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Ecological Modelling 179 (2004) 3–27

ECOLOGICAL MODELLING

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A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics☆

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Received 25 April 2003; received in revised form 17 February 2004; accepted 2 March 2004

Abstract

A classification of spatial simulation models of fire and vegetation dynamics (landscape fire succession models or LFSMs) is presented. The classification was developed to provide a foundation for comparing models and to help identify the appropriate fire and vegetation processes and their simulation to include in coarse scale dynamic global vegetation models. Other uses include a decision tool for research and management applications and a vehicle to interpret differences between LFSMs. The classification is based on the four primary processes that influence fire and vegetation dynamics: fire ignition, fire spread, fire effects, and vegetation succession. Forty-four LFSMs that explicitly simulated the four processes were rated by the authors and the modelers on a scale from 0 to 10 for their inherent degree of stochasticity, complexity, and mechanism for each of the four processes. These ratings were then used to group LFSMs into similar classes using common ordination and clustering techniques. Another database was created to describe each LFSM using selected keywords for over 20 explanatory categories. This database and the ordination and clustering results were then used to create the final LFSM classification that contains 12 classes and a corresponding key. The database and analysis results were used to construct a second classification key so managers can pick the most appropriate model for their application based on computer resources, available modeling expertise, and management objective.
Published by Elsevier B.V.

Keywords: Spatial simulation models; Fire regime; Model evaluation; Ordination; Model selection

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0304-3800/$ – see front matter Published by Elsevier B.V.
doi:10.1016/j.ecolmodel.2004.03.015

1. Introduction

One of the most difficult challenges in predicting large-scale ecological change is the inclusion of non-equilibrium dynamics, disturbance regimes, extreme events, and spatial relationships into ecological simulation models (Solomon, 1986; Dale and Rauscher, 1994; Gardner et al., 1996; Fosberg et al., 1999). Theoretical community models and patch-scale vegetation models have become increasingly successful at dealing with this, but many models of climatic effects on vegetation change have inherent limitations that may reduce their utility for exploring disturbance–climate–vegetation interactions. Some treat vegetation composition and structure as a constant and only simulate climatic effects on biogeochemistry and ecophysiology (Running and Nemani, 1991; Neilson and Running, 1996; Waring and Running, 1998). Others have assumed that vegetation would change instantaneously in response to changing climate (equilibrium biogeographic models, e.g., Prentice et al., 1993). In addition, some models have assumed that natural and human-caused disturbance regimes are only a minor driver of vegetation change (see Dale and Rauscher, 1994). The inclusion of disturbance and other extreme events in coarse scale dynamic models is still in its infancy (Lenihan et al., 1998; Thonicke et al., 2001), and only a few models have explicitly incorporated spatial relationships into ecological processes (see Botkin and Schenk, 1996; Keane and Finney, 2003). It is now recognized that, to function as a comprehensive exploratory tool, vegetation models should simulate transient changes in vegetation in response to climate, disturbance and environmental change in a spatial domain (Foley et al., 1998; Gardner et al., 1996; Hurtt et al., 1998).

Wildland fire, in particular, is a disturbance that is sensitive to vegetation composition and structure, climatic conditions, and other spatially-dependent variables (Clark, 1993; Swetnam and Baisan, 1996; Swetnam, 1997). In addition, the fire regime has a major effect on the rate of vegetation change, the successional sequence of community types following fires, and the carbon budget (Lenihan et al., 1998; Ryan, 1991, Starfield and Chapin, 1996). Modification of the fire regime due to climate warming (e.g., Cary and Banks, 1999) may overwhelm other ecosystem responses to climate change, including species migration, substitution, and extinction (Weber and Flannigan, 1997), or altered ecosystem processes (Ryan, 1991; Keane et al., 1995). Because successional changes of vegetation are dependent on the pattern, severity, and timing (e.g., season) of fire (Agee, 1993; DeBano et al., 1998), large nonlinear changes in vegetation are likely to occur in response to climatic and land use change (Flannigan and Van Wagner, 1991; Crutzen and Goldammer, 1993).

One of the most effective tools for studying the relationships between fire, climate, and vegetation is simulation modeling. Although empirical studies are immensely valuable, they are expensive and time-consuming, making them of limited use for characterizing ecosystem change over the large areas and long time spans needed for exploring climate change. The success of simulation models for studying these effects has been evident by the large number of models and model types that have been produced (see Baker, 1989; Mladenoff and Baker, 1999; Keane and Finney, 2003, for a general overview). A special class of these models, termed landscape fire succession models (LFSMs) in this paper, have been applied to a spectrum of problems based on a variety of conceptual approaches and a wide range of solution techniques. LFSMs are spatial models that simulate the dynamic interaction of fire, vegetation, and often climate. The diversity of these models has created its own problems, including the difficulty of comparing results among different ecosystem types and disturbance regimes, and the selection of the most appropriate model to use in a new geographical area or landscape setting. The diversity of model types and applications also makes it difficult to decide which landscape and ecosystem processes, and the level of detail used to represent them, are most critical for understanding fire effects.

We found more than 40 fire-vegetation coupled models that cover a wide range of ecosystems, geographic areas, and spatial scales. We believe a critical comparison of features in these LFSMs will lead to a better understanding of fire–climate–vegetation linkages and support the development of new model hybrids by identifying the importance of simulation components that are common across models. The comparison would also provide important insight into the tradeoffs inherent in implementing unique approaches into an optimal modeling design for coarse-scale applications, such as dynamic global vegetation models (DGVMs) (Lenihan et al., 1998). This comparison is possible only if the models are evaluated in a consistent and standardized context that emphasizes the relative differences between modeling approaches and design rather than the accuracy of their predictions (Barrett, 2001). To accomplish this, a Landscape Fire Working Group was formed under the aegis of the Global Change and Terrestrial Ecosystems Project (GCTE—Task 2.2.2; GCTE is a Core Project of the International Geosphere-Biosphere Programme, IGBP). The objective of this working group is to use the current, well-developed understanding of fire behavior, fire ecology, and weather to evaluate a set of dynamic fire–climate–vegetation models that simulate fire effects at multiple temporal and spatial scales relevant to vegetation and climate change. The first step toward this end was to develop a model classification that would guide future comparison analyses and model development efforts. Instead of comparing all LFSMs, the GCTE working group compared representative models from categories in the classification. This classification is the subject of this paper. The companion LFSM comparison effort evaluates behavior of five selected LFSMs on neutral landscapes in a simulation experiment where terrain, fuel pattern, and climate are treated as factors (Cary et al., in press). The comparison study will identify the optimal level of detail to simulate fire, vegetation, and climate dynamics at various time and space scales.

Presented here is a classification of 44 LFSMs based on the inherent complexity, mechanism, and stochasticity in their simulation design (see Table 1). This classification can be used for many purposes. It provides the foundation for coordinated LFSM comparisons such as the companion study mentioned above (Cary et al., in press). The classification also provides the context for an evaluation of models and model components for various objectives and it allows managers and researchers to select, compare, and interpret LFSMs in a standardized context. The inclusion of fire in broad-scale vegetation modeling for investigating climate change is specifically addressed in this paper.

2. Background

We define LFSMs as models that simulate the linked processes of fire and succession in a spatial domain. Although the complexity of spatial relationships of vegetation and fire dynamics may vary from model to model, all LFSMs, by definition, produce time-dependent, georeferenced results in the form of digital maps or GIS layers. Additional processes can be incorporated into the LFSM simulation, such as timber harvesting and biogeochemical modeling (explicit simulation of the flow of energy, carbon, water, and other elements within an ecosystem or landscape), but one of the minimum requirements for a LFSM is the explicit linkage between fire and succession. Climatic processes need not be explicitly incorporated into the LFSM, but, because of our interests in climate change, special attention was given to those models that consider the direct effect of weather on fire occurrence and vegetation change.

Several existing LFSMs provide examples of the diverse and complex approaches used to simulate landscape, climate, and fire dynamics (see Table 1). Baker (1989) examined several models of landscape change and groups them into whole, distributional, and spatial landscape models depending on the level of aggregation of simulated entities. Details and general comparisons of other landscape models are presented in McCarthy and Gill (1997), Mladenoff and Baker (1999), Barrett (2001), and McCarthy and Cary (2002). However, to fully understand LFSMs, it is helpful to review some general approaches used in the individual models. At the complex end of the model spectrum, Fire-BGC integrates the FOREST-BGC biogeochemical model (Running and Coughlan, 1988; Running and Gower, 1991) with the FIRESUM gap model, an individual tree model, (Keane et al., 1989) to simulate climate–fire–vegetation dynamics (Keane et al., 1996b). The LANDIS model was used to evaluate fire, windthrow, and harvest disturbance regimes on landscape pattern and structure (Mladenoff et al., 1996; He and Mladenoff, 1999; Mladenoff and He, 1999). Fire is indirectly simulated at the stand-level by quantifying fire effects based on age class structure, and succession is simulated as a competitive process driven by species life history parameters. Roberts and Betz (1999) used life history parameters or vital attributes (Noble and Slatyer, 1977) to drive succession in their model LANDSIM that simulates fire effects at the polygon or stand level without a fire spread model. The DISPATCH model of Baker (1992, 1993, 1999) stochastically simulates fire occurrence and

Table 1
List of LFSMs included in this study with a general description of its application

Model name	Reference(s)	Ecosystem	Geographic area	Scale
ALFRESCO	Rupp et al. (2000)	Spruce-fir	Alaska, USA	Coarse
ANTON*	Antonovski et al. (1992)	Boreal Forest	Siberia	Fine
BANKSIA*	Groeneveld et al. (2002)	*Banksia* shrublands	Western	Fine
BFOLDS	Perera et al. (2002)	Mixed boreal	Ontario, CA	Mid
Biome-BGC	Thornton (1998), Thornton et al. (2002)	Any	Global	Coarse
CAFÉ	Bradstock et al. (1998)	Eucalypts	Southern Australia	Fine
CENTURY*	Peng and Apps (1999)	Boreal Forest	Alberta, CA	Coarse
DISPATCH	Baker et al. (1991), Baker (1995, 1999)	Spruce-fir	Central Rockies, USA	Fine
DRYADES	Mailly et al. (2000)	Conifer Forest	Northwestern USA	Fine
EMBYR	Gardner et al. (1996), Hargrove et al. (2000)	Lodgepole pine forests	Central Rockies USA	Fine
FETM	CH2MHill (1998), Schaaf and Carlton (1998)	Conifer Forests	Western USA	Fine
FIN-LANDIS	Pennanen and Kuuluvainen (2002)	Boreal Forests	Fenno-scandinavia	Fine
FIRE-BGC	Keane et al. (1996)	Conifer Forests	Northern Rockies USA	Fine
FIREPAT	Keane and Long (1997)	Any	Western USA	Coarse
FIRESCAPE	Cary (1997, 1998)	Eucalypts Forest	Southeastern Australia	Fine
FLAP-X	Boychuk and Perera (1997), Boychuk et al. (1997)	Boreal Forests	Canada	Fine
FVS-FFE	Reinhardt and Crookston (in press)	Conifer Forests	Western USA	Fine
GLOB-FIR	Thonicke et al. (2001)	Any	Global	Coarse
INTELAND	Gauthier et al. (1994)	Boreal Forests	Canada	Fine
LADS	Wimberly et al. (2000), Wimberly (2002)	Coastal Forests	Pacific Northwest USA	Mid
LAMOS	Lavorel et al. (2000)	Any	Australia	Fine
LANDIS	Mladenoff et al. (1996), He and Mladenoff (1999)	Broadleaf and Conifer	Mid-western USA	Fine-Mid
LANDSIM	Roberts and Betz (1999)	Conifer Forests	Southwestern USA	Fine
LANDSUM	Keane et al. (1997), Keane et al. (2002)	Any	Northern Rockies USA	Fine
MAQUIS*	Perry and Enright (2002)	Maquis Forests	New Caledonia	Fine
MC-FIRE	Lenihan et al. (1998)	Many	Global	Coarse
MOSAIC	Green (1989)	Forests	Australia	Fine
ON-FIRE	Li (1997)	Boreal Forests	Canada	Fine
QLAND	Pennanen et al. (2001)	Boreal Forests	Quebec, Canada	Fine
QTIP*	Plant et al. (1999)	Hardwood and Rangelands	Sierra Nevada, USA	Fine
RATZ*	Ratz (1995)	Any	Alberta, Canada	Fine
REFIRES	Burrows (1988)	Any	Western USA	Fine
REG-FIRM	Venevsky et al. (in press)	Any	Iberia, Europe	Mid
RMLANDS	McGarigal et al. (2003)	Lodgepole Forests	Central Rockies USA	Fine
SAFE-FORESTS	Sessions et al. (1997, 1999)	Mixed Conifer	Sierra Nevada, USA	Fine
SELES	Fall and Fall (1996)	Any	Canada	Fine
SEM-LAND	Li (2000, 2001)	Spruce-fir Forests	Canada	Fine
SIERRA	Mouillot et al. (2001, 2002)	Mediterranean Forests	Southern Europe	Fine
SIMPPLLE	Chew (1997), Chew et al. (in press)	Any	Northern Rockies, USA	Fine
SUFF1*	Suffling (1995)	Boreal Forests	Ontario, Canada	Fine
SUFF2*	Suffling (1993)	Subalpine Forests	Alberta, Canada	Fine
TELSA	Klenner et al. (2000), Kurz et al. (2000)	Any	Western Canada and USA	Fine
VASL	Noble and Gitay (1996)	Forests and Shrublands	Southern Australia	Fine
ZELIG-B*	Cumming et al. (1994), Cumming et al. (1995)	Mixed Boreal Forests	Alberta, Canada	Fine
ZELIG-L*	Miller (1994), Miller and Urban (1999)	Mixed Conifer Forests	Sierra Nevada, USA	Fine

Models without published names were given labels specifically for this study (identified by the asterisk).

spread based on dynamically simulated weather, fuel loadings and topographic setting, with subsequent forest succession simulated as a change in cover type and stand age. Miller and Urban (1999) implemented a spatial application of fire in the Zelig gap model to assess the interaction of fire, climate, and pattern in Sierra Nevada forests. More simplistic approaches include the SIMPPLLE model (Chew, 1997; Chew et al., in press) that uses a multiple pathway approach (linked sequences or pathways of succession community types) to simulate succession on landscape polygons and a stochastic approach to simulate fire occurrence. This same theme can be found in models by Schaaf and Carlton (1998), Kurz et al. (2000), and Keane et al. (2002).

A series of six GCTE sponsored workshops attended by a wide variety of international ecological modelers and ecologists was held from 1999 to 2003 to synthesize current landscape fire modeling into an organized framework (see Hawkes and Flannigan, 2000, www.nceas.org). One product of these workshops was an objective, quantitative protocol for comparing LFSM simulations for a series of landscapes and climates to determine the relative sensitivity of predictions to model structure and complexity (Cary et al., in press). A standardized set of model descriptive elements (MDE) was also developed to qualitatively contrast and compare LFSMs (Rupp et al., 2001). Information included in the MDE data base included initial purpose of the model, the ecosystem type being simulated, nature of the vegetation being represented and the method of succession, climate variables and drivers, the temporal and spatial scales of predictions, and computing constraints (see Table 2 for all MDEs).

Using the MDE information, we identified four essential components in LFSMs that represent the primary processes governing the simulation of landscape succession and fire: (1) vegetation succession, (2) fire ignition, (3) fire spread, and (4) fire effects. All LFSMs must contain all of these components. We assumed any other ecosystem and landscape process simulated by an LFSM, such as harvesting and insect epidemics, could be added as another component or incorporated into one or more of these four primary components. For example, fuel accumulation would be considered part of the vegetation succession component. We debated whether fire extinguishment (i.e., when a spreading fire actually goes out) was another component, but decided it should be part of the spread component (i.e., extinguishment is the lack of spread) for simplicity.

Each LFSM component can be described by the approach, scale, and strategy (Reinhardt et al., 2001; Keane and Finney, 2003; Keane et al., 2004). The approach defines the general design of the model as probabilistic (based on stochastic processes), empirical (based on relationships described by data), or physical (based on fundamental physical processes). Spatial scales are either regional (1000's of km^2), landscape (10's of km^2), forest stand (<1 ha), or at the level of the individual plant (~m^2). The strategy describes the algorithms, tools, or techniques used to represent a simulation component. Many LFSM components were developed by merging two or more approaches, scales, and strategies. The following discussion of components by strategy provides the background for interpreting the LFSM classification.

2.1. The succession component

The succession component simulates the response of vegetation or ecosystem to various environmental stimuli that either implicitly or explicitly include climate, available water and nutrients, and growing space. Plants respond to both biotic and abiotic changes as the result of fire (DeBano et al., 1998). Succession is an important component of LFSMs for several reasons. First, the structural and functional development of vegetation over time determines important fuel characteristics including biomass, bulk density, size distribution, chemistry, and continuity. Second, vegetation development affects both microclimate and soil physical properties, which in turn influence live and dead fuel moisture dynamics and subsequent fire behavior. The response of vegetation to the postfire environmental gradient determines future successional pathways, which may or may not be different from successional dynamics of the previous fire interval.

We found a wide diversity in strategies for modeling succession. In some LFSMs, succession was represented as the changes in loadings of the fine fuels (Cary, 1997) or simply as an age since last disturbance (Li et al., 1997), while other LFSMs simulated individual plants, diameter or age cohorts (Coffin and Lauenroth, 1990; Miller, 1994; Mladenoff et al., 1996;

Table 2
Items contained in the Model ID card for describing rather than classifying landscape fire succession models

Component	Categories	Keywords
General	Scale	Fine-landscapes with <50 m pixel Mid-large areas with <500 m pixel Coarse-regions with >500 m pixel
	Application	Management, development, research
	Timestep	Day, week, month, year, decade
	Climate, weather	None-no climate included Daily, weekly, monthly, yearly
	Parameterization	Easy, moderate, difficult
	Initialization	Easy, moderate, difficult
	Parent model	Name of original model
	Portability	Low, moderate, high
	Adaptability	Low, moderate, high
Succession	Vegetation representation	Biomes, successional stage, age, carbon pools, cover type, plant functional types, diameter cohorts, fuels, species, individual plants
	Simulation scale	Plants, stand, pixel, polygon, region
	Seed dispersal	None, simple, complex, spatial
	Succession driver	Age, climate, site
	Strategy	Pathway, increment, transition, ecosystem, gap, vital attributes, growth and yield
	Approach	Probabilistic, empirical, physical
Fire ignition	Driver	Biome, weather, age, years since last fire, topography, wind, succession stage, cover type, fuel, random
	Strategy	Probability functions, rule-based, mechanistic
	Approach	Random, probabilistic, empirical, physical
Fire spread	Driver	None, fuel, weather, topography, wind, succession stage, cover type,
	Strategy	Vector, shape, lattice
	Approach	Probabilistic, empirical, physical
Fire effects	Driver	None, fire presence, fire behavior, fire severity
	Strategy	Rule-based, empirical, physical
	Approach	Probabilistic, empirical, physical

These keywords represent criteria in the model key for managers in Table 3. All data are posted on www.frames.gov for reference.

Perry and Enright, 2002). We identified four broad strategies used to simulate succession where all approaches are implemented at all scales: (1) frame, (2) ecosystem process, (3) plant functional type, and (4) individual plant. Although these strategies are tied to scale in terms of their level of detail, they do not represent a specific spatial resolution or approach. In fact, an individual strategy can be implemented at several spatial scales, and different approaches can be implemented at the same scales.

Many land management LFSMs are commonly built using the frame strategy because they are easy to develop, initialize and parameterize. Frame models, also called state-and-transition models or pathway models, represent succession at the stand level by linking vegetation community types, sometimes named for cover types and structural stages, along pathways of development ultimately ending in a climax or stable community type (see example in Fig. 1). Each stage in the pathway represents a frame. Frame models can be developed using an empirical approach where the transition from one state to another is deterministic (Chew, 1997) or using a probabilistic approach where transitions are stochastic, such as Markov process (Acevedo, 1981). The timing and direction of the transitions are often quantified from extensive field and simulation data. Examples of a single pathway frame-based deterministic model are EMBYR (Gardner et al., 1996, Hargrove et al., 2000) and LADS (Wimberly et al., 2000), and examples of a multiple pathway deterministic models are LANDSUM (Keane et al., 2002) and SIMPPLLE (Chew et al., in press).

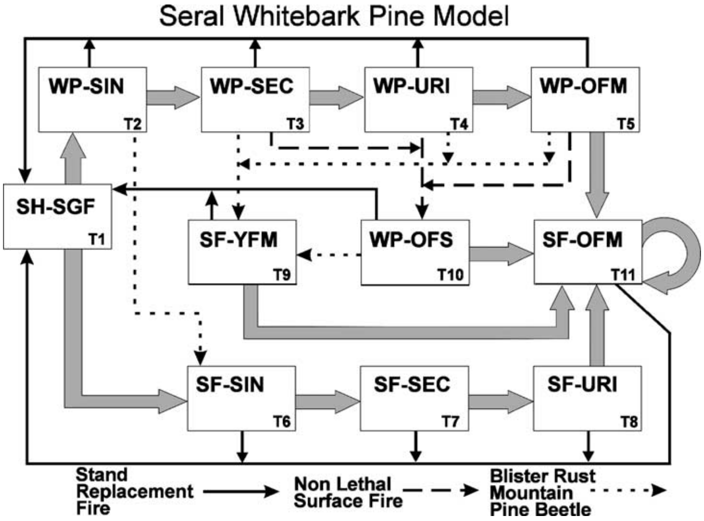

Fig. 1. An example of a frame based approach using pathway modeling for simulating the succession component in a LFSM. Species cover types are WP for whitebark pine, SH for shrub-herb, and SF for subalpine fir. Structural stages are SGF-shrub/grass/forb, SIN-stand initiation, SEC-stem exclusion closed, SEO-stem exclusion open, URI-understory reinitiation, OFM-old forest multistrata, OFS-old forest single strata. Taken from Keane (2001).

The ecosystem process strategy represents successional development by simulating one or more ecosystem processes using a variety of approaches mostly at the stand scale. An ecosystem process can be as simple as deterministically incrementing stand age (Boychuk et al., 1997) or as complex as computing photosynthesis and evapotranspiration using biogeochemical simulations (Lenihan et al., 1998). These processes can be simulated stochastically using probability distributions; modeled empirically using regression equations derived from field data; or computed using biophysical relationships parameterized empirically. Examples of complex ecosystem process LFSMs are the physical models BGC (Thornton et al., 2002) and CENTURY (Peng and Apps, 1999). Cary (1998) simulates succession more simply using only fuel accumulation in FIRESCAPE.

Plant functional type strategies are used when differences in species or species group development over time is critical in simulating succession. Plant functional types are species guilds based on morphological, ecophysiological, taxonomic, or disturbance-response criteria for a specific purpose (Diaz and Cabido, 1997; Bradstock et al., 1998). Vital attributes are often used to create plant functional types in some models (Noble and Slatyer, 1977). Plant functional type succession models have an implicit species-level scale, but mostly are stand models. Examples include the empirical vital attributes models VASL (Noble and Gitay, 1996), CAFÉ (Bradstock et al., 1998) and LANDSIM (Roberts and Betz, 1999).

The most detailed succession components are those that simulate successional development from individual plant dynamics (individual plant). These models explicitly simulate the life cycle (regeneration, growth, reproduction, and mortality) of individual plants within a homogeneous simulation area. An individual plant succession strategy usually allows other important ecosystem characteristics that influence fire and climate, such as fuels (i.e., biomass accumulation and decomposition), available moisture (i.e., evapotranspiration, interception), and nutrient cycling. The most common class of individual plant succession models are gap-phase models built primarily to simulate stand development from individual trees or diameter cohorts based on canopy gap dynamics (Shugart and West, 1980, Botkin, 1993). LFSMs using gap-phase simulation strategies include ZELIG-SP (Miller and Urban, 1999), DRYADES (Mailly et al., 2000), and Fire-BGC (Keane et al., 1996b). Another class of succession models includes those individual tree empirical models developed for forestry growth and yield predictions, such as FFE-FVS (Reinhardt and Crookston, 2003). Most individual plant succession modules were developed for forested ecosystems (Table 1), but there a few have been implemented for grasslands and shrublands (Coffin and Lauenroth, 1990). And, some gap models simulate physical ecophysiological processes, such as photosynthesis, to model tree dynamics (Bonan and Korzuhin, 1989, Leemans and Prentice, 1989).

2.2. The fire ignition component

The ignition component of LFSMs simulates the initiation of a fire event defined as a fire start that consumes some at least one cell or pixel on the simulation landscape. Fire spread is initiated once the fire ignition is simulated. There may or may not be a spotting mechanism (i.e., the starting of a new fire from firebrands produced by the fire in question), but in this classification, spotting is considered part of the spread process of the original fire and not a new fire event. Fire ignition has a spatial and temporal element because the time and location of a fire start must be simulated, and this simulation is dependent on many vegetation, environmental, and climatic characteristics that interact across multiple time and space scales. For example, fire ignition from lightning strikes is dependent on thunderstorm tracking, topographic complexity, presence and absence of lightning attractors (i.e., live and dead trees), and fuel moisture at the strike location. This inherent complexity is extremely difficult to simulate and has caused most modelers to take a stochastic strategy. However, we have also identified a physical approach where ignition is simulated using explicit representation of the dependent physical processes across relevant time and space scales. Both strategies (stochastic and mechanistic) can be developed using probabilistic, empirical, and physical approaches.

The stochastic strategy simulates ignition randomly or from probability functions of fire starts using vegetation characteristics, climatic indicators, and/or topographical settings as independent variables. The most common stochastic fire ignition component uses an empirical approach where probability distribution functions (e.g., Weibull, Pareto) are parameterized from fire history, atlas, or occurrence data, and most use stand age as the independent variable (Johnson and Gutsell, 1994; Gutsell and Johnson, 1996). Some LFSMs using this strategy include SEM-LAND (Li, 2000), SELES fire implementation (Fall and Fall, 1996), and SAFE-FORESTS (Sessions et al., 1999).

The mechanistic strategy simulates ignition by simulating the important biophysical processes that govern fire starts such as lightning dynamics, fuel moisture and accumulation. This complex approach represents a significant challenge to the modeler and has yet to be fully integrated into an LFSM. An empirical approach to the mechanistic strategy utilizes complex statistical relationships to represent the influence of biophysical variables on fire initiation, such as weather, topography, fuel moisture, and vegetation characteristics. The physical approach attempts to explicitly simulate the physical processes that govern fire initiation using driving variables including weather, fuel moisture, and lightning events. This is an extremely difficult challenge that is filled with scale, data, and knowledge limitations. We know of no LFSM that simulates fire ignition using this approach.

2.3. The fire spread component

The spread component simulates the growth of fire across a landscape. It is important because it is responsible for the footprint of fire on the landscape and provides direct spatial linkage to the postfire vegetation dynamics, which in turn feeds back to the fire ignition and spread components. Several strategies have been used to simulate the growth of fire, but none appear to be superior in all aspects (see Andrews, 1989). Accurate fire spread algorithms are often so complex that they require prohibitively large computer and input data resources for century-long, regional simulations. In contrast, the simplest approaches can produce unrealistic fire perimeters and inconsistent fire effects. We identified three major strategies for simulating fire spread: (1) shape, (2) lattice, and (3) vector strategies.

The shape strategy simulates the growth of fire by a “cookie cutter” approach where all lands within a predetermined fire perimeter (often a truncated ellipse of varied size) are burned. Wind, slope, and vegetation can influence fire size and shapes but these are usually model inputs. The SIERRA model would fall into this class (Mouillot et al., 2001). Fires are never really “spread” across the landscape, but rather fire pattern is predetermined without the incorporation of spatial relationships. The size and shape of the pattern can be computed from stochastic functions (probabilistic approach) or statistical and mechanistic fire spread models (McArthur, 1967, Rothermel, 1972) (empirical and physical approach).

Lattice models simulate the spread of fire from one pixel to another in a raster spatial domain (Ball and Guertin, 1992). Cell automata and bond percolation spread models are contained within this strategy. Fire spread in lattice models can be simulated as a stochastic event based on probability distributions, empirical relationships based on cell characteristics, or physical equations based on fuel conditions (Gardner et al., 1999). Lattice spread models commonly included in LFSMs may have a scale problem that consistently creeps into raster spread simulations (Andrews, 1989). Fire spreads at different rates along the perimeter; the heading fire (flaming front at the head or downwind side of the fire) generally moves the fastest while the backing fire (flaming front at the rear or upwind fire boundary) is generally the slowest (Finney, 1998). As a result, cell-to-cell spread simulations tend to oversimplify the fire growth process.

The vector strategy simulates the spread of fire as a continuously expanding fire polygon (Anderson et al., 1982). This polygon is defined by a series of two-dimensional vertices that increase in number as the fire grows over time (Finney, 1998). Vector models often get model inputs from raster layers, but the actual spread of the fire is simulated using vectors. Probabilistic strategies use stochastic functions to compute the rate and direction of fire spread and may integrate environmental variables to determine cell-to-cell spread. Empirical approach use regression functions to drive the spread of fire in directional vectors, while the physical approach uses algorithms that simulate the physical processes that drive fire growth (Albini, 1976). An example of a physical vector model is FARSITE fire growth model constructed by Finney (1998) and implemented into the Fire-BGC model (Keane et al., 1996b).

2.4. *The fire effects component*

An important LFSM component is fire effects, yet it is often simulated in the least detail (Keane and Finney, 2003; Reinhardt et al., 2001). Fire effects are the direct and indirect consequences of the fire and do not always relate to the intensity of the fire. Examples include plant mortality, fuel consumption, smoke, and soil heating (Reinhardt and Keane, 1998). Fire effects simulations in most LFSMs are rule-based, dependent on only whether the cell or stand burned. Rarely do these simulations incorporate fire behavior into the calculation of a fire effect. Selection of the effects to model depends on the objective of the simulation and the detail of other simulation components. For example, it makes little sense to simulate fuel consumption in a frame model because fuels are not explicitly simulated, and consumption does not affect pathway development and transition. We have identified two major strategies for fire effects component development: (1) rule-based and (2) mechanistic.

Rule-based fire effects components use general statements to dictate the fate of a stand or landscape after a fire. For example, if a red spruce stand burns, then it transitions to a shrub stand. Most LFSMs with frame succession components simulate the effects of fire through the immediate transition to another early seral community type. Examples of this include SIMMPLE (Chew, 1997), LANDSUM (Keane et al., 2002), and TELSA (Kurz et al., 2000). Sometimes probability functions or parameters are used to simulate further detail. For example, the LANDSUM model allows the user to specify several transition communities based on their observed probability of occurrence in the field (Keane et al., 1996a). Some individual plant gap models assume all trees die if a fire burns the stand (see Keane et al., 2001 for review), and other models set the stand age to zero if a fire burns a cell (Li, 2001). These rules can be parameterized using empirical field data, expert opinion, or simulation results from other non-LFSM models.

Mechanistic fire effects simulation strategies attempt to simulate a fire effects process using probabilistic, empirical, or physical relationships. The First Order Fire Effects Model (Reinhardt et al., 1997) uses empirically derived logistic regression probability functions to model fire-caused tree mortality, and these equations were implemented in Fire-BGC (Keane et al., 1996b). There are many point-based fire effects models that can easily be implemented in LFSMs, including the Hungerford et al. (1997) physically based soil heating model to simulate soil biota and nutrient dynamics and the Albini and Reinhardt (1995) BURNUP model to simulate consumption of woody fuels from physical relationships.

3. Methods

3.1. Initial classification

In our initial LFSM classification, we attempted to classify models along gradients of inherent design detail represented by model approach and strategy (as presented above) for each simulation component using the MDE database (Rupp et al., 2001) (Fig. 2a). We defined the "classification space" by assigning each simulation component a dimension and organized the LFSMs along a gradient of increasing complexity based on information derived from modelers in our working group and the MDE database. Complexity was defined as the inherent detail embedded in the design of a component and it was calculated from the number of variables, equations, algorithms, or lines of computer code used to represent the component. It was assumed that the approach and strategy adopted for each component could be used to determine its position along the complexity gradient. Similar models could be grouped together based on this arrangement (Fig. 2b).

This proved a useful arrangement for descriptive purposes but somewhat limited for classification for several reasons. First, it was difficult to determine the position of a model along the gradients of approaches for each component. Existing LFSMs consistently had a fusion of simulation approaches and strategies for modeling each component. For example, Keane et al. (1996b)'s Fire-BGC model simulated succession using complex biogeochemical simulation (growth), empirical mortality equations, and stochastic functions (regeneration). Moreover, approaches and strategies do not consistently represent design detail or complexity across all evaluated models. Some probabilistic approaches were quite complex but they were consistently classified at the lower end of the complexity gradient. Moreover, the complexity of one simulation component could influence the development of other components. For example, a detailed simulation of vegetation development, complete with climate, fuel dynamics, and individual tree growth, would allow for a more complex fire spread and effects simulation because of the availability of comprehensive input variables, such as fuels and weather. Last, it was difficult for modelers to choose the most appropriate approach from our list for each model component; most modelers tended to describe their models quite differently than we did. Modelers were heavily influenced by the amount of time they spend on development of individual model components. Previous attempts at classifying models by approaches and strategy have been limited because of diversity in simulation design caused by the integration of many approaches

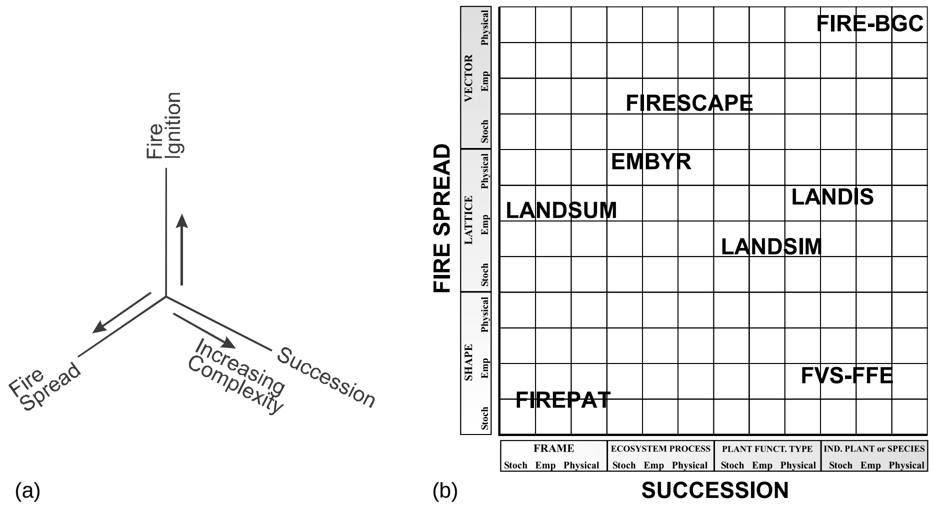

Fig. 2. (a) Initial classification space for grouping similar models using gradients of complexity by the four major components of LFSMs: the succession element, the fire ignition element, fire spread element, and fire effects element (not shown here). (b) An example of the initial mapping of landscape fire succession models in the complexity space using fire spread and succession components. Complexity is increasing as one moves away from the origin and is based on model design.

to develop model components (Schimel et al., 1997; Gardner et al., 1999; Barrett, 2001; Weise et al., 2003).

Since we could rarely categorized LFSM components into discrete classification categories by simulation design with sufficient accuracy or consistency, we decided to use this initial effort as a qualitative framework for describing the models and modifying the structure of the MDE database rather than as a classification to categorize models and components. However, we were still left with the problem of how to classify simulation models for comparison and evaluation projects and for development of coarse scale fire and vegetation models.

3.2. *Final classification*

We eventually abandoned the idea that models could be classified by approach or strategy and decided to use a more general description of the simulation of individual components. After much debate at the workshops, the classification space for each component (succession, fire ignition, fire spread, fire effects) was described in three dimensions by the gradients of stochasticity, complexity, and mechanism inherent in the simulation component. This resulted in 12 evaluation elements (4 components by 3 gradients) for each model. Together, these elements represent a formal description of the model that can be objectively compared to other models. There is some unavoidable ambiguity in these gradients; however, we feel they provide a standardized, comprehensive, and somewhat objective context in which to evaluate LFSMs. Gradients can be modified, removed, or added if this process is used to compare other types of models.

Stochasticity is defined as the amount of randomness inherent in the component design, or the degree at which probabilistic functions influence the simulation of that component. For example, component simulations with low stochasticity have deterministic functions that may or may not be based on physical relationships. Component simulations with high stochasticity treat the forcing functions as probabilistic relationships where the detail of the function relates to the degree of randomness; models with the highest stochasticity treat the simulation of that component as a completely random process. Stochasticity can be indirectly evaluated by the degree of variability across simulation runs; high variability in a simulated output when simulation parameters are constant would indicate high stochasticity.

Complexity is defined as the inherent detail incorporated into the design of a simulated component. Models with low complexity have modest sophistication in simulation detail. For example, a component that is represented as an input by the user (e.g., fire start locations are inputs to the model) would have the lowest complexity. High complexity models have components that are simulated by multiple equations with multiple variables calculated over multiple time spans (e.g., vector-based fire spread in the FARSITE spread component; Finney, 1998). Complexity was determined by the number of variables, equations, algorithms, or lines of computer code needed to simulate a component.

Mechanism is the degree to which fundamental physical or chemical processes are represented in the simulation of a LFSM component. Components with low mechanism would use equations or algorithms that do not represent causal biophysical process such as photosynthesis, evapotranspiration, or decomposition. Examples would include those models that use statistically derived equations (i.e., regression models) to simulate a component (e.g., growth and yield individual plant models, FVS-FFE (Beukema et al., 1997, Reinhardt and Crookston, 2003). High mechanism would be indicated by the complete representation of a component by physically based variables. An example here would be the succession component of the BIOME-BGC model that uses physically based biogeochemical algorithms to simulate biomass development (Thornton et al., 2002).

We conducted a census of existing LFSMs from workshop participants, a review of the literature, and correspondence with modelers. Only models that were published in some form were considered, and this yielded a list of 44 LFSMs that were used to build this classification effort (see Table 1).

We contacted the developers of these models and asked them to rate the simulation of the four components (succession, fire ignition, fire spread, and fire effects) by the three evaluation gradients (stochasticity, complexity, and mechanism) using a scale from zero to 10 (zero meant that it is not modeled or applicable and 10 represented the highest level of stochasticity, mechanism, or complexity). A detailed description of rating criteria complete with examples was also given to each modeler. Some modelers did not reply, so we assigned our own ratings based on a thorough review of publications on the model. The values assigned to each evaluation element were compiled into a database (available from the authors) and then analyzed to identify groups of similar models. To ensure consistency across modeler evaluations of their own models, we created another database with our own assignments of evaluation elements based on published literature and our knowledge of the model.

To identify natural clusters or groups, the evaluation element data were ordinated using principal components analysis (PCA) and clustered using TWINSPAN techniques in the PC-ORD package (McCune and Mefford, 1999). PCA is an eigenanalysis technique that maximizes the variance explained by each successive axis. TWINSPAN is a two-way indicator species analysis producing a two-way table (models by evaluation element) using an agglomerative clustering technique (Gauch, 1982). The See5 statistical software (Quinlan, 2003) was also used to cluster the evaluation element data using Ward's minimum variance hierarchical clustering, which is a divisive clustering technique.

It was evident that the ordination and clustering results alone would not be sufficient for developing the classification because of the high variance in evaluation elements across models. Therefore, we revised the MDE database so that keywords were used to describe various explanatory categories such as approach, strategy, scale and other descriptive attributes by LFSM component (see Table 2 for database structure). These categories and the discrete set of keywords for each category were assigned by modelers at the various workshops and by our review of model publications. We then compared the frequency of keywords for each category in Table 2 across all LFSMs to qualitatively identify similar characteristics.

A general LFSM classification was developed from the fusion of the ordination, clustering, and keyword comparison results. A dichotomous key for the classification was then constructed from the MDE database and another See5 analysis. We used See5's classification tree analysis to identify key criteria for classification categories and as an assessment of the accuracy of our classification. Each LFSM was then keyed to the appropriate classification categories and See5 was used to determine thresholds in evaluation elements that would uniquely identify classified LFSMs. We then related common keywords to the dichotomous key to name and identify important branches in the dichotomy.

4. Results

Overall, results from the PCA ordination analysis using the ratings supplied by the modelers show a common arrangement of the 44 LFSMs (Fig. 3). The first PCA ordination axis was related to complexity and mechanism gradients for the succession component (eigenvectors of –0.56 and −0.46), while the second axis was mostly related to complexity and mechanism gradients for fire spread (eigenvector of −0.62 and –0.55). The third axis appears to be related to fire ignition (eigenvector of −0.74). These three axes explain about 66 percent of the variability across the 12 evaluation elements.

The clustering analysis yielded slightly different results. TWINSPAN results showed LFSMs were grouped first on high values for succession and fire effect components for mechanism and complexity gradients (i.e., gap models) and second on fire effects mechanism and complexity gradients (Fig. 4). There appear to be two main groups among the models, represented by models from 6 to 38 on the left of Fig. 4 (denoted by a zero—0 in the uppermost line of the TWINSPAN binary model groupings), and models from 12 to 44 on the right (denoted by a 1 in the model groupings). The leftmost group is characterized by high stochasticity in fire ignition, spread, and low complexity in succession. The group on the right is characterized by high mechanism and complexity in succession and low complexity in spread and ignition. The See5 Ward's variance technique clustered models mostly on a mechanistic gradient for succession (breakpoint at value of 4) and then along a stochasticity gradient for the spread component element as further criteria. Both See5 and TWINSPAN tended to cluster mainly on succession and fire spread components.

Some results were consistent across ordination and clustering analyses. Fire effects had the least influence in the classification analysis with all fire effects elements. For example, PCA consistently rated the three fire effect elements as 8th, 10th, and 12th out of 12 el-

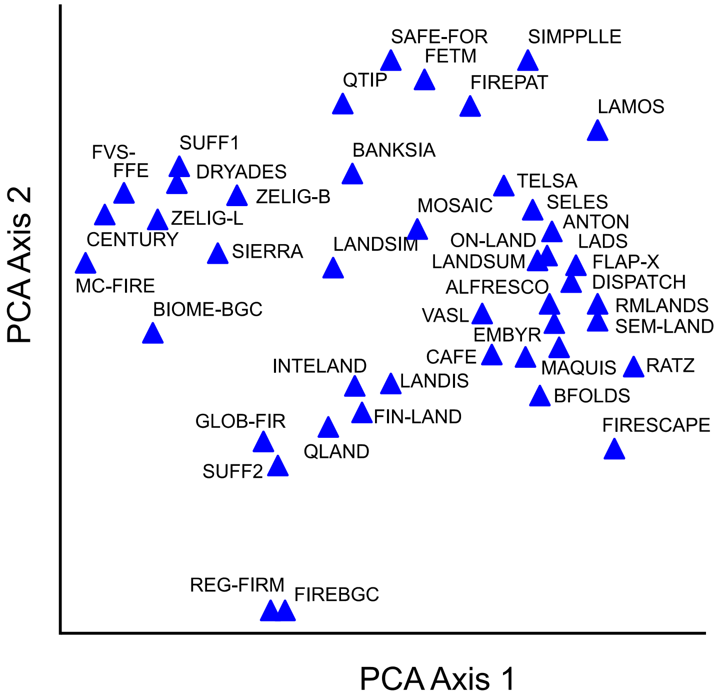

Fig. 3. Results of the principal components analysis (PCA) ordination of the landscape fire succession models (LFSMs) using the 12 evaluation elements that are combinations of complexity, stochasticity, and mechanism gradients by four model components (succession, ignition, spread, effects). The first three axes explained roughly 66% of the variation (28, 18, and 145, respectively) and it took 10 axes to explain over 99% of the variance.

ements for their importance in differentiating between LFSMs. This is primarily because there was a low diversity in fire effects simulation across models. In contrast, succession and fire spread appeared to be the two components that most heavily influenced the clustering and ordination results because of the wide variety of simulation techniques represented. Succession was more important in the clustering than ordination probably because the three evaluation gradients (complexity, stochasticity, and mechanism) were not closely related in succession simulations. This same reason may explain why all evaluation gradients appeared to explain roughly the same amount of variance.

There was little difference in ordination or clustering results when the estimates of the 12 evaluation elements were made by the authors rather than the modelers (Fig. 5). This may indicate that the bias or subjectivity in the rating of LFSMs by their developers was not a significant factor in this analysis. Values of most evaluation elements were nearly the same across the two sources, and those that were different did not have a significant effect on the resultant classification.

The final classification of LFSMs (Table 3) was developed from qualitatively integrating the ordination and clustering results with information in the keyword database and See5 classification tree analysis. It represents a qualitative grouping of similar models in the three-dimensional space of complexity, stochasticity, and mechanism (see Fig. 6 for clusters in PCA ordination space). The first key to these classes, presented in Table 4, was developed using the See5 results and an evaluation of common keywords in the database (keywords were also used to name the classes). The second key in Table 4 presents a synthesis of the results from the classification tree analysis (See5) based on evaluation element values. This key is only 75% accurate because it only recognizes six of the 12 classes, but it does provide insight into the evaluation elements critical in identifying model classes where succession complexity is the primary keying criteria (Table 4). The development of the final LFSM classification was

Model Numbers

```
               1321233   113112234224 23 3112314 213  2344
              69415816128065140431252370482892305379796734

 7  SprdStoc  73123334777656-1615253511-4143511112-----1--  00
 1  SuccStoc  12--1212311112211254333145883121211121121132  010
 8  SprdComp  44149465434442-1558346513-7153458622-----2--  01100
 9  SprdMech  44157274323442-1242145313-7144489722-----1--  01100
 4  IgntStoc  7569757578878878888888898987883718--8--795877  01101
 5  IgntComp  543154243153226233543212224122353--4--224254  01101
10  EfftStoc  732-1-11111112215553111154311111211121161312  01101
 6  IgntMech  352154352243222122212212122135283--2--225234  0111
 2  SuccComp  25--2212322223223333645455517888838563888777  1
 3  SuccMech  45--2111322322221122734544417888968766888778  1
11  EfftComp  74511-12232222223232323232314121572253646525  1
12  EfftMech  75512-12232222212221323322213131772356747625  1

              00000000000000000000000000001111111111111111
              00000000000000001111111111110000001111111111
              00011111111111110000000000110000110011111111
                 00000111111110000111111          00111111
                 0111100000011    000111
```

TWINSPAN Model Binary Groups

Model Names and Numbers

1. ALFRESCO
2. ANTON
3. BANKSIA
4. BFOLDS
5. BIOME-BGC
6. CAFÉ
7. CENTURY
8. DISPATCH
9. DRYADES
10. EMBYR
11. FETM
12. FIN-LANDIS
13. FIREBGC
14. FIREPAT
15. FIRESCAPE
16. FLAP-X
17. FVS-FFE
18. GLOB-FIRM
19. INTELAND
20. LADS
21. LAMOS
22. LANDIS
23. LANDSIM
24. LANDSUM
25. MAQUIS
26. MC-FIRE
27. MOSAIC
28. ON-FIRE
29. QLAND
30. QTIP
31. RATZ
32. REG-FIRM
33. RMLANDS
34. SAFE-FORESTS
35. SELES
36. SEM-LAND
37. SIERRA
38. SIMMPLLE
39. SUFF1
40. SUFF2
41. TELSA
42. VASL
43. ZELIG-B
44. ZELIG-L

Fig. 4. Arrangement of models along the classification gradient in a two-way ordered table created from the TWINSPAN cluster analysis results. The 12 evaluation elements are combinations of model component (succession-Succ, fire ignition-Ignt, fire spread-Sprd, and fire effects-Efft) by complexity (Comp), stochasticity (Stoc), and mechanism (Mech). Values inside the matrix are the ratings assigned to each model by the modeler who built the model. The TWINSPAN classes are identified by binary codes on the bottom for model groups and on the right side for model component groups.

not necessarily based on a repeatable process. Instead, it involved the distillation of patterns in ordination space and classifications from a number of analyses into broad groups of models based on similarities in evaluation elements and keywords. Other authors may come up with slightly different groupings of models. However, we feel that our final classification represents a meaningful system for grouping models for our specified objectives.

5. Discussion

5.1. The classification

This LFSM classification and supporting descriptive material (Tables 3 and 4) can be used for many purposes. It provides a common language for communication between managers, modelers, and research scientists, and the classes can be used to quickly and

Table 3
Final LFSM classification

Classification (category name)	Label	List of models	Simple keyword agreement	Weighed keyword agreement
Coarse scale Biogeochemical	CB	BIOME-BGC, CENTURY, GLOB-FIR, REG-FIRM, MC-FIRE	74	68
Coarse scale Any other model	CN	ALFRESCO, FIREPAT	68	66
Fine scale Individual tree or species Empirical growth Explicit fire growth	FTEF	No models available	NA	NA
Fine scale Individual tree or species Empirical growth Indirect fire growth	FTEN	FFE-FVS	100	100
Fine scale Individual tree or species Gap model Explicit fire growth	FTGF	DRYADES, FIRE-BGC, SIERRA, LAMOS	53	48
Fine scale Individual tree or species Gap model Indirect fire growth	FTGN	ZELIG-B, ZELIG-L	76	80
Fine scale Individual tree or species Diameter or age cohort Explicit fire growth	FTDF	FIN-LANDIS, LANDIS, QLAND	73	69
Fine scale Individual tree or species Diameter or age cohort Indirect fire growth	FTDN	No models available	NA	NA
Fine scale Frame models Succession stages Explicit fire growth	FFSF	ANTON, CAFÉ, EMBYR, INTELAND, LANDSIM, LANDSUM, MAQUIS, MOSAIC, Q-TIP, RMLANDS, SAFE-FOREST, SELES, SIMPPLLE, TELSA	63	62
Fine scale Frame models Succession stages Indirect fire growth	FFSN	BANKSIA, BFOLDS, FETM, VASL	58	58
Fine scale Frame models Age-based Explicit fire growth	FFAF	DISPATCH, FIRESCAPE, LADS, ON-FIRE, RATZ, SELES, SEM-LAND	62	61

Table 3 (*Continued*)

Classification (category name)	Label	List of models	Simple keyword agreement	Weighed keyword agreement
Fine scale				
Frame models				
Age-based				
Indirect fire growth	FFAN	FLAP-X, SUFF1, SUFF2	85	84

Each category was given a name that best described the models in that group. Percent of keyword agreement for each category in the MDE database was computed as the average frequency of keyword occurrence averaged across all categories in Table 2 (simple) and then weighted by number of keywords (weighed).

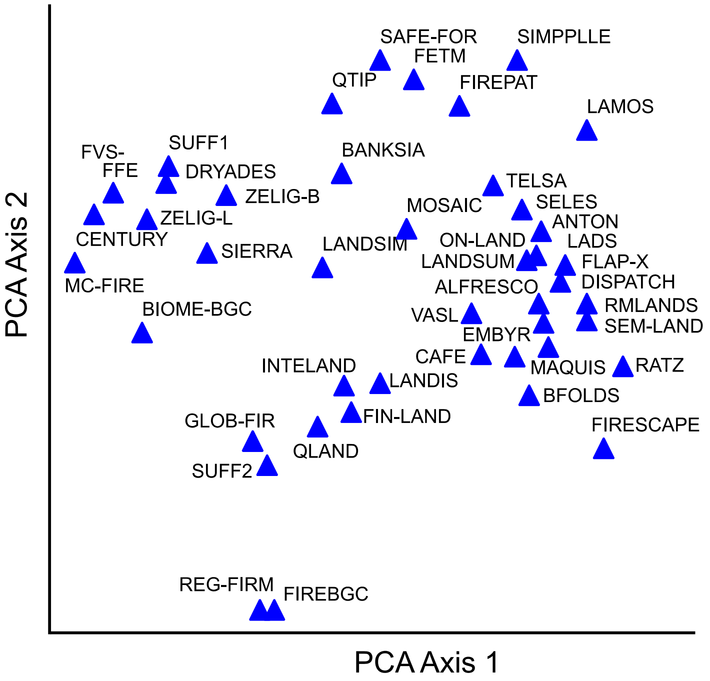

Fig. 5. PCA ordination results from ratings assigned by the authors of this paper. A comparison of these results with those produced when ratings were done by the modelers (see Fig. 3) shows little difference.

efficiently characterize or describe a model relative to others. The classification also provides a starting point for managers to select the most appropriate model to implement for their areas of interest, and for scientists and other modelers to select the most appropriate models to build or refine for their particular situations. The classification also provides the context to evaluate or compare simulation approaches for each component to build new models or refine old ones.

The LFSM classification presented here contains 12 classes of models based on evaluations of individual models along gradients of complexity, stochasticity, and mechanism. As such, this classification is only useful if these gradients are important to selecting, evaluating, or comparing models. The usefulness of this classification for other purposes, such as exploring climate change dynamics, remains unknown.

The three gradients used in this study were not perfectly orthogonal. Highly complex models tend to include many mechanistic functions that tend to have a low degree of stochasticity (Gardner et al., 1999), and they often were built specifically to remove the

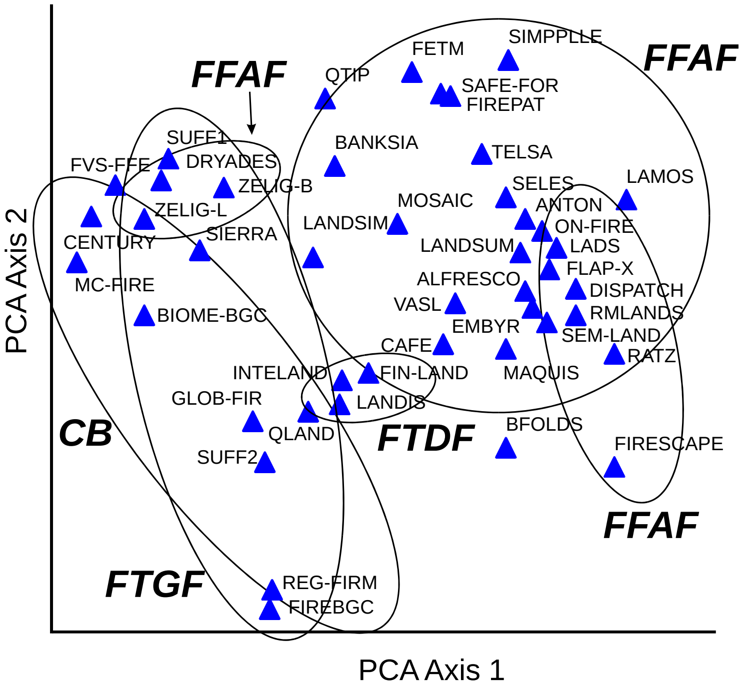

Fig. 6. Delineation of six model classes in ordination space for the developed classification using ratings assigned by the modelers. This shows the relative position between classes and the similarity of models within a class.

stochasticity, so that these approaches could be mutually exclusive and the gradients correlated. However, some highly complex systems, such as lightning dynamics, must be represented by stochastic functions because of scale, computer, and knowledge limitations. Statistical analyses of the three evaluation gradients found correlation only between complexity and mechanism ($R^2 = 0.71$, $P < 0.0132$).

Some LFSMs used in this study may appear unrelated in scale and application, but they all meet the criteria for an LFSM (spatially explicit simulation of fire and vegetation) and were included in this study to ensure that diverse models can be included in the classification. A typical LFSM simulates the four processes at a landscape scale. The biogeochemical process models, REG-FIR (Venevsky et al., in press), BIOME-BGC (Thornton et al., 2002), and CENTURY (Peng and Apps, 1999) have simplistic simulations of fire (i.e., no spread) implemented at a coarse scale (1 km pixel), but they still satisfy LFSM criteria. GLOB-FIR (Thonicke et al., 2001) and MC-FIRE (Lenihan et al., 1998) are implemented into DGVMs for global simulations at very coarse spatial scales and do not simulate fire growth. The QLAND (Pennanen et al., 2001) and INTELAND (Gauthier et al., 1994) models are currently under construction and not available. The models QTIP (Plant et al., 1999), LAMOS (Lavorel et al., 2000), and SELES (Fall and Fall, 2001) are actually simulation platforms but the authors created an LFSM as an application and demonstration of their simulation system. The ZELIG-L model (Miller and Urban, 1999) simulates fire patterns at fine space scales but does not have an explicit landscape implementation.

An estimate of accuracy was an obvious and conscious omission from the classification evaluation criteria. A gradient of accuracy along with complexity and stochasticity would have only complicated the classification and would not have added any pertinent information for several reasons. First, it is extremely difficult to assess simulation accuracy for most spatial models. Historical data of sufficient spatial and temporal extent are rare, low quality, and often not compatible with the input required of

Table 4
Key for classifying LFSMs using gradients of complexity, stochasticity, and mechanism into categories defined in Table 3

LFSM classification keys	
Results using the classification tree analysis	
Succession complexity > 5	
Spread stochasticity > 3	Class FTDF
Spread stochasticity ≤ 3	
Ignition stochasticity ≤ 7	Class CB
Ignition stochasticity > 7	Class FTGF
Succession complexity ≤ 5	
Ignition stochasticity ≤ 1	Class FFAN
Ignition stochasticity > 1	
Ignition mechanism ≤ 2	Class FFSF
Ignition mechanism > 2	
Succession mechanism ≤ 2	Class FFAF
Succession mechanism > 2	Class FFSF
Results using the MDE keyword database	
Spatial resolution greater than 500 m pixel size	
Biogeochemical succession driver	Class CB
Any other model	Class CN
Spatial resolution less than 500 m pixel size	
Individual tree or species succession driver	
Empirical growth and yield design	
Explicit fire growth simulation	Class FTEF
Indirect fire growth simulation	Class FTEN
Gap-phase succession model	
Explicit fire growth simulation	Class FTGF
Indirect fire growth simulation	Class FTGN
Diameter or age cohort succession driver	
Explicit fire growth simulation	Class FTDF
Indirect fire growth simulation	Class FTDN
Frame-based succession driver	
Species-based succession stages explicitly recognized	
Explicit fire growth simulation	Class FFSF
Indirect fire growth simulation	Class FFSN
Age-based succession driver	
Explicit fire growth simulation	Class FFAF
Indirect fire growth simulation	Class FFAN

Keys are designed to stop at the first level that fits. Explicit fire growth simulations include all vector and lattice fire growth approaches.

many models (Keane and Finney, 2003). It would also be difficult to evaluate accuracy for individual LFSM components, especially if they were highly integrated as in FIRESCAPE and Fire-BGC, because sources of the error are hard to trace from simulation component to component. A model can be inaccurate but still be very useful because the relative differences between landscape simulations may be sufficient for land management objectives.

The names and labels of LFSM classes are primarily based on the succession component even though fire spread and ignition were important in the classification analysis. Succession keywords were more common across LFSMs in the MDE database than keywords for ignition or spread. This may be because design of the succession component often dictates the detail of the three fire components; a complex succession simulation yields many intermediate variables, such as fuel loadings and tree densities that can be used in the ignition, spread, and effects simulations. There also tended to be more categories but fewer keywords per category in the succession component than other components.

5.2. Model classification keys

Two classification keys were developed from the results of this study (Table 4). The first key provides a means to classify models based on the three evaluation gradients (complexity, stochasticity, and mechanism) (Classification Tree Analysis). This key was developed from the regression tree analysis on the 12 evaluation elements so it provides insight into the threshold values in evaluation ratings that are important for the delineation of each class. The second key integrates the ordination and clustering results with MDE database and keyword database to uniquely identify the class or category of any LFSM with a descriptive name taken

Table 5
Key for selecting the most appropriate LFSMs for fire management and research applications based on operational characteristics developed from the MDE database

Model selection key	
Management application	
Limited computer resources, modeling expertise, and/or input data available	
Fire pattern important	
Support and documentation available	TELSA
Not as above	LANDSUM
Fire pattern NOT important	
Support and documentation available	FFE-FVS
Not as above	SIMPPLLE, FETM
Abundant computer resources, modeling expertise, and/or input data available	
Individual tree or species level processes important	
Support and documentation available	None
Not as above	LANDIS, QLAND, FIN-LANDIS
Only stand level characteristics important	
Support and documentation available	LANDMINE, SELES
Not as above	BFOLDS, CAFÉ, DISPATCH, EMBYR, INTELAND, LADS, LANDSIM, RMLANDS, SAFE-FOREST, SEM-LAND
Research application	
Explore climate, vegetation and fire dynamics	
Coarse scale applications	BFOLDS, BIOME-BGC, CENTURY, MC-FIRE, GLOB-FIR
Landscape scale applications	
Individual tree or species level processes important	
Fire pattern important	FIRE-BGC, LAMOS, SIERRA
Not as above	DRYADES, ZELIG-L, ZELIG-B
Only stand level characteristics important	
Fire pattern important	MAQUIS, FIRESCAPE
Not as above	REG-FIRM
Explore fire and vegetation dynamics	
Coarse scale applications	ALFRESCO, FIREPAT
Landscape scale applications	
Individual tree level processes important	
Fire pattern important	FIN-LANDIS, LANDIS
Not as above	
Only stand level characteristics important	
Fire pattern important	ANTON, CAFÉ, DISPATCH, EMBYR, INTELAND, LANDSIM, MAQUIS, MOSAIC, QTIP, RATZ, RMLANDS, SELES, SEM-LAND, SUFF2
Not as above	BANKSIA, FLAP-X, ON-FIRE, SUFF1, SUFF2, VASL

This key is designed to stop at the first level that fits within a level.

from the MDE database. This key can be used to categorize other LFSMs not included in this study. The key is best used when one is interested in how LFSMs are similar with respect to complexity, stochasticity, and mechanism, but it is not particularly useful when other specific objectives are desired.

Managers have a pressing need to select the LFSM that best suits their needs, and these needs may be quite different from those of a researcher or modeler. We used the results of this study, and our knowledge of management issues, to construct a third key that would allow the manager to select the most appropriate model (Table 5). This key is based mainly on information in MDE and keyword databases and secondarily on the ordination and clustering results. It uses mostly descriptive characteristics, such as application, availability, and support, as primary key criteria. Inclusion of this key also illustrates how classification objective can dictate the design and influence subsequent groupings. It is recommended that models developed for the target ecosystem or geographical area should be selected first.

5.3. Implications for coarse scale fire modeling

The simulation of fire spread in LFSMs presents a paradox in scale. Results from most LFSMs simulations are summarized over thousands of years across large regions, so the accuracy of daily fire growth seems less important than the accuracy of fire pattern and the fire effects within that pattern. While detailed fire spread algorithms tend to ensure accurate fire perimeters, it comes at a great computer processing cost and may not be feasible or warranted for millennial scale simulations (Keane and Finney, 2003). A common compromise is the simulation of fire perimeter from predetermined shapes (Keane and Long, 1997) or the forcing of fire spread along polygon boundaries (Chew, 1997). However, accurate fire perimeters depend on many factors such as weather, topography, wind, and landform so generalized approaches might oversimplify fire growth processes, especially when exploring climatic effects on fire dynamics. Detail in the fire growth algorithm must match the complexity of the factors that control fire spread for the landscape for the specific modeling objective.

It appears that the explicit simulation of fire spread may not be needed in coarse scale dynamic global vegetation models. Realistic fire regimes have been generated by nearly all LFSMs, even though there were diverse approaches used in fire growth simulation. And, the annual area burned seemed to describe fire regime better than the pattern created by simulated fires as simulation time spans became long (Keane et al., 2002). The combination of the number of ignitions, annual area burned, and fire size appear to be most important for simulations of large areas over long time spans (Lenihan et al., 1998; Fosberg et al., 1999). Therefore, a mechanistic representation of fire ignitions and fire size distributions with climate, vegetation, human activity, and topography drivers should be sufficient for coarse scale fire modeling. Fire effects simulations can be improved by including fire severity and intensity distributions to the appropriate drivers.

6. Conclusions

Classifying landscape models is very much like classifying plant communities; the gradients of inherent complexity and diversity within the population nearly always preclude a perfect classification. Classification design is nearly always governed by its intended application, so there will never be the ideal LFSM classification for all purposes. In our case, we developed the classification to select a set of LFSMs that represent the diversity in the entire population to perform a comprehensive model comparison designed to identify critical vegetation, fire and climate processes to include in coarse scale dynamic vegetation models (Cary et al., in press). It is our hope that this classification can be used for a myriad of other purposes and that the techniques used to classify LFSMs can be used for other simulation models and computer applications.

Acknowledgements

This work was partially conducted as part of the Landscape Fires working group supported by the National Center for Ecological Analysis and Synthesis (NCEAS), a Center funded by the National Science Foundation (Grant #DEB-0072909), the University of California, and the Santa Barbara campus. We also thank all participants in the four NCEAS workshops especially Andrew Fall, Florent Mouillot, Carol Miller, Don McKenzie, Mike Wotton. We also thank Russ Parsons, USDA Forest Service Fire Sciences Laboratory for technical assistance and technical review. This work was also partially funded by a grant (NS-7327) from NASA's Earth Science Applications Division as part of the Food and Fiber Applications of Remote Sensing (FFARS) program managed by the John C. Stennis Space Center.

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