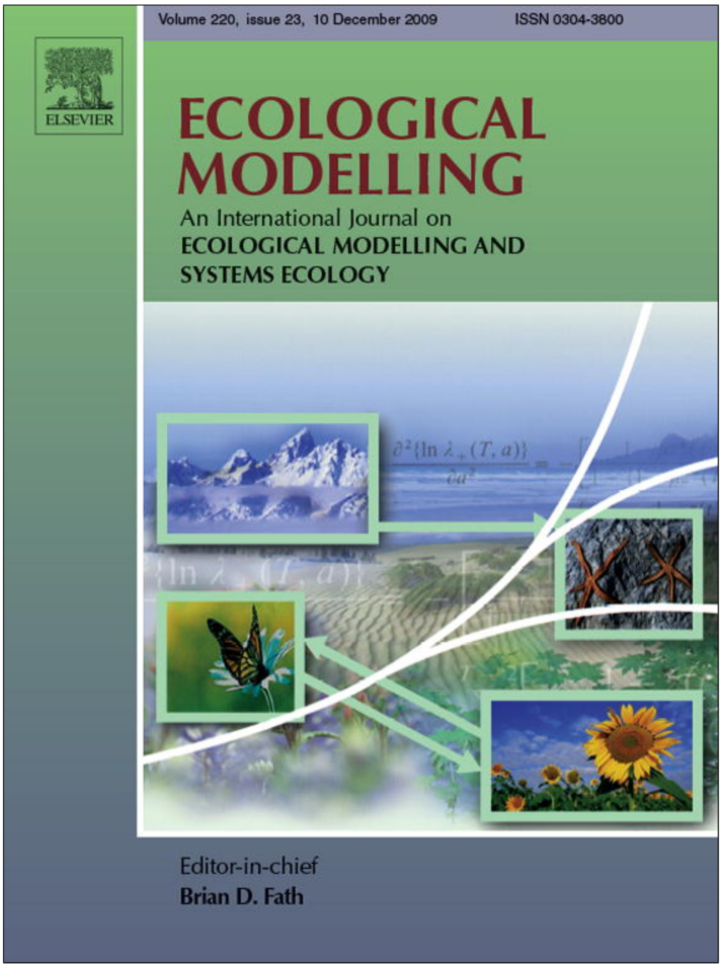
Volume 220, issue 23, 10 December 2009
ISSN 0304-3800
ELSEVIER
ECOLOGICAL MODELLING
An International Journal on
ECOLOGICAL MODELLING AND SYSTEMS ECOLOGY
Editor-in-chief
Brian D. Fath

Ecological Modelling 220 (2009) 3380–3393

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Simulating dynamic and mixed-severity fire regimes: A process-based fire extension for LANDIS-II

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ARTICLE INFO

Article history:
Received 7 April 2009
Received in revised form 28 July 2009
Accepted 31 July 2009
Available online 31 August 2009

Keywords:
LANDIS-II
Fire disturbance
Labrador
Boreal forest
Sierra Nevada
Mixed conifer forest
Fire regime
Fire effects

ABSTRACT

Fire regimes result from reciprocal interactions between vegetation and fire that may be further affected by other disturbances, including climate, landform, and terrain. In this paper, we describe fire and fuel extensions for the forest landscape simulation model, LANDIS-II, that allow dynamic interactions among fire, vegetation, climate, and landscape structure, and incorporate realistic fire characteristics (shapes, distributions, and effects) that can vary within and between fire events. We demonstrate the capabilities of the new extensions using two case study examples with very different ecosystem characteristics: a boreal forest system from central Labrador, Canada, and a mixed conifer system from the Sierra Nevada Mountains (California, USA). In Labrador, comparison between the more complex dynamic fire extension and a classic fire simulator based on a simple fire size distribution showed little difference in terms of mean fire rotation and potential severity, but cumulative burn patterns created by the dynamic fire extension were more heterogeneous due to feedback between fuel types and fire behavior. Simulations in the Sierra Nevada indicated that burn patterns were responsive to topographic features, fuel types, and an extreme weather scenario, although the magnitude of responses depended on elevation. In both study areas, simulated fire size and resulting fire rotation intervals were moderately sensitive to parameters controlling the curvilinear response between fire spread and weather, as well as to the assumptions underlying the correlation between weather conditions and fire duration. Potential fire severity was more variable within the Sierra Nevada landscape and also was more sensitive to the correlation between weather conditions and fire duration. The fire modeling approach described here should be applicable to questions related to climate change and disturbance interactions, particularly within locations characterized by steep topography, where temporally or spatially dynamic vegetation significantly influences spread rates, where fire severity is variable, and where multiple disturbance types of varying severities are common.

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1. Introduction

Developing a better understanding of how forest fires interact with changing environmental conditions is a priority for land managers, conservationists, policy-makers, and others concerned about the potential negative effects of altered fire regimes on biodiversity, natural resource sustainability, and fire risk in human-populated areas (Arno and Allison-Bunnell, 2002). Vegetation conditions, including species composition, stand structure, fuel conditions, and landscape heterogeneity, can strongly influence fire regime characteristics such as fire frequency, severity, and size distribution (Van Wagner, 1983; Turner and Romme, 1994). Fire, in turn, affects vegetation through direct mortality, structural alterations, and changes in hydrological and biogeochemical cycles; and these factors subsequently influence post-disturbance successional dynamics and future disturbance events (DeBano et al., 1998). Fire regimes are also strongly influenced by climate (Clark, 1988; Turner and Romme, 1994) via the collective effects of weather events on the probability of fire ignition (Wotton and Martell, 2005) and subsequent behavior (spread rates, size, duration, and intensity) of

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0304-3800/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.ecolmodel.2009.07.030

individual fires (Amiro et al., 2004). Fire behavior is a dynamic process shaped by stochastic weather events, such as wind speed, wind direction, and relative humidity, and by fuel type and moisture content, landscape heterogeneity, and topography (DeBano et al., 1998; Hély et al., 2001).

Because fire–vegetation interactions typically operate at broad temporal and spatial scales that are unsuitable for investigation via empirical methods, modeling is a useful tool for analyzing these dynamics (Mladenoff and Baker, 1999). For many research and management applications, simulation of interactions among vegetation, fire, and climate is essential to understand how forest landscapes change over time. Spatially-explicit, forest-landscape simulation models (FLSMs) can simulate dynamic fire–vegetation interactions under alternative scenarios, and some FLSMs incorporate additional processes that interact with fire and vegetation, including other disturbance agents (e.g., timber harvest) and changing climate (Scheller and Mladenoff, 2007). FLSMs that simulate fire spread (or behavior) use diverse approaches, ranging from predetermined fire patterns (shapes and sizes) to dynamic lattice or vector spread strategies, determined by probabilistic functions or empirically based equations (Keane et al., 2004). The use of highly detailed fire growth algorithms (e.g., Finney, 1998) within FLSMs to simulate the effects of variable fire weather, fuel type/moisture, and topography on dynamic fire spread rates and fire intensity has been relatively limited (e.g., Keane et al., 1996; Perera et al., 2003), due in part to excessive computation requirements (He and Mladenoff, 1999).

Keane et al. (2004) reviewed and classified more than 40 models that incorporate at least the following four key processes to simulate vegetation–fire dynamics: vegetation succession, fire ignition, fire spread, and fire effects. Models were classified based on the strategies and approaches (e.g., relative stochasticity and complexity) for simulating ecological and disturbance processes, the scales and ecosystems to which those processes apply, and applicability to various research questions and management applications. Keane et al. (2004) emphasized that models incorporating direct effects of weather on fire behavior and vegetation change can be advantageous for many research applications. However, realistically simulating complex interactions among multiple disturbances, vegetation types, and climate conditions typically requires substantial computing and programming capacities (Keane et al., 2004), as well as a greater focus on attenuation of error propagation (Turner et al., 2001). Although computing power continues to increase, the added cost of additional complexity and parameterization remains an important consideration and must be warranted by the question under investigation.

Although complex, the influence of fuel conditions, weather, and topography on fire spread and intensity may be highly relevant for FLSMs that address the spatial and temporal variability of mixed-severity fire regimes. For instance, Pennanen and Kuuluvainen (2002) determined that fire intensity and spatial pattern were more important to vegetation landscape structure than fire frequency when reconstructing (via simulation) contemporary boreal forest conditions in Finland. Surface fire regimes shape millions of hectares of North American forests (Miller and Urban, 1999a), yet fire severity is rarely addressed within FLSMs as they focus primarily on stand-replacing fire regimes (Keane et al., 2004). Spatial and temporal complexity in fire behavior is also relevant when incorporating the effects of other disturbance regimes on vegetation and fuel loads, including insect disturbance, timber harvest, and hazardous fuel reduction treatments (Sturtevant et al., 2004b; Bigler et al., 2005; Blate, 2005; Parker et al., 2006; Didion et al., 2007).

The simulation of dynamic fire weather and fuel conditions may also be required for understanding spatial and temporal interactions between fire regimes and vegetation conditions altered by climate change (Miller and Urban, 1999b). FLSMs that incorporate climate change scenarios using output from global circulation models to project changes in vegetation composition and biomass (Xu et al., 2007) already lend themselves to more accurate projections of changing fuel types and their patterns over time. Coupling specific fire weather parameters with climate change scenarios would likely further improve the accuracy of projected future fire regimes, including recent predictions of increased area burned under hotter and drier future climate scenarios (Flannigan et al., 2005; Westerling et al., 2006). Achieving these research objectives will likely require use of better empirical data, especially for fire behavior and its relationship with tree species autecology (Pennanen and Kuuluvainen, 2002).

We developed a dynamic fire extension and a dynamic fuels extension for the forest landscape simulation model, LANDIS-II (Scheller et al., 2007). The dynamic fire extension was based on fire-growth equations used in the Canadian Fire Behavior Prediction System (FBP) (Forestry Canada Fire Danger Group, 1992) and on components derived from other fire models (He and Mladenoff, 1999; Finney, 2002; Yang et al., 2004). The fire extension allows dynamic interactions between fire, vegetation, climate, and landscape structure, and incorporates realistic fire characteristics (shapes, distributions, and effects) that can vary within and between fire events. The Dynamic Fuel Extension was designed for maximal flexibility to accommodate a broad range of fuel types representing a variety of forest ecosystems. These new extensions are not intended to accurately simulate active fire behavior, but rather to approximate appropriate patterns of fire and fire effects in response to vegetation, climate, topography, and other disturbances at century to millennium time-scales.

Our primary objectives here are to: (1) present an overview of the dynamic fire and fuel extensions in the LANDIS-II framework; (2) provide a sensitivity analysis of model behavior when applying new fire and fuels extensions; and (3) demonstrate the capabilities of the new extensions using two case studies representing considerably different ecosystems: a boreal forest from central Labrador (Canada) and a mixed conifer forest from the Sierra Nevada (California, USA). Demonstrations focus on the effects of climate, topography, and fuel types on landscape burn patterns and forest composition. Simulated burn patterns within Labrador are contrasted with those simulated by the simple fire extension from the original LANDIS model (He and Mladenoff, 1999) to evaluate the consequences of added fire complexity on model behavior.

2. Methods

2.1. LANDIS-II overview

LANDIS-II (Scheller et al., 2007; http://www.landis-ii.org) is a recent elaboration of previous LANDIS models (from LANDscape DIsturbance and Succession; Mladenoff et al. 1996). LANDIS models in general simulate broad-scale (>10^5 ha) landscape dynamics, including succession, disturbance, seed dispersal, forest management, and climate change effects (Mladenoff, 2004). Landscapes are represented as grids of interacting cells with user-defined spatial resolution (cell size) generally ranging from 0.1 to 4 ha in size. Individual cells have homogeneous light environments, and are aggregated into ecoregions with similar environmental conditions (e.g., climate, soils, etc.). Forest composition at the cell level is represented as age cohorts of individual tree species that interact via a suite of vital attributes (i.e., shade tolerance, fire tolerance, seed dispersal, ability to sprout vegetatively, and longevity) to produce nondeterministic successional pathways sensitive to disturbance type and intensity. LANDIS-II was re-engineered as an integrated modeling environment that allows the creation of custom forest landscape disturbance and succession extensions while maintaining and building upon the scientific rigor of the

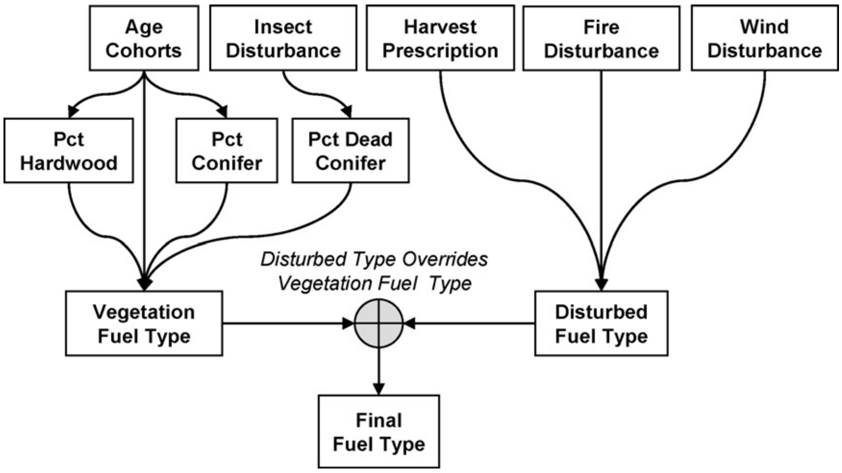

Fig. 1. Dynamic Fuel Extension flow diagram.

original LANDIS model (Scheller et al., 2007, in press-a). Strengths of LANDIS-II include new flexibility introduced through multiple inter-woven time steps, a library of published succession and disturbance extensions (e.g., He and Mladenoff, 1999; Gustafson et al., 2000; Sturtevant et al., 2004a), and the optional integration of additional cohort data and ecosystem dynamics (Scheller and Mladenoff, 2004).

2.2. Fuel reclassification extensions

The dynamic fire extension requires that all forested cells on a simulated landscape be assigned fuel types. Fuel types represent general conditions that exhibit similar fuel behaviors. The Dynamic Fuel System extension (v1.0) uses species age, conifer mortality, and post-disturbance information at each cell to classify every active cell into a season-independent fuel type. An alternative fuel extension, called the Dynamic Biomass Fuel System extension (v1.0), is identical to the Dynamic Fuel System except the calculation of species values (see below) uses cohort biomass in addition to the above variables to classify fuel types and requires the use of a succession extension that calculates aboveground biomass for every cohort. Both extensions are capable of recognizing recent disturbance history and both produce maps of fuel types, percent conifer, and percent dead conifer. User's guides and source code for each extension, referred to henceforth with the generic "dynamic fuel extension" label, are available online at http://www.landis-ii.org, with an overview flow diagram shown in Fig. 1.

The dynamic fuel extensions were designed to be adaptable to any system of generalized fuel types, such as the Canadian Forest Fire Prediction System (Forestry Canada Fire Danger Group, 1992). Up to 100 different fuel types are allowed, organized within the following basic fuel type categories: conifer, conifer plantation, deciduous, slash, and open (e.g., grasses). The relative importance of a tree species in classifying a cell is determined by where a species cohort falls within a fuel type age range:

$$\text{SpeciesValue} = \sum \frac{\text{CohortAge} - \text{RangeMinimum}}{\text{RangeMaximum} - \text{RangeMinimum}} \times \text{SppCoefficient} \in \text{AgeRange} \quad (1)$$

where CohortAge is the age (years) of the oldest cohort of that species that falls between RangeMaximum and RangeMinimum; RangeMaximum is the maximum of the age range for a given fuel type; RangeMinimum is the minimum of the age range for the same fuel type; and SppCoefficient is a user specified weight (0–1.0) that can be assigned to each species (default = 1.0). Equation 1 assumes that species dominance is related to cohort age. The SppCoefficient provides flexibility in determining the influence of a particular species on fire spread rates. For each species, RangeMaximum is truncated to the species longevity if it exceeds longevity.

For the Dynamic Biomass Fuel Extension, species biomass is substituted into Eq. (1):

$$\text{SpeciesValue} = \sum \text{CohortBiomass} \times \text{SppCoefficient} \in \text{AgeRange} \quad (2)$$

where CohortBiomass is the aboveground live biomass (kg ha^{-1}) of all cohorts that falls within the defined age range. For each fuel type, species values are summed if they are associated with the fuel type. Species not typical of a given fuel type can be assigned negative species values. The fuel type with the highest overall score is assigned to the cell, where ties are broken by the order in which fuel types are listed in the input file. This method allows the user to rank order fuel type preference when conditions are ambiguous. Cells without any assigned fuel type cannot burn. As an example, if 30-year cohorts of jack pine (*Pinus banksiana*) and black spruce are present on a site, falling into young jack pine (age range 0–40) and black spruce (age range 0–300), respectively, the SpeciesValue estimated by the Dynamic Fuel Extension would be 0.75 and 0.1 for jack pine and black spruce, respectively, and the fuel type for the site would be classified as young jack pine (assuming the SppCoefficient for each species was set to 1). Fuel type classified by the Dynamic Biomass Fuel Extension would depend on which species had the largest biomass value.

The two fuel extensions provide additional user-defined options to assign fuel types. Percent conifer and deciduous are used to assign cells to fuel types that are purely coniferous, purely deciduous, or mixed fuel types with a weighted mixture of both. Weighted mixtures are only applied to mixed conifer–deciduous fuel types based on the empirical relationships from the Canadian FBP (Forestry Canada Fire Danger Group, 1992). Default fuel types may be assigned to non-vegetated cells (e.g., following recent disturbance) and to represent non-forest community types, such as grasses or wetlands. Specific fuel types can also be assigned for a set duration (years) following disturbance events, such as a slash type following harvesting or an open type following severe fire. Disturbance-specific fuel types, including wind, fire, and harvesting, override the fuel types assigned based on vegetation (Fig. 1). Fuels generated by insect disturbances are handled separately using a dead conifer index calculated from the Base Biological Disturbance Agent (BDA) extension (Sturtevant et al., 2004a). The dead conifer index (0–100) is based on the total number of dead conifer cohorts relative to the current total number of cohorts at each cell. A dead conifer index value greater than zero changes the spread rate for any conifer, conifer plantation, and mixed fuel type.

2.3. Dynamic Fire System extension

The Dynamic Fire System extension (v 1.0, referred to hereafter as “dynamic fire extension”) was designed to capture fire frequency, fire behavior (i.e., fire spread) and fire effects (mortality) based on fuel type(s) and weather. The landscape is divided into fire regime units (FRUs) which are associated with fire frequency and fire weather. FRUs may be defined variously, including but not limited to ecoregion maps, as well as human fire management districts, human ignition sources, and fire weather characteristics.

2.3.1. Fire frequency

Fire initiation follows the hierarchical fire frequency model of Yang et al. (2004) that divides fire occurrence into two separate events: fire ignitions (i.e., first instance of a fire) and fire initiation (likelihood a fire ignition will burn an entire cell). At each time step, the number of fire ignitions is drawn for each FRU from a Poisson distribution with an average number of ignitions (λ) equal to the expected number of ignitions per unit area (Van Wagner, 1978; Yang et al., 2004). For each ignition, the dynamic fire extension randomly selects a cell from the given FRU, and evaluates whether the fire ignition starts a fire event by comparing a uniform random number with the initiation probability of the fuel type present on that cell. Fire ignition rates (number of fires per year) are parameterized independently by FRU, and also stratified by burn season (see Section 2.3.3).

2.3.2. Fire size

Until recently (Yang et al., 2008), former versions of LANDIS used a size-based fire regime, i.e., once a fire was initiated, a fire size was randomly selected from a distribution and the fire spread until it either reached that size or ran out of cells that can burn (He and Mladenoff, 1999). The dynamic fire extension provides two options for fire regimes—size-based and duration-based. Each method estimates a minimum cumulative fire travel time from the ignition point to new cells based on cell to cell rates of spread estimated as a function of fire weather, wind speed and direction, fuel type, and topography (see Section 2.3.4). When the size-based option is applied in this fire extension, a fire size is first randomly selected from a user-defined lognormal distribution. Burned cells for the event are selected in order of increasing travel time until the number of cells selected multiplied by the cell area equals or exceeds the predetermined fire size.

Alternatively, the extension can randomly select a fire duration from a given distribution. Using a distribution of fire durations distribution rather than a fire size distribution to simulate a fire regime allows the fire regime to respond dynamically to changes in landscape fuel composition and configuration (Pennanen and Kuuluvainen, 2002; Didion et al., 2007). When the duration-based option is applied, all cells with a minimum cumulative travel time that is less than or equal to the predetermined fire duration are selected to become the burned area for that individual fire event. Fire duration in this sense refers to the period over which a fire is actively spreading (*sensu* Anderson et al., 2002).

Both fire sizes (size-based option) and fire durations (duration-based option) are assumed to follow a lognormal distribution, with parameters μ (mean of the natural logarithm), σ (standard deviation, also of the natural logarithm), and maximum (size or duration), where minimum size or duration is assumed to be zero. Size units are in hectares and duration units are in minutes. Regardless of the option used, fire regimes are parameterized separately for each FRU. Size-based fire regimes are generally parameterized from historic fire records. However, fire durations are rarely recorded and often must be translated from fire size data. For example, a fire regime may be applied to a study landscape using the size-based option, and durations from simulated fire events may be used to parameterize a duration distribution. Alternatively, the duration distribution can be estimated by iteratively changing μ and σ to calibrate to the fire regime to a known fire size distribution. While fire duration data may be used directly where data exist, care must be taken to limit fire durations to active fire-spread periods (Anderson et al., 2002).

Fires that spread from one FRU into another can affect the integrity of the individual fire regimes. The fire size distribution of the FRU is therefore preserved by adjusting the spread rates by the ratio of the mean fire size or duration of the new FRU to relative to where the fire started. For a size-based fire regime:

$$\mathrm{FRUA}_i = \frac{\mathrm{MFS}_i}{\mathrm{MFS}_{\mathrm{init}}} \tag{3}$$

For a duration-based fire regime:

$$\mathrm{FRUA}_i = \frac{\mathrm{MFD}_i}{\mathrm{MFD}_{\mathrm{init}}} \tag{4}$$

For a particular fire event, rates of spread for each cell in FRU i are recalculated as:

$$\mathrm{ROS}_i = \mathrm{ROS} \times \mathrm{FRUA}_i \tag{5}$$

This adjustment causes fires to burn relatively more area within fire prone units than fire resistant units for a given fire event. However, the original spread rates (i.e., uncorrected for the new FRU) are used to calculate potential fire severity (see Section 2.3.5).

2.3.3. Fire weather

The dynamic fire extension requires weather data listing daily records of wind speed velocity (WSV, km/h), wind direction (degrees), fine fuel moisture code (FFMC, unitless), buildup index (BUI, unitless), and fire weather class (defined below) by FRU and season. FFMC and BUI are indices calculated separately and are derived from the Canadian Forest Fire Weather Index System (Van Wagner, 1987). Three burn seasons are defined as spring (leaf-off, following snow melt but prior to leaf emergence), summer (leaf-on, following leaf emergence and prior to leaf senescence), and fall (leaf-off, following leaf emergence and prior to snow-fall). Fire weather is held constant for a given fire event and represents weather conditions for daylight hours, often the period of most active fire growth (Rothermel, 1983). Weather data can be updated at any time step, allowing the simulation of climate change effects. Larger or longer duration fires may occur if fire weather is more favorable for burning (Bessie and Johnson, 1995). The dynamic fire extension allows the user to define the relative strength of the correlation between fire size (or duration) and fire weather class (weather randomizer; Appendix A).

2.3.4. Fire spread

The dynamic fire extension determines individual fire sizes and shapes using spread equations adapted from the Canadian FBP (Forestry Canada Fire Danger Group, 1992) and an adaptation of the minimum travel time method described by Finney (2002), combined with the predetermined fire size or duration selected from the distribution defined in Section 2.3.2. Equations directly from the Canadian FBP are listed in Appendix B and briefly summarized here. Fuel-type specific parameters are summarized in Appendix C. Spread rate calculations begin with initial spread index (ISI) based on Van Wagner (1987), which is a fuel-independent spread index calculated as a function of WSV in the downwind direction and FFMC. Topography influences spread rates analogously to wind, so the effects of topography on spread are modeled as the wind speed

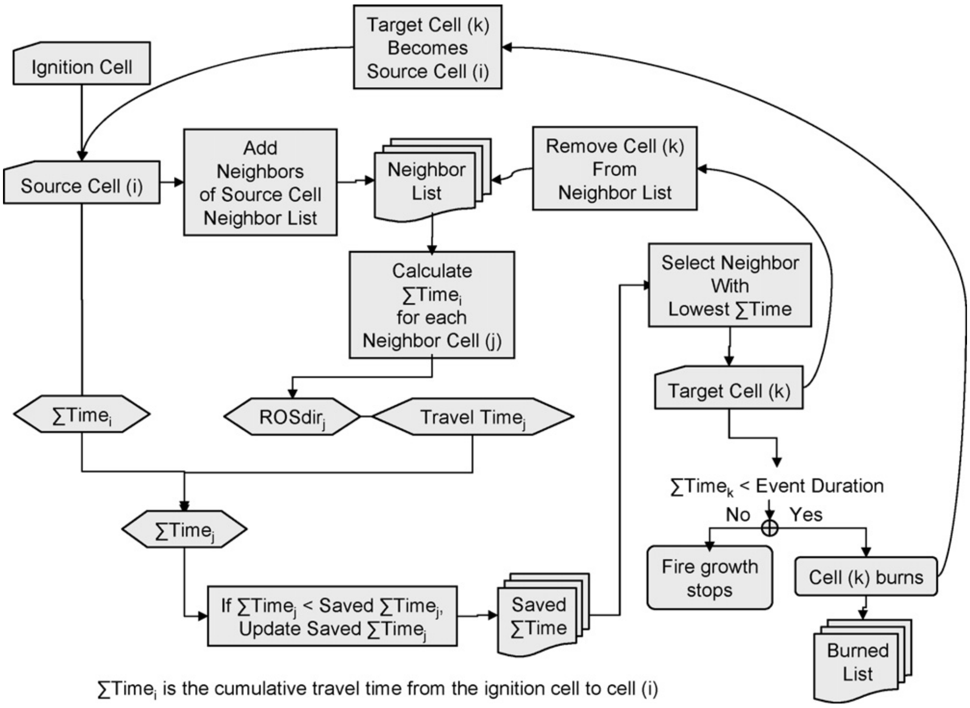

Fig. 2. Flow diagram for the fire spread process. $\sum$Time$_i$ is the cumulative travel time from the ignition cell to cell (i). ROSdir is the rate of spread in the direction of travel between source cell$_i$ to neighboring cell$_j$.

equivalent (WSE) of slope, which is the effect the percent slope would have on the rate of spread if it were a wind speed (Appendix B). When the topography option is selected, WSE is added to the wind speed using vector addition to combine the wind and slope effects. The net effective wind speed and the resulting maximum spread direction are used in place of WSV and wind direction for all subsequent calculations involving a wind speed or direction, including ISI.

The initial rate of spread (RSI) for each fuel type is also calculated using Canadian FBP equations (see Appendix B). Mixed fuel types include those affected by recent insect disturbance and mixed conifer–deciduous types, where mixed fuel types and deciduous types are also affected by burn season (i.e., leaf-on and leaf-off seasons). Spread rates for cells affected by insect disturbance are calculated using the percent dead conifer from the fuel extension. RSI for mixed conifer–deciduous fuel types are estimated as the average RSI for the conifer and deciduous types selected by the fuel extension, weighted by their respective percentages within the cell. RSI in open fuel types is dependent on the degree of curing (i.e., the percentage of dried stems) parameterized by burn season, and may be used to control the seasons over which open types such as grasslands and wetlands can burn. BUI may optionally modify spread rates to account for longer time lags (i.e., 10-day) in fuel moisture. The influence of BUI on rate of spread is dependent on the fuel type, and is expressed as the buildup effect (BE; see Appendix B). The maximum rate of spread (ROS$_{max}$) is the product of RSI and BE and represents the "downwind" rate of spread in the maximum spread direction. Crown fire behavior affecting rates of spread is accounted for within the empirical spread functions of the Canadian FBP with the exception of conifer plantation fuel types that require parameters on crown base height to estimate rates of spread (see Appendix B).

The direction of travel for a fire front changes in response to heterogeneous fuels and topography and the presence of non-forested (barrier) cells. The dynamic fire extension accounts for this behavior by iteratively calculating a cumulative time required to travel from the ignition source to a given cell based on local cell to cell spread, and then retaining the minimum travel time for each cell. The process starts by first calculating the critical dimensions of an ellipse where the rear focus is the center of the source cell, and the perimeter of the ellipse crosses at the center of an adjacent (target) unburned cell. The length-to-breadth ratio (LB) for each local ellipse is determined by the local net effective wind speed (i.e., the combination of wind and slope) using FBP equations (see Appendix B). The rate of spread from the source cell to the target cell is then estimated by first solving for the distance traveled in the maximum direction of spread using the polar equation for an ellipse, calculating fire travel time for that distance based on ROS$_{max}$, and then dividing the distance between cell centers by the estimated fire travel time to estimate a directional ROS (ROS$_{dir}$) distance per unit time. The cumulative travel time from the ignition cell (point of origin) to the target cell is retained within a temporary list until the target cell has burned based on the minimum time travel pathway, described below.

The fire spread algorithm first minimizes the total travel time by choosing neighbors with the lowest travel time from each source; during this first pass, an adjacent neighbor serves as the source. Subsequently, travel time is recursively minimized (up to 2000 recursions) by minimizing the total travel time from the ignition point to each cell subsequently burned (Fig. 2). Recalculation of travel time is halted when travel time improves by less than half a minute. Initially, an area 1.5 times greater than the selected area (or alternatively, a travel time 1.5 times greater than the selected duration) is assigned travel times. The selected area is subsequently reduced by discarding the values with the longest durations. A fire may extinguish prematurely if no potentially burnable cells remain within the neighborhood of any burned cells.

Fire shapes are affected by grid artifacts when fire spread is limited to eight neighboring cells. We correct for these spatial artifacts by stochastically varying the wind direction within a range of ±22.5 degrees. This additional variability in wind direction results in elliptical spread patterns within homogeneous fuel types, but because the rate of spread function is not linear with respect to direction, it also introduces a bias in spread rate that reduces the ROS_{max}. The average amount of bias over a large number of samples that would be caused by the introduced variability can be estimated mathematically. First, solve for the rate of spread in terms of β (i.e., the angle between the wind direction and the direction of spread between cell centers). The average adjusted rate of spread is then estimated by evaluating the integral of the equation over the range of possible β values (±22.5 degrees). The average bias is estimated as the ratio of the average adjusted rate of spread over the initial rate of spread for the true β value. The average bias is used as a correction-factor to keep the average rate of spread after adjustment the same as the unadjusted rate of spread.

2.3.5. Fire effects

Within the first LANDIS model, simulated fire disturbances applied a simple relationship between time since the previous fire and fire intensity when a cell burned (He and Mladenoff, 1999). The dynamic fire extension uses equations from the Canadian FBP (Forestry Canada Fire Danger Group, 1992) to estimate crown fraction burned (CFB) as an indicator of potential fire severity. Analogous to previous fire modeling approaches in LANDIS, actual fire severity (i.e., the combination of cohorts killed and those that survive) depends on the tree species cohorts present on the cell and their relative susceptibility to fire. Crown-fraction burned is estimated using a combination of ROS_{dir}, foliar moisture content (FMC), and fuel-type specific parameters defining crown base height and surface fuel consumption for each cell burned during a given fire event (see Appendix C). FMC is parameterized for each season and FRU and may be calculated from geographic location (latitude and longitude), elevation, and Julian date (Forestry Canada Fire Danger Group, 1992, Equations 1–8). Two FMC values may be defined for each season because phenology-based seasons do not necessarily coincide with the seasonality of FMC. For example, the “spring dip” in FMC associated with elongation of conifer shoots often overlaps with the transition between spring “leaf-off” and summer “leaf-on” periods (Johnson, 1992). If FMC is divided into subseasons, then proportions of fires for each subseason must also be assigned.

Potential fire severity is an integer index ranging from 1 to 5, with 1 being the least severe and 5 being the most severe. Potential severity classes 1 and 2 assume surface fire behavior, defined when CFB is less than or equal to 0.1, and where ROS_{dir} below this threshold in CFB is divided evenly into the 2 classes. Potential severity class 3 assumes torching fire behavior, defined when CFB is greater than 0.1 but less than 0.5. Potential severity class 4 assumes intermittent crown fire behavior, defined when CFB is greater than or equal to 0.5 but less than 0.9. Potential severity class 5 assumes running crown fire behavior, defined when CFB is greater than or equal to 0.9. If potential (in this case actual) fire severity is 5, then all cohorts of all species will be killed. For lower potential severity classes, species cohort mortality is dependent upon the age of the cohorts present on a given cell and the fire tolerance of each species, where youngest cohorts are most vulnerable (He and Mladenoff, 1999). For each species, the difference between the potential fire severity class and fire tolerance class is calculated. The difference determines which cohorts are killed; all cohorts below an age threshold will be killed, where the relative age threshold is a user-defined parameter defined as a percent of species longevity. The fire log records the mean potential fire severity as the average of the potential severities at all of the cells within the burned area for a given event.

User's guides and source code for the Dynamic Fire System extension are available online at http://www.landis-ii.org, with an overview flow diagram shown in Fig. 3.

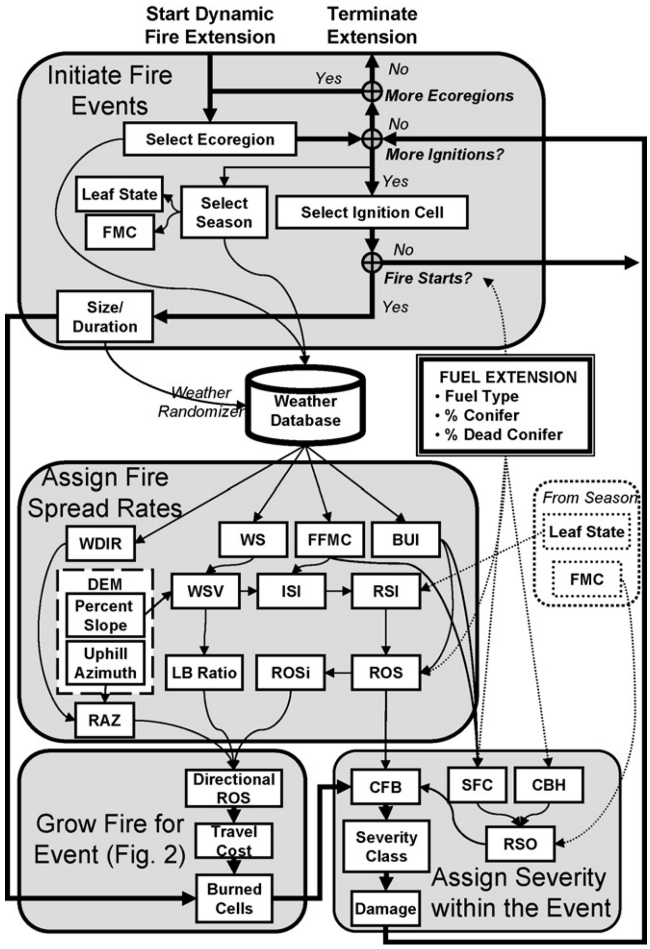

Fig. 3. Dynamic Fire Extension flow diagram. Abbreviated variables are defined in Table A1 in Appendix B.

2.4. Test cases

Test cases for the dynamic fire and fuel extensions represent very different ecosystems, one in a boreal forest of central Labrador (Canada) and the other within a mid-elevation mixed conifer forest of Sierra Nevada Mountains in the Western United States (Fig. 4).

2.4.1. Labrador

The Labrador test case is located within a high boreal system dominated by black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*) (Forsyth et al., 2003). Spruce-fir stands are embedded within a diverse mosaic of open sphagnum forest, lichen woodlands, black spruce bogs, lakes, open wetlands, and scattered mixed hardwood stands (*Betula* spp., *Populus* spp.). Fire is the dominant natural disturbance, though fire is both less prevalent and less intense relative to more continental regions further south and west (Simard, 1973). Topography is characterized by moderate relief underlain by glacial moraines and drumlins (Roberts et al., 2006). Climate is cold with long harsh winters and annual precipitation averaging between 900 and 1100 mm (Roberts et al., 2006).

For the Labrador test case we contrasted a duration-based fire regime implemented with the new dynamic fire and fuels extensions with a size-based fire regime implemented with the Base Fire extension (v1.2) derived from the original LANDIS model (He and Mladenoff, 1999). In the Base Fire extension fire initiations are probabilistic functions of FRUs and time since last fire. Fire events are selected from a lognormal size distribution and events spread prob-

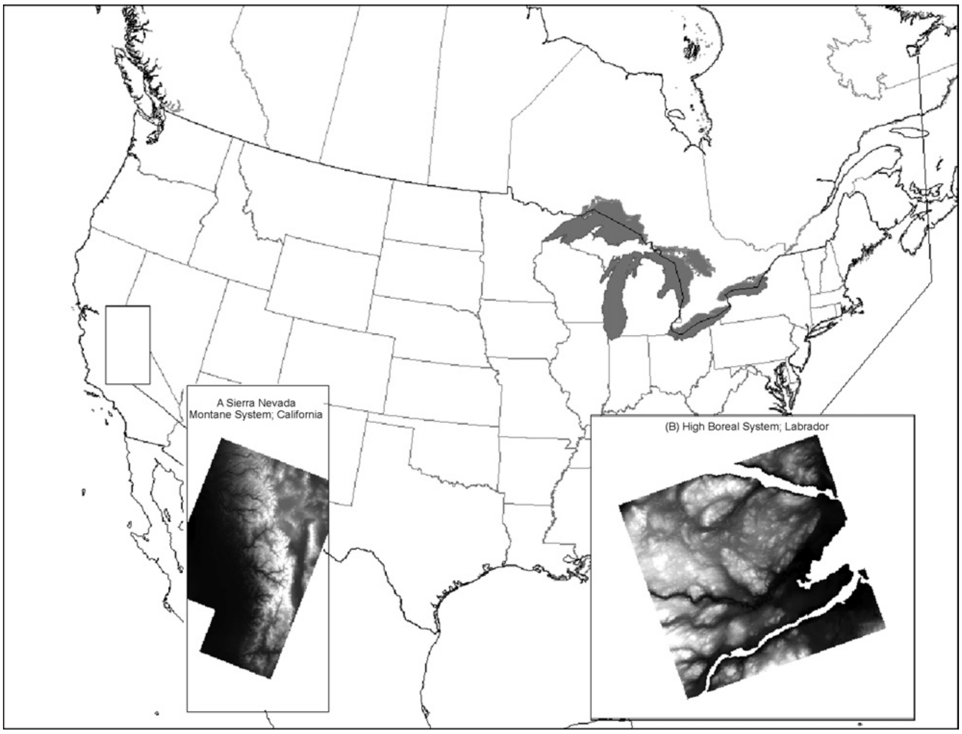

Fig. 4. Study area locations for (a) the Sierra Nevada (elevation range: 31–4409 m) and (b) central Labrador (elevation range: 0–469 m), showing topographic relief.

abilistically until either the preselected size has been reached or the fire runs out of cells to burn. Fire regimes for each extension were parameterized using the same fire size data (Table 1). Fire intensity curves for Base Fire were parameterized analogously to the dynamic fire and fuel extensions, such that the mean potential fire severity was similar.

2.4.2. Sierra Nevada

The Sierra Nevada test case represents a mid-elevation, mixed coniferous forest landscape within the Sierra Nevada Mountains of the western United States (Fig. 4). The study area includes portions of the Sierra, Sequoia, and Stanislaus National Forests and Yosemite and Sequoia-Kings Canyon National Parks. The area ranges in elevation from 31 to 4409 m (102–14,456 ft) and is primarily composed of federally owned lands. The climate is generally Mediterranean and the majority of precipitation occurs as snow in the winter, and the fire season occurs in the summer and fall.

For the Sierra Nevada test case, we applied two contrasting weather regimes—one representing the recent past (base weather) and a second where only the most extreme fire weather (i.e., above the 90th percentile of FWI) from the base weather records were used (extreme weather). Using only these records in the simulations allowed the model to naturally respond to weather conditions that were more "severe." We stratified the study area into three primary FRUs that reflect the effect of elevation (or, moisture) on regional fire regimes (Agee, 1993), including lightning ignitions (van Wagtendonk and Fites-Kaufman, 2006) The FRUs included low (up to 1190 m), medium (~1190–2120 m), and high (above 2120 m) elevations. These FRUs roughly correspond to the foothill shrubland and woodland, lower montane forest, and upper montane forest ecological zones in the region (van Wagtendonk and Fites-Kaufman, 2006).

Methods for the parameterization of the dynamic fire and fuel extensions for each test case are provided in Appendix D. Methods for parameterization of the succession extension can be found in Simon et al. (2006) and Sturtevant et al. (2007) for the Labrador test case and in Syphard et al. (in press) for the Sierra Nevada test case. For each test case we contrasted responses to alternative scenarios using the cumulative area burned, the proportion of fuel types burned, and spatial patterns of fire frequency averaged over replicate simulations (Labrador = 5, Sierra Nevada = 10). Labrador replicates represent 500-year simulations using a 10-year time step. Sierra Nevada replicates represent 50-year simulations using a 5-year time step.

Table 1
Fire regime target outputs and input parameters for Labrador and Sierra Nevada.

Target outputs	Description	Labrador	Sierra Nevada		
		All FRUs[a]	Low	Mid	High
MFS	Mean fire size (ha)	1146	401	513	577
STD_FS	Standard deviation fire size (ha)	4721	4788	2822	4789
Fire rotation	Mean fire rotation (years)	352	90	140	120
Parameters					
mu	Mean of the lognormal duration distribution ln(min.)	6.80	5.15	4.95	5.36
Sigma	Standard deviation of the lognormal duration distribution ln(min.)	0.78	0.80	0.95	0.9
Max duration	Maximum fire duration (min.)	5760	2000	4500	4500
Ignition rate	Number of ignitions per decade	6.89	16300	2750	8500

[a] Fire regime unit.

2.5. Sensitivity and uncertainty analyses

We performed a standardized sensitivity analysis on fuel-specific input parameters for the dynamic fire and fuel extensions for each test case: three parameters defining individual fuel spread rates (a, b, and c); two parameters defining the build-up effect (q and BUI_0), and fuel-specific ignition rates. Spread rate parameters are used in the following equation:

$$RSI = a \times [1 - e^{(-b \times ISI)}]^{c} \quad (6)$$

where RSI is the initial rate of spread in the downwind direction, and ISI is the initial spread index that is a function of fuel moisture and wind speed (Forestry Canada Fire Danger Group, 1992, Appendix B). The build-up effect (BE) is a multiplier affecting the rate of spread that accounts for long-term fuel moisture, estimated using the following equation:

$$BE = e^{[50 \times \ln(q) \times ((1/BUI) - (1/BUI_0))]} \quad (7)$$

where BUI is the build-up index (Forestry Canada Fire Danger Group, 1992, Appendix B). Fuel-specific parameters are listed in Appendices C and D for Labrador and Sierra Nevada test cases, respectively. Each variable was varied ±10%, simultaneously applied to all fuel types. Response variables included potential fire severity and fire rotations averaged across five replicate simulations of 50 and 200 years for Sierra Nevada and Labrador, respectively. Potential fire severity was estimated in two ways—the mean potential severity when averaged across fire events, and the mean potential severity when averaged across all cells burned. Mean potential severity of fire events gives more weight to small fires that are more common, whereas area-weighted potential fire severity gives more weight to large fires that, while rare, represent the greatest proportion of area burned. Sensitive parameters were indicated where the response variables indicated greater than 10% difference relative to the base scenario.

The dynamic fire extension allows the user to define the degree of correlation between fire weather and fire duration (or size) as well as a maximum fire duration (or size) for a given fire regime. Fire duration distributions inferred from fire size data may be sensitive to these assumptions. We evaluated the influence of these two assumptions, as well as their interactions, on simulated fire behavior by comparing fire regimes across a range of each assumption as a factorial experiment applied to both case studies. Each assumption has three levels (i.e., weather and duration can be random, semi-coupled, or coupled, and maximum fire durations = 4, 25, or unlimited days) resulting in nine unique combinations. We applied ANOVA to the same three response variables examined in the sensitivity analyses for ten replicate simulations of 50 and 200 years for Sierra Nevada and Labrador, respectively.

3. Results

3.1. Labrador case study

Comparison of the two fire extensions (simple vs. dynamic) applied to the Labrador landscape revealed little difference in the average area burned per decade, and neither extension showed any long-term trend in area burned over a 500 year period (Fig. 5a and b). Variability of fires differed substantially, with much greater variation in decadal area burned using the dynamic fire extension. Nonetheless, simulated fuel type composition averaged across the five replicates was similar between the two extensions (Fig. 5c and d), though the fuel type proportions were more variable when influenced by the dynamic fire extension, corresponding with greater variability in decadal area burned. Consistency in the temporal pattern in fire and vegetation within each of the two fire extensions suggests that the vegetation is in equilibrium with a historic fire regime.

The two extensions differed substantially in the frequency at which different fuel types burned (Fig. 6). The simple fire extension burned fuel types at similar frequencies. Though deciduous and open fuel types burned proportionately less in the simple extension, the difference among fuel types was slight compared to the differences in fuel types burned by the dynamic fire extension, where conifer and bog fuel types burned at a proportionately higher

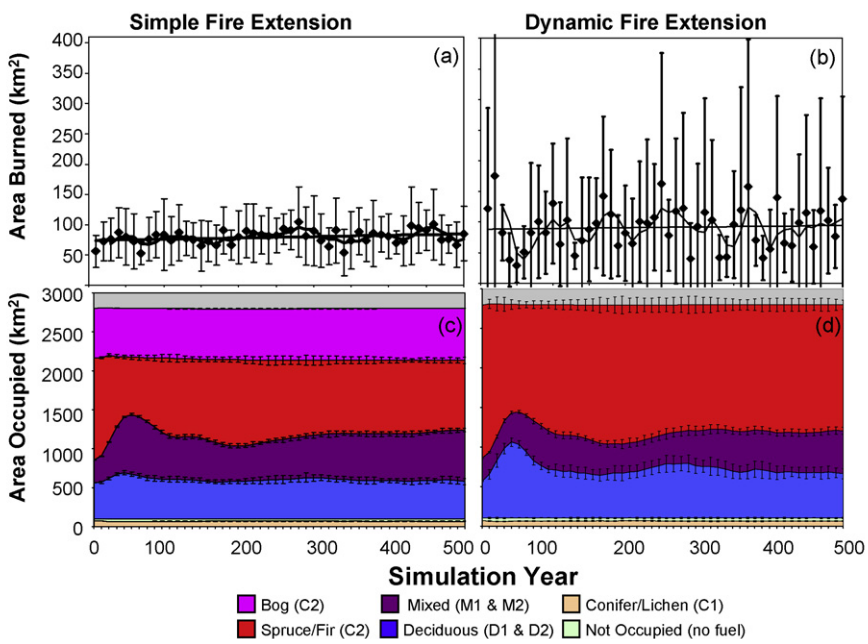

Fig. 5. Comparison between the simple fire extension (empirical size distribution) and the dynamic fire extension (duration-based) applied to the Labrador study area for area burned and area occupied by fuel type. Error bars indicate one standard deviation of the mean based on five replicates for each extension. Trend lines for area burned represent the linear trend for the entire simulation (straight lines) and localized trends averaged over three decades. “Bog” and “Spruce/Fir” cover types use the same fuel model (C2) and are therefore not distinguished in the output from the dynamic fire extension (shown here in red).

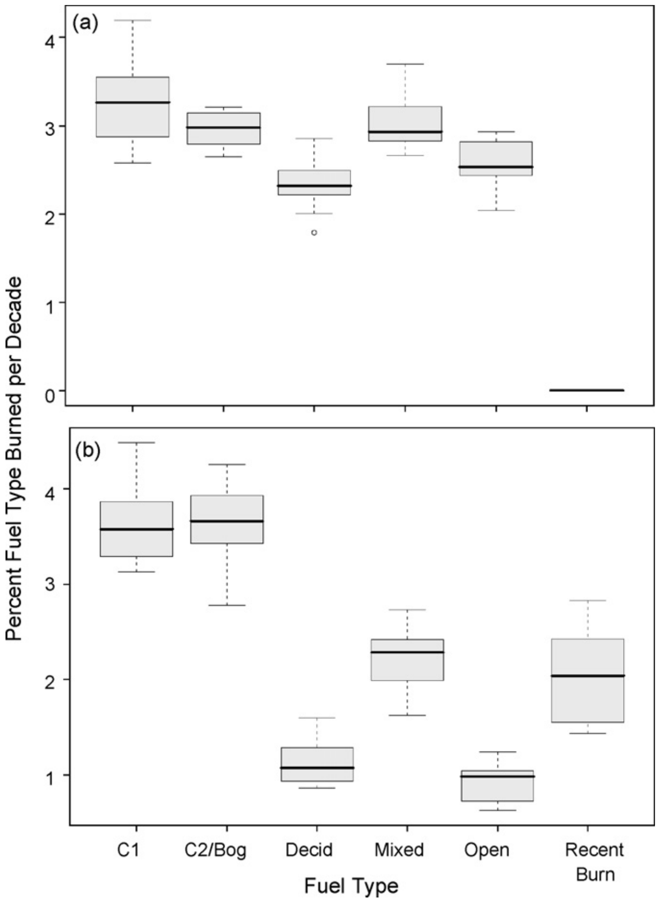

Fig. 6. Differences in the percentages of each fuel type burned between the (a) simple fire extension and (b) dynamic fire extension, when applied to Labrador. Standard Tukey box plots are based on five replicates.

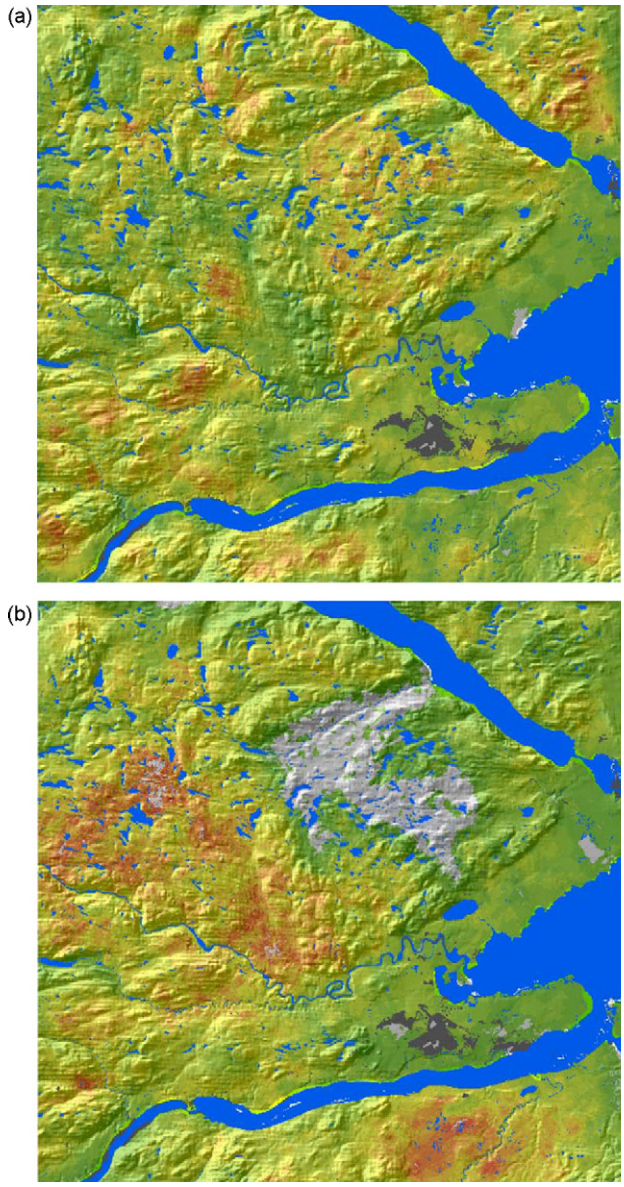

Fig. 7. Spatial differences in the cumulative area burned between (a) the simple fire extension, and (b) the dynamic fire extension applied to Labrador. Warmer colors burned more often than green shades, and gray areas never burned during any of five replicate simulations of 500 years. The large gray area in b corresponds with a persistent deciduous patch.

rate. This difference in simulated fire behavior resulted in different spatial patterns of burn frequencies across the landscape. Burn frequency patterns created by the dynamic fire extension were much more heterogeneous than those simulated by the simple fire extension (Fig. 7). For example, a large and persistent deciduous region near the center of the study landscape remained largely unburned across the replicate simulations using the dynamic fire extension. Presumably the area was large enough that later successional conifer species could not fully colonize it. The simple model, by ignoring spatial pattern in fuels, was not influenced by this type of spatial legacy.

3.2. Sierra Nevada case study

The Sierra Nevada case study demonstration focused on the effects of three factors (weather regimes, fuel types, and topography) on cumulative burn patterns. Comparison of two weather regimes showed that the more extreme weather regime – a coarse approximation of potential climatic changes – decreased fire rotation periods indicating a larger area burned relative to the current weather regime (Fig. 8). However, the degree of influence from the more extreme weather regime varied by FRU. The decrease in fire rotation due to weather was strongest within the mid-elevation and high-elevation FRUs, which were dominated by large, contiguous areas of conifers. On the other hand, the lower elevation FRU was dominated by more fire-prone oaks and chaparral and experiences more frequent, human-caused ignitions. Because fire rotation is already relatively low in the low-elevation FRU, there is less potential for additional fire due to an altered weather regime.

Due to the large area simulated (low-elevation FRU = ~825,000 ha, mid-elevation = ~875,000 ha, high elevation = ~600,000 ha), there was broad variation in fuel types within each FRU. This variation in fuel type properties resulted in large variation in the percentage that each fuel type burned (Fig. 9; current weather only). In contrast to the effects of weather, variation due to fuel type was much larger at lower elevations compared to the mid or higher elevations. Topography is also steep and complex within the Sierra Nevada and has a potentially large influence on fire behavior (Agee, 1993). While the dynamic fire extension cannot accurately capture – nor was intended to capture – active fire behavior, we expected to see appropriate patterns of landscape fire frequency (i.e., largely corresponding to topography) over the longer time scales for which LANDIS-II is typically deployed. Visually examining an area with relatively high frequency fires (Fig. 10), we observed patterns of fire behavior consistent with expectation. Areas with relatively gentle slopes

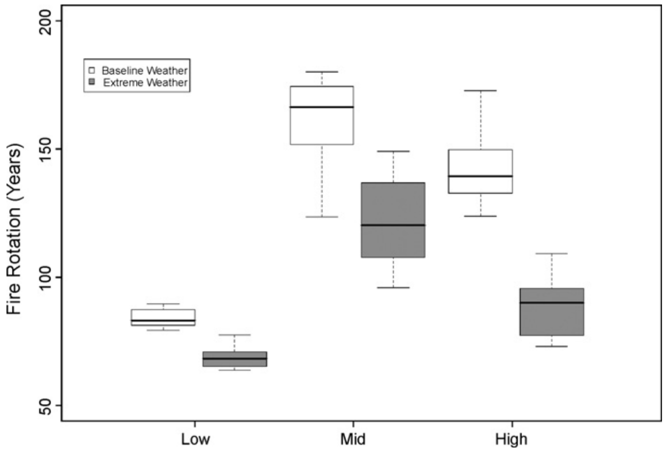

Fig. 8. Differences in fire rotations when fires are simulated using current weather values, (white) and weather representing a warmer climate (gray) for each of three fire regime units of the Sierra Nevada. Standard Tukey box plots are based on ten replicates.

burned most frequently. Areas with steep slopes (within steep valleys and along riparian corridors) burned less frequently. This behavior was seen when fires traveling down slope (down hill in the direction of the prevailing winds, typically from the west) spread at a lower speed and therefore often served as slope 'fire

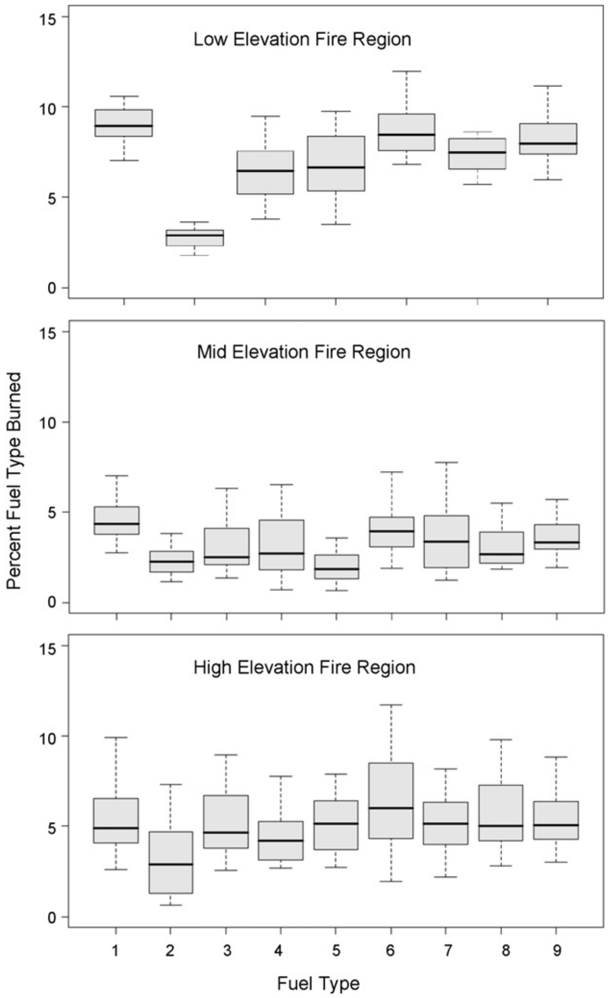

Fig. 9. Differences in the percentage of fuel types burned in each of three fire regime units for the Sierra Nevada. Standard Tukey box plots are based on ten replicates.

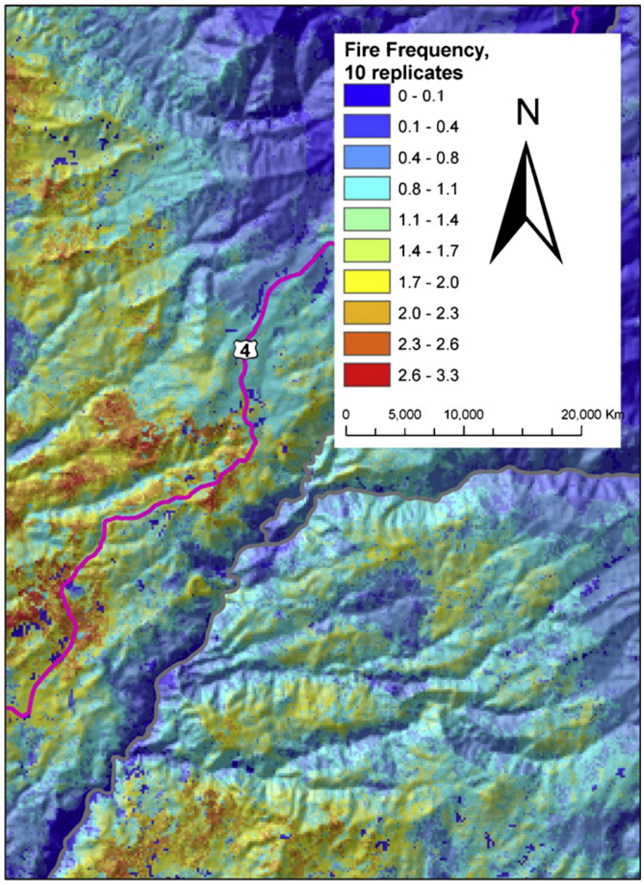

Fig. 10. Spatial patterns in the cumulative area burned based on ten replicate 50-year simulations for the Sierra Nevada study area, using the extreme fire weather scenario. Warmer colors burned more often than green shades, and gray areas never burned during any of five replicate simulations.

breaks' whereby the duration of an individual fire was reached while slowly burning down slope. Although the region's climate, vegetation and fuel types, and fire distribution broadly correspond with the elevation belts that are distinguished through the three FRUs (van Wagtendonk and Fites-Kaufman, 2006), the visually apparent association between fire frequency and topographic pattern cannot be explained by the patterns of our initial fuel types, which generally did not closely follow fine-scale topography (with the exception of rare inclusions of deciduous types along rivers). By comparison, topography had minor influence on fire frequency patterns in Labrador, where topographic relief was lower (Fig. 7).

3.3. Sensitivity and uncertainty analyses

Sensitivity results indicate that fire rotations are moderately sensitive to some fuel-specific parameters. A 10% change in ignition probability and the three parameters (a, b, and c) affecting the curvilinear relationship between fire spread and weather resulted in generally larger average change in fire rotations relative to other parameters across both study areas (Fig. 11). Fire rotations were sensitive to a small decrease in ignition probability in Labrador, but they were insensitive to this change in the Sierra Nevada. In both study areas, fire rotation was relatively insensitive to parameters affecting fuel-specific response to the build-up effect (i.e., BUI_0, and q). Changes in potential fire severity were small, and therefore insensitive, in response to changes in the above fuel parameters (results not shown).

ANOVA indicated that fire rotations in both study areas were sensitive to the parameterized degree of correlation between fire

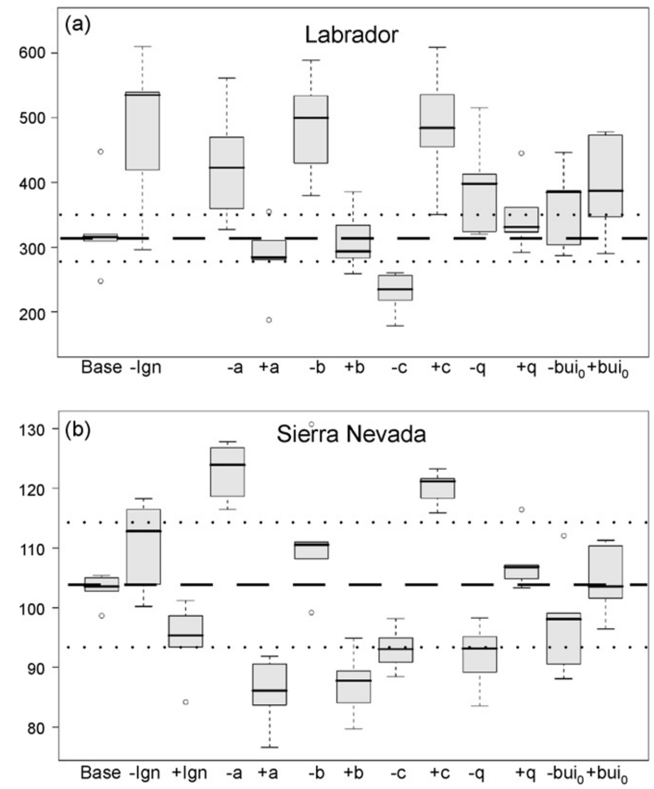

Fig. 11. Sensitivity analysis for fuel-specific parameters applied to the fire rotations for both (a) Labrador and (b) Sierra Nevada. The "Base" simulations refer to parameterization applied during this study. The remaining comparisons represent individual parameters increased (+) or decreased (−) by 10%. Individual parameters were adjusted simultaneously across all fuel types. Fuel ignition probabilities in Labrador were assumed to be identical and equal to 1, therefore Ign+ was not included in the sensitivity analysis for that study area. Dashed line represents the average fire rotations estimated for the Base simulations, and dotted lines represent ±10% change from the mean. Standard Tukey box plots are based on ten replicates.

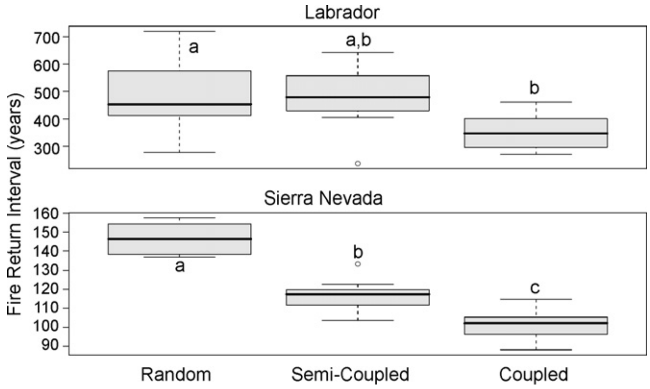

Fig. 12. Uncertainty analysis results showing the consequences of the relative correlation between weather variables and fire duration for both Labrador and the Sierra Nevada. Fire durations were coupled with the build-up index (BUI) for Labrador, and the fire weather index (FWI) for the Sierra Nevada. Simulations were not sensitive to the maximum fire duration cut-off, so results are shown for a maximum duration cut-off of four days. Factor levels with different letters were significantly different at $\alpha = 0.05$. Standard Tukey box plots are based on ten replicates.

weather and fire size, where increasing the degree of correlation (i.e., relative coupling) between fire duration and fire weather increased fire size and therefore reduced fire rotation (Labrador: $F = 9.7$, $p = 0.0002$; Sierra Nevada: $F = 189.2$, $p < 0.0001$; Fig. 12). In Labrador mean potential fire severity, when averaged across fire events, was not affected by degrees of fire weather correlation ($p > 0.05$). Area-weighted potential fire severity slightly increased with increasing correlation between fire duration and fire weather ($F = 4.2$, $p = 0.018$). By contrast the Sierra Nevada fires burned with increasing potential severity as the correlation between fire weather and fire duration increased, regardless of how mean potential fire severity was calculated (mean potential severity of events: $F = 18.6$, $p < 0.0001$; mean potential severity of burned cells: $F = 41.63$, $p < 0.0001$, respectively). None of the dependent variables in either of the study areas were significantly affected by maximum fire duration ($p > 0.05$). Examination of simulated fire durations for both study areas revealed that the maximum fire durations rarely exceeded four days in the Sierra Nevada and seven days in Labrador, explaining this lack of sensitivity.

3.4. Discussion

A large variety of published FLSMs and other landscape models are now available to address a broad array of questions centered on the spatiotemporal interactions between disturbances and forest vegetation, and the majority of those models have focused on fire-vegetation questions (Keane et al., 2004). Despite the large diversity of published FLSMs, the LANDIS model and its derivatives remain among the few that track individual tree species such that successional pathways are neither predefined nor deterministic (Keane et al., 2004; Scheller and Mladenoff, 2007). This design provides flexibility to investigate a wide array of forest vegetation-disturbance interactions that can be sensitive to tree species composition, including not only fire but also insect disturbance and forest management (Frelich and Reich, 1995; Radeloff et al., 2000; Raffa et al., 2008). Over time, fire-related questions to which LANDIS models have been applied have become increasingly complicated, including understanding how alternative vegetation or fuel treatments affect fire risk (Gustafson et al., 2004; He et al., 2004), how climate change might affect interaction between fire and succession (He et al., 2002; Xu et al., 2009; Gustafson et al., in press), and how anthropogenic land use and activities affect fire regimes (Syphard et al., 2007; Sturtevant et al., 2009). The new dynamic fuel and fire extensions described in this paper were designed with these more sophisticated questions in mind.

FLSMs have both commonalities and differences in their approach and level of detail when simulating fire spread, behavior, effects, and regime characteristics (Keane et al., 2004). Many FSLMs offer realistic spread that responds to moisture, wind, fuel types, and topography (Cary et al., 2006). Most such FSLMs, including LANDIS-II, apply simplifying assumptions to focus on long-term trends in fire patterns (Keane et al., 2004) rather than hourly behavior of fire—the domain of fire behavior models such as FARSITE and PROMETHEUS (Finney, 1998; Tymstra, 2002; Tymstra et al., 2009). This strategy effectively scales decades of research in fire behavior to landscape-scale phenomena, and it reflects a scale and range of conditions over which fire behavior has typically been quantified (i.e., within a patch and between patches). However, this approach will largely fail to reflect fire behavior that surpasses key thresholds and results in nonlinear spread dynamics, such as fire storms that create their own weather (Peters et al., 2004). Some processes characteristic of extreme fire events, such as fire spotting, have been incorporated into a few FSLMs (e.g., EMBYR, Hargrove et al., 2000) but others (e.g., fire-generated weather) are at the frontier of research in fire behavior (Viegas, 2006) and not yet addressed in the context of landscape-scale fire regimes.

An important consequence of explicitly linking burn behavior to vegetation patterns is that succession processes become more tightly coupled to the fire behavior simulated for a given fire event than when alternative assumptions are used (e.g., fire intensity is a simple function of time since last fire). This type of feedback is essential for many applied questions—such as the consequences of alternative fuel management strategies on future fire risk. The Labrador case study illustrates the sensitivity of fire patterns to vegetation, as a persistent deciduous patch created by a past burn event created a lasting legacy in subsequent burn patterns (Fig. 7). In this case the persistence of the deciduous patch is likely an artifact of oversimplified initial conditions, i.e. homogeneous deciduous shrubs where a mixture of shrubs and trees was more likely (Simon and Schwab, 2005). Hence the more direct coupling between vegetation and fire requires more accurate input data and understanding of local drivers of vegetation change than simpler fire-modeling approaches. Recent advancements in vegetation mapping via remote sensing (Wolter et al., 2008) and scaling plot data to landscapes (Ohmann and Gregory, 2002) as well as improved understanding of vegetation response to different disturbances (Brown and Smith, 2000) become increasingly important as modeled linkages between vegetation and disturbance processes become stronger.

Fewer FSLMs address fire effects explicitly—for example most simply assume that all fires are stand-replacing (Keane et al., 2004). The empirical relationships between fire behavior and crown fraction burned (Forestry Canada Fire Danger Group, 1992), applied here, provided a logical method to relate tree mortality to the species age cohort design of LANDIS-II, resulting in fire burn patterns with heterogeneous fire effects. In the case of Labrador, low crown structure and relative sensitivity of tree species to fire resulted in mostly stand-replacing fires, though there were instances of lightly burned residuals that can have important consequences for future forest composition (Simon and Schwab, 2005). By contrast, simulated fires in the Sierra Nevada resulted in highly heterogeneous effects that are critical to understand for assessing vegetation change in that region (Miller and Urban, 2000).

The fire regime is a critical component of vegetation-disturbance interactions. FSLMs have applied a spectrum of approaches to simulating fire regimes ranging from strict "top-down" methods that apply a predetermined fire regime (e.g., He and Mladenoff, 1999) to strict "bottom-up" methods where the fire regime is an emergent property of finer-scale fire behavior (Li, 2000; Perera et al., 2003). The duration option of the dynamic fire extension is intermediate to these two extremes because it uses fire regime statistics from the past to guide fire patterns in the model, but also allows fire patterns to change through time in response to changing conditions, such as climate, forest composition, and landscape structure. This increased sensitivity to context for individual fire events typically results in greater variability in fire sizes for duration-based models compared to more traditional size-based approaches (Yang et al., 2008, Fig. 5), and it may permit more sophisticated research questions regarding factors affecting future fire patterns. Nonetheless simulated fire variability is still somewhat constrained by the regime characteristics of the past. For example, the integrity of fire regime units (defined based on past fire patterns) is preserved despite dynamic changes in vegetation, weather, or other factors. Such constraints on system behavior may be justified. For example, strong differences in soil texture may have consistent effects on fire frequency not fully captured by vegetation differences alone (Sturtevant and Cleland, 2007). The model design also retains the flexibility to input a time series of fire regime units to allow for future changes in the fire regime, such as future climate or fire management scenarios. Yet there are trade-offs between simulation of purely emergent fire patterns and constraints on system behavior based on past observations (Li et al., 2005), and the assumption of spatially consistent fire regimes may artificially constrain potential variability in simulated burn patterns.

Some other key simplifying assumptions of the model may similarly affect forecasts of future fire regimes. One such assumption is that weather remains constant during a given weather event. While our primary focus is on long-term fire patterns rather than short-term fire behavior, the assumption of constant fire weather at the event scale may affect even long-term fire patterns. Future model enhancements could include more dynamic weather during fire events. The model also requires fire ignitions as an input parameter. Simulated fire initiations depend on landscape fuel composition; hence the number of simulated fires may change over time. However the number of ignitions may also change over time due to changes in human activity, climate, or both (Anderson et al., 2002; Guyette et al., 2002). Ultimately it would be preferable to estimate fire ignitions internally as a function of such drivers, but the science underlying such relationships has not yet reached the point that such changes can be estimated reliably across multiple systems, though research in this area is progressing (Krawchuk et al., 2006, 2009; Krawchuk and Cumming, 2009). Hence while the dynamic fire extension allows the flexibility to change fire regime parameters (e.g., fire ignitions, Gustafson et al., in press), we leave it to the user to address this question using external analyses.

The new detail added to the dynamic fire extension also introduces additional uncertainties into the model. Fire durations are rarely recorded within historic fire records, so the statistical distribution of fire durations is not well understood. Fire severity is similarly absent from most fire records and must be inferred from the interactions between fire weather, vegetation, and simulated fire behavior. Indeed, few data exist that can define generalized relationships between fire weather patterns, burn patterns, and fire intensity affecting tree mortality across broad landscapes and over long time scales. Our model does not increase or decrease such uncertainties but, rather, elicits the importance of these undefined relationships. For example abundant data are available to support the specifics of weather interactions and burn patterns for a given event (Forestry Canada Fire Danger Group, 1992). Considering the sensitivity of our simulated fire regimes to fuel parameters (Fig. 11) this is an important strength. By contrast our uncertainty analysis suggests that the degree of correlation between fire duration and weather has influence on the area burned, whereas the sensitivity of potential fire severity to this interaction differed across study areas. Future investigation of the underlying drivers of fire durations should therefore improve duration-based modeling approaches, such as that presented here.

4. Conclusions

Modeling is always a balance between process-level detail and model elegance (Mladenoff, 2004). The fire modeling approach described here should be applicable to a host of questions, especially those related to climate change and disturbance interactions, disturbance in locations characterized by steep topography, dynamic vegetation that significantly influences spread rates, and multiple disturbance types and their interactions. Most of these complex vegetation-disturbance dynamics involve outcomes where a "time-since disturbance" approach is less relevant. As a case in point, the southern Sierra Nevada landscape is a complex mosaic of fuel types and topography. Capturing emergent patterns of fires responding to this mosaic and repeatedly occurring over many decades is critical to understanding the longer term effects of fuels management and the effects of fires on rare species (Scheller et al., in press-b). By contrast, the Labrador landscape has lower topographic relief, simpler forest composition, a regime characterized primarily by stand-replacing fires, and (until very recently) few disturbance types as important as fire. Investigating the coarse-scale role of fire as it relates to the historic range of natural variability may be appropriately handled by a simpler fire model. However this area is rapidly changing due to recent and planned timber harvest and climate change influences that may be affecting insect activity. Assessing how changing disturbance interactions will affect potential future fire patterns may require a more dynamic modeling approach, such as that described here.

In summary, if fire behavior is not a central question or it can be considered a minor process driving landscape change, a simpler FLSM may suffice. Moreover, it should be recognized that additional parameterization in complex models requires caution and a reasonable understanding of the modeled processes and their interactions. Thus, with careful consideration of modeling needs and parameterization requirements, the dynamic fire and fuel extensions can fill a strong need for a simulation approach recognizing dynamic fuel types, topography, variable weather, and heterogeneity in fire effects.

Acknowledgements

Funding for this project was provided by the USDA Forest Service, including the National Fire Plan, Northern Research Station, and Pacific Southwest Region (Region 5). Input on Sierra Nevada fire parameters was provided by Donald Yasuda, Bernhard Bahro, Klaus Barber, and Joe Sherlock. Data resources and cross-fertilization of ideas between American and Canadian scientists was made possible through a grant from the Sustainable Forest Management Network of Canada (Christian Messier, lead investigator) and cooperation with the Newfoundland and Labrador Department of Natural Resources. Input on Labrador fire and succession parameters were provided by Neal Simon, Darren Jennings, Frederick Doyon, Leanne Elson, and Daniel Kneeshaw. We thank Eric Gustafson, Steve Van Tuyl, Stephen Yamasaki for critical feedback on the conceptual model and beta versions of the model. Robert Costanza, and Tina Scupien performed the sensitivity analysis runs and summarized the output. We also thank Andrew Fall, Stephen Yamasaki, and two anonymous reviewers for helpful comments on the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2009.07.030.

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