Utilizing Inventory Information to Calibrate a Landscape Simulation Model

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Abstract.—LANDIS is a spatially explicit model that uses mapped landscape conditions as a starting point and projects the patterns in forest vegetation that will result from alternative harvest practices, alternative fire regimes, and wind events. LANDIS was originally developed for Lake States forests, but it is capable of handling the input, output, bookkeeping, and mapping that occur during landscape simulations for virtually any forest region. We recently calibrated LANDIS for the forest conditions in the Missouri Ozarks, and we based that calibration on a combination of traditional forest inventory data, silvics information, and expert opinion. To ensure realistic model performance, we used inventory data to test species dynamics of the model and establish initial landscape conditions. Landscape simulation examples from the Missouri Ozarks illustrate the methodology by comparing results from even-aged management, uneven-aged management, and no-harvest scenarios.

In the past decade, forest management and planning has expanded to include a wide range of ecosystem values and attributes other than timber. This trend is particularly prevalent on public lands where characteristics such as nongame wildlife species, threatened and endangered plants and animals, water quality, biodiversity, and landscape diversity must be explicitly addressed. Issues of scale present some of the greatest difficulties in managing forest ecosystems for an array of attributes. Silvicultural operations for timber production are implemented on stands that typically range from 2 to 10 ha in size in the midwestern United States. Other attributes such as water quality, wildlife habitat quality, and biodiversity must be addressed at larger scales—often across hundreds or thousands of hectares. Characterization of these attributes often requires information on the juxtaposition of vegetation age classes across a landscape.

Several tools and procedures to facilitate planning and management across forest landscapes already exist. Products such as UTOOLS (Mcgaughey and Ager 1996, Mcgaughey 1998), CRBSUM (Keane *et al.* 1996), LANDIS (He *et al.* 1996, Mladenoff *et al.* 1996), and many others (Mowrer 1997) all have demonstrated the capacity to support aspects of landscape-scale forest management in other regions. Until recently, none of these tools has been applied in the Midwest.

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In 1994, we began developing tools to predict response of central hardwood forests to disturbance. The ability to predict responses to both natural and anthropogenic disturbances is essential in managing forest ecosystems here. Our intent was to develop a system to predict forest change at sufficiently large spatial scales (thousands of hectares) and long time frames (at least a century) to support simultaneous analysis of an array of forest attributes (e.g., timber, wildlife, aesthetics, and economics). Although there is information about each of these attributes individually, how they interact under different disturbance regimes has been hard to predict because the relevant spatial and temporal scales differ among the attributes of interest.

Our approach was predicated on the following assumptions:

- Central hardwood forests are constantly responding to (or recovering from) disturbance by fire, wind, and tree harvest.
- At a coarse scale, patterns of forest growth and succession are predictable.
- Landscapes can be divided into ecologically similar units that improve the predictability of vegetation response to disturbance.
- We can infer things about other ecosystem components such as wildlife habitat quality, forest products, landscape diversity, and aesthetics from knowledge of vegetation composition and structure across a landscape.

Our challenge was to find a means to predict forest structure and composition in a spatially explicit model capable of tracking the location of disturbance events, linking disturbances to the specific forest vegetation communities affected, and predicting how the forest vegetation and other attributes will change over time.

This required creating a dynamic map of predicted forest conditions through time.

Conceptually, this problem is easy to grasp; forest planners think about this every day. However, creating a quantitative framework to manipulate a mapped landscape requires a tremendous amount of detailed bookkeeping and data manipulation. Rather than build a new model, we used LANDIS, an existing landscape simulation model for the Lake States (Mladenoff *et al.* 1996, He *et al.* 1996). LANDIS operates on a map (raster) of the forest landscape and effectively deals with many of the computational complexities associated with tracking forest conditions through time on a mapped landscape. It accommodates up to 256 ecological land units and can be calibrated so that patterns of vegetation change are specific to each ecological land unit. Model resolution can be varied by changing the map pixel size from less than 100 m^2 to a square kilometer or more. LANDIS's algorithms to model fire and wind disturbance, coupled with the newly developed routines to model timber harvest (Gustafson *et al.* in prep.), provide a general framework to predict forest response to disturbance. Compared to traditional forest growth and yield models, the resolution of LANDIS for a given site on the landscape is low. It tracks only the presence or absence of tree species by age class. It does not estimate the density or volume of overstory vegetation; that must be inferred from the age structure and disturbance history at a given site. But for landscapes consisting of millions of mapped sites, the level of resolution is appropriate for many forest planning tasks, and greater detail can quickly lead to intractable computing and data manipulation problems.

The major barrier to applying LANDIS in the central hardwood region was the need to calibrate the vegetation dynamics and disturbance processes for local conditions. In this paper we describe the procedures used to recalibrate and apply LANDIS in the Missouri Ozarks. The process required a combination of existing inventory data and professional judgment. An example illustrates the application of the model to examine the results of alternative harvest strategies on a forest landscape in Missouri.

METHODS

Model calibration included three major phases: (1) calibrating species dynamics by ecological land type, (2) setting appropriate rates of fire disturbance, and (3) setting appropriate rates of wind disturbance. We focused on upland forest sites in the Missouri counties of Carter, Dent, Reynolds, and Shannon where a large quantity of high-quality multi-resource data was already available. Previous and ongoing research there provided a large body of multi-resource data and extensive maps of ecological land types and current forest cover.

Data

Inventory data to support calibration of species dynamics by ecological land type came from three sources. The first was the Missouri Ozark Forest Ecosystem Project (MOFEP), a landscape-scale field experiment investigating the effect of harvest methods on a host of ecosystem characteristics (Brookshire and Hauser 1993, Brookshire and Shifley 1997) (fig. 1). This inventory included 648 0.2-ha circular plots where species, diameter, and other characteristics were measured for trees ≥ 11 cm dbh. This inventory was conducted in 1991-1993, prior to any treatments associated with the MOFEP experiment. The forest is predominantly in the 60- to 80-year age class and is unique in having received virtually no fire or harvest disturbance in the preceding 40 years. The second source of data was the Sinkin Experimental Forest, located on the Mark Twain National Forest in southeast Missouri (fig. 1). This 1,600-ha tract also was largely undisturbed in the previous 40 years, and the forest overstory is also in the 60- to 80-year age class. The inventory included 71 0.1-ha circular plots that sampled trees ≥ 10 cm in areas of the forest that had been excluded from silvicultural experiments. The third and final inventory sampled trees ≥ 10 cm on 60 0.1-ha inventory plots split between two remnant old-growth forests: Big Spring in Carter County and Roaring River in Barry County (fig. 1). Both of these areas have been preserved from harvest activity and are considered excellent examples of undisturbed old-forest. Dominant canopy trees range from 100 to well over 200 years old on these old-growth sites, and the canopy is punctuated by tree fall gaps that have resulted in a multi-aged forest (Shifley 1994; Shifley *et al.* 1995, 1997). Before the 1940's, all study sites were subject to the periodic wildfires (usually ground fires of anthropogenic origin) and open-range livestock grazing that were practiced then throughout the Ozarks. Since that time, all study sites have been free from major anthropogenic disturbances.

Data on recent forest fire patterns in the study region came from electronic wildfire records maintained by the Mark Twain National Forest and the Missouri Department of Conservation (Westin 1992). Historical fire frequencies were obtained from Guyette (1996) and Guyette and Dey (1997). Data on wind disturbance in the Missouri Ozarks came from 96 km of line transects in the Missouri Ozarks sampled by Alan Rebertus in 1995-1996 (personal communication).

Analysis

Calibration

The 20 ecological land types (ELTs) (Miller 1981) represented in the inventory data were combined to create a reduced set of seven principal ecological land types that

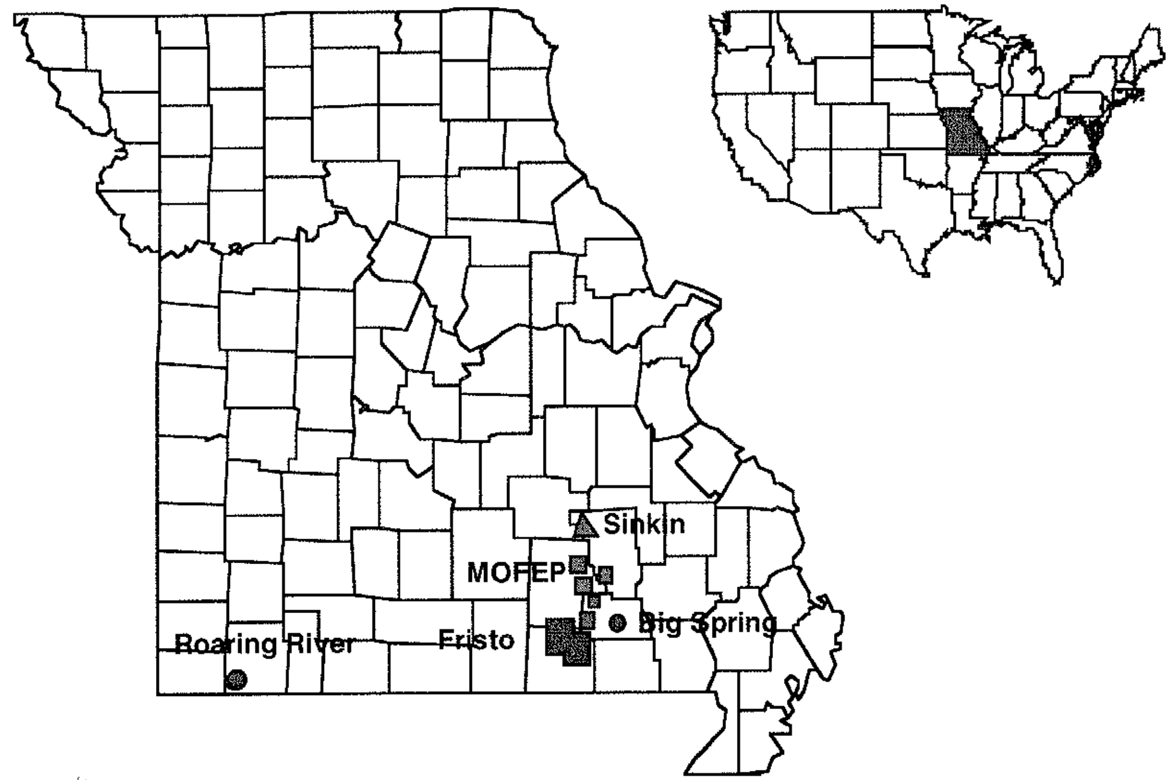

Figure 1.—*Location of study sites in southern Missouri used to calibrate and implement the model.*

were used in LANDIS (table 1). Groupings were based on frequency of ELT occurrence and similarity of associated site conditions. This reduced set of seven ELTs was used in subsequent simulations. Woody vegetation data were summarized by plot and ecological land type. These data were further summarized to tally species presence/absence probabilities by age class in a format that corresponded with LANDIS's internal representation of trees on a forest site (fig. 2). The combined data for the MOFEP, Sinkin, and old-growth sites were used to develop a set of provisional species presence/absence values (i.e., target percentages) for undisturbed, mature forests. These targets served as a first approximation to the expected equilibrium species composition in a lightly disturbed forest on a given ELT. These targets were further refined by three local ecologists (Sybill Amelon, Mark Twain National Forest, Houston, Missouri; Alan Rebertus, University of Missouri, Columbia, Missouri; Tim Nigh, Missouri Department of Conservation, Columbia, Missouri) who estimated expected long-term (i.e., over a century) shifts in species composition in the absence of disturbance by wind, fire, or harvest.

We then calibrated LANDIS for the four principal overstory species groups in the study area: white oaks, red/black oaks, shortleaf pine, and maple. Life history characteristics for each species (e.g., shade tolerance, fire susceptibility, sprouting capacity, longevity) were determined from published silvical guides. Species reproduction probabilities in LANDIS were then established for each ELT. Initial estimated reproduction probabilities were iteratively adjusted until, for an initial landscape with (a) all species groups present in equal proportions, (b) all sites randomly populated with one of the four species groups, and (c) all trees in the youngest (10-year) age class, the projected species composition by ELT over time moved to within 10 percent of the target proportions for that ELT.

Based on fire data between 1970 and 1995, we computed a mean fire-free interval of 300 years (i.e., the mean time between repeat fires at the same location) for current fire suppression practices. Minimum and maximum fire sizes were set at 0.1 ha and 41 ha, respectively. Fire severity was set low to simulate the ground fires that commonly occur in the region. Simulated fires will kill trees in the smallest age classes with greatest frequency, and maple is more susceptible to fire damage than either the oak or shortleaf pine species groups. Major stand-replacing wind disturbances were simulated with an 800-year mean return interval, a minimum event size of 0.1 ha, and a maximum size of 20 ha.

Table 1.—*Major ecological land unit groupings used for landscape simulations in the Missouri Ozarks*

Composite ecological land units used for model calibration and simulation	Proportion of studysites	Included ecological land types from Miller (1981)	Proportion of study sites
	Percent		*Percent*
Dry chert forest on south and west slopes	34	17 Dry chert forest, south and west aspects	34
Dry-mesic northeast slopes	29	18 Dry–mesic chert forest, north and east aspects	29
Ridge tops and upland flats	27	10 Xeric chert forest, ridge top	<1
		11 Dry chert forest, ridge top	5
		14 Xeric chert forest, flat	1
		15 Dry chert forest, flat	20
Upland drainage	6	4 Gravel wash, upland waterway	<1
		5 Dry bottomland forest, upland waterway	2
		6 Dry-mesic bottomland forest, upland waterway	4
Mesic floodplain or low terrace	2	1 Wet-mesic bottomland forest, low floodplain	1
		2 Calcareous wet forest floodplain or low terrace	<1
		3 Mesic bottomland forest, floodplain or low terrace	1
		7 Mesic forest, toe slope	<1
		35 Mesic forest, sinkhole	<1
		36 Acid seep forest, sinkhole	<1
Side slope on limestone	1	20 Dry-mesic limestone forest, side slope	<1
		22 Xeric limestone forest, side slope	<1
		23 Dry limestone forest, side slope	1
Glade	<1	19 Glade savanna, side slope	<1
		21 Dolomite or limestone glade, side slope	<1

Trees by 10 year age classes 1 = present, 0 = absent

Species	**Youngest ——————> oldest**
Maple group	0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Shortleaf pine	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Black oak group	1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0
White oak group	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Figure 2.—*Numerical representation of trees on a site (i.e., 0.9 ha raster) within LANDIS. For a given 10-year age class a value of "1" indicates the presence of one or more trees of the indicated species. A value of "0" indicates absence of the species in the age class. During a decade where a site is undisturbed, trees (i.e., "1"s) will simply move one space to the right in the age class matrix. If the trees in an age class are killed by wind, harvest, or fire, the "1" in that age class is replaced by a "0." Differences in the number of age classes for each species reflect differences in species longevity.*

Initial Conditions

In addition to the model parameterization procedures outlined above, application of LANDIS requires an initial raster map of ecological land types. The raster elements (i.e., "sites" in the terminology associated with LANDIS documentation) can be scaled by the user to accommodate different model resolutions, but for our applications they were 30 m square or 0.09 ha. To simulate harvest, additional raster maps showing the location of stands and management areas were required. Management areas designate groups of stands that, over time, will receive the same harvest regime. For these simulations, the entire landscape was treated as a single management area. For more complicated simulations, multiple management included different harvest activities. A given stand must be wholly contained within a single ELT and a single management area.

There are few areas where stand boundaries and ecological land units have been mapped and vegetation conditions have been inventoried. Two such mapped landscapes in Missouri are the 200,000 ha Fristo unit of the Mark Twain National Forest and the 3,800 ha in the Missouri Ozark Forest Ecosystem Project. To facilitate display of the simulated results, we confined our examples to the forest landscape comprised of the 842 contiguous ha in MOFEP units 7 and 8 (Brookshire *et al.* 1997). The initial vegetation conditions (i.e., species and age class) were summarized by ecological land type from the 141 forest inventory plots located on those units. For the first year of simulation, sites (i.e., the individual 0.9 ha raster units) within a given ecological land type were randomly populated with species in the same proportion they were observed in the initial inventory data.

Disturbance Regimes

We simulated three forest management regimes: intensive even-aged management, uneven-aged management, and no timber harvest (table 2). We simulated each regime for 100 years and compared the resulting landscape characteristics.

RESULTS

Differences in the age structure that result from the different management practices are evident in maps of age class over time (fig. 3). After 100 years there are obvious differences in the area of early-successional (0-29 years) and late-successional forest (> 120 years) and their spatial distribution across our modeled landscape. Although harvest patterns (fig. 3) are responsible for most age-class differences among the three management treatments, the effects of simulated fires are also visible. For the no-harvest management alternative, all sites < 180 years old are the result of simulated fire and wind events. The pattern of cumulative fire and wind events for the no-harvest alternative (fig. 4) matches the pattern of sites that were regenerated during the simulation. The effects of fire are also evident in the relatively large patches of young forest in the uneven-aged management alternative at year 100. Although less obvious in the even-aged management alternative, age class variation within stand boundaries did result from fire events. Effects of large-scale wind damage (≥ 0.09 ha in extent) are far less a factor in shaping landscape age structure than are the effects of fire.

Table 2.—*Simulated disturbance regimes applied across the 842-ha landscape comprised of MOFEP units 7 and 8*

Harvest regime	Harvest method	Area harvested	Harvest ranking algorithm	Mean interval between fires	Mean fire size	Min fire size	Max fire size	Mean interval between wind	Mean wind size	Min wind size	Max wind size
		%/decade		*Years*	*ha*	*ha*	*ha*	*Years*	*ha*	*ha*	*ha*
Intensive even-aged management with fire suppression	Clearcut	10	Oldest stands first; don't harvest adjacent stands in same decade	300	8	0.1	607	800	1	0.1	20
Uneven-aged management with fire suppression	Group selection, mean group size 0.2 ha	5	Harvest oldest stands first	300	8	0.1	607	800	1	0.1	20
No harvest with fire suppression	None	0	N/A	300	8	0.1	607	800	1	0.1	20

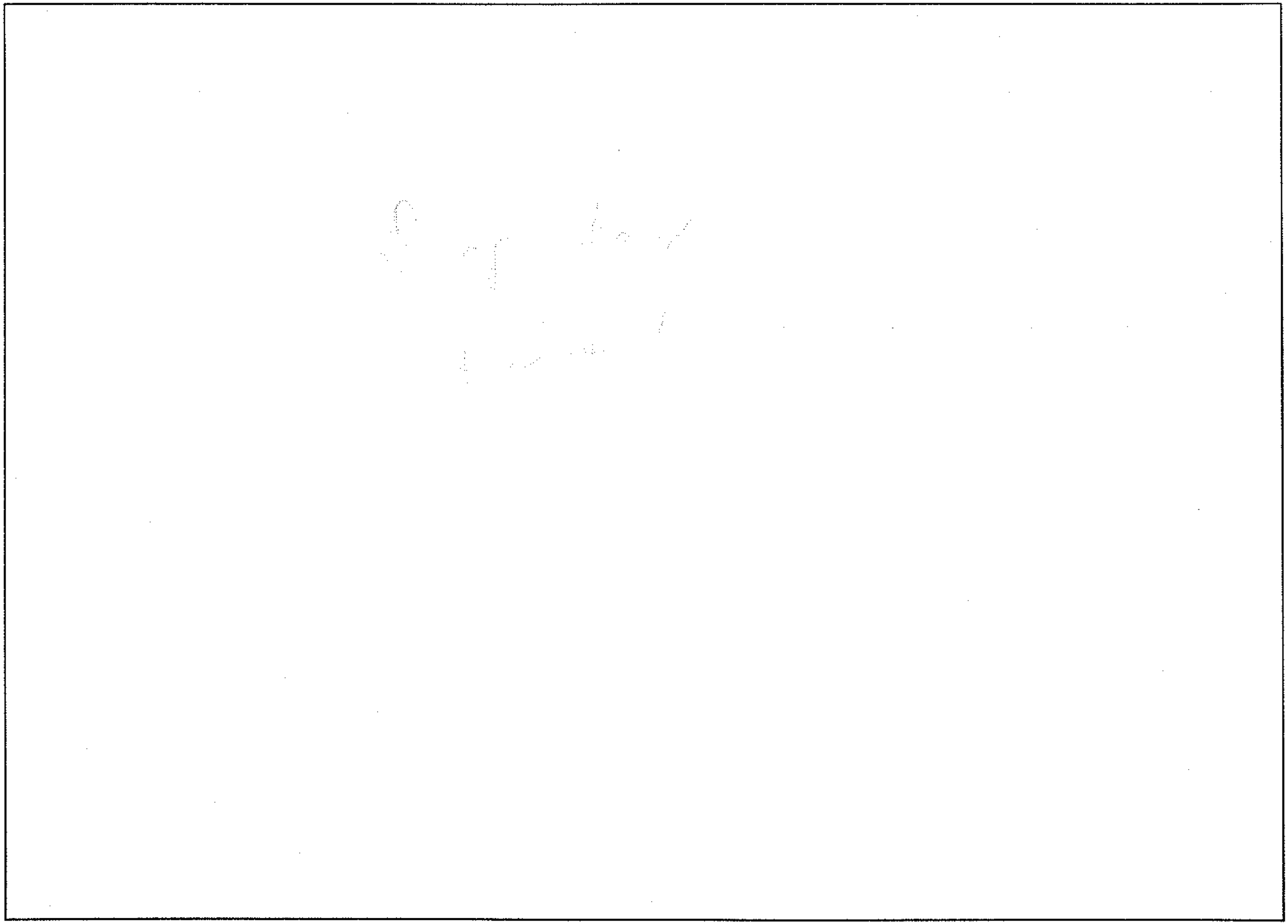

Figure 3.—*Change in landscape age structure over 100 years of simulation comparing even-aged, uneven-aged, and no-harvest alternatives. Harvested stands and group openings are shown for the even-aged and uneven-aged harvest alternatives, respectively.*

Figure 4.—*Cumulative fire disturbance and cumulative wind disturbance over 100 years for each of the simulated alternatives. Location of fire and wind events varies among repeated runs of the same landscape unless the same random number sequence is repeated. Harvest patterns can affect simulated fires by altering the proportion of species and size classes most susceptible to fire damage.*

Mapped images are useful for displaying change through time and spatial diversity of landscape characteristics. Other maps produced from the simulations included species presence/absence and species presence/absence by age class. These values were further combined across stands to estimate forest type and size class (seedling, sapling, pole, and sawlog) combinations. The simulated landscape conditions at each point in time are stored as one or more raster maps of forest species and age characteristics for each 0.09-ha site. Further analysis using GIS software provided additional summaries of landscape condition by species and size class (tables 3 and 4).

The proportion of sites with shortleaf pine increased under all management alternatives, but the increase was most dramatic under the even-aged and uneven-aged

Table 3.—*Proportion of sites with each species present under the three simulated management alternatives. At year 0 each 30- by 30-m site contained only one species. In subsequent years sites often contained more than one species, and row totals for a single year may exceed 100 percent.*

Year	White oak group	Black oak group	Shortleaf pine	Maple group
		Percent		
NO-HARVEST				
0	33	56	10	1
10	33	56	10	1
20	36	55	12	2
30	36	54	13	3
40	38	53	14	3
50	40	51	16	4
60	40	51	16	5
70	40	51	17	5
80	41	51	17	6
90	41	50	18	7
100	41	50	19	8
EVEN-AGED				
0	33	56	10	1
10	36	59	13	1
20	38	57	14	2
30	40	51	17	2
40	41	48	19	2
50	47	46	25	2
60	51	45	30	1
70	55	44	36	1
80	59	42	41	1
90	60	42	47	0
100	62	43	51	0
UNVEN-AGED				
0	33	56	10	1
10	37	58	14	1
20	41	59	19	2
30	45	60	23	2
40	49	60	28	2
50	53	59	33	2
60	56	61	37	3
70	59	64	41	3
80	61	65	44	3
90	62	64	48	3
100	63	64	51	3

Table 4.—*Area (ha) by size class for 100-year simulation of three management alternatives*

Year	No harvest			Even-aged			Uneven-aged		
	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog
0	0	0	842	0	0	842	0	0	842
10	0	0	842	87	0	755	66	0	777
20	26	0	816	199	0	644	147	0	696
30	36	0	807	247	65	530	155	51	636
40	28	25	789	286	122	434	159	114	569
50	38	32	772	300	203	339	187	154	501
60	22	49	771	311	229	303	168	174	499
70	11	42	789	297	261	285	146	188	508
80	18	35	789	310	265	267	158	184	501
90	27	27	789	338	268	237	182	166	494
100	28	19	795	332	274	237	188	156	498

management alternatives (table 3). The proportion of sites with white oak species increased relative to black oak species under all management regimes. Distribution of size classes at year 100 differed substantially among the three management alternatives. In the even-aged management alternative, the relative proportion of sites was evenly split among the seedling-sampling size class (0-29 years old), the pole size class (30-59 years old), and the sawlog size class (> 60 years old) (table 4). For the uneven-aged management alternative, 60 percent of the sites were in the sawlog size class, and the pole and seedling-sapling size classes each had approximately 20 percent of the area. Through the action of fire and wind disturbance, the no-harvest alternative consistently maintained 1 to 5 percent of sites in the pole and seedling-sapling size classes. Mean patch size by size class varied over the 100-year simulation period (table 5). In general, the even-aged management regime produced the largest patches in the seedling-sapling and pole size classes. The no-harvest management regime produced the largest patches of forest in the sawlog size class.

DISCUSSION

The amount of data and information required to calibrate and operate LANDIS in a new region is substantial. Calibration requirements include information about:

- wildfire size, frequency, and severity
- wind disturbance size, frequency, and severity
- species life history characteristics including
  - shade tolerance
  - fire tolerance
  - sprouting capacity
  - seed dispersal distance
  - age of reproductive maturity
  - longevity

Table 5.—*Mean patch size (ha) for 100-year simulation of three management alternatives*

Year	No harvest			Even-aged			Uneven-aged		
	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog
0	0	0	842	0	0	842	0	0	842
10	0	0	842	7	0	377	0.2	0	777
20	4	0	102	12	0	64	0.3	0	46
30	3	0	90	5	3	20	0.3	0.2	32
40	1	4	72	4	3	13	0.3	0.2	15
50	1	2	41	4	3	9	0.4	0.3	9
60	0.8	2	41	4	2	6	0.4	0.4	8
70	0.2	1	66	4	3	5	0.3	0.4	11
80	0.5	1	66	4	3	3	0.3	0.4	10
90	0.6	0.6	72	5	3	3	0.4	0.4	10
100	0.6	0.4	199	4	3	3	0.4	0.3	13

species reproduction success by ecological land type
a quantitative baseline against which to evaluate appropriate model performance

A calibration baseline (e.g., the species proportion targets that we described in the Methods section) is used to appropriately calibrate the model. Long-term databases suitable for evaluating long-term species dynamics are exceedingly rare. The best sources available were examples of undisturbed old-growth forests and mature, lightly disturbed second-growth forests. Except for extreme events such as tornadoes, information on the extent of wind disturbance to forests is virtually nonexistent. Even with the best available data, calibration of LANDIS (or similar long-term, landscape-scale simulation models) will require a combination of inventory data and professional judgment.

After model calibration, information needed to initialize and implement LANDIS may still be hard to find and/or create. Application of LANDIS requires a raster map of ecological land units (often based on a local ecological land classification system) and a map of the initial vegetation conditions (species presence/absence by age class for each site). There are few places where this information has been assembled in sufficient detail to initialize LANDIS for a large, contiguous landscape. Application of the harvest algorithms requires additional maps of stand boundaries and management unit boundaries.

One of the most powerful aspects of this methodology is the ability to simulate a wide variety of fire, wind, and harvest disturbances in a spatially explicit manner (i.e., on a mapped landscape). The LANDIS software provides methods to alter the size, frequency, and severity of fire and wind events. It also provides a means to map and display the simulated wind, fire, and harvest disturbances over time. Outputs can be further analyzed by standard GIS software.

Although the exact locations of future wind and fire disturbance cannot be predicted with accuracy, the overall pattern of these events across the landscape through time provides new insights into forest dynamics. Maps displaying general patterns of disturbance through time convey different information than numeric tabulations traditionally compiled from forest inventory plots and used to predict and analyze forest change. For example, statistics indicate that with current levels of fire suppression, a given hectare of forest will burn once every 300 years. However, a map of cumulative fire events (fig. 4) clearly shows that (1) fire will affect about one-third of the landscape over the course of a 100-year planning cycle, and (2) some fires will be severe enough to result in stand reinitiation. The probable impacts of future fire disturbance must be factored into management plans that try to regulate the area of early-successional forest. Without maps of cumulative fire and wind impacts on forest age structure over time, the potential impact of expected fire disturbances is easily overlooked.

For many landscapes, effects of harvest on forest structure will far exceed the impact of natural disturbances. The harvest algorithms recently added to LANDIS are extremely flexible and can simulate a great variety of harvest patterns (Gustafson *et al.*, in prep.). The user can specify the time of harvests, percentage of the landscape affected, regions where harvests will be located, species and age classes to remove, and size of harvest openings. The major reproduction systems can be simulated including uneven-aged management by group selection (group opening size must be ≥ the size of one pixel) and even-aged management by clearcut, shelterwood, or seedtree harvest. Harvests may be constrained to follow stand boundaries and to avoid removals in adjacent stands. Sites may be selected for harvest based on a variety of ranking algorithms including stand age and estimated product values. Harvests may be restricted to specific age cohorts and species groups. The ability to visualize, analyze, and summarize patterns of forest age and size distribution in response to timber harvest is essential in forest planning. It is also prerequisite to analyzing effects of disturbance on other ecosystem attributes such as wildlife habitat quality, economic value, or aesthetic quality that are dependent on forest vegetation.

The internal representation of overstory vegetation in LANDIS as simply the presence (or absence) of a given species by age class is sufficiently detailed for many large-scale simulation problems. But the lack of traditional measures of stand (or site) density by species can complicate how the results are used and interpreted. Logically, one might simply link each stand (or each site) on the initial landscape map to a conventional stand inventory that includes tree-level detail. Then tree-based forest growth and yield models such as TWIGS (Miner *et al.* 1988), Prognosis (Wykoff *et al.* 1982), or FVS (Teck *et al.* 1996) could be used to forecast detailed changes in the forest structure and species composition with or without management. Although such an approach would be elegant in its simplicity and compatibility with existing inventory systems, several operational problems currently limit implementation of that methodology. Most tree-based simulation models lack the ability to predict ingrowth and to simulate long-term successional changes in the absence of disturbance. Nor can they simulate the effects of wind and fire disturbance on individual trees. LANDIS is able to minimize these problems by minimizing the amount of tree-level detail that is associated with a given site. Also, linking a tree-based forest projection model to a landscape simulation system would require far more computational resources than are required by

LANDIS. However, over time, computing resources will increase and the computational limitations will be far less of a problem than the issue of how to model wind and fire disturbance effects on individual trees.

Application of LANDIS is computationally intensive. Simulations like the ones presented as examples in this paper can be completed in a few minutes after all files are prepared. However, the largest mapped landscape in Missouri encompasses approximately 200,000 ha. For that landscape, a single 100-year simulation with management can take 8 hours on a medium-size workstation, exclusive of input map preparation and subsequent analysis of results. Output maps and summaries can exceed several gigabytes of storage.

LANDIS is not a simple program to operate. The user-interface continues to improve and simplify the process of adjusting parameters and managing files. However, the program is complex. The user has the flexibility to adjust the fire, wind, and harvest disturbance processes as well as the parameters that regulate species dynamics within the model. Intelligent exercise of that control requires an understanding of how the algorithms work and how they interact at the species level. For example, a small reduction in reproduction probability for one species may lead to large increases in presence of another species that has similar life-history characteristics. These and other subtle insights related to initializing landscape conditions and interpreting results are best learned through extensive trial simulations and interaction with LANDIS developers or other users.

The outcome of any given landscape simulation is the net result of thousands or even millions of stochastic events. Within LANDIS, species establishment on each site, mortality, fire location, fire severity, and sprouting after disturbance are all simulated as event probabilities. Consequently, due to stochastic variation, repeated simulations on the same landscape will result in slightly different patterns of disturbance and vegetation response. This directly reflects the uncertainty associated with projections of natural disturbances. Due to the stochastic nature of the processes involved, repeat runs of the same scenario provide a mechanism to examine variation in the simulated landscape and the opportunity to compute probabilities for outcomes of special interest.

Users of long-term simulation results need to be cognizant of other social, political, and ecological factors that may affect disturbance patterns in future decades. Population shifts across the landscape, changes in forest land ownership, laws regulating harvest practices, attitudes about the role of fire in ecosystems, introduction of new pests (e.g., gypsy moth), and development of new utilization technologies (e.g., chip mills) could greatly affect future disturbance patterns on a forest landscape. These effects should be considered in the development of simulated disturbance scenarios. The LANDIS simulation environment is sufficiently flexible to accommodate simulation scenarios that incorporate assumptions about the future impact of these and other potential disturbance processes over the coming decades.

The next step in applying these results to forest management is the development of linkages to other ecosystem attributes of interest. Some attributes are easier to derive than others. Timber yields through time can be estimated from local or regional yield tables applied to the simulated harvest patterns. These can even be adjusted for known differences in site quality in different ecological land types. Converting timber yield to dollar values is also straightforward. Recent information about the relationship of down wood to disturbance patterns and stand age in central hardwood forests (Jenkins and Parker 1997) provides a means to link stand age and disturbance history to the volume of down wood. Even general levels of scenic beauty can be linked to the age and disturbance history of a forest site (Hetherington and Burde 1977). Linking landscape simulation results to key wildlife species generally requires more complicated linkages and the application of ancillary models to the simulated landscape conditions.

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LITERATURE CITED

Brookshire, B.; Hauser, C. 1993. The Missouri Forest Ecosystem Project. In: Gillespie, A.R.; Parker, G.R.; Pope, P.E.; Rink, G., eds. Proceedings, 9th Central hardwood forest conference. Gen. Tech. Rep. NC-161. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 289-307.

Brookshire, B.L.; Jensen, R.; Dey, D.C. 1997. Design of the Missouri Ozark Forest Ecosystem Project (MOFEP). In: Brookshire, B.L.; Shifley, S.R., eds. Proceedings of the Missouri Ozark Forest Ecosystem Project symposium: an experimental approach to landscape research. Gen. Tech. Rep. NC-193. St.

Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 1-25.

Brookshire, B.L.; Shifley, S.R. 1997. Proceedings of the Missouri Ozark Forest Ecosystem Project symposium: an experimental approach to landscape research. Gen. Tech. Rep. NC-193. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 378 p.

Gustafson, E.J.; Shifley, S.R.; Mladenoff, D.J.; Nimerfro, K.K. In preparation. Simulating timber harvest and forest succession using LANDIS.

Guyette, R. 1996. A tree-ring history of wildland fire in the Current River watershed. Columbia, MO: School of Natural Resources, University of Missouri.

Guyette, R.P.; Dey, D. 1997. Fire and logging history at Huckleberry Hollow, Shannon County, Missouri. Forest Res. Rep. 1. Jefferson City, MO: Missouri Department of Conservation. 10 p.

He, H.S.; Mladenoff, D.J. In press. Dynamics of fire disturbance and succession on a heterogeneous forest landscape: a spatially explicit and stochastic approach. Ecology. 80(1): 81-99.

He, H.S.; Mladenoff, D.J.; Boeder, J.E. 1996. LANDIS: a spatially explicit model of forest landscape change. LANDIS 2.0 user's guide. Madison, WI: Department of Forestry. University of Wisconsin-Madison.

Hetherington, J.; Burde, J. 1997. Perceived impacts of disturbance in central hardwood ecosystems. In: Pallardy, S.G.; Cecich, R.A.; Garrett, H.G.; Johnson, P.S., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 47.

Jenkins, M.A.; Parker, G.R. 1997. Changes in down deadwood volume across a chronosequence of silvicultural openings in southern Indiana forests. In: Pallardy, S.G.; Cecich, R.A.; Garrett, H.G.; Johnson, P.S., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 162-169.

Keane, R.E.; Menakis, J.P.; Long, D.; Hann, W.J.; Bevins, C. 1996. Simulating coarse scale vegetation dynamics with the Columbia River Basin Succession Model—CRBSUM. Gen. Tech. Rep. INT-340. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 50 p.

Mcgaughey, R.J. 1998. Techniques for visualizing the appearance of forest operations. Journal of Forestry. 96: 9-14.

Mcgaughey, R.J.; Ager, A. 1996. UTOOLS and UVIEW: analysis and visualization software. In: Proceedings of the Sixth Biennial USDA Forest Service Remote Sensing Application Conference; 1996 April 29-May 3; Denver, CO. Bethesda, MD: American Society of Photogrammetry and Remote Sensing: 319-329.

Miller, M.R. 1981. Ecological land classification terrestrial subsystem, a basic inventory system for planning and management on the Mark Twain National Forest. U.S. Department of Agriculture, Forest Service, Eastern Region. 87 p.

Miner, C.L.; Walters, N.R.; Belli, M.L. 1988. A guide to the TWIGS program for the north central United States. Gen. Tech. Rep. NC-125. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 105 p.

Mladenoff, D.J.; Host, G.E.; Boeder, J.E.; Crow, T.R. 1996. LANDIS: a spatial model of forest landscape disturbance, succession, and management. In: Goodchild, M.F.; Steyaert, L.T.; Parks, B.O., eds. GIS and environmental modeling: progress and research ideas. GIS World Books: 175-179.

Mowrer, T.W., tech. comp. 1997. Decision support systems for ecosystem management: an evaluation of existing systems. Gen. Tech. Rep. RM-296. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 154 p.

Shifley, S.R. 1994. Old growth forests in the central states: observations on a unique resource. In: Foresters together: meeting tomorrow's challenges. Society of American Foresters National Convention Proceedings; 1993 November 7-10; Indianapolis, IN. Bethesda, MD: Society of American Foresters: 527-528.

Shifley, S.R.; Brookshire, B.L.; Larsen, D.R.; Herbeck, L.A. 1997. Snags and down wood in Missouri old-growth and second-growth forests. Northern Journal of Applied Forestry. 14: 165-172.

Shifley, S.R.; Roovers, L.M.; Brookshire, B.L. 1995. Structural and compositional differences between old-growth and mature second-growth forests in the Missouri Ozarks. In: Gottschalk, K.W.; Fosbroke, S.L.C., eds. 10th Central hardwood forest conference proceedings. Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 23-36.

Teck, R.M.; Moeur, M.; Eav, B. 1996. Forecasting ecosystems with the forest vegetation simulator. Journal of Forestry. 94(12): 7-10.

Westin, S. 1992. Wildfire in Missouri. Jefferson City, MO: Missouri Department of Conservation. 161 p.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Integrated Tools for Natural Resources Inventories in the 21st Century

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INTEGRATED TOOLS
FOR NATURAL RESOURCES
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PREFACE

Inventory has always been and continues to be central to forest management at all levels of practice. Designing, planning, and implementing inventories draws upon the expertise of many individuals within a forestry organization. For these reasons it is not surprising that our 1998 conference drew a contingent of over 325 forestry and related professionals from multiple organizational levels. There was also a distinct international flavor to the conference with over 30 foreign countries represented—again, evidence of the importance and pervasiveness of inventory in forestry practice.

By all accounts the gathering was a complete success: good attendance, a rich variety of papers, well-done presentations, fine hospitality and weather from the good folks of Boise, Idaho, and ample good food around which discussions could be continued and acquaintances made or reestablished. All this was made possible by the hard work of many people involved in organizing the conference and, of course, the enthusiastic participation of attendees.

Consideration of the papers presented at the conference points to several trends in inventory practice. The new "annual inventory" systems being developed were the subject of several papers, as well as a special session. Increased pressure on forest management has called for a corresponding increase in the need for timely data for which the annual inventory systems provide one approach. Concern over possible forest decline in many areas across the globe has spurred efforts in more effective forest health monitoring. These efforts continue to be improved in terms of statistical rigor and are now being seen as an integral component of a comprehensive inventory system. Growth modeling efforts and inventory have always been closely linked, but the use of models in the design of repeated inventories has grown considerably. Use of inventory data for model calibration and evaluation, as opposed to research plots, is receiving increased attention.

Remote sensing techniques continue to be evaluated for generating useful auxiliary data in forest inventories. Much has been learned with current efforts better matching imagery capability with data needs. Still greater gains will be needed as managers and decisionmakers call for more frequent inventories with broader applicability. Finally, a healthy call for simplicity in design was heard from many at the conference. Inventory data are being used to address an increasingly diverse set of questions by an increasingly diverse set of users. Optimality has little meaning under such circumstances, and statistical efficiency may not be conducive to broad application.

In addition to the conference paper and poster sessions, vendors shared the latest in technologies useful in inventories throughout the conference, and five half-day workshops presented the latest inventory tools. The conference ended with six field trips demonstrating a variety of current inventory techniques and implementations.

The papers that follow are generally "as provided" by the author. All authors were asked to obtain peer review of their manuscript, and we assume that was uniformly the case. Reviewers are identified in the acknowledgments of each paper. We have organized the papers into seven topical areas to give some sense of meeting themes.

Again, thanks to all those involved in organization and execution of this successful conference, especially to the members of the conference planning commitee—people who all put in lots of hard work and had great ideas—and to our sponsors who provided financial and other logistical assistance. We would also like to thank Lucy Burde and Mary Peterson for the hard work they did in editing and putting together these proceedings.

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