843. Andrew G. Birt (abirt@tamu.edu) is postdoctoral research scientist, Knowledge Engineering Laboratory, Texas A&M University, College Station, TX 77843. Kier D. Klepzig (kklepzig@fs.fed.us) is project leader of Unit of Insects, Diseases, Invasive Plants, US Forest Service Southern Research Station, 2500 Shreveport Highway, Pineville, LA 71360. This research was supported through US Forest Service cooperative agreement SRS03-CA-11330129-168 and SRS03-CA-11330129-048. The authors thank Ms. Audrey Bunting and Dr. Lei Wang for their assistance during the project and John Nowak, Coleman Doggett, Henry McNab, James Guldin, and Eric Gustafson for their input at various stages of this project. The authors are grateful to Dr. Timothy Harrington and two anonymous reviewers for their constructive comments and Dr. David Mladenoff, Dr. Hong He, Dr. Robert Scheller, Dr. Brian Sturtevant, Dr. Zongbo Shang, and Dr. Jian Yang for providing LANDIS and LANDIS-II programs and aiding in LANDIS use.

Copyright © 2008 by the Society of American Foresters.

Forest restoration is affected by two compounding problems. First, the goals of restoration often are unclear and involve the simultaneous consideration of a number of diverse criteria including aesthetics, biodiversity, recreation, and economic cost. Second, restoration management is a long-term process such that effects are difficult to measure at the time of implementation. Moreover, restoration goals and strategies may vary considerably according to region. Efficient and effective methods are needed to analyze the potential outcomes and impacts of multiple restoration goals and strategies for different forest types.

Spatially explicit landscape models are promising tools for evaluating management alternatives, including restoration strategies in damaged forest areas (Gustafson et al. 2000, Urban 2006). Spatial issues are important for forest management and restoration (Bettinger et al. 2005). Spatially explicit landscape models are increasingly being used to contribute to the evaluation of management and monitoring in strategic forest planning (Mladenoff 2004, Perry and Enright 2006, Scheller et al. 2007). Recent examples of modeling in forestry include linking optimization models (linear programming) with spatial simulation models (Bettinger 2001, Gustafson et al. 2003), using spatially explicit models in assessing forest timber harvesting strategies (Gustafson et al. 2000), and strategic management planning alternatives (Mehtaa et al. 2004).

We recently used LANDIS (landscape disturbance and succession; He et al. 2002, Mladenoff 2004, Scheller et al. 2007) to examine forest landscape dynamics and to evaluate restoration strategies for forests damaged by SPBs in the southern Appalachian Mountains (Waldron et al. 2005, 2007, Lafon et al. 2007, Xi et al. 2007, Cairns et al. 2008a). This region represents an important case for restoration strategies because biodiversity is high and multiple disturbances, including invasive pests, are reducing the existence of yellow pine forests (Southern Appalachian Man and the Biosphere 1996). The yellow pines here are four members of the genus *Pinus* (subsection *Australes* Loud.): Table Mountain pine (*Pinus pungens*), pitch pine (*Pinus rigida*), shortleaf pine (*Pinus echinata*), plus Virginia pine (*Pinus virginiana*).

In this article, we provide a framework for using this approach to assist strategic forest management and restoration planning. We describe the methods we used to assess

the succession of forests given a number of biotic, abiotic, and management scenarios relevant to the landscape. We present a case study in western North Carolina. Finally, we discuss the usefulness of this approach including both its strengths and its limitations.

A Modeling Framework

Forest Landscape Models. Forest landscape models simulate vegetation change through time using spatially referenced data across a broad spatial scale generally larger than a single stand (~100–1,000,000 ha). Spatial interactions between stands are a key component of such models. Therefore, these models can be used to simulate vegetation change with regards to multiple stand management within a given area (i.e., a watershed or a Ranger District of National Forest; Turner et al. 1994, Boston and Bettinger 2001). Such models have also been used to simulate the effects of a variety of timber harvesting practices (Gustafson et al. 2000), to project habitat loss and alteration resulting in impacts on biodiversity (Li et al. 2000, Akcakaya 2001, Shifley et al. 2006), and to assess the impact of land-use activities on ecological resources (e.g., Dale 2003).

Restoration Goals. The goals of forest restoration may vary greatly depending on the temporal and spatial scales considered. In some cases, the goal of restoration may be known and well defined a priori. For example, the restoration goals for national forests often are clear and defined in land and resource management plans (e.g., Gustafson et al. 2000). Where the goal of a restoration strategy is known and well defined, a modeling approach can be used to determine an effective management strategy that leads to the landscape structure that best fits this goal. For example, the purpose of restoration may be to recreate a historical forest condition (supported by scientific data) or a forest structure crucial for the rehabilitation of an endangered species. Using spatially explicit landscape models, outcomes of various forest management and restoration practices can be evaluated according to various criteria, including the cost of the management strategy, economic gains, biodiversity protection, and resistance to pests and disease.

However, the limitations of historical data (e.g., a full picture of a historic forest may not be known) and the fact that effective management involves optimal allocation of limited economic resources often makes determining a priori restoration goals

difficult. In these cases, spatially explicit landscape models can help transform general or conceptual goals into more quantitative and realistic goals. An iterative modeling approach may allow the exploration of various management strategies and their consequences. This approach may facilitate the identification of appropriate, practical, and pragmatic restoration goals. Clearly, the success of this approach is dependant on a model that is flexible enough to represent a variety of disturbances and management practices, that is simple to use, and that accommodates available data.

The Modeling Framework. Our approach is to integrate natural disturbance agents and restoration/management alternatives into a spatially explicit landscape model capable of simulating forest vegetation dynamics through space and time. We used LANDIS as our primary modeling environment because it provides a general framework for determining the combined effect of major natural and anthropogenic disturbances (e.g., fire regimes, insects, harvesting, and planting) that are capable of driving changes in forest structure (Figure 1).

LANDIS is a stochastic simulation model that allows forest succession and disturbances to operate on cellular landscapes comprising heterogeneous patterns of tree species, age class, and seed dispersal (He et al. 1999, Gustafson et al. 2003, Mladenoff 2004). It has been used in North America as well in some areas of Europe and Asia to investigate forest dynamics and fire management strategies across landscapes. Examples of applications relevant to forest restoration include harvesting and fires (He et al. 2002, Shang et al. 2004, Scheller et al. 2007), pests and disease (Sturtevant et al. 2004), risk assessment and landscape habitat models (Larson et al. 2003, Shifley et al. 2006), landscape change and management practices (Shifley et al. 2006), and succession and harvesting (He et al. 2002, Gustafson et al. 2000, 2003).

A Case Study in the Southern Appalachians

Study Areas. We used the Appalachian Mountains of western North Carolina and eastern Tennessee as our general study area. From 2000 to 2003, SPBs caused catastrophic damage to the yellow pine forests. SPB is the most destructive native insect affecting the southern US forests. Over the past 40 years, SPBs have caused billions of

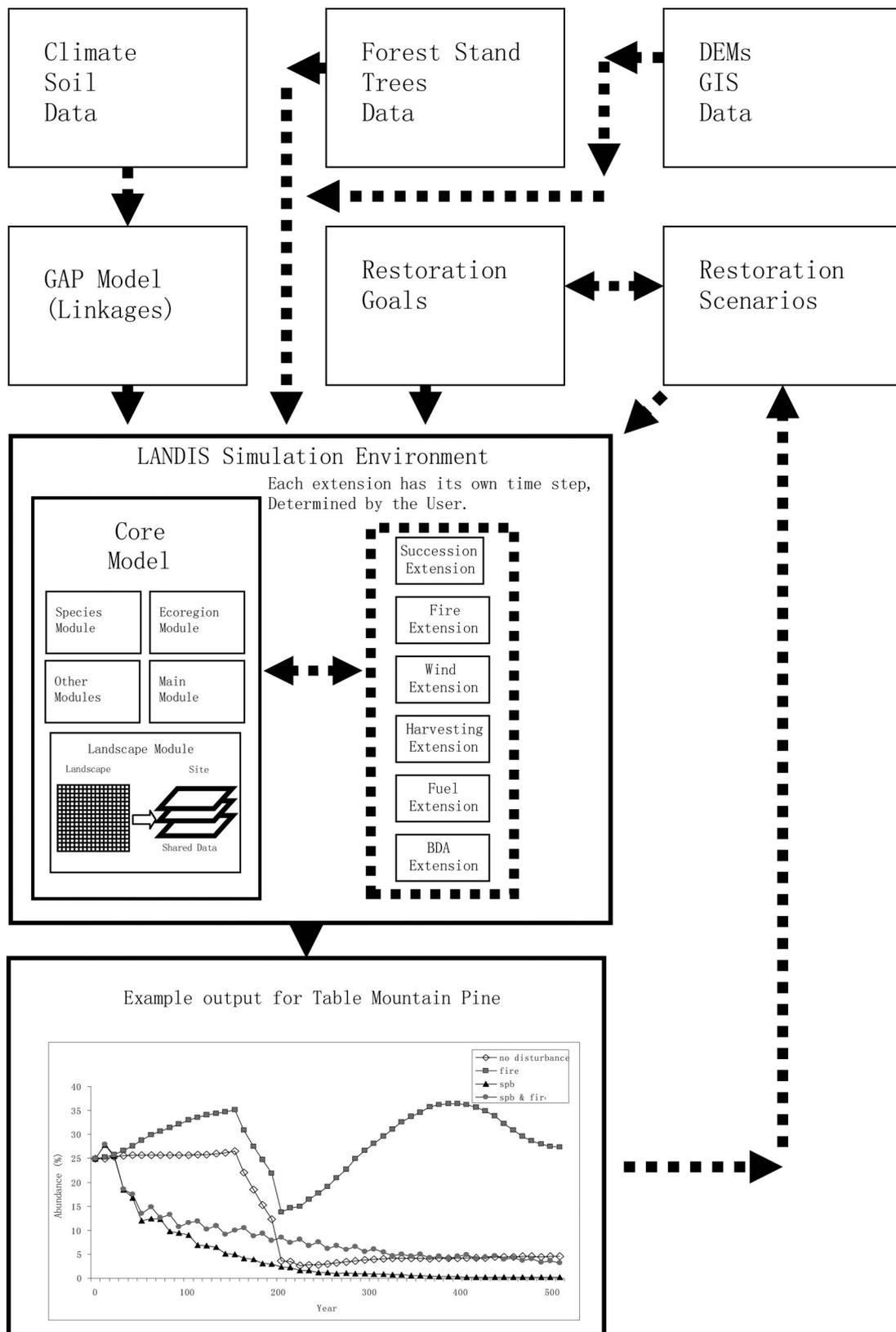


Figure 1. The working flow using the LANDIS model for southern pine beetle restoration planning and evaluation.

dollars of timber damage in the southern United States (National Association of State Foresters 2001, Coulson et al. 2004, Pye et al. 2005; Figure 2).

Restoring the yellow pine forest has been identified as a significant task for landowners and forest managers in the southern United States. The yellow pine

forest is an important habitat for the endangered red-cockaded woodpecker and other birds such as pine warbler and quail (Coulson et al. 1999). These forests are



Figure 2. Infestation of southern pine beetles (SPBs) in the Little Lake Creek Wilderness illustrating the damage caused by this pest species on forest resources. The Little Lake Creek Wilderness consists of a 1,796-ha forested landscape located in southeast Texas on the Sam Houston National Forest. When the US Congress designated the Little Lake Creek Wilderness Area in 1985, the pine component of the vegetation cover was dominated by “old-growth” loblolly (*Pinus taeda*) and shortleaf pine (*P. echinata*), which is the preferred host condition for the SPB (*Dendroctonus frontalis*). The wilderness designation removed the Little Lake Creek Wilderness from normal US Forest Service management practices, including insect suppression. Shortly after being designated a wilderness area, a massive outbreak of the SPB occurred. The large contiguous areas of mature host species coupled with favorable weather conditions triggered the SPB outbreak. Because the SPB can have six to eight overlapping generations per year, the effect of the insect on the forest environment was quick and dramatic. The result was widespread mortality to the mature loblolly and shortleaf pine present on the landscape (Photo by R.N. Coulson, June 1990).

also important sources of recreation and raw materials for wood processing facilities, such as paper manufacturing and log home building.

Model Simulation. Our goal is to provide information that is necessary for planning strategic forest restoration after SPB damage by creating a simulation environment to evaluate the efficacy of various restoration strategies. We implemented our work in a stepwise fashion and performed the following steps: (1) parameterized LANDIS to simulate forest succession in the absence of SPBs and fire, (2) explored the interactions of fire and vegetation dynamics, (3) investigated the combined roles of fire and SPB outbreaks, and (4) examined the reciprocal effects of landscape structure and insect outbreaks in landscapes with controlled structural characteristics. We elected to use hypothetical landscapes based on data from Great Smoky Mountains National Park to investigate the combined roles of wildfires, fire exclusion, and SPB outbreaks

(Lafon et al. 2007, Waldron et al. 2007) and to examine the reciprocal effects of landscape structure and insect outbreaks (Cairns et al. 2008b).

In LANDIS, tree species are simulated as the presence or absence of user-defined age cohorts on each cell. At the site (cell) level, LANDIS uses parameters representing life history traits of selected species (e.g., longevity, minimum age at reproduction, shade tolerance, fire tolerance, seed dispersal distances, and resprout probability) to simulate vegetation dynamics at user-defined time steps. Succession in LANDIS is based on life history attributes of a species and the composition of different species within a cell (He et al. 2002).

We created a pool of the 30 most dominant trees species within the study area. Life history parameters were based on work by Burns and Honkala (1990), which has served as the basis for a number of previous forest modeling studies (e.g., Sturtevant et al. 2004). LANDIS uses an establishment

coefficient to represent the habitat suitability of each land type for each species. We derived relevant establishment coefficients based on the patterns of species abundance along elevation and moisture gradients (Lafon et al. 2007).

The Biological Disturbance Agent (BDA) module in LANDIS was parameterized to represent the temporal and spatial pattern of SPB outbreaks in the southern Appalachians. The timing of outbreaks was determined by a uniformly distributed random number with a minimum interval of 10 years and a maximum interval of 30 years, consistent with historical SPB trends in the area.

Fire regime effects were simulated by deriving parameter values for fire event size (maximum, mean, and minimum) and the ignition probability for different land types. We also examined the effect of a fire exclusion scenario, considering fire exclusion as a disturbance for the yellow pine forest.

Results

Our modeling projections suggest that a combination of fire and SPB disturbance creates sustainable yellow pine forests, and the regime of multiple interacting disturbances have important implications for the successional dynamics and vegetation characteristics in yellow pine woodlands of the southern Appalachian Mountains. When acting alone, fire leads to conditions favoring pine presence, while SPB disturbance acting alone resulted in the removal of yellow pines (Waldron et al. 2005, 2007, Lafon et al. 2007; Figure 3). When fire is not present as a disturbance type, these ecosystems succeed into hardwood-dominated ecosystems (Figure 4). Our conclusion is consistent with the hypothesis that fire and SPBs are part of a disturbance regime that maintains yellow pine woodlands (Williams 1998). Specifically, historically, fire played an important role in yellow pine forests and is thought to have interacted with SPBs to maintain open, pine-dominated woodlands on dry upland sites (Schowalter et al. 1981). In addition, the model projections imply that reintroducing fire will help maintain open pine stands in the southern Appalachians similar to those thought to have occupied dry sites on the southern Appalachian landscapes in the past. Such open stands have low basal area and, hence, should not be conducive to the development or spread of large SPB infestations.

Our results also suggest that there is a

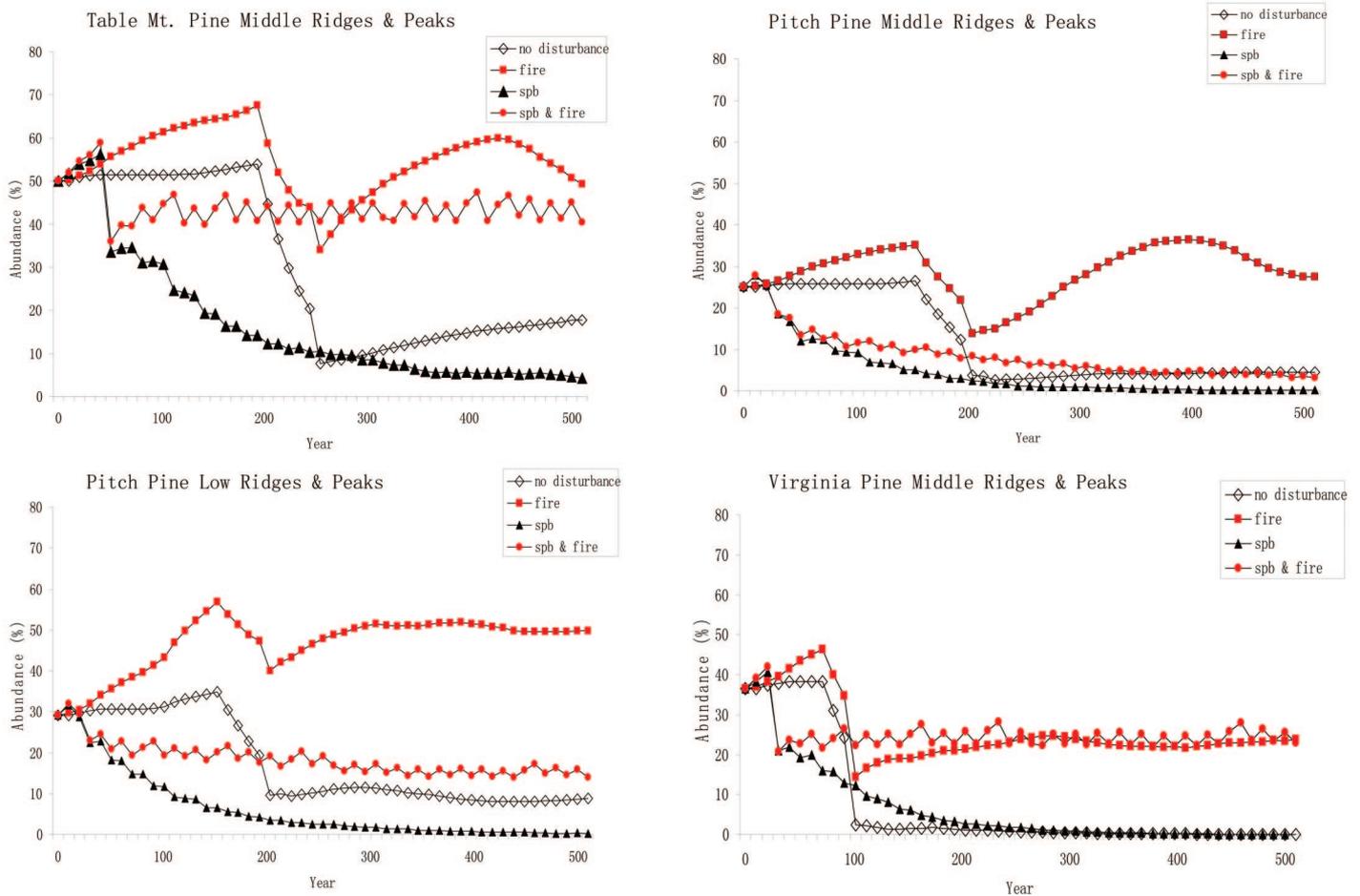


Figure 3. Change in species abundance (percentage of landscape covered) over time. Note the differences that exist between scenarios (no disturbance, fire only, southern pine beetles (SPBs) only, and fire and SPBs combined), species (Table Mountain pine, Virginia pine, and pitch pine), and positioning on the landscape (middle elevation ridges and peaks; low elevation ridges and peaks).

strong relationship between landscape structure and SPB outbreaks (Cairns et al. 2008a, 2008b). As the aggregation of pines on the landscape increases, so does the proportion of pines infested with SPBs. This relationship between pine aggregation and outbreak severity results because the BDA module incorporates mechanisms by which the mixture of tree species and ages in a neighborhood can influence herbivory, as observed empirically in forest stands (e.g., Schowalter and Turchin 1993, Jactel and Brockerhoff 2007). A large body of empirical research shows that insect herbivory is greater in pure stands of host trees than in mixed stands containing host and nonhost species (Jactel and Brockerhoff 2007). Several mechanisms may contribute to lower herbivory in mixed stands, including low host availability, chemical or physical interference with location of hosts by the insects, and a larger number of parasites and predators (Jactel and Brockerhoff 2007). The

representation of the influence of these stand-level mechanisms in BDA permitted us to assess their possible implications for landscape-scale outbreak patterns (Cairns et al. 2008b). Our LANDIS simulations suggest that landscape-level SPB disturbance patterns can emerge as a consequence of the characteristic way in which tree neighborhoods are arranged on a landscape. Hence, these simulations concur with the conclusions derived from small-scale field studies.

Simulations suggest that regardless of the initial proportion of the landscape occupied by pines, the proportion of pines on the landscape decreases over time in the presence of SPB (Cairns et al. 2008a). We also show that there appears to be some “memory” associated with the initial pattern of the landscape. Specifically, although pines decrease within the landscape and although pine stands become less aggregated over time, the general outlines of the initial patches remain on the

landscape over the 500-year span of the simulations. These results indicate that when considering restoration strategies for insect-affected forests, it is necessary to consider the patterns of hosts on the landscape as well the landscape composition. Restoration scenarios for Table Mountain pine, e.g., should consider not only how best to implement fire or other techniques to regenerate pines in decadent stands (e.g., Williams 1998), but also how management actions influence the spatial arrangement of pine stands throughout a landscape (Cairns et al. 2008b).

Land managers and forestry practitioners will also note that while pines are removed in the SPB disturbance scenario, there is an initial abrupt drop at the first large infestation (around year 40) followed by a more gradual decline over several hundred years (Figure 3). If we assume that the typical forest professional works 30 years, the trend and ultimate severity of these de-

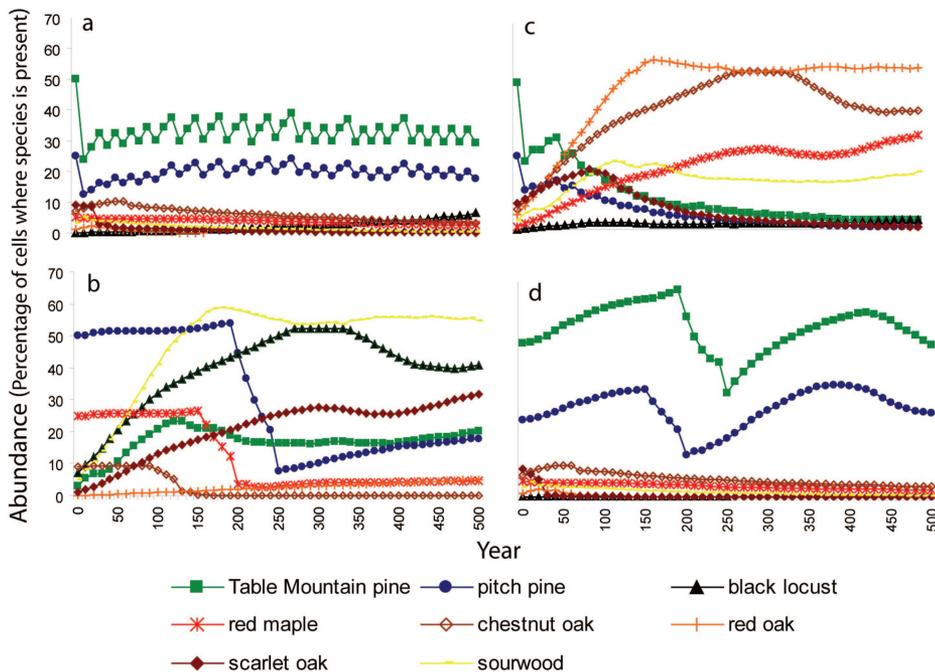


Figure 4. Change in abundance (percentage of landscape covered) over time of species on middle elevation ridges and peaks. Scenarios include no disturbance, southern pine beetles (SPBs) only, fire only, and SPBs and fire combined.

clines might only be recognizable to field observers after several generations.

Lessons and Implications

Through this ongoing research and discussion of our results with the US Forest Service, we conclude that a modeling approach has considerable potential for assisting managers in the decisionmaking process for a number of reasons. First, the relationships between ecosystem function, anthropogenic impacts, and desired forest conditions are too complex to formulate and explore without quantitative modeling tools. Second, quantitative and mapped outputs are commonly required for decisions that involve federal agencies and multiple stakeholders. Third, forest landscapes are at spatial and temporal scales that prohibit in situ experiments. Fourth, landscape modeling encourages the collection and organization of data and knowledge. In the context of forest restoration, this is important because while forest changes operate over relatively long time periods, the costs of restoration practices are high, and the needs for effective strategies are often immediate.

Although we can justify the large spatial and temporal scales of the LANDIS approach, it is also important to note that this approach does not preclude the use of modeling at a finer scale. In fact, the success of the LANDIS approach requires a strong un-

derstanding of the dynamics of vegetation in smaller areas. For example, some critical parameters such as species establishment coefficients were calculated by using certain finer-scale forest gap models such as LINKAGES (Post and Pastor 1996, He et al. 1999; Figure 1).

Strengths. Landscape models provide projections of long-term and broad-scale change and allow experimentation and comparisons among scenarios. The nature of the complexity of forest landscapes and restoration activities make it unlikely that these sorts of insights can be gained by using intuition or reasoning alone. In a broader context, they can be used in a multidisciplinary manner to incorporate concepts and theories from landscape, ecosystem, and community ecology.

LANDIS provides a proven framework for investigating the complex interactions over broad landscapes (He et al. 1999, Gustafson et al. 2003). Many forest restoration and management problems are represented by the spatial and temporal scales of the LANDIS approach, and when quantitative explorations are needed, LANDIS can be effectively parameterized for many different forest landscapes. In doing so, researchers and managers gain the benefit of using a model that has been well studied, has a significant user base, and produces comparable quantitative outputs.

Limitations. Potential users need to assess the suitability of this approach for their own research or practice. To date, most landscape models have been developed primarily by ecological modelers from a research perspective and are still undergoing technical modifications. More work is needed both to assess and to improve their accuracy and to make them more user-friendly.

LANDIS simulations are based on a set of stochastic equations with simple assumptions. The interpretation of results must be based on the limitations of the input and are only valid for the simulated input conditions. In addition, the current simulation of forest management and restoration in LANDIS is still less sophisticated than forest growth and yield models and optimization (linear programming) models. Some important management considerations, such as economic comparison among scenarios, cannot be adequately simulated. The specificity of a single study (for a specific ecosystem), in addition to its requirement of extensive computer power, technical expertise, and data, currently restrict for its application in some situations.

Conclusions and Future Work

Our research suggests that landscape models are a useful research tool and a valuable aid for the forest management decision-making process. The landscape modeling approach allows forest managers to determine the impact of various disturbances on the forests. The result is the identification of the best strategies for managing key landscapes that may be significantly impacted by multiple, interacting threats.

Our goals for future research are to test the capability of the landscape modeling approach to evaluate changes in composition and structure of eastern US forests undergoing multiple interacting environmental threats and global warming, to develop methods that make the parameterization of the model and the interpretation of its results more efficient and available to a wider scientific and practical audience, and to test the results of landscape models by implementing recommendations based on the modeling scenarios in test locations and then monitoring those areas to determine the effectiveness of using the model for forest management decisionmaking.

Literature Cited

- AKCAKAYA, H.R. 2001. Linking population-level risk assessment with landscape habitat models. *Sci. Total Environ.* 274:283–291.
- BETTINGER, P. 2001. Challenges and opportunities for linking the modeling of forest vegetation dynamics with landscape planning models. *Landscape Urban Plann.* 56:107–124.
- BETTINGER, P., M. LENNETTE, K.N. JOHNSON, AND T.A. SPIES. 2005. A hierarchical spatial framework for forest landscape planning. *Ecol. Model.* 182(1):25–48.
- BOSTON, K., AND P. BETTINGER. 2001. Development of spatially feasible forest plans: A comparison of two modeling approaches. *Silva Fenn.* 35(4):425–435.
- BURNS, R.M., AND B.H. HONKALA. 1990. *Silvics of North America*. US For. Serv. Agric. Handb., Washington, DC, 654 p.
- CAIRNS, D.M., C.W. LAFON, A.G. BIRT, J.D. WALDRON, M.D. TCHAKERIAN, R.N. COULSON, W. XI, AND K.D. KLEPZIG. 2008a. Simulation modeling as a tool for understanding the landscape ecology of southern pine beetle infestations in southern Appalachian forests. *Geogr. Compass* 3, doi:10.1111/j.1749-8198.2008.00098.x. Online Published Mar. 2008.
- CAIRNS, D.M., C.W. LAFON, J.D. WALDRON, M.D. TCHAKERIAN, R.N. COULSON, K.D. KLEPZIG, A.G. BIRT, AND W. XI. 2008b. Simulating the reciprocal interaction of forest landscape structure and southern pine beetle herbivory using LANDIS. *Landscape Ecol.* 23(4): 403–415.
- COULSON, R.N., M.D. GUZMAN, K. SKORDINSKI, J.W. FITZGERALD, R.N. CONNER, D.C. RUDOLPH, F.L. OLIVERIA, D.F. WUNNEBURGER, AND P.E. PULLEY. 1999. Forest landscapes: Their effect on the interaction of the southern pine beetle and Red-cockaded Woodpecker. *J. For.* 97(1):4–11.
- COULSON, R.N., K.D. KLEPZIG, T.E. NEBEKER, F.L. OLIVERIA, S.M. SALOM, F.M. STEPHEN, AND H.J. MEYER (EDS.). 2004. The research, development, and applications agenda for a southern pine beetle integrated pest management program. *Proc. of a Facilitated workshop*, Mountain Lake, VA, Aug. 11–14, 2003. 56 p.
- DALE, V.H. (ED.). 2003. *Ecological modeling for resource management*. Springer-Verlag, New York. 328 p.
- FOOD AND AGRICULTURE ORGANIZATION (FAO). 2002. *Proc. of second expert meeting on harmonizing forest-related definitions for use by various stakeholders*, Rome, Italy, Sept. 11–13, 2002. Available online at www.fao.org/docrep/005/y4171e/y4171e00.htm; last accessed June 2008.
- GUSTAFSON, E.J., S.R. SHIFLEY, D.J. MLADENOFF, K.K. NIMERFRO, AND H.S. HE. 2000. Spatial simulation of forest succession and harvesting using LANDIS. *Can. J. For. Res.* 30(1):32–43.
- GUSTAFSON, E., J. NESTLER, L. GROSS, K. REYNOLDS, D. YAUSSY, T. MAXWELL, AND V. DALE. 2003. Evolving approaches and technologies to enhance the role of ecological modeling in decision-making. P. 135–164 in *Ecological modeling for resource management*, Dale, V. (ed.). Springer-Verlag, New York.
- HE, H.S., D.J. MLADENOFF, AND J. BOEDER. 1999. Object-oriented design of LANDIS, a spatially explicit and stochastic landscape model. *Ecol. Model.* 119(1):1–19.
- HE, H.S., D.J. MLADENOFF, AND E.J. GUSTAFSON. 2002. Study of landscape change under forest harvesting and climate warming-induced fire disturbance. *For. Ecol. Manag.* 155(1):257–270.
- JACTEL, H., AND E.G. BROCKERHOFF. 2007. Tree diversity reduces herbivory by forest insects. *Ecol. Lett.* 10:835–848.
- KENT, B., B.B. BARE, R.C. FIELD, AND G.A. BRADLEY. 1991. Natural resource land management planning using large-scale linear programs: The USDA Forest Service experience with FORPLAN. *Oper. Res.* 39(1):13–27.
- LAFON, C.W., J.D. WALDRON, D.M. CAIRNS, M.D. TCHAKERIAN, R.N. COULSON, AND K.D. KLEPZIG. 2007. Modeling the effects of fire on the long-term dynamics and restoration of yellow pine and oak forests in the southern Appalachian Mountains. *Restor. Ecol.* 15(3):400–411.
- LI, H.B., D.I. GARTNER, P. MOU, AND C.C. TRETIN. 2000. A landscape model (LEEMATH) to evaluate effects of management impacts on timber and wildlife habitat. *Comput. Electro. Agric.* 27(1):263–292.
- LARSON, M.A., W.D. DIJAK, F.R. THOMPSON III, AND J.J. MILLSAUGH. 2003. *Landscape-level habitat suitability models for twelve species in southern Missouri*. US For. Serv. Gen. Tech. Rep. NC-233. 51 p.
- MEHTAA, S., L.E. FRELICHA, M.T. JONESB, AND J. MANOLISC. 2004. Examining the effects of alternative management strategies on landscape-scale forest patterns in northeastern Minnesota using LANDIS. *Ecol. Model.* 180(1):73–87.
- MLADENOFF, D.J. 2004. LANDIS and forest landscape models. *Ecol. Model.* 180(1):7–19.
- NATIONAL ASSOCIATION OF STATE FORESTERS. 2001. *Southern pine beetle: A time for action to protect the South's forests*. Available online at www.stateforesters.org/positions/2002.SP-B.html; last accessed Feb. 18, 2008.
- PERRY, G.L.W., AND N.J. ENRIGHT. 2006. Spatial modelling of vegetation change in dynamic landscapes: A review of methods and applications. *Prog. Phys. Geogr.* 30:47–72.
- POST, W.M., AND J. PASTOR. 1996. LINKAGES—An individual-based forest ecosystem model. *Climatic Change* 34(2):253–261.
- PYE, J.M., T.S. PRICE, S.R. CLARKE, AND R.J. HUGGETT JR. 2005. *A history of southern pine beetle outbreaks in the Southeastern United States through 2004*. Available online at www.srs.fs.usda.gov/econ/data/spb/index.htm; last accessed Feb. 18, 2008.
- SOUTHERN APPALACHIAN MAN AND THE BIOSPHERE (SAMAB). 1996. *The Southern Appalachian assessment terrestrial technical report*. Rep. 5 of 5, US For. Serv., Southern Region, Atlanta, GA. 248 p.
- SCHELLER, R.M., J.B. DOMINGO, B.R. STURTEVANT, J.S. WILLIAMS, A. RUDY, D.J. MLADENOFF, AND E.J. GUSTAFSON. 2007. Introducing LANDIS-II: Design and development of a collaborative landscape simulation model with flexible spatial and temporal scales. *Ecol. Model.* 201(3–4):409–419.
- SCHOWALTER, T. D., R.N. COULSON, AND C.A. CROSSLEY JR. 1981. Role of southern pine beetle and fire in maintenance of structure and function of the southeastern coniferous forest. *Environ. Entomol.* 10:821–825.
- SCHOWALTER, T.D., AND P. TURCHIN. 1993. Southern pine-beetle infestation development interaction between pine and hardwood basal areas. *For. Sci.* 39:201–210.
- SHANG, Z.B., H.S. HE, T.R. CROW, AND S.R. SHIFLEY. 2004. Fuel load reductions and fire risk in central hardwood forests of the United States: A spatial simulation study. *Ecol. Model.* 180(1):89–102.
- SHIFLEY, S.R., F.R. THOMPSON III, W.D. DIJAK, M.A. LARSON, AND J.J. MILLSAUGH. 2006. Simulated effects of forest management alternatives on landscape structure and habitat suitability in the Midwestern United States. *For. Ecol. Manag.* 229:361–377.
- STANTURF, J.A., AND P. MADSEN (EDS.). 2005. *Restoration of boreal and temperate forests*. CRC Press, Boca Raton, FL. 569 p.
- STURTEVANT, B.R., E.J. GUSTAFSON, W. LI, AND H.S. HE. 2004. Modeling biological disturbances in LANDIS: A module description and demonstration using spruce budworm. *Ecol. Model.* 180(1):153–174.
- TURNER, M.G., W.H. ROMME, AND R.H. GARDNER. 1994. Landscape disturbance models and the long-term dynamics of natural areas. *Nat. Area. J.* 14(1):3–11.
- URBAN, D.L. 2006. A modeling framework for restoration ecology. P. 238–256 in *Foundations of restoration ecology*, Falk, D.A., M.A. Palmer, and J.B. Zedler (eds.). Island Press, Washington, DC.
- USDA FOREST HEALTH PROTECTION. 2005. *Southern Pine Beetle Prevention and Restoration Program*. Available online at www.stateforesters.org/positions/2002.SPB.html; last accessed Feb. 18, 2008.
- WALDRON, J.D., R.N. COULSON, M.D. TCHAKERIAN, C.W. LAFON, D.M. CAIRNS, AND K.D. KLEPZIG. 2005. Utilizing a landscape scale model of forest disturbance and succession for forest decision-making in the southern Appalachians. *Papers Proc. Appl. Geogr. Conf.* 28:160–169.
- WALDRON, J.D., C.W. LAFON, R.N. COULSON, D.M. CAIRNS, M.D. TCHAKERIAN, A.G. BIRT, AND K.D. KLEPZIG. 2007. Simulating the impacts of southern pine beetle and fire on pine dynamics on xeric southern Appalachian landscapes. *Appl. Veg. Sci.* 10(1):53–64.
- WILLIAMS, C.E. 1998. History and status of Table Mountain pine-Pitch pine forests of the southern Appalachian Mountains (USA). *Nat. Area. J.* 18(1):81–90.
- XI, W., J.D. WALDRON, R.N. COULSON, M.D. TCHAKERIAN, D.M. CAIRNS, C.W. LAFON, A.G. BIRT, AND K.D. KLEPZIG. 2007. Landscape modeling for forest restoration: Concepts and applications. P. 92–95. in *Proc. of the IUFRO conf. on Forest landscape restoration*, Seoul, Korea May 14–19, 2007, Stanturf, J. (ed.). Korea Forest Research Institute, Seoul, Korea. 268 p.