MODELING FIRE AND OTHER DISTURBANCE PROCESSES USING LANDIS

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Abstract.—LANDIS is a landscape decision support tool that models spatial relationships to help managers and planners examine the large-scale, long-term, cumulative effects of succession, harvesting, wildfire, prescribed fire, insects, and disease. It can operate on forest landscapes from a few thousand to a few million acres in extent. Fire modeling capabilities in LANDIS are detailed, but intuitive. Modeled fires kill trees based on the fire intensity and each tree species' fire tolerance, and spatially explicit ignition probability maps can be incorporated but are not required. As the LANDIS model runs through many annual or 10-year iterations, it illustrates how and where forest vegetation is expected to change in response to succession, fire, harvesting, and other disturbances. LANDIS output can be mapped, summarized, and linked to other attributes of interest, such as wildlife habitat suitability. Although it is possible to run the LANDIS model using generic or default values, the real benefits come when the model is calibrated to reflect the unique conditions associated with a specific forest ecosystem. Applications of LANDIS include analyses of fire regimes, separately or in combination with harvesting, on the Mark Twain National Forest (Missouri), the Hoosier National Forest (Indiana), and the Chequamegon-Nicolet National Forest (Wisconsin). These analyses can guide the selection of long-term management alternatives for forested landscapes. LANDIS has also proven useful in more theoretical investigations that compare long-term effects of alternative fire regimes on the expected direction and rate of tree species composition change across an array of ecological land types.

INTRODUCTION

Comprehensive forest management requires consideration of the long-term, large-scale, cumulative effects of management activities and natural disturbances on forest commodities, amenities, and services, which include forest products (type and quantity over time), wildlife habitat (quality by species over time), water quality (usually addressed through implementation of best management practices), and biodiversity (diversity of plant and animal species, diversity of forest age and size structure, and diversity of habitats over time). Recently, increasing emphasis also has been placed on managing forests for ecological services such as carbon sequestration.

Foresters are skilled at forecasting the effects of management on products, forest size structure, and tree species composition at the stand scale. But keeping track of those details for thousands or hundreds of thousands of acres requires a landscape decision support system, which is usually in the form of a landscape computer simulation model. There are many forest landscape models available. They vary in the details of how they operate, but they all provide a means to forecast and display expected changes in forest conditions across landscapes in response to management and natural disturbances caused by wildfire, wind, insects, and disease. Forest landscape models are especially useful for forecasting expected impacts of wildfires, which, unlike harvests, are not constrained by stand boundaries, and from year to year vary considerably in location, extent, and severity. Modeling fire effects using a landscape decision support system provides a mechanism to examine average tendencies, expected variation over time, and potential impacts of fire mitigation strategies.

Examples of forest landscape models include the Forest Vegetation Simulator (Dixon 2003, USDA Forest Service 2008), HARVEST (Gustafson and Rasmussen 2005), the Landscape Management System (University of Washington 2008), LANDSUM (Keane et al. 1997, 2002), SIMPPLLE (Chew et al. 2007), and VDDT/

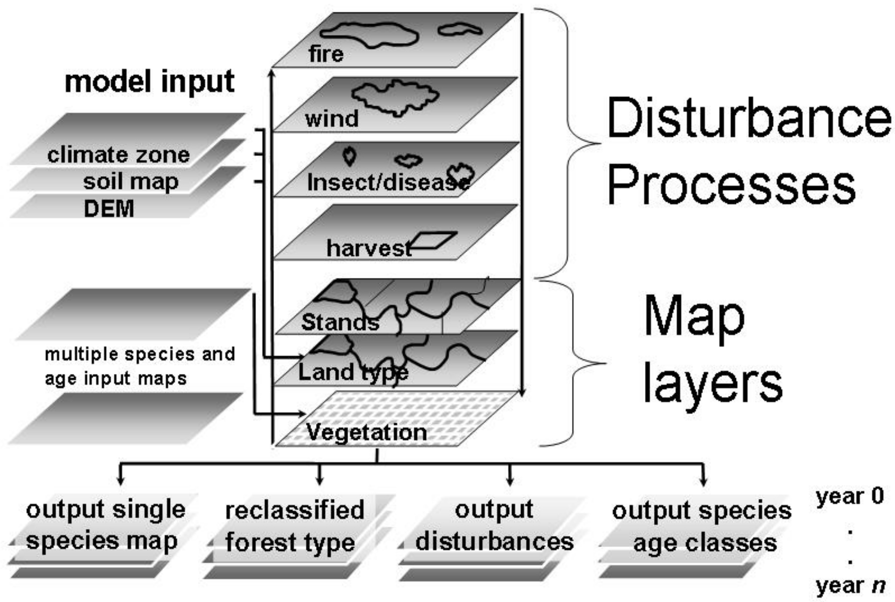

Figure 1.—Schematic of LANDIS design. This diagram illustrates the map and data layers used for LANDIS input, processing, and output. Succession and the other disturbance processes shown alter the vegetation map layer for each time period of a modeled scenario. Additional detail is available from He et al. (2005).

TELSA (Beukema and Kurz 1998). They all differ in the details of how they operate and in their relative strengths and weaknesses (Barrett 2001, Keane et al. 2004). Our experience has been with the LANDIS forest landscape model (He and Mladenoff 1999, He et al. 2005), which has been in use for about 15 years with ongoing development and applications in the United States, Canada, and Europe.

The following sections draw from previous applications of LANDIS to Midwestern forest landscapes to illustrate how LANDIS can be used to model fire effects as part of a comprehensive analysis system that also includes the effects of alternative silvicultural practices on forest growth, species succession, and wildlife habitat.

THE LANDIS MODEL

LANDIS Design

LANDIS represents a forest landscape as a mosaic of square sites (He et al. 2005) (Fig. 1). In the jargon of geographic information systems, the sites can be referred to as rasters or pixels. Although the site size can be set by the model user, we typically use sites that are about a quarter-acre (30 m on each side) or about 0.025 acre (10 m on each side). A 0.025-acre site corresponds to roughly the canopy size of a mature hardwood tree, so it is possible to create highly detailed representations of forest landscapes composed of millions of adjacent sites. LANDIS projections are made on a 1-year or a 10-year time step (iteration), and LANDIS will produce maps and summary statistics of forest conditions at each time step of a projection that may cover a few decades or a few centuries.

At each site, LANDIS tracks which tree species are present by age class. In the Midwest we used up to 18 species groups to describe vegetation in LANDIS. Sites are grouped into contiguous stands that can have complex age structure and species composition. Stands are grouped into management areas that need not be contiguous, similar to National Forest management areas used in forest planning.

When forecasting forest change, LANDIS modifies trees on each site according to a set of succession rules and equations. For example, in the absence of disturbance, the trees grow older. When trees become older, they have an increasing probability of mortality. Shade-tolerant tree species can regenerate on sites with older trees, according to a set of probabilities. When trees die, they are replaced according to a set of regeneration probabilities that differ

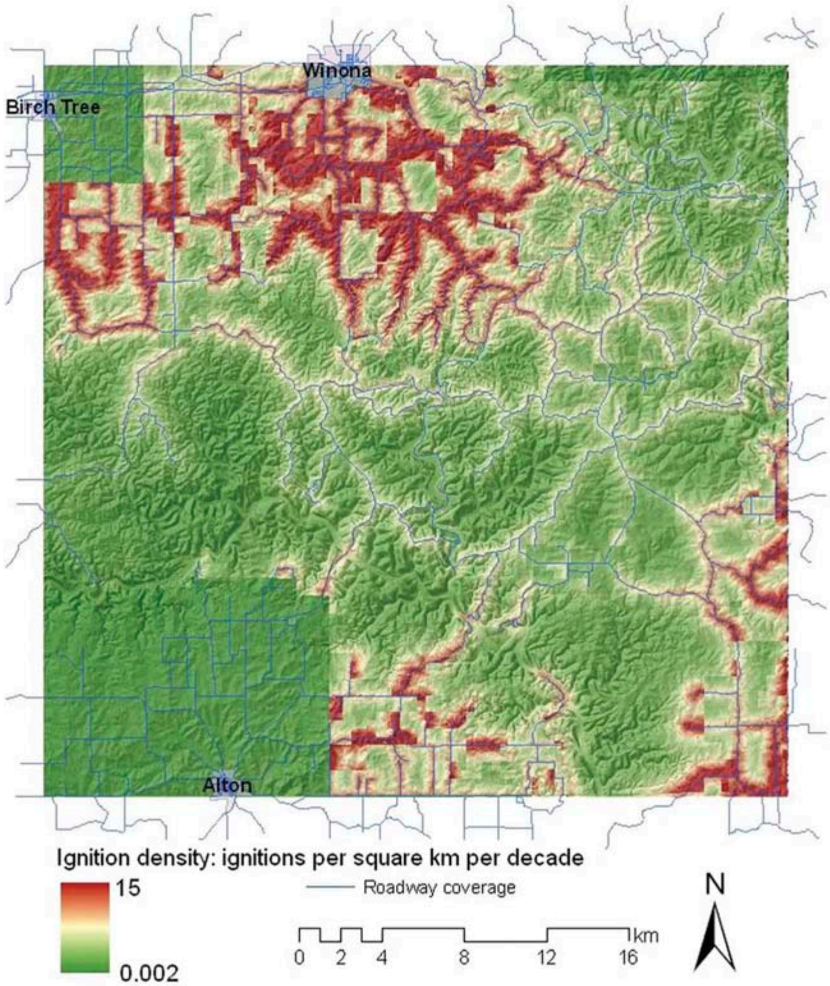

Figure 2.—Estimated probability of fire ignition based on 32 years of fire records in southern Missouri. (See also Yang et al. 2007.)

by ecological land type. Rules and probabilities can be modified to accommodate conditions for a wide array of ecosystems.

Simulated disturbances alter patterns of forest development within LANDIS. Simulated harvests can be applied to individual stands and entire management areas. Users control the type, frequency, and location of harvests based on rules that can account for stand age (e.g., oldest first), location (e.g., do not harvest adjacent stands), desired rotation length, desired species, and desired tree age or size. Windthrow is modeled according to probabilities indicating the likelihood of damaging wind events of various sizes. Usually, many small wind events and a few large ones result (Rebertus and Meier 2001), but users can modify this pattern. The location of wind events on the landscape is random, and there is greater probability of windthrow for large trees than for small trees.

Modeling Fire in LANDIS

Fire modeling in LANDIS consists of three subcomponents: fire occurrence, fire spread, and fire effect. Fire occurrences on the landscape are modeled as a two-stage process (ignition and initiation) in LANDIS (He et al. 2005, Yang et al. 2007). In the first stage, fires are ignited based on a fire ignition probability map layer. Whether an ignition can become a successful fire or not is determined by fire initiation probability in the second stage. The fire ignition probability map layer can be very simple (e.g., every location has the same probability of fire ignition), or very complex. Recent analysis of 32 years of fire records for part of the Mark Twain National Forest (Missouri) produced a detailed map showing the probability of fire ignition for each location (Fig. 2). People cause about 98 percent of fires in that region, with 75 percent of fires due to arson. The analysis of spatial patterns showed the greatest probability of fire ignition is along roads through lands owned by the Mark Twain National Forest and near local communities (Yang et al. 2007). Similar methods can be applied to other regions with long fire records. Alternatively, fire ignition probabilities for other ecosystems could be estimated by experienced observers using simple relationships based on distance from roads, ecological land type, elevation, or any other factor believed to be associated with local ignition patterns.

The quality and accessibility of historical fire ignition data is improving to the point where developing ignition probability maps for large areas is possible. Once developed, such maps are useful for many years and for purposes beyond the application of LANDIS (e.g., for distribution of fire suppression resources or communication with the public).

After an initiation is simulated, the simulated fire spreads across the modeled landscape based on fuel load, topography, and prevailing wind direction. Rates of fire spread across a site and into an adjacent site are computed using the relationships described in FARSITE (Finney 1998) and BEHAVE fire models (Anderson 1982, Andrews et al. 2005). By computing and storing the rate of fire spread for all combinations of fuel class, slope class, and wind speed for a given landscape, LANDIS can efficiently model detailed patterns of fire spread. Fires modeled in LANDIS spread until they reach a specified area or a specified time to suppression, either of which can be based on local experience when such information is available.

Tree mortality following a fire is modeled according to a set of rules that the LANDIS user can modify. Fire intensity for each burned site is classified into five categories based on the fuel load at the time of the fire. Each tree species and age class combination is categorized by fire tolerance. The youngest trees are the most susceptible to fire-caused mortality, so for a given fire intensity the tree species with lower fire tolerance will have older trees killed than will species with higher fire tolerance. Following a modeled fire, the fuel load is adjusted to a lower value that can be set to match local observations.

When the above procedures are used to model wildfires, the timing and location of the modeled fire events are based on random draws from probability distributions. Consequently, for any two separate simulation runs, the timing and location of the modeled wildfire events will differ. However, the total area affected by wildfire for the entire landscape will be similar for both runs. This element of randomness does not work well for modeling prescribed fires, where the fire location, frequency, and intensity are specified as part of a silvicultural prescription. However, prescribed fires for specific stands and years can be simulated using the flexible set of silvicultural treatments available in LANDIS fuel module (Gustafson et al. 2000, He et al. 2005).

LANDIS APPLICATIONS

In the Midwest, we have applied LANDIS to investigate the outcomes of alternative management scenarios for parts of the Mark Twain National Forest, for the entire 180,000-acre Hoosier National Forest in Indiana, and for two Ranger Districts of the Chequamegon-Nicolet National Forest in northern Wisconsin (Shifley et al. 2006, 2008; USDA Forest Service 2006; Rittenhouse 2008; Zollner et al. 2008). National Forests, like many public forest ownerships, often have digital maps, forest inventories, wildfire records, and ecological classification systems prepared for large areas. Those are valuable assets when initializing a forest landscape for use in LANDIS. Moreover, managers of public forests have a mandate to consider the cumulative effects of their management practices on the multiple commodities, amenities, and services their forests can provide.

Changes in species composition related to alternative fire regimes applied at the landscape scale can be examined over time (Fig. 3). As expected, increased fire on the landscape pushes the anticipated species composition toward fire-adapted species. While that general result is not surprising, analysis of fire effects using LANDIS provides additional insights about rates of change in species composition and age structure over time, the effects of different ecological land types (e.g., slope, aspect, hydrology) on those changes, the spatial distribution of changes, and cumulative effects over space and time.

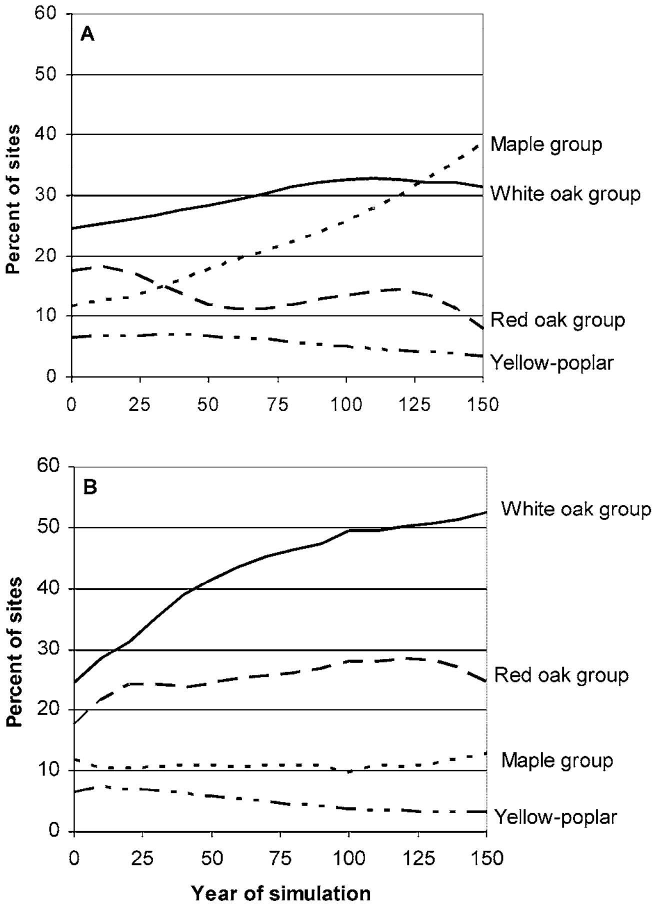

Figure 3.—LANDIS projection of the proportion of sites dominated by major species groups for two management alternatives applied to the 200,000-acre Hoosier National Forest in southern Indiana. (A) Managed with no prescribed burning and no harvest. (B) Managed with a total of 360,000 acres of prescribed burning and 52,000 acres of harvest over the 150-year projection period. (See also USDA Forest Service 2006.)

Results can be evaluated for specific landscapes, but analyses based on hypothetical landscape conditions can also provide important results to guide managers. For example, Lafon et al. (2007) created a hypothetical landscape with two elevation classes and three ecological land types representative of conditions found in the southern Appalachian Mountains. They then used LANDIS to apply two fire regimes and systematically explore the differential effects of each combination on changes in tree species composition over time. They found that when suitably calibrated, the LANDIS predictions were consistent with ecological theory. They provided evidence that (1) reintroduction of fire can reverse undesirable shifts in biodiversity; (2) species responses will differ by land type and elevation; (3) there can be interactions involving multiple factors; and (4) changes in species composition will occur gradually over one to two centuries. These results are useful to develop site-specific management plans with reasonable expectations about the likely rate of species change during restoration efforts. Other applications on real landscapes have systematically analyzed the sensitivity of LANDIS predictions to differences in fire regimes and to simplifying assumptions about seed dispersal and species establishment rates. Results for the Georgia Piedmont have shown that assumptions about seed dispersal and the effect of topographic differences on fire regimes have a relatively large effect on LANDIS forecasts (Wimberly 2004).

To investigate the long-term effects of fire suppression on central hardwood forests in the Missouri Ozarks, Shang et al. (2007) examined two management scenarios: (1) a fire suppression scenario circa 1990; and (2) a historical fire regime scenario prior to fire suppression, with a mean fire-return interval of 14 years. They found that both fuel and fire hazard increased to a medium-high level after a few decades of fire suppression. A century of fire suppression could result in more than three-quarters of the fires having medium- to high intensity levels, uncharacteristic for those Central Hardwood ecosystems. Fire suppression could also lead to distinct changes in species abundance; the pine and oak-pine forests common in the study area prior to fire suppression would be replaced by mixed-oak forests.

Forest planning is an important activity in which forest landscape models can provide valuable assistance. Using LANDIS, Zollner et al. (2008) demonstrated a way to evaluate alternative management plans and assess whether they are likely to meet the stated, multiple objectives. They predicted forest composition and landscape pattern under seven alternative forest management plans drafted for the Chequamegon-Nicolet National Forest. In most cases, the modeled results showed that multiple objectives were obtainable without conflict, but in 20 percent of the cases, land managers needed to prioritize among eight timber and wildlife management objectives. Some desired outcomes were obtainable only by mutually exclusive management activities.

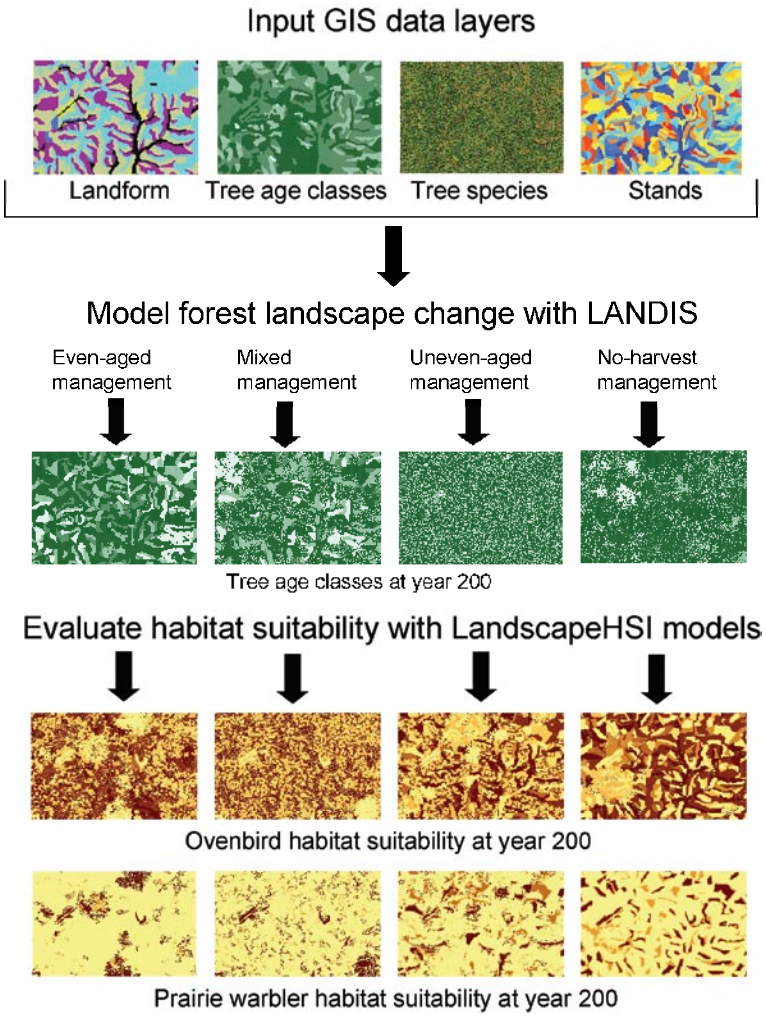

Figure 4.—Illustration of the LANDIS results for four management alternatives. Darker shades indicate older tree age classes and greater wildlife habitat suitability. Harvest practices, wind disturbance, and fire regimes affect tree species composition and tree age class, which in turn affect estimated wildlife habitat suitability. Similar maps or tabular summaries can be generated for each decade of each modeled scenario (from Shifley et al. 2008).

The predicted outcome of alternative management scenarios projected using LANDIS can be displayed graphically as well as in tabular summaries (Figs. 3 and 4). One of the most powerful attributes of LANDIS is the ability to simultaneously incorporate multiple, spatially explicit disturbance factors (fire, wind, harvest, insects, disease) and evaluate the combined effects on multiple forest attributes. Figure 4 shows a small subset of the information that can be mapped for each decade of a scenario. The even-aged management scenario illustrates the effects of regenerating 10 percent of the forest area per decade via clearcutting. The uneven-aged management scenario illustrates the impact of group selection harvesting that regenerates about 10 percent of the forest area per decade. The mixed management scenario blends those two practices to regenerate about 10 percent of the forest area per decade. In each of those scenarios the spatial distribution of vegetation age is heavily influenced by the patterns of harvest on the landscape. All scenarios included wildfires occurring with a mean fire-free interval of approximately 300 years, a value that is based on wildfire observations over the prior 30 years. The effects of wildfire are apparent in the no-harvest management scenario, where modeled fire events create the largest patches of young forest on the projected future forest landscape.

In addition to the forest characteristics illustrated in Figure 4, we can use LANDIS output to estimate, tabulate, and map habitat suitability for other wildlife species, tree species composition, harvest area, harvest volume, standing volume, snags, and coarse woody debris. Scenarios that have been modeled for the Hoosier National Forest mimic the forest management alternatives proposed as part of the formal forest-planning process. Forecasts of the cumulative effects of forest management (including prescribed fire, wildfire, and timber harvest) were factored into the selection of a preferred management alternative (USDA Forest Service 2006).

DISCUSSION AND CONCLUSIONS

LANDIS provides an extremely versatile approach for modeling the long-term, large-scale cumulative effects of forest management, disturbance, and succession on forest landscapes. Modeled landscapes can range from a few thousand to a few million acres in extent, and the approach has been used to support National Forest Planning (USDA Forest Service 2006, Rittenhouse 2008, Zollner et al. 2008).

The procedures for simulating fire ignition and spread and modeling fire effects on fuel and vegetation have been greatly expanded in the most recent revision of LANDIS (version 4.0, Yang et al. 2004, He et al. 2005). Fire spread algorithms are consistent with established fire behavior models (Anderson 1982, Finney 1998, Andrews et al. 2005) and can be adapted to accommodate a wide range of fire regimes and detailed fire effects. The only drawback of having such versatility is the need to actually specify fire ignition probabilities, fuel loads, fire spread rates, fuel treatment effects, and fire effects on vegetation. The LANDIS fire routines can be readily operated using default or generic values for these factors, but that approach fails to take full advantage of the fire modeling capabilities. For most landscapes, our ability to model detailed fire ignition, spread, and responses with LANDIS exceeds our ability to locally calibrate the model with site-specific data on fire occurrence and fire effects. To date, modeling fire effects with LANDIS has been hindered primarily due to lack of detailed information on (1) the spatial distribution of current fuels; (2) fire effects by fire intensity class on tree mortality and regeneration; and (3) effects of fire and other treatments on residual fuels. Other presentations and posters from the Third Fire in Eastern Oak Forests Conference (see the remainder of this proceedings) provides reassurance that such data are being accumulated and will become available to calibrate the LANDIS fire models for specific ecosystems.

Modeling fire effects is one reason to apply LANDIS, but LANDIS also is a framework for synthesizing many forest succession and disturbance processes that also include wind, silviculture, regeneration, and land use change (e.g., Syphard et al. 2007). Results for alternative scenarios can be summarized, illustrated, and/or mapped through time to show differences in forest vegetation structure and composition, wood volume, down wood, forest fragmentation, species diversity, and wildlife habitat suitability (e.g., Dijak and Rittenhouse 2008). The ability to analyze landscape-scale forest change provides opportunities for foresters, wildlife biologists, ecologists, and planners to collaborate and examine interactions or tradeoffs of various management alternatives on a large forest landscape.

In our experience it can take many months to initialize and calibrate LANDIS for a new, large landscape. By comparison, running various alternatives through LANDIS requires a relatively short time (a few hours or a few days), and summarizing results may take a few days to a few months depending on the complexity of the attributes of interest. For example, summarizing wildlife habitat quality for multiple species is notoriously time-consuming, but some summaries of forest vegetation require only a few minutes to summarize and map. Although substantial effort can be required to calibrate LANDIS for a large landscape, we have discovered large benefits from that up-front investment. Each time we have initialized a large landscape for use with LANDIS, we have attracted new partners with new questions that we can explore collaboratively on those same landscapes.

Application of LANDIS is best pursued through a team approach that incorporates competencies in a variety of specialties such as geographic information systems, data processing, programming, forest management/silviculture, ecology, wildlife biology, fire behavior and management, timber and markets, and planning. That collaboration makes the process efficient by drawing on a diverse array of technical specialists. It also facilitates communication across disciplines, and it helps ensure that results are practical and relevant for multiple purposes.

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