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Simulating forest fuel and fire risk dynamics across landscapes—LANDIS fuel module design

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Abstract

Understanding fuel dynamics over large spatial (10^3–10^6 ha) and temporal scales (10^1–10^3 years) is important in comprehensive wildfire management. We present a modeling approach to simulate fuel and fire risk dynamics as well as impacts of alternative fuel treatments. The approach is implemented using the fuel module of an existing spatially explicit forest landscape model, LANDIS. The LANDIS fuel module tracks fine fuel, coarse fuel and live fuel for each cell on a landscape. Fine fuel is derived from vegetation types (species composition) and species age, and coarse fuel is derived from stand age (the oldest age cohorts) in combination with disturbance history. Live fuels, also called canopy fuels, are live trees that may be ignited in high intensity fire situations (such as crown fires). The amount of coarse fuel at a given time is the result of accumulation and decomposition processes, which have rates defined by ecological land types. Potential fire intensity is determined by the combination of fine fuel and coarse fuel. Potential fire risk is determined by the potential fire intensity and fire probability, which are derived from fire cycle (fire return interval) and the time since last fire. The LANDIS fuel module simulates common fuel management practices including prescribed burning, coarse fuel load reduction (mechanical thinning), or both. To test the design of the module, we applied it to a large landscape in the Missouri Ozarks. We demonstrated two simulation scenarios: fire suppression with and without fuel treatment for 200 years. At each decade of a simulation, we analyzed fine fuel, coarse fuel, and fire risk maps. The results show that the fuel module correctly implements the assumptions made to create it, and is able to simulate basic cause–effect relationships between fuel treatment and fire risk. The design of the fuel module makes it amendable to calibration and verification for other regions.
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Keywords: Fine fuel; Coarse fuel; Fire intensity; Fire risk; Fuel treatment; Landscape model; LANDIS

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1. Introduction

Identifying areas of high fire risk on forest landscapes and understanding how this risk changes over time is essential for prioritizing forest management activities aimed at reducing fire risk. This requires characterizing fuel types and quantifying fuel loads that influence fire behavior. The quantity and quality of forest fuels are influenced by both biotic (e.g., vegetation type, species composition, stand age, stand history, disturbance history) and abiotic factors (e.g., climate, terrain, and soil) (Brown et al., 1982). The complex interactions among these factors make simulating fuel and fire risk challenging, especially when the study landscape is large (e.g., 10^6 ha), the study time frame is long (e.g., 10^1–10^3 years), and spatially explicit predictions are required.

Computer simulation models are useful tools for studying such complex issues (Keane et al., 1996; Gardner et al., 1996; Miller and Urban, 1999; Mladenoff and He, 1999; Finney, 2001; Hargrove et al., 2000; Yemshanov and Perera, 2002). Variables and interactions can be precisely defined in simulation models that have testable assumptions defined by mathematical and/or logical relationships. Management alternatives can be compared as simulation scenarios and evaluated as working hypotheses. Models allow us to deduce results, such as the effects of various fuel load reduction treatments on fire risk and vegetation dynamics, since it is impractical to examine these dynamics in the real world. Spatially explicit forest landscape simulation models are particularly useful in simulating fuels because conditions of each individual site at time t are derived from the conditions at $t-1$. Therefore, they are capable of tracking the dynamics of vegetation, fuel, and fire over time (Keane et al., 1996; Hargrove et al., 2000). If such models are realistically parameterized at year 0 and internal assumptions are valid, simulation results can provide insight on long-term management issues.

Challenges of simulating fuel dynamics using models include decisions of how much mechanistic detail to incorporate and how models are connected to reality (Crookston et al., 1999; Stage, 2003). These are often more difficult problems than developing a model representation of a variable or a relationship. The level of detail included in a model is often dictated by management options, questions to be answered, and data availability. In most US national forests, forest management plans are made on a multi-year basis, and from a practical standpoint, fuel treatments to prevent wildland fire are limited to less than 1% of the area on average year. The actual quantity of fuel is usually not available or impractical to obtain for each individual site, so fuel treatment decisions are often made based upon qualitative or semi-quantitative data derived indirectly from knowledge of other biotic and abiotic factors. Thus, our selection of model representation of fuels is based upon the following general assumption: for a large landscape, managers and scientists may not know the actual fuel quantity for each site, but based upon empirical knowledge they can have fairly reliable estimates using nominal scales such as high, medium, and low (Brown and DeByle, 1989). Such empirical knowledge can be quantified from known vegetation and environmental relationship using specific models (e.g., Anderson, 1982; Andrews, 1986; Beukema et al., 1999).

In this study, we present a modeling approach to simulate fuel and fire risk dynamics and the effects of fuel treatment at large spatial (10^3–10^6 ha) and temporal scales (10^1–10^3 years). The approach is implemented as the fuel module of an existing spatially explicit and object-oriented forest landscape model, LANDIS (Mladenoff et al., 1996; Mladenoff and He, 1999; He et al., 1999). A major purpose of LANDIS is to simulate changes on large forested landscapes, where available input data may be coarse or parameters poorly estimated, such as those associated with fuel data. The level of detail incorporated in LANDIS is generally consistent with available data and knowledge of fuel and fire risk dynamics at landscape scales.

2. LANDIS model description

LANDIS and its various modules have been described extensively elsewhere (Mladenoff and He, 1999; He and Mladenoff, 1999a,b; He et al., 1999; Gustafson et al., 2000). Here we provide a general description of the model. In LANDIS, a landscape is organized as a grid of cells (or sites), with vegetation information stored as attributes for each cell (Fig. 1). Cell size (side) can be varied from 10 to 500 m depending on the research scale. At each cell or site, the model tracks a matrix containing a list of species by rows and

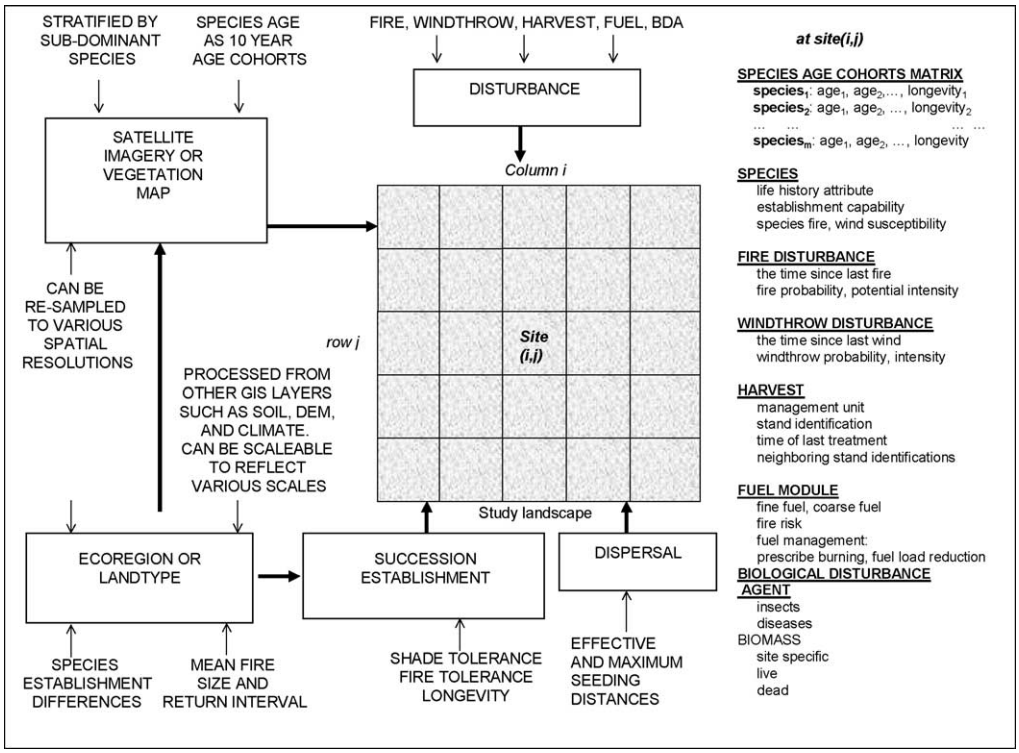

Fig. 1. LANDIS model structure (modified from Fig. 2 in He et al., 1999). In LANDIS, a landscape is divided into equal-sized individual cells or sites. Each site (i, j) resides on a certain land type and includes a unique list of species present and their associated age cohorts. The species/age cohort information varies via establishment, succession, and seed dispersal, and interacts with disturbances.

the 10-year age cohorts by columns. The model does not track individual trees. This differs from most forest stand simulation models that track individual trees (Grimm, 1999). An exception is FORCLIM (Bugmann, 1996). Applications of FORCLIM have demonstrated that tracking age cohorts rather than individuals does not significantly reduce realism for landscape-scale applications (Bugmann, 1996). Additionally, computational loads are greatly reduced, because actual species abundance, biomass, or density is not calculated. A species presence/absence approach allows LANDIS to simulate large landscapes and avoids any false precision of predicting species abundance measures with inadequate input data or parameter information.

LANDIS stratifies a heterogeneous landscape into land types (also called ecoregions for broad scale studies), which are generated from GIS layers of climate, soil, or terrain attributes (slope, aspect, and landscape position). It is assumed that a single land type contains a somewhat uniform suite of ecological conditions, resulting in similar species establishment patterns and fire disturbance characteristics, including ignition frequency, fire cycle (mean fire return interval), and fuel decomposition rates (He and Mladenoff, 1999a). These assumptions have been supported by many empirical and experimental studies (e.g., Kauffman et al., 1988; Brown and See, 1981). Furthermore, land types can be redefined by users to partition the landscape into strata that are most relevant for a particular application.

LANDIS 3.7 simulates four spatial processes and numerous non-spatial processes. The spatial processes are fire, windthrow, harvesting, and seed dispersal (He et al., 2003). Fire is stochastic process based on the probability distributions of fire cycle and mean fire sizes for various land types (He and Mladenoff, 1999a). LANDIS simulates five levels of fire intensity from surface fires to crown fires. Fire intensity is determined by the amount of fuel on a site (see below). Tree species

are also grouped into five fire-tolerance classes based upon their fire-tolerance attributes and five age-based fire susceptibility classes from young to old, with young (small) trees being more susceptible to damage than older (larger) trees. Thus, fire severity is the interaction of susceptibility based on species age classes, species fire tolerance, and fire intensity (He and Mladenoff, 1999a). A new LANDIS fire module (Yang et al., 2004) employs hierarchical probability theory to allow even more explicit simulation of different fire regimes across landscapes.

Windthrow is also stochastically simulated. In the LANDIS wind module the probability of windthrow mortality increases with tree age and size. Windthrow events interact with fire disturbance such that windthrow increases the potential fire intensity class at a site due to increased fuel load. In general, windthrow is more important on mesic landtypes, which typically have long-lived species and low fire frequency (Mladenoff and He, 1999).

The LANDIS harvest module simulates forest-harvesting activities based upon management area and stand boundaries (Gustafson et al., 2000). These maps are predefined and are only used by the LANDIS harvest and fuel modules. Harvest activities are specified through rules relative to spatial, temporal, and species age-cohort information tracked in LANDIS. The spatial component determines where harvest activities occur and may be used to enforce stand boundary and adjacency constraints. The temporal component determines the timing (rotations) and manner (single versus multiple-entry treatments) of harvest activities. The species age-cohort component allows specification of the species and age cohorts removed by the harvest activities. For example, a clearcut removes all species and all ages, whereas a selection harvest typically removes only a few species and age cohorts. The ability to use a combination of spatial, temporal, species, and age information to specify harvest action independently allows a great variety of harvest prescriptions to be simulated (Gustafson et al., 2000).

LANDIS simulates seed dispersal based upon species' effective and maximum seeding distance (He and Mladenoff, 1999b). Seed dispersal probability is modeled for each species using an exponential distribution that defines the effective and maximum seed dispersal distances (He and Mladenoff, 1999b).

Non-spatial processes of succession and seedling establishment are simulated independently at each site. They also interact with spatial processes such as seed dispersal, harvesting, and disturbances. Succession is a competitive process driven by species life history parameters in LANDIS. It is comprised of a set of logical rules primarily using the combination of shade tolerance, seeding ability, longevity, vegetative reproduction capability, and the suitability of the landtype (Mladenoff and He, 1999). These rules are used to simulate species birth, growth and death at 10-year intervals. For example, shade intolerant species cannot establish on a site where species with greater shade tolerance are present. On the other hand, the most shade tolerant species are unable to occupy an open site. Without disturbance, shade tolerant species will dominate the landscape given that other attributes (e.g., dispersal distances) are not highly limiting and the environmental conditions are otherwise suitable. Species establishment is regulated by a species-specific establishment coefficient (ranging from 0 to 1.00), which quantifies how different land types favor or inhibit the establishment of a particular species (Mladenoff and He, 1999). These coefficients, which are provided as input to LANDIS, are derived either from the simulation results of a gap model (e.g., He et al., 1999) or from estimates based on existing experimental or empirical studies (Shifley et al., 2000).

Due to the stochastic nature of processes such as fire, windthrow, and seedling dispersal simulated in the model, LANDIS is not designed to predict the specific time or place that individual disturbance events will occur. Rather, it is a cause–response type of scenario model that simulates landscape patterns over time in response to the combined and interactive outcomes of succession and disturbance. It can provide managers with guidance about management practices that can mitigate current or anticipated problems on the forest landscape, and provide a better understanding of long-term, cumulative effects that may result from the combination of natural disturbances and management practices. LANDIS has been applied and tested with different species and environmental settings (e.g., Mladenoff and He, 1999; He and Mladenoff, 1999a,b; Shifley et al., 1999, 2000; Gustafson et al., 2000, 2004; Franklin et al., 2001; He et al., 2002; Pennanen and Kuuluvainen, 2002; Akçakaya et al., 2004; Zollner et al., in press; Sturtevant et al., 2004).

3. LANDIS fuel module design

3.1. Definitions

Surface fuel has two distinct types: fine fuel and coarse fuel. Fine fuels are primarily foliage litter fall and small dead twigs falling from live trees (Deeming et al., 1977). They are less than 1/4 in. in diameter and usually decompose in a few years. Fine fuel typically corresponds to 1 and 10-h lag (Brown and Davis, 1973) and is the primary determinant of fire ignitions (Andrews and Chase, 1989). For the non-forested land types, fine fuel can also be simulated by parameterizing a generic ground cover species (hereafter called a pseudo-species) that will allow simulated fires to ignite and/or spread from non-forested areas into forests (He et al., 2003). Coarse fuels, also called coarse woody debris (CWD), include any dead tree materials that have a diameter $\geq$3 in. (Deeming et al., 1977). This may include snags, stems, boles, stumps, or standing dead trees. Coarse fuels correspond to 100- and 1000-h fuels and are primarily responsible for determining fire intensities (Burgan, 1987). Live fuels, also called canopy fuels, are live trees that may be ignited in high intensity fire situations (such as crown fires). The LANDIS fuel module simulates all these fuel types for each cell. Assumptions and algorithms are discussed in the following sections for each component.

Many mechanistic details related to fire ignition and spread (e.g., physical and chemical fuel properties, air temperature, and wind speed) are not tracked and predicted by the LANDIS fuel module. Thus, fire intensity, fire risk, and fire severity are defined in a more general way in this paper. Potential fire intensity is determined by the combination of fine fuel and coarse fuel loads (Section 3.4). Fire probability is based on the historical distribution of fires, and it is assumed to encapsulate the effects of climate and terrain (He and Mladenoff, 1999a). Potential fire risk (Section 3.5) is calculated from both potential fire intensity and fire probability. Fire severity is determined the effects of a fire event on individual species age cohorts present at a burned site. Fire is a bottom-up disturbance, where low intensity fires affect only the younger age classes, and as fire intensity increases, more (older) age classes are affected (He and Mladenoff, 1999a).

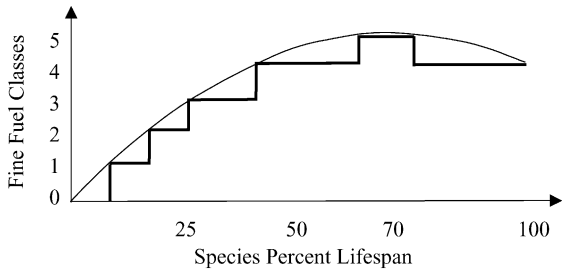

Fig. 2. Fine fuel production changes through the lifespan of a given species. In this example, the amount of fine fuel created by each species (the thin line) is positively correlated with age until approximately 70% of the species lifespan is reached, and is negatively correlated with age as the species age approaches maximum species longevity. In the LANDIS fuel module, fine fuel accumulation is converted into five categorical classes represented by the thick solid line. The relationship between fine fuel and species lifespan (which may include multiple peaks) for each species is derived from empirical data.

3.2. Fine fuels

3.2.1. Assumptions

The amount of fine fuel for each cell is approximated in LANDIS by vegetation types (species composition) and stand age, variables that are already tracked in LANDIS. In general, mature, old trees produce more needles, leaves, and dead twigs than small, young trees. Generally, fine fuel builds-up, levels off, and decreases with stand age (Fig. 2). In a landscape that may contain millions of cells it is not feasible to derive the exact amount of fine fuel for each cell. However, users can define the relationship between fine fuel and a species lifespan based on empirical studies (e.g., Fig. 2). Fine fuel from different species may have different flammability due to differences in physical and chemical attributes (Brown et al., 1982). We use a *fuel quality coefficient* ($0 < \text{FQC} \leq 1$) to summarize such differences on a relative scale. Species with low FQC contribute less to the flammability of fine fuels than species with high FQC. FQCs are ranked and parameterized by users, and the same value (e.g., FQC = 1) can be used for all species if there are no discernable differences among species.

Model users provide empirical estimates that define the general relationship of fuel quantity by species age (Fig. 2). To reduce the potential for false precision (of exact amount of fine fuels) derived from such empirical relationships, the calculated amount of fine fuel is

converted into five categorical classes (very low, low, medium, high, and very high). This is consistent with the design of disturbance intensity and severity in the LANDIS fire, wind, and BDA modules.

Decomposition rates of litter vary by sites. A study by Trofymow et al. (2002) for 18 upland forest sites across Canada suggests that about 80% of the original litter mass decomposed within their 6-year experiment. We assume that most fine fuels decompose in less than 10 years (e.g., Agee and Huff, 1987), which is shorter than the LANDIS 10-year time step. Thus, at each time step, fine fuels are re-calculated based on the live species/age cohorts actually found on each cell; the quantity of fine flues on a cell is not carried forward to accumulate from decade to decade. This assumption may cause underestimates of fine fuels in systems where fine fuel decomposition requires more time (>10 years) due to cold climate and other environment factors.

The relationship between fine fuel accumulation and age can be sensitive to site conditions, and therefore, one may propose to define fine fuel accumulation curves by species and by land types. However, because there are typically many species and land type combinations, this would dramatically increase the parameterization burden for the user. Therefore, we use the same species-specific curves across all land types because (1) such curves are user-defined and can be modified to capture the predominant relationship for a specific study area; (2) subtle variations in the curves are not important when fine fuel amounts are lumped into categorical classes; and (3) site specific effects may be incorporated in the land type modifiers along with fire, wind, and biological disturbance modifiers (see Section 3.2.3).

3.2.2. Calculations of fine fuel

The actual calculation the amount of fine fuel involves deriving a fine fuel amount based on species age and modified by FQC. The result is not the absolute quantity of fine fuels, but rather an "effective index" of the amount of fine fuel that accounts for its flammability. If there are n species in a cell, the total amount of fine fuel (FF) in this cell is calculated as

$$\mathrm{FF} = \left(\frac{(\sum_{i=1}^{n} \mathrm{Age}_i / \mathrm{Long}_i \, \mathrm{FQC}_i)}{n} \right) \quad (1)$$

where Age_i is the age of the oldest cohort of the ith species, Long_i is the maximum longevity of the ith species (also used elsewhere in LANDIS), and FQC is as previously defined. Dividing by n averages the amount of fuel across all species present in the cell. Because LANDIS tracks only the presence and absence of species/age cohorts; the design for simulating fine fuels assumes that all species present in a cell have the same density. Such an assumption may not be realistic for individual cells, but at the landscape scale with millions of cells, relative species abundance can be realistically approximated (He et al., 1998). The actual value calculated is translated into fine fuel classes using the user-defined relationship (Fig. 2).

Understory life fuel is not explicitly tracked in this design. To track understory species, one or more pseudo-species can be parameterized to represent a general shrub layer. Pseudo-species in LANDIS are parameterized using the same set of species life history attributes (e.g., longevity, maturity, shade tolerance, etc.) as canopy species, except they do not affect the overstory species competition and succession. Eq. (1) can also include understory species for ecosystems that track shrub live fuels are necessary.

3.2.3. Fine fuel modifiers

Land type, fire, wind, harvest, and biological disturbance can modify the fine fuel classes calculated by Eq. (1). Fine fuel decomposition rates may vary by land types (Agee and Huff, 1987). Thus, a land type modifier may decrease or increase the fine fuel class derived from species age cohorts. For example, a fine fuel class 3 on a mesic land type might decrease to class 2 because the decomposition rate is relatively high, while the same fuel class (3) on a xeric land type might increase to class 4, since the decomposition rate is relatively low. The user defines the modifier in the land type parameter file, and the default is no modification. Disturbances may increase or decrease the fine fuel class in a similar way. For example, as a parameter for a Biological Disturbance Agent (BDA) (e.g., insect pest), the user defines how a BDA disturbance event will increase the fine fuel class, depending on the type and severity of the event. Similarly, fire events can reduce the fine fuel class based on user-defined rules (Armour et al., 1984). The simplest and most common case is that fires remove all fine fuels. Alternatively, a rule could remove fine fuels in proportion to fire severity. Wind

disturbances primarily increase coarse fuel. However, it can also increase fine fuels by producing dead leaves and needles. Increases in fine fuel classes caused by windthrow can be determined by windthrow severity. Harvest activities can also modify the fine fuel class. The user can also define how each harvest prescription defined in the Harvest module will modify the fine fuel class. Some prescriptions may reduce fine fuels by one or more classes (e.g., prescribed burn), while others may increase fine fuels (e.g., clear cutting).

3.3. Coarse fuels

3.3.1. Assumptions

Unlike the fine fuels, coarse fuels are not derived using species-specific age cohorts. Instead, stand age (the oldest age cohorts) in combination with disturbance history (time since last disturbance) are used to determine the coarse fuel accumulation for a cell (Brown and See, 1981; Harmon et al., 1986; Spies et al., 1988; Sturtevant et al., 1997; Spetich et al., 1999). Coarse fuel amount is the interplay between input and decomposition (Spies et al., 1988; Sturtevant et al., 1997). Such interplays may vary by land types (Harmon et al., 1986), which encapsulate environmental variables (e.g., climate, soil, slope, and aspect) (Fig. 3).

In the absence of disturbance, the accumulation process dominates until the amount of coarse fuel reaches a level where decomposition and accumulation are in balance (Sturtevant et al., 1997; Bergeron and Flannigan, 2000), as depicted in Fig. 3. For example, on a mesic land type with high decomposition rates, the amount of coarse fuel can be low, whereas on a xeric land type with low decomposition rates, the amount of coarse fuel can be high.

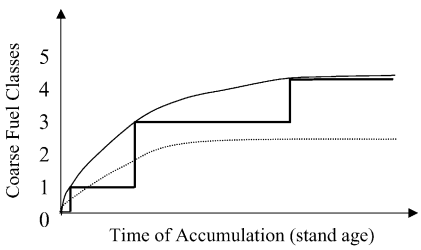

Fig. 3. Coarse fuel accumulation is a continuous process. The solid and dotted thin lines represent different fuel accumulation rates on two land types (e.g., mesic and xeric land type) in the absence of disturbances. In the LANDIS fuel module, coarse fuel accumulation is converted into categorical classes represented by the thick solid line (the conversion of the thin dotted line into categorical classes is not shown).

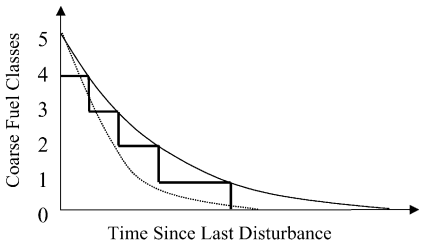

Fig. 4. Coarse fuel accumulation after disturbance is a continuous process. The solid and dotted thin lines represent different fuel decomposition rates on two land types (e.g., mesic vs. xeric land type) after windthrow, insect defoliation, or harvest events. In the LANDIS fuel module, the coarse fuel decomposition process is converted into categorical classes as represented by the thick solid line (the conversion of the thin dotted line into categorical classes is not shown).

The decomposition process is modeled based on the decomposition curve (Lambert et al., 1980; Foster and Lang, 1982; MacMillan, 1988; Hale and Pastor, 1998) (Fig. 4). Such a decomposition curve is also user-defined for each land type. The example suggests two decomposition trajectories of coarse fuels on two different land types (Fig. 4).

The accumulation and decomposition curves together form the general "U-shaped" temporal pattern observed in many forest ecosystems (Sturtevant et al., 1997; Spetich et al., 1999). In many boreal and northern hardwood forest ecosystems, a land type can seldom accumulate enough coarse fuel to reach class five unless there are other disturbance events occurring such as windthrow, BDA, and/or harvest. Users can define these disturbance-related accumulations using coarse fuel accumulation and decomposition curves (Figs. 3 and 4).

Due to the long temporal scales involved in estimating the amount of coarse fuels, uncertainty is high. Collapsing the estimates of the quantity of coarse fuel into five categorical classes (very low to very high) reduces the potential for false precision and the parameterization burden for the module.

3.3.2. Coarse fuel modifiers

Fire, windthrow, harvest, biological disturbance, and natural mortality can all modify coarse fuel classes (Bergeron and Flannigan, 2000; Sturtevant et al., 1997).

Table 1
Example of coarse fuel modifiers for a generic land type[a]

Fire modifier					
Fire severity classes	5	4	3	2	1
Coarse fuel loads reduction	−3	−2	−1	0	0
Windthrow modifier					
Windthrow severity	5	4	3	2	1
Coarse fuel class increase	+4	+3	+1	+0	+0
BDA modifier					
BDA Severity	3	2	1		
Coarse fuel class increase	+4	+3	+2		
Harvest modifier					
Harvest impacts on coarse fuel 5	4	3	2	1	
Coarse fuel class increase	+4	+2	+2	+1	+1

[a] The severity of fire, windthrow and BDA disturbance are represented in categorical classes in LANDIS. Users can define how coarse fuel classes are modified based on each disturbance severity class. For example, a windthrow of severity class 5 will increase coarse fuel class by four classes. Harvest events can be ranked on a 1–5 scale by the amount of stumps and cull material left behind. In this example, the event that ranks 5 on this scale increases coarse fuel by four classes.

In LANDIS, a fire of given severity removes coarse fuels based upon a set of user-defined rules (Table 1). In general, high severity fires remove more coarse fuels than do low severity fires (Lang, 1985). A fire alters the time of fuel accumulation based on the relationship defined in the fuel curve (Fig. 3). Windthrow or insect defoliations modeled with the BDA module (Sturtevant et al., 2004) can increase coarse fuel load as defined by the modifiers specified in each module, and the added fuels decompose according to the user-defined decomposition curve (Fig. 4). These relationships can be defined differently on different land types (Table 1). The same principles also apply to harvest activities, which can alter coarse fuel loads (Gore and Patterson, 1986). Natural tree mortality also increases coarse woody debris, and adds to the coarse fuel load.

3.3.3. Calculations of coarse fuel

The elapsed time of fuel accumulation (TFC) is used to determine the current amount of coarse fuel as shown in Fig. 4. The various modifiers, once activated, will determine how much the coarse fuel class is increased or reduced. The relationships defined for each modifier (Table 1) and the decomposition status defined in Fig. 4 are used to determine the final coarse fuel amount. The highest class ($\leq$5) will be retained as the final coarse fuel class. For example, based upon the time of coarse fuel accumulation for a site, the coarse fuel class is determined to be class 2. However, a severe windthrow disturbance and an insect defoliation would each raise the coarse fuel class by 3 (e.g., Table 1). This leads to a final coarse fuel class for this site that is larger than 5 (2 + 3 + 3). In such a case, the model will set the coarse fuel class to 5.

3.4. Potential fire intensity

3.4.1. Assumptions and calculations

Potential fire intensity is determined by the combination of fine fuel and coarse fuel in each cell. A set of rules can be defined (Table 2) based upon the assumption that coarse fuel is the primary contributor to the fire intensity class, since in many forest ecosystems coarse fuel accounts for about 90% of forest floor mass (Grier and Logan, 1977; Lang and Forman, 1978; Lambert et al., 1980). Users can define other rules according to the ecosystems they study. In the example (Table 2), high intensity fires are not common compared to low intensity fires. Seven fine and coarse fuel combinations result in fire intensity = 1 (very low), seven in fire intensity = 2, six in fire intensity = 3, three in fire intensity = 4, and two in fire intensity = 5 (very high) (Table 2).

3.4.2. Live fuel—fire intensity modifier

Live fuels are live trees that may be ignited in high intensity fire situations (such as crown fires). Thus, live fuels can be a fire intensity modifier. A mid-level intensity fire ($\geq$3) may change into a crown fire (in-

Table 2
Potential fire intensity table (default)[a]

	FF class 1	FF class 2	FF class 3	FF class 4	FF class 5
CF class 1	1	1	1	1	2
CF class 2	1	1	1	2	2
CF class 3	2	2	2	3	3
CF class 4	2	3	3	4	4
CF class 5	3	3	4	5	5

[a] CF represents coarse fuel and FF represents fine fuel. The table lists all the possible combinations of fine fuel and coarse fuel classes and defines for each combination the resulting potential fire intensity class. For example, if fine fuel class is 1 and coarse fuel class is 5, the potential fire intensity class is 3. Potential intensity class 1–5 represents “very low”, “low”, “medium”, “high”, and “very high” fire intensity.

tensity class = 5) if there are suitable conifer species present (e.g., FQC = 1). However, changing from low intensity fire to crown fire is not a deterministic event and a probability function is used to predict its occurrence. For example, the probability of low intensity fire changing to a crown fire is 0.01–0.05 based on the empirical knowledge for Missouri central hardwoods (B. Cutter, Department of Forestry, University of Missouri–Columbia, personal communication). Such a probability (P) can be user defined. In the fuel module, when fire intensity reaches level 3 and there are species with FQC = 1 (can be determined by user) present, the fire intensity can reach 5 if the uniform random number > P.

3.5. Potential fire risk

Potential fire risk is determined by the potential fire intensity and fire probability. Fire probability is a numerical quantity derived from fire cycle and the time since last fire for each cell in LANDIS 3.7 (He and Mladenoff, 1999a). In the LANDIS fuel module fire probability is converted into five classes, from very low to very high, based upon the "equal area" approach (the fire probability density function is divided into five areas of equal size).

Fire risk is also classified into five classes based upon fire probability and fire intensity, from very low (class 1) to very high (class 5) (Table 3). We assume that potential fire probability and fire intensity equally contribute to the fire risk. Thus, in Table 3, five unique combinations of fire probability and potential intensity classes are identified for each fire risk class (Table 3). Again, users can define this table based upon the characteristics of their study area.

Table 3
Potential fire risk table (default)[a]

	FP class 1	FP class 2	FP class 3	FP class 4	FP class 5
FI class 1	1	1	1	1	2
FI class 2	1	2	3	3	4
FI class 3	1	3	3	4	5
FI class 4	2	3	4	5	5
FI class 5	2	4	4	5	5

[a] FP represents fire probability and FI represents potential fire intensity. The table lists all the possible combinations of potential fire intensity classes (derived from Table 2) and fire probability classes derived from the LANDIS fire module (not discussed in this paper), and defines the potential fire risk class for each combination. For example, if fire probability class is 1 and potential fire intensity class is 5, the potential fire risk class is 2. Potential fire risk class 1–5 represents "very low", "low", "medium", "high", and "very high" fire risk. Users may modify fire risk classes for other ecosystems.

3.6. Fuel management

The LANDIS fuel module simulates fuel management practices that fall into two categories: prescribed burning and physical fuel load treatments (removal and mechanical thinning). Fuel management is integrated with the LANDIS harvest module (Gustafson et al., 2000), which operates on the management area and stand maps. LANDIS fuel management has spatial, temporal, and treatment components. The spatial component uses parameters on the desired treatment size (e.g., the percent area of a management unit to be treated) and determines where such a treatment can be spatially allocated (e.g., how stands are selected for treatments). The allocation criteria can be based upon rankings of potential fire risk, where stands with highest potential fire risk are treated first, or by using random selection. The temporal component of fuel management determines what year (decade) a given treatment is performed and how often it is repeated. Single, multiple, or periodical entry years can be specified. The treatment component specifies the treatment types (e.g., prescribed burning) and treatment intensity. Since the three components are independent, combinations of the three are capable of simulating most fuel treatment practices.

3.6.1. Prescribed burning

In LANDIS, prescribed burning mainly affects fine fuel but it can also reduce coarse fuel based upon the user specification. The following examples illustrate a low intensity and a high intensity prescribed burning method. The choice of low versus high intensity prescribed burning treatments depends on the field conditions, resources, and potential fire risk (Brose and Wade, 2002). The following examples suggest that for each management unit within the simulation area, we can specify how fine fuel classes are changed to mimic the effect of the prescribed burning activity. For example, a low intensity prescribed burning might reduce the fine fuel load by a maximum of two classes. We assume that fine fuel can never be completely removed, so the resulting fine fuel class can never reach 0, as shown:

Fine fuel classes before treatment	1	2	3	4	5
Fine fuel classes after treatment	1	1	1	2	3

A high intensity prescribed burn might remove most fine fuel loads (reduced to 1):

Fine fuel classes before treatment	1	2	3	4	5
Fine fuel classes after treatment	1	1	1	1	1

These examples show that users have the flexibility to design their own fine fuel reduction scenarios by specifying how fuel classes are reduced by the prescription.

3.6.2. Physical fuel load removal

Mechanical thinning primarily targets coarse fuels, including reducing the fuel size and removing/reducing coarse fuel load. This example shows a low and a high intensity physical fuel load reduction for a management unit. The low intensity treatment reduces coarse fuel load by two classes when the coarse fuel class is >3:

Coarse fuel classes before treatment	1	2	3	4	5
Coarse fuel classes after treatment	1	2	1	2	3

The high intensity treatment removes most coarse fuels (reduced to 1). Similar to the assumption made for fine fuel, we assume that coarse fuel is never completely removed.

Coarse fuel classes before treatment	1	2	3	4	5
Coarse fuel classes after treatment	1	1	1	1	1

3.6.3. Other fuel treatments

The following example illustrates how to specify chipping and thinning of coarse fuel. In this example, treatment is prescribed only for high (4) and very high (5) coarse fuel classes, and classes 4 and 5 are reduced to class 2. Note that coarse fuel treatments can result an increase in fine fuels. In this example, all fine fuel classes are increased by one.

Coarse fuel load class before treatment	0	1	2	3	4	5
Coarse fuel load class after treatment	0	1	2	3	2	2
Fine fuel load class before treatment	0	1	2	3	4	5
Fine fuel load class after treatment	1	2	3	4	5	5

These examples show that that the design of the fuel model provides flexibility in specifying fuel treatments and allows numerous combinations of fine fuel and coarse fuel reduction practices.

4. Application

To test the design of the LANDIS Fuel module, we applied LANDIS with the new fuel module to a Central Hardwood forest in Missouri Ozarks.

4.1. Study area

Our study area includes portions of the Mark Twain National Forest in the Eleven Point and Current River watersheds in the Missouri Ozark Highlands (refer to Shang et al., 2004, for a more detailed study area description). The study area contains approximately 70,000 ha and is largely forested with white oak (*Quercus alba* L.), post oak (*Q. stellata* Wangenh.), black oak (*Q. velutina* Lam.) and scarlet oak (*Q. coccinea* Muenchh) as the dominant species. Forest age structure in this region is relatively simple due to historical cutting patterns and more than a century of human impacts. Topographic variation is high for this region, with elevations ranging from 140 to 410 m, and many slopes of 30° or greater (Bellchamber et al., 2002). The climate is continental with mean high temperatures ranging from 6 °C (January) to 32 °C (July) and lows ranging from −7 °C (January) to 18 °C (July). Mean annual precipitation is relatively high (107 cm), but many sites are dry where soils are cherty and excessively drained. These environmental variations are largely captured by ecological land types (ELT), a data layer that is available for the study area (Nigh and Schroeder, 2002). The landscape was represented by 30 m × 30 m cells raster.

4.2. Model parameterization

Detailed descriptions of model parameterization for the study area can be found elsewhere (Shifley et al., 1999, 2000; He et al., 2004; Shang et al., 2004). We evaluated a fuel treatment scenario that combines both prescribed burning and physical fuel load reduction of coarse fuels. Ten percent of the landscape where potential fire risk class was high (class 4) or very high (class 5) was treated per decade (approximating 1% of the total landscape per year). The specific treatment prescriptions and the definition of the user defined fine fuel curve, coarse fuel accumulation and decomposition are shown in Table 4. Additional fuel treatment scenarios and their effects are presented in Shang et al. (2004).

Table 4
Example of fuel model parameters defined for the southwest land type in the Missouri Ozark Highlands[a]

Fine or coarse classes	1	2	3	4	5
Fine fuel accumulation curve by species					
Maple group in year	10	20	50	110	170
Pine group in year	10	20	40	100	170
Read Oak group in year	10	30	80	160	220
White oak group in year	10	30	50	90	120
Find fuel modifiers					
Land type	+1	+1	+1	+1	0
Fine fuel load modified by fire	−2	−3	−4	−3	−3
Coarse fuel accumulation curve					
Accumulation years	20	70	120	160	200
Coarse fuel classes	1	2	3	4	5
Coarse fuel decomposition curve					
Years since last disturbance	20	70	120	160	200
Coarse fuel classes	4	3	2	1	0
Coarse fuel modifiers					
Land type	2	3	4	5	5
Fire	−1	−2	−3	−4	−4
Fuel management prescription					
Management area identifier			1		
Rank algorithm (1 = highest potential fire risk processed first)			1		
Entry decade			1		
Final decade			20		
Reentry interval			1		
Proportion of the management area to treat			0.1		
Minimum potential fire risk for management			3		
Treatment intensity					
Fuel load class before treatment	1	2	3	4	5
Fine fuel class after treatment	0	0	0	0	0
Coarse fuel class after treatment	0	1	2	1	1

[a] This table provides an example of LANDIS fuel module input data for one management area and southwestern land type. Fine fuel accumulation is globally defined. For example, according to the table, 10-year-old white oak group produces class 1 (very low) level of fine fuel, 30-year-old white oak group produces class 2 (low) level of fine fuel, 50-year-old at class 3 (medium), 90-year-old at class 4 (high), and 120-year-old and above, at class 5 (very high). Similar logic works for coarse fuel accumulation and decomposition. According to this example, it takes 20 years for class 5 coarse fuels to decompose to class 4, 70 years to class 3, 120 years to class 2, and 160 years to class 1. The land type modifier increases fine fuel by one class due to relatively low decomposition rate on this land type. Severity class 1 fire decreases fine fuel class by 2, severity two fire decreases fine fuel by 3, severity 3 × 4, severity 4 and 5 × 3 (assuming the situation of canopy fires).

Studies of fire history for the period prior to the European settlement show a very short fire cycle (<10 years) and low intensity fires (Guyette, 1995). Current fire regimes are influenced by suppression and have fire cycles varying from 300 to 415 years, with the exception of managed savannas, which have a much shorter (10 years) fire cycle (Westin, 1992; Shifley et al., 1999, 2000). We parameterized LANDIS using the current fire suppression regime.

4.3. Simulation scenarios

We demonstrated two simulation scenarios: current fire regimes (fire suppression) with and without fuel treatment. Both scenarios were simulated for 200 years. LANDIS generates output maps for every decade showing fine fuel, coarse fuel, potential fire risk, fire severity, and individual species and age classes. At each decade of a simulation, the proportions and classes of fine fuel, coarse fuel, and fire risk of each landscape

cell were recorded. To demonstrate the capability of LANDIS fuel module to track fuel and fire risk dynamics, and simulate fuel treatments, we selected the snapshot output of year 0, 50, 100, 150, and 200 from our simulations.

4.4. Results and discussion

4.4.1. Fine fuel

The average fine fuel class increased with simulation year, shifting from low to high at about year 150 as forests grew older, and then decreased to medium and high levels after many age cohorts reached their maximum longevity and were replaced by young cohorts (Fig. 5). Such a response reflects the assumptions made about fine fuel (Fig. 2), where fine fuels primarily come from foliage litter fall and small dead twigs, and they are assumed to decompose within a few years. Since the quantity of fine fuel in each cell is updated based on the live species age cohorts present at each 10-year LANDIS simulation time step, the quantity corresponds closely to the species age cohorts present. The treatment (prescribed burning) removes fine fuel within a single simulation time step. This reduces the opportunity for additional fire ignitions at that site in the same decade since fine fuels are the primary requirement for successful fire ignitions. In general, however, fine fuels are replenished rapidly relative to the 10-year LANDIS time step, and therefore, fine fuel load does not differ substantially between the two scenarios over the 200-year simulation (Fig. 5).

4.4.2. Coarse fuel

Coarse fuel varies with time of fuel accumulation (stand age) and disturbance history, which corresponds to the time since last fire in this study as windthrow, biological, and harvest disturbances were not simulated. Coarse fuel load is low at year 0 due to the relatively young initial forest ages (40–70 years) (Fig. 5). This is expected since the fuel accumulation curve is user-defined (Fig. 3). As the stands aged and accumulated fuel, the coarse fuel load gradually increased to class 3 (the medium level) by year 50, to class 4 (the high level) by year 100, and to class 5 (the very high level) on most of the landscape by year 150 (Fig. 5). In some parts of the landscape, high severity fires occurred as a result of high coarse fuel loads, especially in the scenario with no fuel treatment. These fires reduced coarse fuel at those sites and created a patchy structure with large patches of classes 1 and 2 coarse fuels (Fig. 5).

Simulation results illustrate how simulated fuel treatments reduced coarse fuel. With 10% of the landscape selected for intensive coarse fuel reduction per decade (classes 4 and 5 treated to class 1, Table 4), coarse fuel loads were maintained at low levels for most of the landscape throughout the simulation (Fig. 5). The results match our empirical knowledge about coarse fuels in this region and show that the LANDIS fuel module can track fuel dynamics and can reasonably simulate the cause–effect relationships of fuel treatments, when appropriately calibrated.

4.4.3. Fire risk and fire severity

We examined the potential fire risk and the fire severity under both simulation scenarios. The two scenarios showed distinctly different levels of fire risk on the landscape. At year 0, the landscape generally had a low to medium level fire risk (Fig. 6). It increased to medium and high fire risk on the majority of the landscape in about 50 years, and became a landscape with high to very high fire risk after year 150. In other words, fire management depending only on fire suppression without fuel reduction treatments cannot control fire risks in this central hardwood landscape under this simulation scenario. When fire suppression is coupled with a simulated fuel treatment, our results show that the landscape can be maintained at the medium fire risk level.

To examine simulated fires over time, we output the cumulative fires as a fire severity map over the 200-year simulation. Fire severity is derived based upon the interactions of species fire tolerance (a species attribute), species fire susceptibility (age), and fire intensity (fuel) (He and Mladenoff, 1999a). For cells that burned more than once, the highest fire severity was recorded (Fig. 6). Simulated fires show very different results for the two simulation scenarios. Under the fire suppression without fuel treatment scenario, much of the landscape experienced very high severity fires, and fire sizes tended to be large due to the continuity of available fuel. However, fire suppression with fuel treatment effectively reduced high severity fires on the simulated landscape. Most simulated fires following fuel treatments were of low severity and small in size.

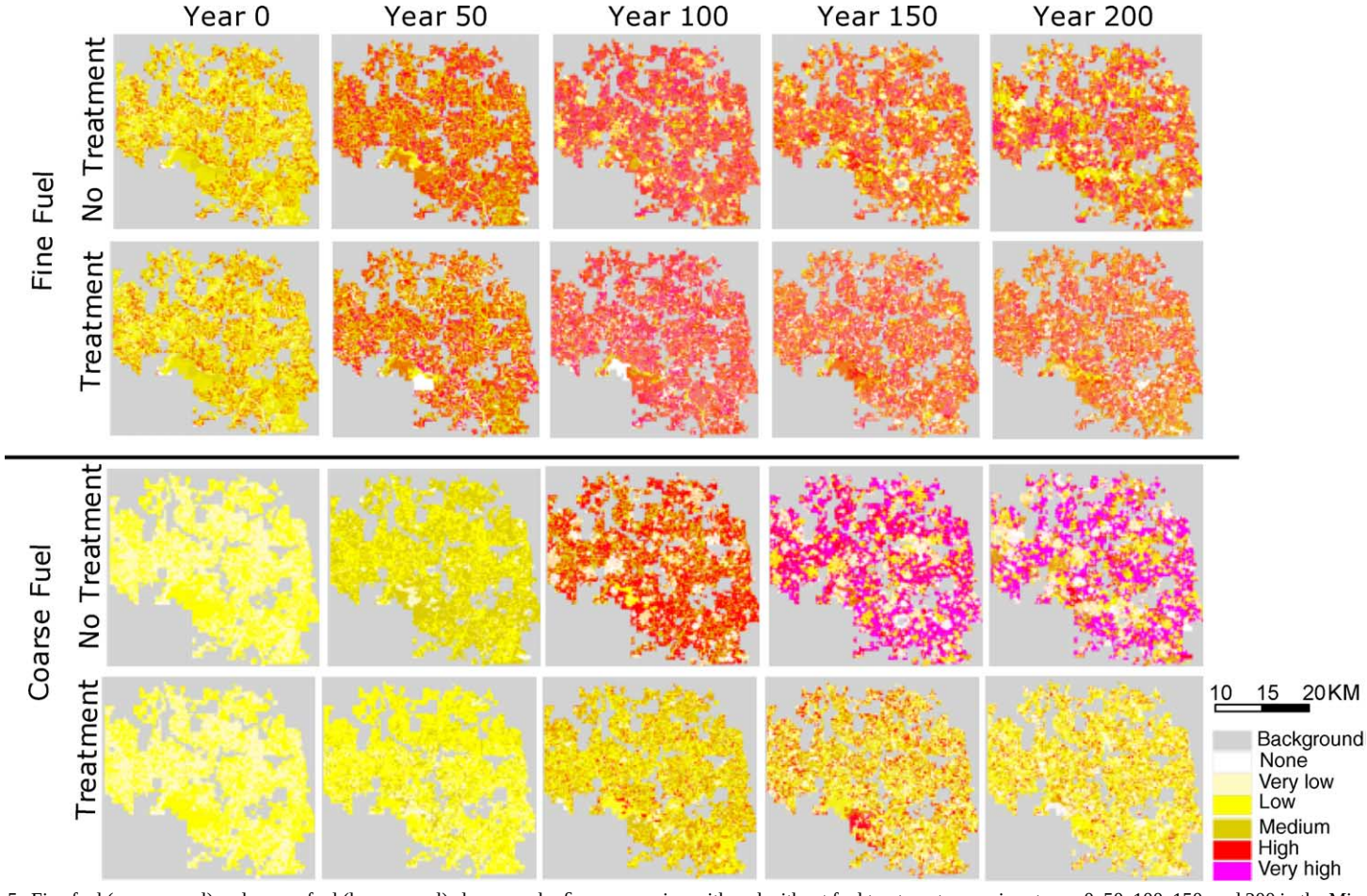

Fig. 5. Fine fuel (upper panel) and coarse fuel (lower panel) classes under fire suppression with and without fuel treatment scenarios at year 0, 50, 100, 150, and 200 in the Missouri Ozark Highlands study area.

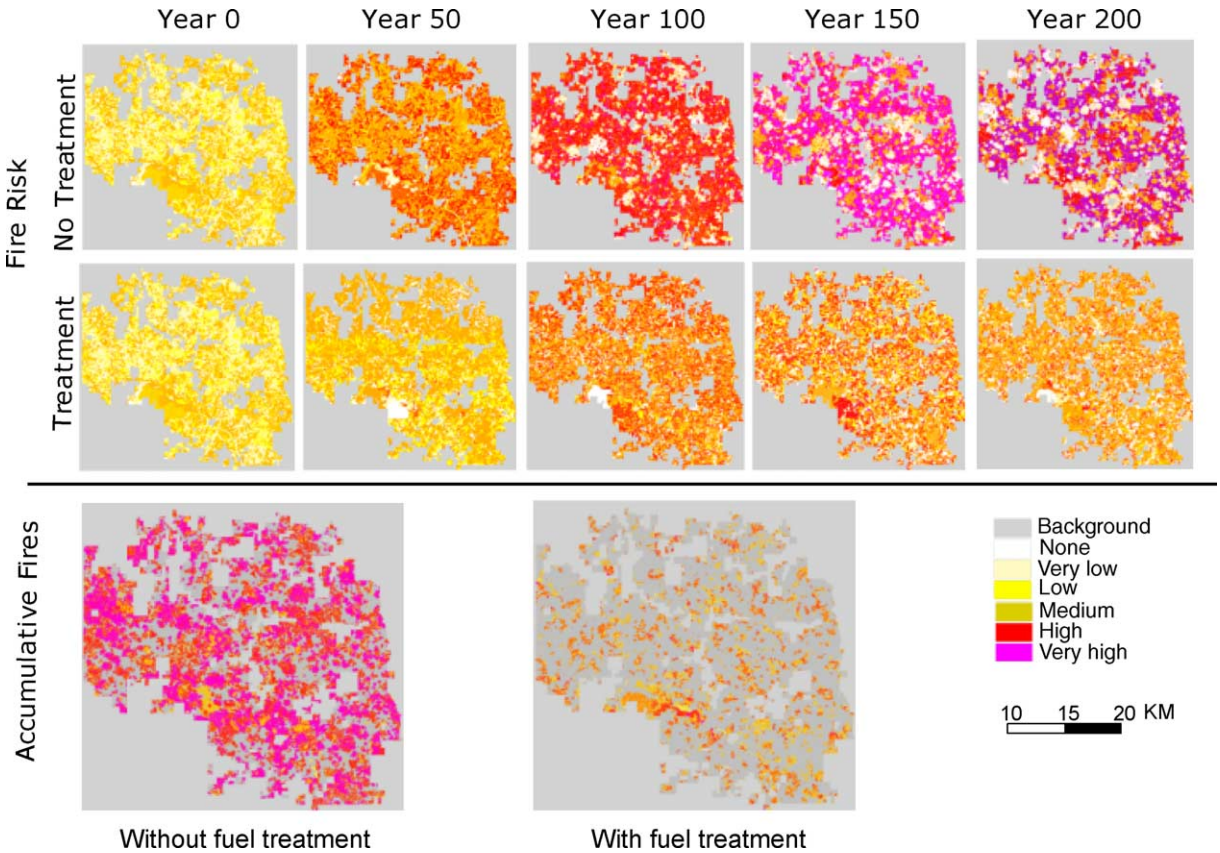

Fig. 6. The upper panel shows the simulated fire risk under two scenarios at year 0, 50, 100, 150, and 200 in the Missouri Ozark Highlands study area. The lower panel shows the accumulated fires (over 200-year simulation) mapped as fire severity for two scenarios (with and without fuel treatment).

5. Conclusions

We demonstrated the design of LANDIS fuel module and its capability of simulating fuels, fire risk dynamics, and fuel management. The design uses semi-quantitative or categorical data to represent fuels and fire risk on the landscape. Such a design fully utilizes information currently tracked in LANDIS and does not add much computational load that could limit the model from being applied to large landscapes.

No models can answer questions at all scales. Explicit and implicit assumptions made in each component limit the model to answering questions within the scales for which it was designed. The LANDIS fuel module is different from LANDSUM (Keane et al., 2002), BEHAVE (Andrews, 1986; Andrews and Chase, 1989), and the fire and fuels extension (FFE) (Beukema et al., 1999; Crookston et al., 1999) to the forest vegetation simulator (FVS). LANDIS uses a probability-based approach to simulate stochastic processes such as fire, windthrow, and seed dispersal and is not designed to predict individual events that may occur at a particular place and time. Rather, the modeling approach serves as a useful tool for examining long-term spatial dynamics and the consequences of various disturbance changes and management effects. LANDSUM also simulates fire using a probability-based approach (Keane et al., 2002), but it does not simulate fuel explicitly. Rather, it uses the time since last fire as a surrogate for fuel build-up. Vegetation dynamics are simulated at the polygon level using predefined successional pathways for all vegetation types involved. This is different from LANDIS that tracks vegetation information at species age cohort level. Both BEHAVE and FFE oper-

ate at smaller spatial scales (e.g., stands) and simulate fuel in a more mechanistic and deterministic way than LANDIS does. However, BEHAVE does not simulate the temporal dynamics of fuel.

LANDIS operates at much larger spatial and temporal scales and many mechanistic-level interactions are synthesized. For example, fine fuel in LANDIS fuel module is derived from canopy species age cohorts because species abundance is not available. Also fine fuels generated from shrubs and grasses are not explicitly tracked (although they can be indirectly simulated using a generic ground cover). Therefore, treatments based upon the exact measures of fuels in T/ha (Pyle and Brown, 1999), may not be available for the LANDIS fuel module. For coarse fuels, the LANDIS fuel module tracks fuel quantity by five abundance classes, not by specific fuel size classes. Therefore, size-class-based fuel load reduction cannot be specified.

LANDIS is designed to operate at a wide range of species and environment settings over large spatial (10^6 ha) and temporal (1000s in year) scales. It has been applied in northern hardwood forests (e.g., He and Mladenoff, 1999a; Gustafson et al., 2000), southern hardwood forests (Shifley et al., 1999, 2000; He et al., 2004); boreal forests in North America (Donald Sacks, unpublished data), Europe (Pennanen and Kuuluvainen, 2002) and China (He et al., 2002). It has also been applied in chaparrals in southern California (Franklin et al., 2001). It has proven to be useful in answering landscape-scale disturbance, harvesting, and succession questions. However, due to its current 10-year time step, LANDIS is not suitable for simulating systems with finer temporal dynamics such as <10-year fire cycles or <10-year species life cycles.

The fundamental question is whether such a fuel module design can answer questions in forest management at large spatial and temporal scales. One essential management issue is whether or not it can help in identifying the high fire risk areas and determining the optimal treatment extent and frequency combinations. Such information is necessary to allocate fire management effort over a long planning horizon and across the landscape to maximize the treatment effects. We have demonstrated that the LANDIS fuel module can be used to compare alternative management scenarios at a large spatial and temporal scale. The general assumptions in the fuel module can be modified to accommodate a wide range of ecological conditions. Furthermore, LANDIS allows studies of interacting effects of multiple factors such as the interactions among disturbance agents (fire, windthrow, BDA, and harvest) as well as the effects of species composition and spatial patterns (interior, edge, patchiness) in resisting fire spread or insect outbreaks.

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References

Agee, J., Huff, M., 1987. Fuel succession in a western hemlock/Douglas-fir forest. Can. J. For. Res. 17, 697–704.

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

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Re INT-122. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 22 pp.

Andrews, P.L., 1986. BEHAVE: fire behavior prediction and fuel modeling system-BURN subsystem. Part 1. Gen. Tech. Re INT-194. US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 130 pp.

Andrews, P.L., Chase, C.H., 1989. BEHAVE: fire behavior prediction and fuel modeling system-BURN subsystem. Part 2. Gen. Tech. Re INT-260. US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 93 pp.

Armour, C.D., Bunting, S.C., Neuenschwander, L.F., 1984. Fire intensity effects on the understory in ponderosa pine forests. J. Range Manage. 37, 44–49.

Bellchamber, S.B., He, H.S., Shifley, S.J., Thompson, F.R., Palik, B., 2002. Using GIS functionalities to generate riparian buffer zones for the interpretation of best management practices. In: Proceedings of the Missouri Natural Resources Conference, Lake of Ozarks, MO, USA.

Bergeron, C.H.Y., Flannigan, M.D., 2000. Coarse woody debris in the southeastern Canadian boreal forest: composition and load variations in relation to stand replacement. Can. J. For. Res. 30, 674–687.

Beukema, S.J., Reinhardt, E.D., Kurz, W.A., Crookston, N.L., 1999. An overview of the fire and fuels extension to the forest vegetation simulator. In: Proceedings of Joint Fire Sciences Workshop, Boise, ID, USA.

Brose, P., Wade, D., 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. For. Eco. Manage. 163, 71–84.

Brown, A.A., Davis, K.P., 1973. Forest Fire Control and Use. McGraw-Hill, New York, NY.

Brown, J.K., Oberheu, R.D., Johnston, C.M., 1982. Handbook for inventory surface fuels and biomass in the interior west. USDA Forest Service General Technical Report INT-129, pp. 1–48.

Brown, J.K., DeByle, N.V., 1989. Effects of prescribed fire on biomass and plant succession in western aspen. USDA Forest Service IRS Research Paper INT-412, pp. 1–18.

Brown, J.K., See, T.E., 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. USDA Forest Service General Technical Report INT-117, pp. 1–47.

Bugmann, H.K.M., 1996. A simplified forest model to study species composition along climate gradients. Ecology 77, 2055–2074.

Burgan, R.E., 1987. Concepts and interpreted examples in advanced fuel modeling. Gen. Tech. Re INT-238. US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 40 pp.

Crookston, N.L., Kurz, W.A., Beukema, S.J., Reinhardt, E.D., 1999. Relationships between models used to analyze fire and fuel management alternatives. In: Proceedings of Joint Fire Sciences Workshop, Boise, ID, USA.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The national fire-danger rating system. USDA Forest Service General Technical Report INT-79, pp. 1–77.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47, 219–228.

Foster, J.R., Lang, G.E., 1982. Decomposition of red spruce and balsam fir boles in the White Mountains of New Hampshire. Can. J. For. Res. 12, 617–626.

Franklin, J., Syphard, A.D., Mladenoff, D.J., He, H.S., Simons, D.K., Martin, R.P., Deutschman, D., O'Leary, J.F., 2001. Simulating the effects of different fire regimes on plant functional groups in southern California. Ecol. Model. 142, 261–283.

Gardner, R.H., Hargrove, W.W., Turner, M.G., Romme, W.H., 1996. Climate change, disturbances and landscape dynamics. In: Walker, B.H., Steffen, W.L. (Eds.), Global Change and Terrestrial Ecosystems. Cambridge University Press, Cambridge, UK, pp. 149–172.

Gore, J.A., Patterson III, W.A., 1986. Mass of downed wood in northern hardwood forest in New Hampshire: potential effects of forest management. Can. J. For. Res. 16, 335–339.

Grier, C.C., Logan, R.S., 1977. Old-growth *Pseudostuga menziesii* communities of a western Oregon watershed: biomass distribution and production budgets. Ecol. Monogr. 47, 373–400.

Grimm, V., 1999. Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future? Ecol. Model. 115, 129–148.

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

Gustafson, E.J., Zollner, P.A., Sturtevant, B.R., He, H.S., Mladenoff, D.J., 2004. Influence of forest management alternatives and land type on susceptibility to fire in northern Wisconsin, USA. Landsc. Ecol. 19, 327–341.

Guyette, R.P., 1995. A tree-ring history of wildland fire in the Current River Watershed. Missouri Department of Conservation, Columbia, MO, USA.

Hale, C.M., Pastor, J., 1998. Nitrogen content, decay rates and decompositional dynamics of hollow versus solid hardwood logs in hardwood forests of Minnesota, USA. Can. J. For. Res. 28, 1276–1285.

Hargrove, W.W., Gardner, R.H., Turner, M.G., Romme, W.H., Despain, D.G., 2000. Simulating fire patterns in heterogeneous landscapes. Ecol. Model. 135, 243–263.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Solkins, P.J., Gregory, S.V., Lattin, J.P., Andersen, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Gromack Jr., K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.

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

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

He, H.S., Mladenoff, D.J., 1999b. The effects of seed dispersal on the simulation of long-term forest landscape change. Ecosystems 2, 308–319.

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

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

He, H.S., Mladenoff, D.J., Gustafson, E.J., Nimefro, K.K., 2003. LANDIS 3.7 User's Guide. School of Natural Resource, The University of Missouri–Columbia, Columbia, MO, USA, 66 pp.

He, H.S., Shifley, S.R., Dijak, W., Gustafson, E.J., 2004. Spatial simulation of forest fire and timber harvesting in Missouri Ozarks Highlands. In: Perera, A.H., Buse, L.J., Weber, M.G (Eds.), Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, New York, NY, USA.

Kauffman, J.B., Uhl, C., Cummings, D.L., 1988. Fire in the Venezuelan Amazon. 1. Fuel biomass and tree chemistry in the evergreen rainforest of Venezuela. Oikos 53, 167–175.

Keane, R.E., Morgan, P., Running, S.W., 1996. Fire-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. Research Paper INT-RP-484. USDA Forest Service, Intermountain Forest and Range Experiment Station.

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

Lambert, R.L., Lang, G.E., Reiners, W.A., 1980. Loss of mass and chemical change in decaying boles of a subalpine balsam fir forest. Ecology 61, 1460–1473.

Lang, C.E., Forman, R.T.T., 1978. Detritus dynamics in a mature oak forest: Hutcheson Memorial Forest, New Jersey. Ecology 57, 580–595.

Lang, G.E., 1985. Forest turnover and the dynamics of bole wood litter in subalpine balsam fir forest. Can. J. For. Res. 15, 262–268.

MacMillan, P.C., 1988. Decomposition of coarse woody debris in an old-growth Indiana forest. Can. J. For. Res. 18, 1353–1362.

Miller, C., Urban, D.L., 1999. Interactions between forest heterogeneity and surface fire regimes in the southern Sierra Nevada. Can. J. For. Res. 29, 202–212.

Mladenoff, D.J., Host, G.E., Boeder, J., 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 Issues. GIS World, pp. 175–180.

Mladenoff, D.J., He, H.S., 1999. Design and behavior of LANDIS, an object-oriented model of forest landscape disturbance and succession. In: Mladenoff, D.J., Baker, W.L. (Eds.), Advances in spatial modeling of forest landscape change: approaches and applications. Cambridge University Press, Cambridge, UK, pp. 125–162.

Nigh, T., Schroeder, W., 2002. Atlas of Missouri ecoregions. Department of Conservation, Jefferson City, MO, USA.

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

Pyle, C., Brown, M.M., 1999. Heterogeneity of wood decay classes within hardwood logs. For. Eco. Manage. 114, 253–259.

Shang, B.Z., He, H.S., Crow, T.R., Shifley, S.R., 2004. The effects of various fuel load reductions on potential fire risk—a spatial simulation study. Ecol. Model. 180, 89–102.

Shifley, S.R., Thompson III, F.R., Dijak, W.D., Larsen, D.R., 1999. Modeling landscape changes in the Missouri Ozarks in response to alternative management practices. In: Stringer, J.W., Loftis, D.L. (Eds.), Proceedings of the 12th Central Hardwood Forest Conference. 28 February, 1–2 March 1999, Lexington, KY, General Technical Report SRS-24. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp. 267–268.

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

Spetich, M.A., Shifley, S.R., Parker, G.R., 1999. Regional distribution and dynamics of coarse woody debris in midwestern old-growth forests. For. Sci. 45, 302–313.

Spies, T.A., Franklin, J.F., Thomas, T.B., 1988. coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69, 1698–1702.

Stage, A.R., 2003. How forest models are connected to reality: evaluation criteria for their use in decision support. Can. J. For. Res. 33, 410–421.

Sturtevant, B.R., Bissonette, J.A., Long, J.N., Roberts, D.W., 1997. Coarse woody debris as a function of age, stand structure, and disturbance in boreal Newfoundland. Ecol. Appl. 7, 702–712.

Sturtevant, B.R., Gustafson, E.J., Li, W., He, H.S., 2004. Spatio-temporal patterns of tree mortality caused by insects and disease: incorporating biological disturbances into the LANDIS framework. Ecol. Model. 180, 153–174.

Trofymow, J.A., Moore, T.R., Titus, B., Prescott, C., Morrison, I., Siltanen, M., Smith, S., Fyles, J., Wein, R., Camire, C., Duschene, L., Kozak, L., Kranabetter, M., Visser, S., 2002. Rates of litter decomposition over 6 years in Canadian forest: influence of litter quality and climate. Can. J. For. Res. 32, 789–804.

Westin, S., 1992. Wildfire in Missouri. Missouri Department of Conservation, Columbia, MO, USA.

Yang, J., He, H.S., Gustafson, E.J., 2004. A hierarchical statistical approach to simulate the temporal patterns of forest fire disturbance in LANDIS model. Ecol. Model. 180, 119–133.

Yemshanov, D., Perera, A., 2002. A spatially explicit stochastic model to simulate boreal forest cover transitions: general structure and properties. Ecol. Model. 150, 189–209.

Zollner, P.A., Gustafson, E.J., He, H.S., Radeloff, V.C., Mladenoff, D.J., in press. Modeling the influence of dynamic zoning of forest management on ecological succession. Environ. Manage.