

## Evaluating the ecological benefits of wildfire by integrating fire and ecosystem simulation models<sup>☆,☆☆</sup>

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### ABSTRACT

Fire managers are now realizing that wildfires can be beneficial because they can reduce hazardous fuels and restore fire-dominated ecosystems. A software tool that assesses potential beneficial and detrimental ecological effects from wildfire would be helpful to fire management. This paper presents a simulation platform called FLEAT (Fire and Landscape Ecology Assessment Tool) that integrates several existing landscape- and stand-level simulation models to compute an ecologically based measure that describes if a wildfire is moving the burning landscape towards or away from the historical range and variation of vegetation composition. FLEAT uses a fire effects model to simulate fire severity, which is then used to predict vegetation development for 1, 10, and 100 years into the future using a landscape simulation model. The landscape is then simulated for 5000 years using parameters derived from historical data to create an historical time series that is compared to the predicted landscape composition at year 1, 10, and 100 to compute a metric that describes their similarity to the simulated historical conditions. This tool is designed to be used in operational wildfire management using the LANDFIRE spatial database so that fire managers can decide how aggressively to suppress wildfires. Validation of fire severity predictions using field data from six wildfires revealed that while accuracy is moderate (30–60%), it is mostly dictated by the quality of GIS layers input to FLEAT. Predicted 1-year landscape compositions were only 8% accurate but this was because the LANDFIRE mapped pre-fire composition accuracy was low (21%). This platform can be integrated into current readily available software products to produce an operational tool for balancing benefits of wildfire with potential dangers.

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### 1. Introduction

The accumulation of canopy and surface fuels, coupled with a general warming of the climate, have contributed to an increase in the frequency, severity, and size of wildfires in the western United States (Laverty and Williams, 2000; Running, 2006; Westerling et al., 2006). Contemporary wildfires and their control have become a contentious issue in the US because of their high cost, capacity to damage property and hurt people, and potential to cause ecological harm (Agee, 1997). On the other hand, these same wildfires can also reduce fuels, return fire to fire-adapted ecosystems, and improve ecosystem health (Keane et al., 2008). Unfortunately, government agencies in charge of suppressing wildfires have few tools

available to evaluate whether a wildfire is causing ecological harm or providing ecological benefits to the landscapes in which it burns (Hann and Bunnell, 2001). If wildfires pose no threat to humans and they are improving ecosystem health and integrity, then why not let them burn? The challenge is to develop a real-time, operational tool that fire managers could use to evaluate if a wildfire is improving or reducing ecosystem health and landscape condition (Barrett et al., 2000; Miller et al., 2000; Calkin et al., 2008).

The integration of fire ecology into management decision-making during a wildfire has been lacking (Calkin et al., 2008), and few tools are available to evaluate the value of the wildfire or wildland fire use to ecological resources. Miller and Landres (2004) identified a comprehensive list of landscape characteristics that could be considered when evaluating the benefits and risk of a fire, and Miller et al. (2000) describe a Risk-Benefit GIS model for wildland fire use. Black (2005) developed the fire effects planning framework to provide fire managers with a quick and effective tool for providing a more “complete picture of potential benefits and risk” of wildland fire. Lehmkuhl et al. (2007) presents a computer tool called FuelSolve to evaluate ecological values for planning fuel treatments. RAVAR (Rapid Assessment of Values At Risk) is a fire economics tool within the Wildland Fire Decision

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Support System (WFDSS) that assesses the likelihood of different resources being impacted by a current and ongoing wildfire ([http://www.fs.fed.us/rm/wfdss\\_ravar](http://www.fs.fed.us/rm/wfdss_ravar)) (Calkin et al., 2008). These tools can be difficult to employ in operational, real-time wildfire applications, and they do not provide a general, easily understood index that describes the overall change in ecosystem condition.

This paper describes a process implemented into a computer software application that can be used to provide wildfire suppression teams an objective evaluation of the potential of a wildfire to improve or degrade landscape and ecosystem health. This computer program, called FLEAT (Fire and Landscape Ecology Assessment Tool), merges currently available fire behavior, fire effects, and landscape simulation models together into a platform that estimates the degree to which a wildfire is moving the landscape towards or away from optimum ecosystem health as evaluated from a simulated range of historical conditions. This estimate is synthesized into a simple index that can provide wildfire managers valuable information to determine how aggressive to fight a wildfire and where to put fire fighting resources. While this tool does not directly assess all potential values at risk that can occur during a wildfire (e.g., power lines, water supply, structures), it provides a generalized, simplistic, and easily understood ecological index that can be used with other analyses, such as RAVAR, to manage both wildland fire use fires (i.e., lightning fires that are allowed to burn under acceptable climate parameters) and wildfires. This process is an important step towards describing the benefits and detriments of suppressing wildland fires in an ecological context.

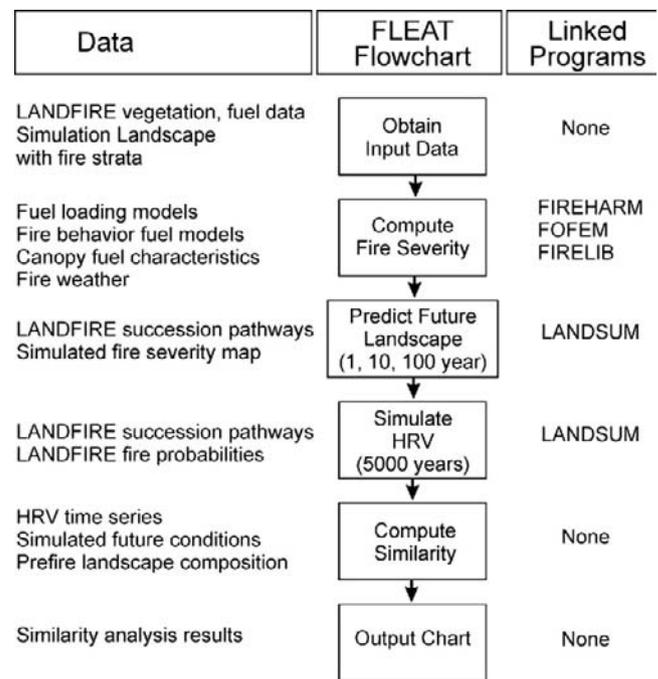
## 2. Methods

### 2.1. The FLEAT platform

FLEAT is a C++ program that integrates several existing software packages (also programmed in C) to compute an index that describes if a wildfire is improving or degrading the landscape in an ecological context. FLEAT is more of a software platform than a simulation model because it fuses previously developed fire and landscape simulation models into a cohesive application and does not contain any new simulation methods or models. FLEAT was designed to be used as an operational tool to generate information for managing wildfires in real-time, operational situations; the program will run overnight to provide simple, easy-to-understand output for the morning briefing. Currently, FLEAT is a research program but it can eventually be merged into a more friendly, simple, and efficient interface for input and output data management (Keane et al., 2010).

The FLEAT program requires the completion of the following six major steps (Fig. 1) to compute an ecological index that informs the fire manager of the benefits or drawbacks of a wildfire:

- *Obtain input data.* The program uses standardized spatial data as inputs to the various models incorporated in its design. These data must be reformatted into a structure suitable for simulation.
- *Compute fire severity.* FLEAT uses remotely sensed imagery-derived fire severity maps or simulates fire severity using fire behavior and effects models.
- *Predict future landscape composition.* FLEAT simulates vegetation development using state-and-transition models, and then predicts what the landscape will look like both inside and outside the burn, for 1, 10, and 100 years post-wildfire.
- *Simulate HRV.* FLEAT uses a landscape fire succession model to simulate the historical range and variation (HRV) of historical landscape composition.



**Fig. 1.** Flow chart of important steps in the FLEAT model to compute an index that describes if a wildland fire is improving or degrading landscape health. The models are: FIREHARM—a fire hazard and risk model (Keane et al., 2008), FOFEM—a First Order Fire Effects Model (Reinhardt et al., 1997), FireLib—a set of C programs to compute fire behavior (Bevins, 1996), and LANDSUM—a Landscape fire succession model for simulating vegetation and fire dynamics (Keane et al., 2002).

- *Compute similarity.* An estimate of similarity is calculated by comparing HRV time series with the pre-fire and 1, 10, 100 year post-fire landscape compositions.
- *Output chart.* A general index of departure is output and displayed in a simple graphic summary chart.

The structure and content of the FLEAT model will be discussed by these steps (see Fig. 1 for flow chart).

*Obtain input data.* FLEAT is designed to use the national LANDFIRE spatial database for most of its spatial input data requirements and simulation parameters (Rollins, 2009; Rollins and Frame, 2006). LANDFIRE raster data layers are downloaded from the website [www.landfire.gov](http://www.landfire.gov) and then processed to assign summarized pixel values from the LANDFIRE layers to polygons on the simulation landscape. Using standard GIS software, we create the simulation landscape in FLEAT as polygons that are adjacent pixels of similar vegetation and site conditions where similarity is based on the LANDFIRE existing vegetation type (EVT), Structural Stage (SS), and Biophysical Settings (BS) layers, respectively (Keane and Holsinger, 2006) (Table 1). Each polygon is assigned attributes from the LANDFIRE data layers based on modal values, and these attributes are then used as inputs to both compute fire behavior and fire effects and to simulate landscape dynamics. A complete discussion of all polygon attributes and how to build the polygon layer from LANDFIRE GIS layers is contained in Keane and Holsinger (2006) and Keane et al. (2010).

The most important attributes taken from the LANDFIRE layers and assigned to polygons are the fire behavior and fire effects fuel models, which are classifications of fuel characteristics, primarily biomass loadings ( $\text{kg m}^{-2}$ ) (Table 1). Either one of the two LANDFIRE fire behavior fuel model layers can be specified in FLEAT: the Anderson (1982) standard 13 model classification or the Scott and Burgan (2005) new 40+ fuel model classification (Reeves et

**Table 1**  
Spatial data layers used as inputs to the FLEAT model. The LANDFIRE vegetation layers are discussed in Rollins (2009) and the fuels layers are discussed in Reeves et al. (2009).

Polygon attribute	Taken or developed from LANDFIRE layers	Used for	Map description
<i>Categorical maps</i>			
Polygon	Biophysical setting, existing vegetation type, structural stage	Describing pre-fire landscape, initialization for landscape simulation modeling	The polygon layer consists of a contiguous group of pixels of the same biophysical setting, cover type, and structural stage.
Fire strata	Created by user from fire boundary information	Determining the extent of the past, present and future fire spread, explicitly specifying extent of landscape	Consists of pixels in the simulation landscape that are assigned values from 1 to 4 as defined in text.
Fire behavior fuel model (13 Anderson Fuel Models or 40 Scott and Burgan Fuel Models)	Assigned to combinations of biophysical settings, existing vegetation type, and structural stage	Computing fire intensity that is then used to compute tree mortality that is then used to compute fire severity	Fire behavior fuel models represent distinct distributions of surface fuel loading by major components (live and dead), size classes, and fuel types that express an expected fire behavior (Anderson, 1982; Scott and Burgan, 2005)
Fuel loading model	Assigned to combinations of biophysical settings, existing vegetation type, and structural stage	Compute soil heating and fuel consumption that is then used to compute fire severity	Fuel loading models are categories in a surface fuel classification that is based on unique fire effects simulation results from fuelbed data (Lutes et al., 2009)
<i>Continuous maps</i>			
Canopy bulk density	Biophysical layers, cover type, imagery	Simulating crown fire intensity that is then used to compute tree mortality then fire severity,	Canopy bulk density (CBD) is the mass of canopy fuel available to burn per unit volume ( $\text{kg m}^{-3}$ )
Canopy base height	Biophysical layers, cover type, imagery	Simulating crown fire initiation that is then used to compute tree mortality then fire severity	Canopy base height (CBH) is the lowest point in a stand where there is sufficient available fuel to propagate fire vertically through the canopy (canopy bulk density $> 0.012 \text{ kg m}^{-3}$ )
Elevation, slope, aspect	DEM	Simulating fire growth, simulating fire behavior	Meters above mean sea level

al., 2009). FLEAT also uses the LANDFIRE canopy fuels layers of canopy bulk density ( $\text{kg m}^{-3}$ ) and canopy base height (m) to simulate crown fire behavior (Table 1).

LANDFIRE also provides a layer called Fuel Loading Models (Lutes et al., 2009) developed by Reeves et al. (2009), that describe actual fuel loadings to use in fire effects prediction systems, such as CONSUME (Ottmar et al., 1993) or FOFEM (Reinhardt et al., 1997), to simulate the major fire effects of fuel consumption, smoke, and soil heating (Sikkink et al., 2009) (Table 1). Each polygon is also assigned a tree list (a list of tree cohorts that represent stand conditions and each item in list includes attributes of tree density stratified by species, diameter, height to base of crown, and tree height) to compute tree mortality (Drury and Herynk, in press).

Another critical polygon attribute is “fire strata”. Polygons on the simulation landscape are assigned one of four fire strata based on the present and future perimeter of the wildfire (Table 1; Fig. 2):

- *Simulation buffer.* An area around a context landscape that is needed to minimize boundary effects (Keane et al., 2002, 2006). This area is not included in any of the analyses and is only used in the simulation of landscape dynamics.
- *Context landscape.* An area that represents the landscape in which the wildfire is burning. This area should be big enough to contain future fire growth but small enough to adequately represent the ecosystems being burned by the fire (approximately two to three times the burn area) (Karau and Keane, 2007).
- *Burned area.* Area that has been burned by the wildfire.
- *Projected burn area.* Area forecast to be burned by the wildfire. This can be for any time horizon but it is usually for 3–10 days into the future.

The fire strata map must be created from available spatial data that describe the burn perimeter and possible spread projections (Calkin et al., 2008).

Three other digital map layers are required as input to FLEAT (Fig. 1; Table 1). The LANDFIRE digital elevation model (DEM) layer is needed to spatially simulate fire spread for HRV simulations. A raster polygon layer is needed because it contains polygon ID attribute assignments to each pixel on the landscape. The last input raster layer is a fire severity input map for both burned and future burned areas entered into FLEAT in one of the following forms:

- *Burned area.* A digital layer with the four values: buffer, unburned, burned, and future burned area.
- *Fire intensity.* A layer of fire intensity for burned and future burned areas as computed from the FSPRO program that uses the fire growth model FARSITE (Finney, 1998).
- *Burn severity.* A layer representing a three-category burn severity assessment for present and future burned area as quantified from remote sensing (Lutes et al., 2006).

The FLEAT program adjusts the calculation of fire severity (see next section) depending on which fire input map is specified. These maps are usually created by fire behavior analysts on the wildfire using a variety of remote sensing techniques and products (Lentile et al., 2007).

*Compute fire severity.* The calculation of fire severity is entirely dependent on the selected fire severity map described above. If the simple burned area map is input, then FLEAT simulates fire severity based on the output of two fire models implemented in the FIRE-HARM program (Keane et al., 2010) (Fig. 1). FLEAT first calculates the fire behavior variables of fireline intensity, flame length, and crown fire intensity using routines in the Firelib C library developed by Bevins (1996) that implement the Rothermel (1972) fire behavior algorithm and use the LANDFIRE fire behavior fuel models. Then, the fire effects variables of fuel consumption, soil heating, and tree mortality are computed from the First Order Fire Effects Model



**Fig. 2.** The four landscape strata that are assigned to each polygon on the simulation landscape: the landscape buffer that surrounds the landscape in question (blue), the context landscape that represents the landscape in which the fire is burning (beige), the projected burned area that represents future fire growth (green), and burned area that has been previously burned by the fire (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(FOFEM) (Reinhardt et al., 1997) as implemented in the FIREHARM program (Keane et al., 2010). FLEAT then uses simulated fireline intensities to calculate scorch heights using the Van Wagner (1973) equation and input wind conditions, and then calculates tree mortality for each tree in the polygon's assigned tree list from scorch height, flame length, and crown fire intensity using the FOFEM sub-program (Keane et al., 2010). If a fire intensity map is specified, then this mapped intensity is used to compute tree mortality as above instead of the simulated intensity from the Bevins (1996) Firelib C routines.

FLEAT computes a three-category ordinal index of fire severity based on the simulated estimates of three fire effects variables – fuel consumption, soil heating, and tree mortality – as implemented in the FIREHARM program (Keane et al., 2010). The following thresholds were used:

- *Low severity.* Total fuel consumption less than 20% and soil heating at 2 cm depth less than 60 °C, and mortality for trees above 15 cm diameter is less than 30%.
- *Moderate severity.* Total fuel consumption between 20% and 50%, soil heating at 2 cm depth between 60 and 250 °C, and tree mortality is between 30% and 70%.
- *High severity.* Total fuel consumption greater than 50%, soil heating at 2 cm depth greater than 250 °C, and tree mortality greater than 70%.

These classes were designed to match severity classes used in common burn severity applications, such as BAER (Ryan and Noste, 1985; Simard, 1996; Lentile et al., 2007).

If a remotely sensed assessment of burn severity (burn severity map described above) is used for the fire input map, then FLEAT uses this mapped burn severity in the subsequent steps in Fig. 1 instead of the above simulations. Values in the input burn severity map must be consistent with the fire severity used in the LANDSUM landscape model so that all steps in Fig. 1 are consistent. This burn severity map is usually generated using dNBR techniques correlated with a field estimate of severity called the composite burn index (Lutes et al., 2006).

*Predict future landscape composition.* FLEAT uses the landscape fire succession model LANDSUM (Keane et al., 2006) coupled to the disturbance regime and vegetation development parameters quantified in the LANDFIRE project (Long et al., 2006; Rollins, 2009) to simulate 100 years of landscape development for the entire simulation landscape. Initial landscape conditions are taken from the LANDFIRE vegetation layers to represent the landscape at the time of burn. The simulated landscape compositions (percent area by vegetation type) at year 1, 10, and 100 are stored for comparison in later steps.

LANDSUM (LANDscape SUCcession Model) is a parsimonious spatially explicit computer model that deterministically simulates vegetation development at the polygon-level using state-and-

transition pathway models and spatially simulates fire ignition (stochastic), spread (deterministic), and effects (stochastic) using cellular automata approaches (Keane et al., 2006). It has been used to explore the use of simulation to generate historical time series of landscape characteristics (Keane et al., 2002, 2006) and to investigate effects of alternative management treatments implemented across landscapes (Cary et al., 2006). A version of LANDSUM is currently being used to generate historical range and variation (HRV) time series for the conterminous United States in the LANDFIRE project (Rollins and Frame, 2006).

LANDSUM simulates succession within a polygon using the multiple pathway succession modeling approach that assumes all pathways of successional development will eventually converge to a stable or climax plant community called a Potential Vegetation Type (PVT) which is considered analogous to a LANDFIRE Biophysical Setting. A PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under constant climate (Daubenmire, 1966; Pfister and Arno, 1980). There is a unique set of successional pathways for each PVT mapped on the simulation landscape (Steele, 1984; Arno et al., 1985). Each pathway is composed of a sequence of plant communities called *succession classes* that are linked along gradients of vegetation development to form a state-and-transition model. Each succession class is represented by a cover type (dominant species defined by the LANDFIRE EVT categories) and a structural stage (cover and height classes defined by the LANDFIRE categories). Successional development in a polygon is simulated at an annual time step where the polygon's succession class will change if the length of time spent in the current succession class (transition time) exceeds a defined maximum residence time that is held constant throughout the simulation.

Disturbances can disrupt succession by delaying or advancing the time spent in a succession class, or they can cause an abrupt change to another succession class. Disturbances are stochastically modeled from probabilities based on historical frequencies that are input as probabilities to LANDSUM by PVT and succession class; each succession class in a PVT pathway is assigned historical fire occurrence probabilities (Keane et al., 2006). All disturbances specified by the user in the input file are simulated at a polygon-level, except for wildland fire, which is simulated at the pixel level as a spatial cell-to-cell spread process across the landscape (Keane et al., 2002). The spatial simulation of fire in LANDSUM is represented by three phases: ignition, spread, and effects. Ignition is stochastically simulated from the fire probabilities that are input into the model by PVT and succession class. Fire is spread from the ignition point to cells across the landscape using directional vectors of wind (input to model) and slope (derived from an input DEM layer) Fire spread is limited by stochastically calculating a maximum fire size (ha) for each fire from a fire size distribution that is input to the program. The effect of the fire on the burned polygon (modification of succession class) is stochastically determined from probabilities of each fire severity type specified in the input file by PVT and succession class.

*Simulate HRV.* The HRV of landscape composition is used as an empirical reference to compare the landscape composition of the pre- and post-burn simulated landscape to assess if the wildfire is causing harm or good (Fig. 1). The FLEAT platform again uses the LANDSUM model to simulate 5000+ years of landscape dynamics using the LANDFIRE vegetation and fire parameters that were quantified from historical data. Unlike the landscape predictions mentioned in the previous section, the FLEAT program creates the initial HRV simulation landscape by assigning the most mature (oldest) succession class in the pathway for each mapped PVT (Pratt et al., 2006) to decrease simulation times and mitigate initial landscape effects. The compositions (area by PVT and associated succession classes) of the simulation landscape for each of the

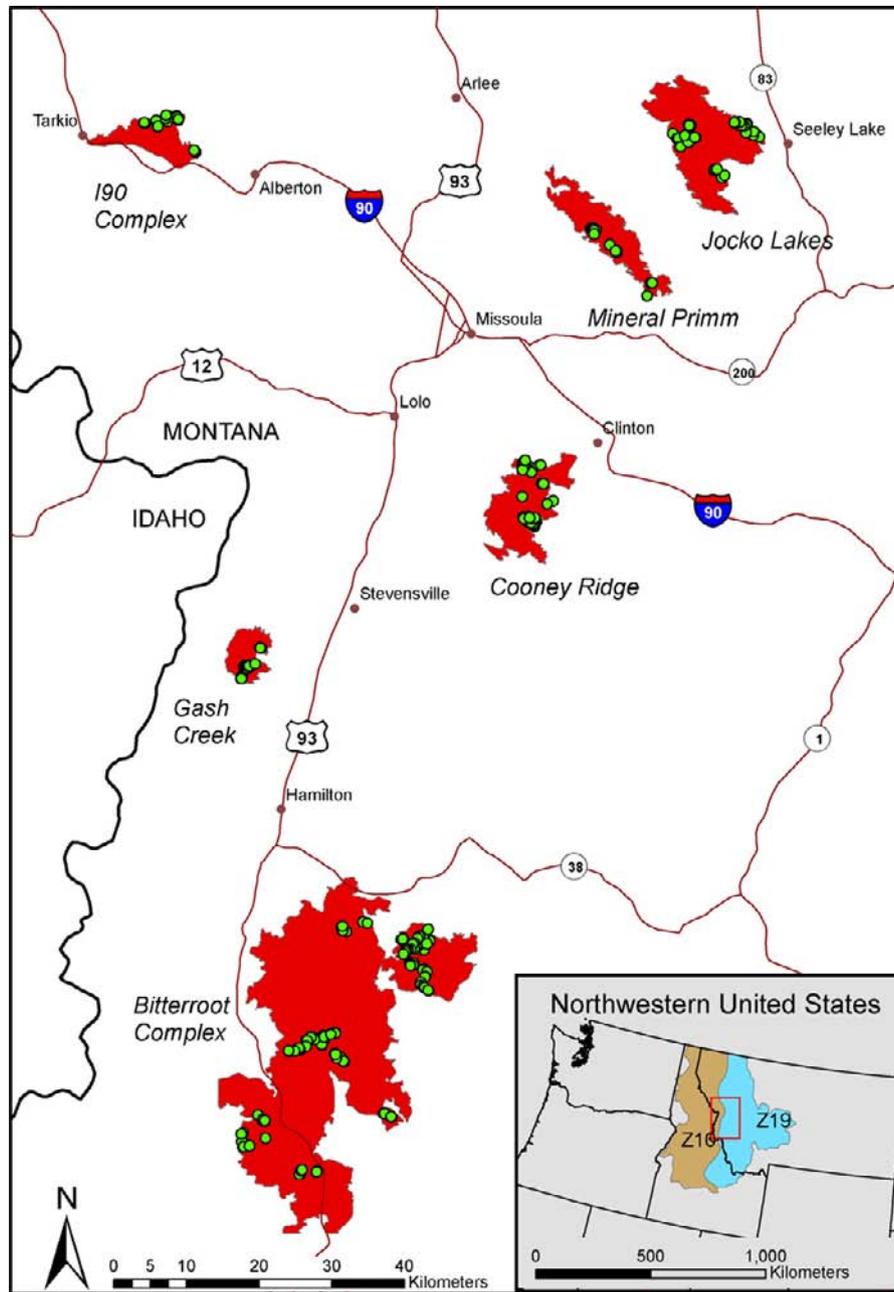
four fire strata are stored every 50 years to create the simulated HRV time series that is used to compare with landscape composition before the fire, and at 1, 10, and 100 years after the fire. Previous studies have shown that LANDSUM simulation landscapes will equilibrate with the input vegetation and fire parameters after approximately 200–300 years to minimize impacts of the initial simulation landscape on HRV time series (Keane et al., 2002, 2006; Pratt et al., 2006). Therefore, simulated landscape composition output is not recorded until simulation year 250 and then recorded and stored every 50 years thereafter to achieve 100 observations (i.e., 5250 simulation years).

*Compute departure.* The similarity of each observation in the simulated HRV time series to each of the three landscapes (burned, soon-to-be burned, and unburned) for each of the four times (pre-burn, 1, 10, and 100 year into the future) is computed using a form of the Sorensen Index (SI) (Sorensen, 1948). The Sorensen's index is a variable that represents similarity of landscape composition relative to reference conditions. SI is often used to measure the similarity between two plant communities or lists of species (Pratt et al., 2006; Mueller-Dombois and Ellenberg, 1974; Sorensen, 1948). In FLEAT, we used SI to measure the similarity in landscape composition (area occupied by succession class) between a reference (A-pre-, 1, 10, and 100 years after fires) and all 100 simulation output time periods (B). We calculated the SI as follows:

$$SI = 100 \left( \frac{\sum_{i=1}^n \min(A_i, B_i)}{Area_{LRU}} \right)$$

where the area of each particular succession class  $n$ , common to both reference A and simulation output interval B, is summed over all succession classes  $n$ , divided by the total area of the landscape reporting unit and then converted to a percentage by multiplying by 100. The resulting value has a range of 0–100, where 100 is completely similar (identical, no departure) and 0 is completely dissimilar (maximum departure).

*Output general index.* We calculated the similarity index statistics for all combinations of the three target landscapes (burn, soon-to-be burned, and unburned) and four assessment times (pre-fire, 1, 10, 100 years post-fire) from the 100 HRV time series observations. The average, range, and standard deviation of these measures for each combination are stored in FLEAT for further processing and output. However, we assumed that any detailed quantitative analysis of these similarity measures would be too much information for most wildfire managers to assimilate under real-time operational conditions. Therefore, we developed a one-page simplistic chart that summarizes FLEAT output into an easy to read and interpret figures. Each figure is a “stoplight” and the colors of the stoplight represent movement towards (green) and away from historical conditions, which can be interpreted as a more passive (green) or aggressive (red) suppression effort may need to be employed. The size of the colored circle indicates the magnitude of change that is caused by the wildfire with the size standardized to a 33% change in similarity—a relatively large change in the Sorensen's Index. There are two columns for the fire strata: (1) burned area and soon-to-be burned area (burned), and (2) entire context landscape (landscape). And, there are three columns for each of the important evaluation times (1, 10, and 100 years after wildfire). Output with large green circles would indicate that the wildfire is providing great ecological benefits and its suppression may not be warranted. There is a stoplight for each of the three target landscapes and the four time periods and the size of the stoplight indicates the magnitude of change.



**Fig. 3.** Wildfires used in the validation of the FLEAT intermediate products with locations of all field plots shown as green dots. Inset shows the northern Rocky Mountains with the two LANDFIRE mapping zones that contain these fires.

## 2.2. FLEAT validation

Assessing the accuracy of the FLEAT HRV and stoplight output is difficult because real historical time series for landscapes in the western US are limited to less than 70 years and are usually spatially inconsistent (Keane et al., 2006). Therefore, we tested the accuracy of the intermediate simulated variables of fire severity and predicted landscape composition in the FLEAT process (Fig. 1) assuming that their accuracy is somewhat indicative of the accuracy of the FLEAT output. We measured burn severity and succession class on plots established after several wildfires in the western Montana USA and compared these attributes to the values simulated from the FIREHARM and LANDSUM models as implemented in FLEAT.

**Field methods.** Six recent large wildfires were selected in western Montana based on amount of field data measured within

the burned areas in past studies (Fig. 3). Climate in these Montana Rocky Mountain landscapes is cool, temperate, with a minor maritime influence. Mean annual temperature ranges from 2 to 8 °C. Summers are dry and precipitation ranges from 410 to over 2540 mm, with most falling as snow in spring, autumn and winter (McNab and Avers, 1994).

The fires burned through varying topography (valleys, rolling foothills, steep sided ridges and peaks) ranging from 876 to 2524 m in elevation. The Mineral Primm and Cooney Ridge fires started in early August of 2003 and each grew to over 10,000 ha by the time they were contained in mid September. Vegetation cover in both fire areas is dominated by temperate coniferous forests and woodlands of Douglas-fir (*Pseudotsuga menziesii*) (26% in Mineral Primm, 64% in Cooney Ridge), Engelmann spruce – subalpine fir (*Picea engelmannii* – *Abies lasiocarpa*) (26% in Mineral Primm, 11% in Cooney Ridge) and lodgepole pine (*Pinus contorta*)

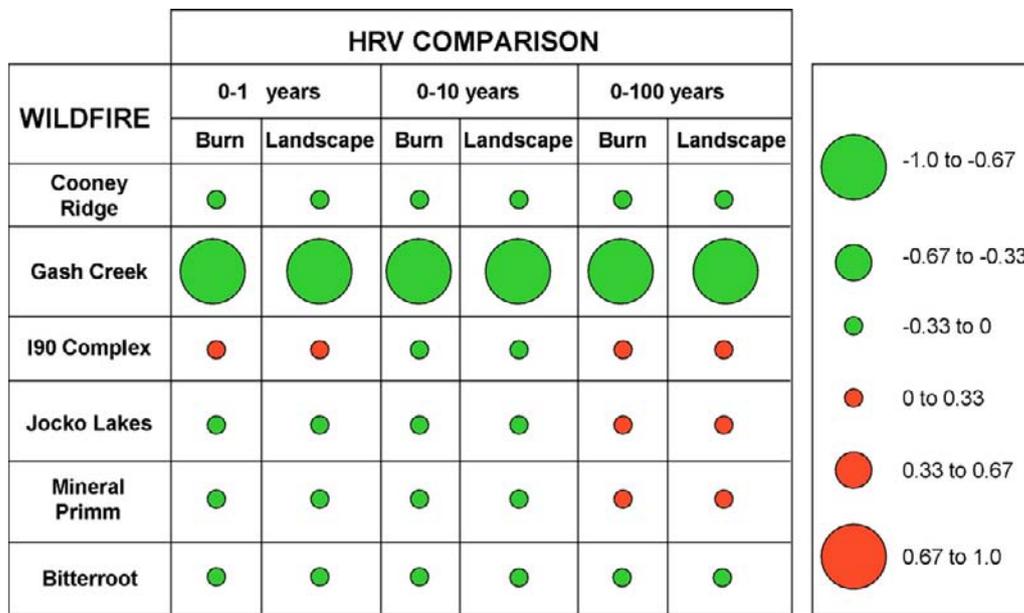


Fig. 4. Final product generated from the FLEAT program. Color of circle denotes if the fire is moving the areas towards (green) or away (red) from historical conditions for the three areas input to the model (burned, soon-to-be burned, and entire landscape) and the four time periods of assessment (pre-fire, 1, 10, and 100 years after fire). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

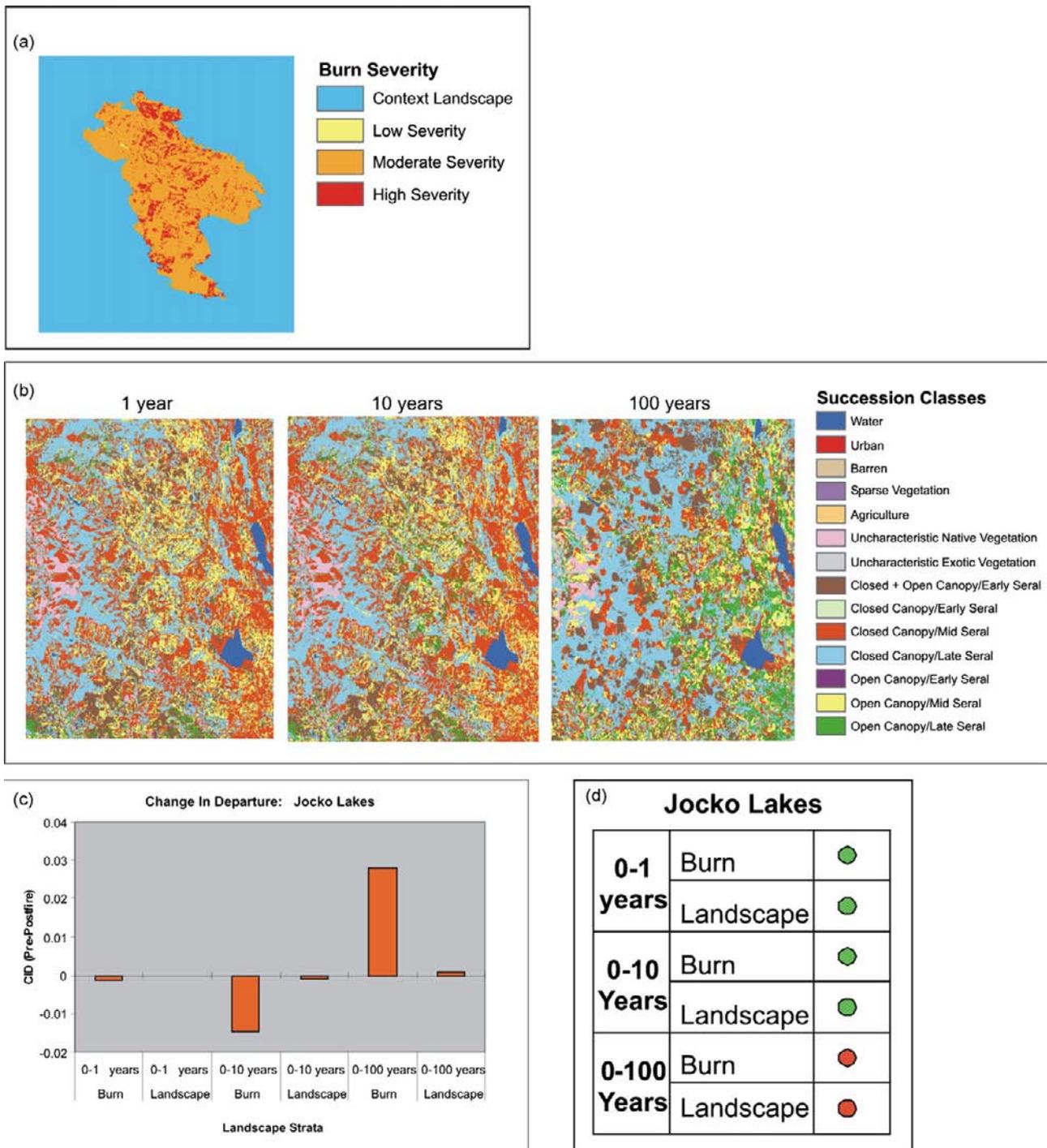
(15% in Mineral Primm, 7% in Cooney Ridge). The following cover types each comprise between 5% and 7% of the fire area landscapes: mesic montane meadows (tall forbs), deciduous shrublands and grassland/herbaceous cover types. Other less dominant cover types (each less than 1%) include sage (*Artemisia tridentata*) shrublands, and western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa*) and aspen (*Populus tremuloides*) forest types. The 190 complex started on August 4, 2005 directly adjacent to Interstate 90, near the town of Alberton, Montana, USA. The fire burned primarily through Douglas-fir dominated mixed conifer forests (41% of the fire landscape), grassland/herbaceous communities (28%) and ponderosa pine forests (13%). The final fire area at containment was reported as 4452 ha. The high elevation Gash Creek fire was ignited by lightning on July 24, 2006 in the northern Bitterroot Mountains near the town of Victor, Montana. The fire grew to 3561 ha burning through landscapes dominated by mid to high elevation forest types: Engelmann spruce–subalpine fir (46%), Douglas-fir (23%), whitebark pine (10%) and lodgepole pine forests (5%). Other cover types included grassland (5%), deciduous shrubland (3%) and ponderosa pine forest (1%). Approximately 3% of the area within the fire perimeter was non-vegetated.

We established 0.04 ha circular plots in accessible stands within the wildfires using an opportunistic approach where burned areas were sampled if there was a major change in vegetation composition (EVT), stand structure (SS), biophysical setting (BS), and fire severity assessed in the context of the LANDFIRE categories for each of these four classifications (Rollins and Frame, 2006). Plots were located in representative portions of the selected stands where representativeness was evaluated based on the four classifications above. At each plot, we completed a fuel and tree inventory using FIREMON methods described in Lutes et al. (2006). Prior conditions were estimated by sampling adjacent unburned areas using paired plot techniques (Karau and Keane, in press) and by assessing whether each sampled tree on burned plot was dead or alive prior to burn.

We also assessed the most appropriate category for each of the three LANDFIRE classifications mentioned above for both before and after the fire using LANDFIRE classification keys (Rollins, 2009). Conditions prior to the wildfire were visually recreated from the post-burn stand conditions to the best of our ability. We also completed a FIREMON Plot Description form (Lutes et al., 2006) for each plot to describe general biophysical characteristics including

Table 2  
Distribution of plots across pre-fire existing LANDFIRE vegetation types.

Pre-fire LANDFIRE existing vegetation types (EVT) ( <a href="http://www.landfire.gov">www.landfire.gov</a> )	Wildfire study areas						
	Bitterroot	Cooney ridge	Gash Creek	190	Jocko Lakes	Mineral Primm	Total
Rocky Mountain Aspen Forest and Parkland	0	0	0	0	1	0	1
Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest	35	41	10	11	23	9	129
Northern Rocky Mountain Mesic Montane Mixed Conifer Forest	0	0	1	1	4	0	6
Rocky Mountain Lodgepole Pine Forest	8	6	2	2	21	2	41
Northern Rocky Mountain Ponderosa Pine Woodland	20	1	2	2	0	0	25
Rocky Mountain Subalpine Dry-Mesic Spruce-fir Forest and Woodland	37	8	3	4	8	1	61
Rocky Mountain Subalpine Wet-Mesic Spruce-fir Forest and Woodland	11	4	1	0	2	3	21
Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland	0	0	0	0	1	0	1
Middle Rocky Mountain Montane Douglas-fir Forest and Woodland	1	1	2	2	0	0	6
Northern Rocky Mountain Subalpine Deciduous Shrubland	0	2	0	0	0	1	3
Pseudotsuga menziesii Forest Alliance	8	1	0	0	1	1	11
<i>Larix occidentalis</i> Forest Alliance	0	2	0	0	4	2	8
<b>Total</b>	<b>120</b>	<b>66</b>	<b>21</b>	<b>22</b>	<b>65</b>	<b>19</b>	<b>313</b>



**Fig. 5.** Intermediate output from the FLEAT program illustrating the detail of simulation to obtain the final product in Fig. 4 using the Jocko Lake wildfire as an example. (a) The simulated fire severity map, (b) succession predictions for 1, 10, and 100 years, (c) box plots of Sorensen's Index for the HRV time series illustrating statistics for pre-fire, 1, 10, and 100 years post-fire, (d) stoptlight summary chart (see Fig. 4).

post-burn species dominance, ground cover estimations, and tree structure. Two fire severity estimates were assessed at each plot:

1. LANDSUM fire severity class. A three-category ordinal classification based on general fire regime characteristics (Keane et al., 2006). Categories are (1) non-lethal surface fire (<10% overstorey tree mortality), mixed severity fire (10–90% overstorey tree mortality), and stand-replacement fire (>90% overstorey tree mortality). This severity classification was included because it is integrated into the LANDSUM successional pathways and it was needed to validate FIREHARM severity estimates.

2. FIREHARM fire severity class. Tree mortality, fuel consumption, and soil heating were rated at each plot using the thresholds presented in the previous section (Keane et al., 2010). These same variables are used to estimate LANDSUM fire severity using thresholds presented in Keane et al. (2010).

*Validation methods.* To evaluate the ability of the FIREHARM submodel in FLEAT to accurately estimate fire severity, we used the validation procedure presented in Karau and Keane (in press) to compare assessed burn severity for each plot with simulated predictions. Tree mortality and fuel consumption were computed

**Table 3**  
FLEAT burn severity accuracy assessment using the FIREHARM and LANDSUM definitions for fire severity across all six sampled fires. Cell values represent percentages of total plots for each fire where FLEAT burn severity output are in rows, and field sampled burn severity data are in columns. Overall accuracy (in bold) is shown in the lower right cell. FIREHARM severity is based on tree mortality, soil heating, and fuel consumption estimates while LANDSUM severity values describe distinct fire regimes based on severity and are mostly based on tree mortality.

Severity classes	Low	Moderate	High	Total	User's accuracy (%)
FIREHARM fire severity classes					
Low	0.3	0.0	0.0	0.3	100.0
Moderate	17.6	33.9	22.0	73.5	46.1
High	5.4	11.5	9.3	26.2	35.4
Total	23.3	45.4	31.3	100.0	0.0
Producer's accuracy (%)	1.4	74.6	29.6		<b>43.5</b>
LANDSUM fire severity classes					
Low	0.3	0.0	0.0	0.3	100.0
Moderate	12.1	24.6	36.7	73.5	33.5
High	2.9	8.0	15.3	26.2	58.5
Total	15.3	32.6	52.1	100.0	0.0
Producer's accuracy (%)	2.1	75.5	29.4		<b>40.3</b>

from pre- and post-fire tree and fuel inventories, and these variables were then used to compute burn severity using the FIREHARM severity classes. The field-estimated fire severity classes for the two severity classifications were compared with the simulated FLEAT severity class using contingency tables.

Extensive LANDSUM validations have been conducted using various techniques and comparison data (Keane et al., 2002, 2006; Pratt et al., 2006). In this study, we decided to evaluate the ability of the successional pathways developed by LANDFIRE to accurately predict vegetation 1 year into the future. The sampled post-burn vegetation classes (LANDFIRE EVT categories) were compared to the simulated EVT classes from LANDSUM using the field-estimated pre-burn LANDFIRE classification categories as inputs. In addition, we estimated the accuracy of the LANDFIRE vegetation maps prior to the fires. Contingency tables were used to evaluate categorical accuracy.

### 3. Results

#### 3.1. FLEAT demonstration

Output from the FLEAT model was used to make a simple and straightforward chart for the fires evaluated in this study (Fig. 4). As a review, green colors represent movement towards HRV and red means fire is moving landscape away from historical conditions, and the size of the colored circle indicates the magnitude of change (for interpretation of the references to color in this sentence, the reader is referred to the web version of the article.) has been incorporated in this sentence). Output with large green circles would indicate that the wildfire is providing great ecological benefits and its suppression may not be warranted. Note that the all wildfires improved ecosystem health 1 year after fire, except for the I90 Complex, probably due to exotic weed invasion (exotics are

**Table 4**  
FLEAT pre-fire and post-fire succession class accuracy assessment. Cell values represent percentages of total plots where pre-fire LANDFIRE succession class data are in rows, and estimated pre-fire field sampled succession class data are in columns. Overall accuracy (in bold) is shown in the lower right cell.

All plots											
LANDFIRE succession classes	B	UN	UE	BE	CM	CL	OE	OM	OL	Total	User's accuracy
Pre-fire accuracy assessment (%)											
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
UN	0.0	0.0	0.0	0.0	3.2	0.0	0.0	4.8	0.3	8.3	0.0
UE	0.0	0.0	0.0	0.0	0.3	0.0	0.0	1.0	0.3	1.6	0.0
BE	0.0	0.0	0.0	0.0	2.6	0.0	0.0	2.6	0.3	6.4	0.0
CM	0.0	0.0	0.0	0.0	13.1	1.9	0.0	8.3	1.6	26.9	48.8
CL	0.0	0.0	0.0	0.0	21.8	4.2	0.0	14.4	4.2	46.8	8.9
OE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0
OM	0.0	0.0	0.0	0.0	1.9	0.3	0.0	3.5	1.9	8.3	42.3
OL	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.6	1.0	66.7
Total	0.0	0.0	0.0	0.0	42.9	6.4	0.3	35.3	9.3	100.0	0.0
Producer's accuracy	0.0	0.0	0.0	0.0	30.6	65.0	0.0	0.9	6.9		<b>21.5</b>
Post-fire accuracy assessment (%)											
B	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0
UN	0.0	0.0	0.0	4.8	1.6	0.0	0.3	1.3	0.0	8.0	0.0
UE	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.3	0.3	1.9	0.0
BE	0.0	0.0	0.0	2.9	1.3	0.0	0.0	2.3	0.3	6.8	42.9
CM	0.0	0.0	0.0	17.7	2.6	0.3	0.0	5.5	1.6	27.7	9.3
CL	0.0	0.0	0.0	27.3	5.8	0.0	0.0	10.3	2.3	45.7	0.0
OE	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.6	0.0
OM	0.0	0.0	0.0	3.2	1.6	0.3	0.3	2.3	0.3	8.0	28.0
OL	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.3	1.0	33.3
Total	0.0	0.0	0.0	58.5	13.2	0.6	0.6	21.9	5.1	100.0	0.0
Producer's accuracy	0.0	0.0	0.0	4.9	19.5	0.0	0.0	10.3	6.3		<b>8.0</b>

Succession class is represented by the following letter codes: B = barren, UN = uncharacteristic native vegetation, UE = uncharacteristic exotic vegetation, BE = both open and closed canopy/early seral, CM = closed canopy/mid seral, CL = closed canopy/late seral, OE = open canopy/late seral, OM = open canopy/mid seral, OL = open canopy/late seral.

not included in the PVT pathways because they were historically absent). The shift towards historical conditions was especially dramatic for the Gash fire (i.e., a beneficial wildfire). Also note that after 100 years, three of the landscapes started to move outside historical conditions, also due to the fact that the initial LANDFIRE layers contained exotic weeds.

Intermediate FLEAT output is presented in Fig. 5 to illustrate the detail behind the final product in Fig. 4. In this example, fire severity is calculated from the LANDFIRE Fuel Loading Model layer, an associated tree list keyed to the LANDFIRE vegetation categories, and the weather at the time of the burn (Fig. 5a). The severities are used to simulate succession for 1, 10, and 100 years after the fires (Fig. 5b). These landscapes are compared with the HRV simulated time series to obtain a distribution of Sorensen's Index (Fig. 5c). Sorensen's Indices for the 1, 10, and 100 year predictions are compared to pre-fire indices to create the colored circles (Fig. 5d).

### 3.2. Accuracy assessment

Over 300 plots were collected during the 2008 field sampling effort (Fig. 3). These plots were somewhat unevenly distributed across the most common LANDFIRE existing vegetation types and biophysical settings relative to their aerial extent for the six burns (Table 2). Salvage logging activities, closed roads, and complex burn severity patterns reduced the number of potential plots we could establish in each burn and many vegetation types are rare on the landscape (Fig. 2).

Agreement between FIREHARM fire severity classes and the field sampled FIREHARM severity classes ranged from 31.6% for the Mineral Primm Fire to 61.9% for the Gash Creek Fire. Considering all plots across all fires, agreement was 43.5% (Table 3). While agreement between FIREHARM severity and field sampled LANDSUM fire severity was similar to the agreement between model and FIREHARM fire severity, it was slightly weaker. For individual fires, agreement ranged from 35.7% for the Mineral Primm fire to 57.1% for Gash Creek wildfire with an average of 40.3% (Table 3). The moderate fire severity class had the strongest agreement while the weakest was often the low severity class (Table 3).

Accuracies for the predicted succession class assessment were much lower than the burn severity assessment mainly because of the low accuracies of the pre-fire LANDFIRE mapped succession classes. For the pre-fire succession classes, accuracies varied from 14.3% for the Gash Creek fire to 37.0% for Mineral Primm fire. Agreement across all plots was 21.5% (Table 4). Agreement for post-fire succession classes was poor, ranging from 0% for Gash Creek and I90 Complex to 18.5% for the Mineral Primm fire. Overall agreement was 8% (Table 4). Kappa agreement statistics were not computed because there were few FLEAT simulated plots classified in the low severity category for the majority of fires.

## 4. Discussion

There are many possible applications of the FLEAT program for evaluating ecological benefits and risks. Because FLEAT can be run overnight, fire managers can use the FLEAT output product in real-time for wildfire decision support during the morning briefing. In planning, FLEAT can be used to prioritize landscapes for fuel treatments by executing the program for a set of fire weather scenarios to evaluate if subsequent fires can move the landscape towards or away from historical conditions. FLEAT can also be used to generate fire severity maps in real-time or planning time frames so that other resource characteristics can be evaluated, such as watershed erosion (Karau and Keane, in press; Keane et al., 2010). Last, FLEAT output could be used before a wildfire to strategically identify those portions of the landscape where active suppression is indicated and

where wildland fire use will be the most effective (Black, 2005).

A comprehensive assessment of the benefits of wildfire is greatly needed during wildfires, but it is inherently difficult and nearly always subjective (Black, 2005). Williamson (2007) shows that ecological benefits are rarely addressed when deciding to manage a fire for resource benefit. Quantification of the loss and gain of non-market based values of ecosystems is impracticable because there are substantial gaps in scientific understanding about how the spatial and temporal provision of non-market values are affected by wildfire, and challenges in evaluating social welfare change arising from specific wildfire events. This presents serious impediments to adapting price-based decision-support tools to incorporate non-market values. Venn and Calkin (2007) mention that an alternative is using HRV concepts to support wildland fire management decisions. This FLEAT program is the first step towards addressing non-market values in operational wildfire management.

The utility of FLEAT products is currently being field tested on additional wildfires and prescribed wildland fire use fires. FLEAT products (fire severity, similarity measures, stoplight diagrams) can be fully integrated into the Wildland Fire Decision Support System, especially if the LANDFIRE input fuels and vegetation maps improve, to provide other resource groups fire severity maps to evaluate resource benefits and risk and as a separate product in the RAVAR collection of decision-support information. As mentioned, FLEAT is currently a research tool and has not yet been implemented into a user-friendly, management-ready system. We recommend that FLEAT algorithms or concepts be implemented in commonly used software systems, such as the Wildland Fire Assessment Tool (<http://www.fs.fed.us/fmi>), FARSITE, or FLAMMAP (Finney, 2005) to avoid the release of yet another software tool to an already overburdened fire manager. We envision the complete implementation of FLEAT into wildfire management after the following steps: (1) integration of FLEAT into a well-used fire management software package (this is almost completed), (2) improvement of LANDFIRE vegetation maps (this will be done over the next 2 years), and (3) continual testing on current wildfires (ongoing).

As with any spatial data application, the accuracy and consistency of the FLEAT product is mostly dependent on the quality of three major inputs: (1) LANDFIRE vegetation layers, (2) LANDFIRE succession pathways, and (3) input burn severity map. In this case, the accuracy of the LANDFIRE input layers was poor (~20%), and that coupled with a low simulated burn severity accuracy (~41%), lead to a low LANDSUM succession class prediction accuracy (~8%). The simulation of burn severity requires detailed information on fuel loadings, tree populations, and soil characteristics that are difficult to map consistently and accurately, and the mapping of successional stages using satellite imagery is difficult because the understory is often obscured. Burn severity simulation also depends on the accurate simulation of fire intensity to drive calculations of scorch height that is then used to estimate tree mortality. These accuracies presented here are worst-case because the higher accuracy satellite-derived burn severity maps coupled with high quality local high resolution vegetation input maps can replace the simulated burn severity and LANDFIRE maps, respectively. The FLEAT program is easily modified to accept locally developed data layers that might be more accurate, but these layers must be linked to LANDSUM successional pathways. More detailed and accurate input spatial data layers would greatly improve the reliability of FLEAT output along with more detailed succession pathway models. The LANDFIRE project is currently updating most fuel and vegetation maps to improve overall accuracy.

Some of the assumptions used in FLEAT simulations could affect the quality of the predictions. For example, we assumed that only one prediction for the 1, 10, and 100 year landscape composition was needed in the HRV analysis even though modules in LANDSUM are stochastic. Comprehensive analysis of LANDSUM simulations

found that predicted succession class compositions varies between 8% and 15% over a 500 year simulation, so we assumed that the effect of the stochasticity would be minimal over 100 years. The succession and disturbance LANDSUM parameters from LANDFIRE represent best estimates from existing historical studies, but many PVTs and succession classes were never studied for historical fire frequencies and successional trajectories (Long et al., 2006). The estimate of FLEAT severity to compute successional trajectories is overly simplistic and may not always match LANDFIRE disturbance dynamics. Future work in these areas would improve model predictions.

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