Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 247 (2007) 1–17
Forest Ecology and Management
www.elsevier.com/locate/foreco

Evaluating wildland fire danger and prioritizing vegetation and fuels treatments

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Received 28 April 2006; received in revised form 30 January 2007; accepted 13 March 2007

Abstract

We present a decision support application that evaluates danger of severe wildland fire and prioritizes subwatersheds for vegetation and fuels treatment. We demonstrate the use of the system with an example from the Rocky Mountain region in the State of Utah; a planning area of 4.8 million ha encompassing 575 subwatersheds. In a logic model, we evaluate fire danger as a function of three primary topics: fire hazard, fire behavior, and ignition risk. Each primary topic has secondary topics under which data are evaluated. The logic model shows the state of each evaluated watershed with respect to fire danger. In a decision model, we place summarized fire danger conditions of each watershed in the context of the amount of associated wildland–urban interface (WUI). The logic and decision models are executed in EMDS, a decision support system that operates in ArcGIS. We show that a decision criterion such as relationship to WUI can significantly influence the outcome of a decision to determine treatment priorities. For example, we show that subwatersheds that were in the relatively poor condition with respect to fire hazard, behavior, and ignition risk may not be the best candidates for treatment. Additional logistical factors such as proximity to population centers, presence of endangered species, slope steepness, and road access all might be taken into account in selection of specific watersheds within a management area for treatment. Thus, the ecological status of each ecosystem can be placed in one or more social values contexts to further inform decision-making. The application can be readily expanded to support strategic planning at national and regional scales, and tactical planning at local scales.
Published by Elsevier B.V.

Keywords: EMDS; NetWeaver®; Decision support; Landscape evaluation; Fire danger; Monitoring; Forest restoration; Fire hazard; Fire behavior; Ignition risk; Wildland–urban interface

1. Introduction

Wildland fuels have accumulated in many western forests of the United States (US) for the past 100 years due to 20th century management activities (Agee, 1998; Hessburg and Agee, 2003), and ever-changing climatic conditions (Burkett et al., 2005; Schoennagel et al., 2004). As demonstrated by recent fires, added fuels are fostering more intense wildfires that are more difficult to contain and control. Consequently, valuable property and natural resources have been destroyed, costs of fire management have escalated, fire-dependent forest ecosystems have deteriorated, and risks to human life and property continue to rise (GAO, 2002, 2003, 2004).

Historically, fires of varying size, frequency, and intensity maintained spatial patterns of forest vegetation, as well as temporal variation in those patterns (Agee, 2003; Hessburg et al., 2005; Schoennagel et al., 2004; Turner, 1989). In fact, many agents interacted to shape vegetation patterns and their spatio-temporal variation, including forest insect outbreaks, forest diseases, fires, weather and climatic events, and intentional aboriginal burning (Hessburg and Agee, 2003; Whitlock and Knox, 2002). Their interactions resulted in characteristic landscape patterns and caused variation in forest structural attributes, species composition, and habitats that resonated with the dominant disturbance processes. Patterns of forest vegetation were directly linked with the processes that

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2007.03.068

created and maintained them (Pickett and White, 1985; Turner et al., 2001).

Circumstances are different today—patterns and processes are still tightly linked, but not as before. Human influences have created anomalous vegetation patterns, and these patterns support fire, insect, and disease processes that display uncharacteristic duration, spatial extent, and intensity (Ferry et al., 1995; Hessburg et al., 2005; Kolb et al., 1998). For example, 20th century fire suppression and prevention programs significantly reduced fire frequency in many dry mixed coniferous forests. Contemporary wildland fires are now larger and more intense on average than those of the prior two or three centuries (GAO, 2002, 2003, 2004; U.S. Government, 2003). In short, settlement and management activities have altered spatial patterns of forest structure, composition, snags, and down wood at patch to province scales. As a result, significant changes in fire frequency, severity, and spatial extent are linked to changes in forest vegetation patterns at patch to province scales (Agee, 1998, 2003; Ferry et al., 1995; Hessburg et al., 2005).

Here, we present a decision support system for evaluating danger of severe wildland fire and prioritizing subwatersheds for vegetation and fuels treatment. In our descriptions, we adopt standardized nomenclature of the National Wildfire Coordinating Group (NWCG, 1996, 2005) and Hardy (2005). The decision support system consists of a logic model and a decision model. In the logic model, we evaluate danger as a function of three primary topics: fire hazard, fire behavior, and risk of ignition. Each primary topic has secondary topics under which data are evaluated. The logic model shows the state of each evaluated landscape with respect to fire danger. In the decision model, we place the fire danger summary conditions of each evaluated landscape in the context of the amount of associated wildland–urban interface (WUI). The logic and decision models are executed in EMDS (Reynolds et al., 2003), a decision support system that operates in ArcGIS. We show that a decision criterion such as relationship to WUI can significantly influence the outcome of a decision to determine treatment priorities. We demonstrate use of the system with an example from the Rocky Mountain region in the State of Utah, which represents a planning area of about 4.8 million ha and encompasses 575 complete subwatersheds. We discuss considerations for extending the application to support strategic planning at national and regional scales, and tactical planning at local scales.

This decision support system is comparable in some aspects to the National Fire Danger Rating System (NFDRS, Deeming et al., 1977; Burgan, 1988), but there are important differences and advances too. For example, the NFDRS summarizes fire danger information pertaining to fire hazard, fire behavior, and ignition risk, the primary topics of fire danger, at a regional scale using annual weather and forest conditions information. The fire danger variables computed by FIREHARM and used in this application reflect a broader set, are computed at a stand or patch scale and summarized to subwatersheds, and the variables are computed as probabilities of exceeding a severe fire threshold using 18 years, rather than a single year of data.

2. Methods

2.1. Study area

We selected one map zone as a proving ground for our modeling approach, but these methods could be applied to all US map zones. Map zones were developed in the US by the Earth Resources Observation and Science (EROS) Data Center (http://www.nationalmap.gov). They are broad biophysical land units represented by similar landforms, land cover conditions, and natural resources; there are 66 in the continental US (Fig. 1). Map zone 16 falls almost entirely within the State of Utah. Within this study area, we evaluated wildland fire danger for the 575 subwatersheds that were entirely contained within map zone 16 (Fig. 2). The average size of subwatersheds was 8300 ha, and size ranged from 2800 to 18,000 ha. For reference, a subwatershed represents the sixth level in the watershed hierarchy of the US Geological Survey (Seaber et al., 1987).

2.2. Data sources

Most spatial data used in this study came from the LANDFIRE prototype project mapping effort (Table 2, Rollins et al., 2006). The LANDFIRE project created spatial data layers of topography, biophysical environments, vegetation, and fuels at 30-m resolution for two map zones in the Rocky Mountains (map zones 16 and 19). All layers were available at the www.landfire.gov web site.

The fuels layers used in this study included two surface fuel classifications: (1) the 13 fire behavior fuel models (FBFM) of Albini (1976), defined by Anderson (1982), and mapped using methods described by Keane et al. (1998, 2000, 2007) and (2) the default fuel characterization classes defined in the Fuel Characterization Classification System (FCCS) described by Sandberg et al. (2001) (http://www.fs.fed.us/pnw/fera) and mapped using methods described by Keane et al. (2007). The FBFMs, which do not represent actual surface fuels, provided an indication of the expected surface fire behavior,[1] while the FCCS classes indicated the characteristics of the actual surface fuelbed, information useful for fire effects[2] simulation (Ottmar et al., 2004). In the next update of our fire danger model, we will incorporate the 40 fire behavior fuel models of Scott and Burgan (2005).

The canopy fuels layers used were the LANDFIRE canopy bulk density and canopy base height layers. Canopy bulk density (CBD) represents the mass of available canopy fuel per unit volume of canopy in a stand (Scott and Reinhardt, 2002) and it is defined as the dry weight of available canopy fuel per unit volume of the canopy including the spaces between the tree crowns (Scott and Reinhardt, 2001). Canopy base height (CBH) represents the level above the ground at which there is enough

[1] When we refer to ''fire behavior'' we are referring to the physical characteristics of the combustion process (Rothermel, 1972).

[2] When we refer to 'fire effects'' we are referring to the direct and indirect consequences of the combustion process (DeBano et al., 1998).

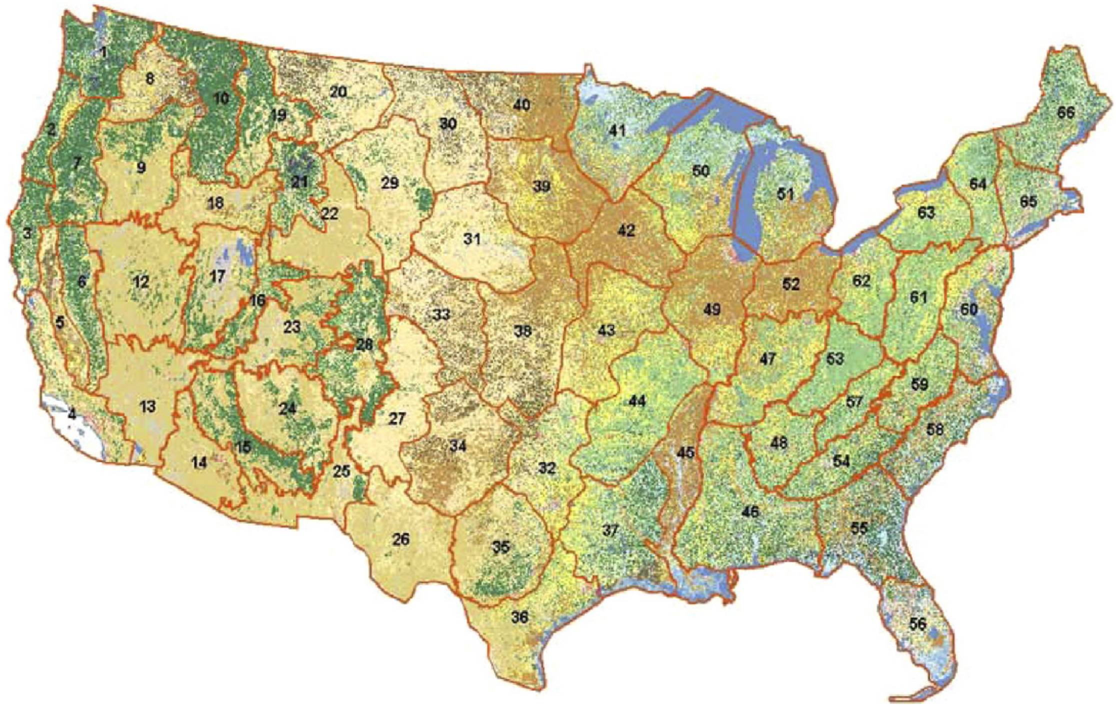

Fig. 1. Map zones of the United States from the Earth Surface Resources and Science (EROS) Data Center. There are 66 map zones in the continental United States. The highlighted area shows the position of the study area, map zone 16.

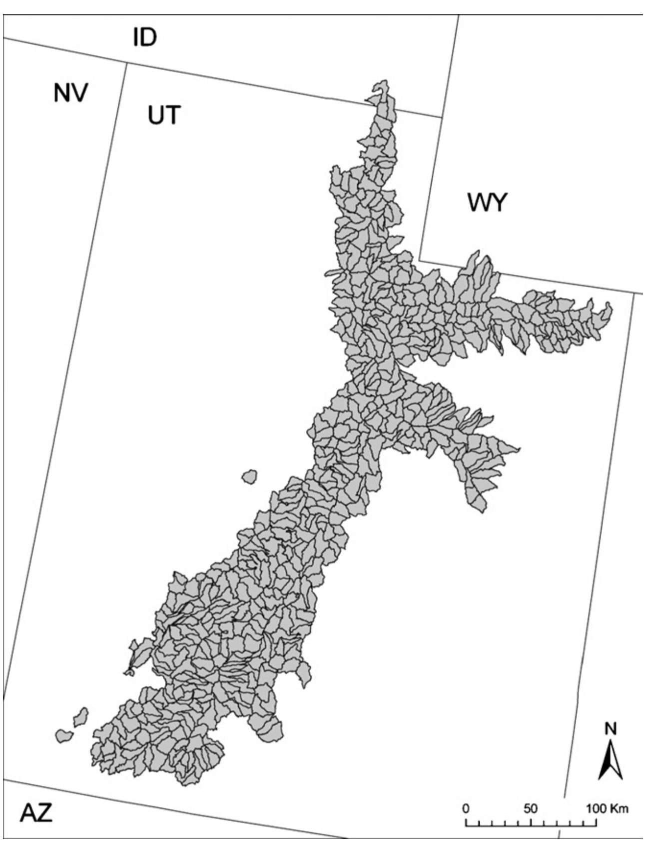

Fig. 2. Subwatersheds of map zone 16 in State of Utah, USA. The average size of subwatersheds was about 8274 ha (min 5000 ha, max 10,000 ha). A subwatershed represents the sixth level in the established US Geological Survey watershed hierarchy (Seaber et al., 1987).

aerial fuel to carry the fire into the canopy, and it is defined as the height from the ground to the bottom of the live canopy (Scott and Reinhardt, 2001) but may also include dense, dead crown material that can carry a fire. These two map layers were developed for the forested lands of map zone 16 using a predictive landscape modeling approach that integrated remotely sensed data, biophysical gradients, and field reference data (Keane et al., 2007). The canopy fuel characteristics were calculated for numerous plots distributed throughout the map zone using the FUELCALC model (Scott and Reinhardt, 2001) and each plot was described from a set of predictor variables computed and mapped specifically for the LANDFIRE project. The predictor variables were related to CBD and CBH using a classification and regression tree (CART) approach.

Fire behavior was simulated with these surface and canopy fuels layers assuming 90th percentile weather conditions using the FIREHARM (Keane et al., 2004) program. FIREHARM is a computer program that calculates four fire behavior variables (fireline intensity, spread rate, flame length, crown fire potential), five fire danger variables (spread component, burning index, energy release component, Keetch-Byram drought index (Burgan, 1993), ignition component), and five fire effects variables (smoke emissions, fuel consumption, soil heating, tree mortality, scorch height) for each day across an 18-year climate record (6574 days), and for every polygon in a user-specified landscape. Daily values across the 18-year period can be used to estimate probabilities that fire behavior, fire danger, or fire effects variables may exceed important thresholds. These probabilities can be mapped onto the landscape in a GIS, and maps can be used to prioritize, plan, and implement fuel or fire treatments. In this application, FIREHARM was used to estimate surface fire spread rate, flame length, and fireline intensity using the Rothermel (1972) fire spread model, and crown fire intensity and spread using Rothermel (1991) and the Scott (1999) crown fire algorithms.

In addition, LANDFIRE provided a fire regime condition class (FRCC) digital map created by simulating historical landscape conditions and comparing these simulations with current vegetation conditions derived from satellite images. FRCC is an ordinal index with three categories that describe how far the current landscape has departed from presettlement-era conditions (Hann, 2004) (see www.frcc.gov for additional details).

Several other data layers were used to derive ignition risk. Relative plant greenness was estimated from an AVHRR image from 1 June 2004 (Burgan and Hartford, 1993). These data were obtained from the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory. The effects of long-term drought were estimated from Palmer Drought Severity Index (PDSI) data obtained from the National Climate Data Center (Table 2). Available PDSI data represented a span of 20 years (1971–1990), and data were derived from a 2.5° continental scale grid of PDSI reconstructed by Cook et al. (2004). Lightning strike data were obtained from the National Lightning Detection Network (Table 2).

Data made available for map zone 16 will ultimately be available for all 66 map zones of the continental US. Map zones of the western US to eastern Montana and New Mexico (map zones 1–24, 28) will be completed in 2006, and the entire continental US by the end of 2008 (http://www.landfire.gov/schedule_map.php).

2.3. Broad outline

We evaluate relative fire danger in individual subwatersheds of an entire map zone. We show how evidence for fire danger can be modeled as a logic-based discourse in a decision support system to support national, regional, and local landscape analysis and planning. Results of evaluations are expressed in terms of evidence for low wildfire danger in each subwatershed. This information is used subsequently in a decision model to prioritize subwatersheds for treatment, considering additional logistical information.

2.4. Implementation steps

Under the fire hazard topic (Table 1), we estimated for each elementary topic (lowest level in the model where data are evaluated) the percentage area and degree of aggregation of observations exceeding a specified threshold value using spatial data layers provided by the LANDFIRE project and a spatial analysis program (FRAGSTATS, McGarigal et al., 2002, Table 2). For each elementary topic under fire behavior and ignition risk, we estimated the probability that conditions within a given watershed exceeded a specified threshold value based on spatial layers of fire spread rate and intensity generated by the FIREHARM model using the Rothermel (1972) spread model. We constructed a logic model within the EMDS modeling system to show how all elementary topics contributed to an evaluation of fire danger. We evaluated evidence for low wildfire danger within watersheds of a map zone to provide an ecological basis for determining treatment priority. A decision analysis was then run in a separate but related decision model to incorporate ecological and logistical considerations for planning fuels treatment across the study area.

2.5. Logic model design

We graphically designed the logic model for evaluating the relative danger of wildland fire (hereafter, fire danger) with the NetWeaver® Developer (Rules of Thumb, Inc., North East, PA)[3] modeling system. We present the formal logic specification both as a topic outline for readability and compactness (Table 1), and as a dendrogram (Fig. 3). Each topic in a NetWeaver® model represents a topic for which a premise or proposition is evaluated. For example, the overall fire danger topic, representing the top level in the model, evaluates the proposition that wildland fire danger is low (Table 1, Fig. 3). All other propositions in the model similarly take the null form; i.e., the test for all topics is always for a low condition.

The complete evaluation of fire danger depends on three primary topics – fire hazard, fire behavior, and ignition risk – each of which incrementally contribute to the evaluation of fire danger, as indicated by the *union* operator (Table 1). Moreover, because the *union* operator specifies that premises incrementally contribute to the proposition of their parent topic, low strength of evidence for one topic can be compensated by strong evidence from others. Notice that if the fire danger topic is thought of as testing a conclusion, then the three topics on which it depends can be thought of as its logical premises. Similarly, each of the three topics under fire danger has its own logic specification that includes a set of secondary topics or premises. The full logic structure (Table 1), considered in its entirety, constitutes what we referred to earlier as the logical discourse. We note that this logic model represents one of many possible logical configurations, and the current configuration may be readily adapted. Any of the primary and secondary topics may be modified, and topics may be added or removed with relative ease. Likewise, thresholds of elementary topics (discussed below) can be modified to fit customized or evolving evaluations as a function of adaptation and learning.

2.5.1. Primary topic—fire hazard

Evaluation of fire hazard (Table 1, Fig. 3) depends on the *union* of topics addressing surface fuels, canopy fuels, and fire regime condition class, each of which depends on two additional elementary topics that directly evaluate data (Tables 1 and 2). Evaluation of each elementary topic under

[3] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1
Logic outline for evaluation of wildfire danger[a]

Model topic	Primary topic[b]	Secondary topic	Elementary topic	Proposition[c] (stated in the null form)	Data inputs[d]
Fire danger (*union*[e])				Danger of severe wildfire is low	
	Fire hazard (*union*)			Fuel conditions do not support severe wildfire	
		Surface fuels (*union*)		Condition of surface fuels is not conducive to severe wildfire	
			Fire behavior fuel model	Expected fire behavior is not severe	FBFMarea, FBFMaggregation
			Fuel characterization class	Observed fuel load classes are not conducive to severe wildfire	FCCarea, FCCaggregation
		Canopy fuels (*union*)		Condition of canopy fuels is not conducive to severe wildfire	
			Canopy bulk density	Canopy bulk density is not conducive to severe wildfire	CBDarea, CBDaggregation
			Canopy base height	Canopy base height is not conducive to severe wildfire	CBHarea, CBHaggregation
		Fire regime condition class		Fire regime condition class is not conducive to severe wildfire	FRCCarea, FRCCaggregation
	Fire behavior (*union*)			Expected fire behavior associated with wildfire is relatively benign or low impact	
			Spread rate	Likelihood of high spread rate of surface fire is low	spreadRate
			Flame length	Likelihood of high flame length is low	flameLength
			Fireline intensity	Likelihood of high fire line intensity is low	firelineIntensity
			Crown fire potential	Likelihood of high crown fire spread potential is low	crownfirePotential
	Ignition risk (*union*)			Likelihood of wildfire ignition is low	
			Palmer drought severity index	Likelihood of long-term drought is low	palmerIndex
			Keetch-Byram drought index	Likelihood of short-term drought is low	keetch-byramIndex
			AVHRR NDVI	Relative plant greenness for the subwatershed is high	AVHRR-NDVI
			Lightning strike	Relative lightning strikes in the subwatershed are low	lightningStrike

[a] The logic outline specifies how data related to wildfire danger (Table 2) are interpreted in NetWeaver®, a logic modeling system.
[b] The level of each primary, secondary, and elementary topic in the outline is indicated. The overall topic of the model is wildfire danger. Evaluation of overall fire danger depends directly on the evaluation of the primary topics—fire hazard, fire behavior, and ignition risk. Terms in parentheses following a topic indicate the logic operator used to evaluate the propositions under a topic. For example, fire danger is evaluated as the *union* of hazard, behavior, and ignition risk. Subtopics shown under 'Elementary topics evaluated' indicate the elementary topics occurring at lowest level in the logic model where data are evaluated (Table 2).
[c] Each proposition evaluates a set of premises (see footnote b) or data relative to a specific landscape unit. For this analysis, subwatersheds were the landscape units.
[d] Definitions of data items are presented in Table 2.
[e] The *union* operator treats the premises of a proposition as factors that incrementally contribute to the proposition. Note that this definition of *union* is distinct to the NetWeaver® system and should not be confused with a Boolean *union* operator.

hazard involved two class metrics computed by the FRAGSTATS program: (1) the proportion of subwatershed area exceeding a specified threshold value, and (2) an index that shows the degree of spatial aggregation of observed values exceeding the threshold value. Threshold values were based on the fire literature, and where literature values were lacking, were based on our judgment. Use of the metrics to evaluate the elementary topic for canopy bulk density (CBD) is presented below as an example; methods for evaluation of each of the other elementary topics under hazard are analogous.

Within the elementary topic for CBD, the logic first tests the value of *CBDarea*; the percentage of the subwatershed area with CBD exceeding a threshold value of $0.15\ \text{kg m}^{-3}$ (Table 2):

If *CBDarea* is <0.29 (i.e., $<29\%$ of the subwatershed area exhibits CBD values $>0.15\ \text{kg m}^{-3}$), then evidence for low CBD is fully satisfied, else
If *CBDarea* is >0.79 (i.e., $>79\%$ of the subwatershed area exhibits CBD values $>0.15\ \text{kg m}^{-3}$), then there is no evidence for low CBD, else
Evidence for low CBD is evaluated as a function of *CBDaggregation*.

The value 0.29 represents the lower bound of the median 80% range for the set of all *CBDarea* data in map zone 16. The value 0.79 represents the upper bound of the median 80% range (Table 2). If the last condition above was satisfied, then we tested the observed value for *CBDaggregation* against a fuzzy membership function (Fig. 4). This was done to determine the

Table 2
Definition of data inputs evaluated by elementary topic, data source, and reference conditions for each datum[a]

Datum	Definition	Data source	Reference conditions[b]	
			No evidence	Full evidence
AVHRR-NDVI	AVHRR-NDVI[c] relative greenness value on 1 June 2004	Missoula Fire Lab[d]	0.00	1.00
CBDaggregation[e]	Aggregation index for canopy bulk density> 0.15 kg m^{-3}	LANDFIRE[f] (derived)	93.02	75.97
CBDarea	Likelihood[g] of canopy bulk density > 0.15 kg m^{-3}	LANDFIRE	0.79	0.29
CBHaggregation	Aggregation index for canopy base height < 3.1 m	LANDFIRE (derived)	72.99	36.92
CBHarea	Likelihood of canopy base height < 3.1 m	LANDFIRE	0.38	0.04
crownfirePotential	Likelihood of index for crown fire potential > 7	FIREHARM[d] (derived)	1.00	0.89
FBFMaggregation	Aggregation index for fire behavior fuel model > 9[h]	LANDFIRE (derived)	35.83	3.05
FBFMarea	Likelihood of value for fire behavior fuel model > 9	LANDFIRE	1.00	0.02
firelineIntensity	Likelihood of fireline intensity > 400 kW/m	FIREHARM	0.97	0.59
flameLength	Likelihood of flame length > 1.2 m	FIREHARM	0.92	0.09
FCCaggregation	Aggregation index for fuel loading > 56 Mg/ha[i]	FCCS[i] (derived)	89.73	33.00
FCCarea	Likelihood of fuel loading > 56 Mg/ha	FCCS	0.80	0.03
FRCCaggregation	Aggregation index for fire regime condition class[j]	FIREHARM (derived)	99.50	97.76
FRCCarea	Likelihood of fire regime condition class > 2	FIREHARM	0.28	0.01
keetch-byramIndex	Likelihood of a Keetch-Byram drought index value[k] > 400	FIREHARM	0.84	0.46
lightningStrike	Probability of cloud-to-ground lightning strike indexed by the maximum value[l]	NLDN[m]	1.00	0.00
palmerIndex	Likelihood of summer Palmer drought severity index[n] value < −2	NCDC[o]	37.00	0.00
spreadRate	Likelihood of a wildfire spread rate > 8.0 kph	FIREHARM	1.00	0.89

[a] Data items in this table correspond to data listed for elementary topics evaluated in Table 1. Each datum represents on observation for a subwatershed, the unit of analysis in this study.

[b] Reference conditions for no evidence and full evidence define critical values for which the fuzzy membership function of the associated elementary topic (Table 1) indicates no support and full support, respectively, for the proposition. The range of the reference conditions is the median 80% range of data for the variable of interest. An observed value for the associated datum that falls in the open interval defined by the two reference conditions maps to partial support for the proposition based on linear interpolation. Data with the suffix, Area, are not evaluated with respect to reference conditions; however, they are compared to minimum and maximum conditions within conditional tests to determine the logic for evaluation of elementary topics (see text for additional explanation).

[c] The normalized difference vegetation index (NDVI), obtained from NOAA-11, AVHRR satellite image, represents relative greenness, and in this usage, the effect of apparent moisture level on vegetation drying or curing. For further details see Burgan and Hartford (1993), White et al. (1997), and http://www.fs.fed.us/land/wfas/wfas11.html.

[d] Obtained from the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Laboratory, Missoula, MT, rbartlette@fs.fed.us.

[e] An aggregation index was computed with FRAGSTATS (McGarigal et al., 2002) for each attribute of hazard (see also Table 1) by reclassifying data in the 30-m resolution raster grid for the attribute to 0 (attribute ≤ threshold) or 1 (attribute > threshold).

[f] LANDFIRE (http://www.landfire.gov/) is a multi-partner wildland fire, ecosystem, and fuel mapping project, one of whose partners is the Missoula Fire Sciences Laboratory of the USDA Forest Service, Rocky Mountain Research Station, Missoula, MT, who provided the data. Data sources labeled ‘‘LANDFIRE’’ indicate base data layers provided by the LANDFIRE project. Data sources labeled ‘‘FIREHARM’’ indicate data derived from base LANDFIRE layers by the FIREHARM model (Keane et al., 2004) of the LANDFIRE project. With the exception of the data source for crownfirePotential, data sources labeled ‘‘(derived)’’ indicate an aggregation statistic that we derived from the LANDFIRE base layers with the FRAGSTATS (McGarigal et al., 2002) spatial analysis package. In the case of crownfirePotential, ‘‘(derived)’’ indicates a composite index that we developed from FIREHARM crown fire ignition and crown fire spread outputs.

[g] Each likelihood was estimated as the proportion of raster grid cells in the subwatershed area that exceeded the specified threshold for the attribute. All likelihoods were estimated from 30-m resolution data, except those for lightningStrike, and palmerIndex, which were estimated from available 1-km resolution data.

[h] Fire behavior fuel models represent 13 distinct distributions of fuel loadings found among surface fuel components (live and dead), fuel size classes, and fuel types. The fuel models are described by the most common fire carrying fuel type (grass, brush, timber litter, or slash), fuel loading and surface area-to-volume ratio by size class and component, fuelbed depth, and moisture of extinction. Further detail about the original fire behavior fuel models can be found in Albini (1976), Anderson (1982), and Rothermel (1972, 1983).

[i] Fuel Characteristic Class System (Sandberg et al., 2001, http://www.fs.fed.us/pnw/fera/nfp/haze/FCCS-lower48.zip).

[j] Fire regime condition class is a qualitative measure of departure from historic vegetation and fire regime conditions (Schmidt et al., 2002).

[k] In contrast to the Palmer drought severity index, the Keetch-Byram drought index represents the short-term effects of precipitation and temperature on duff, litter, and soil drying in the top 20 cm. An index value of 400 corresponds to a deficit of 10 cm of water in the top 20 cm.

[l] The lightning strike probability is based on actual strikes triangulated and recorded over 15 years (1990–2004, Schmidt et al., 2002).

[m] Data were obtained from the National Lightning Detection Network (NLDN, http://ghrc.msfc.nasa.gov/).

[n] The Palmer drought severity index is used to characterize effects of long-term drought. An index value of −2 corresponds to moderate drought conditions. Continuous maps of PDSI for the continental US were interpolated by Cook et al. (2004) based on their reconstructions of drought at grid points on a 2.5° grid of the continent.

[o] Website for the National Climate Data Center (NCDC), NOAA (http://www.ncdc.noaa.gov/paleo/newpdsi.html).

strength of evidence for a low degree of aggregation of high CBD values (i.e., values of CBD exceeding the threshold value of 0.15 kg m^{-3}) relative to a set of reference conditions that defined the median 80% range of the *CBDaggregation* data from the set of all subwatersheds (Table 2). Each elementary topic (Table 2) is similarly evaluated against the median 80% range of its associated datum, hence our characterization of fire danger as relative.

If *CBDaggregation* is ≤76 (i.e., ≤76% of the maximum value of aggregation), then evidence for low aggregation of high CBD values is fully satisfied, else

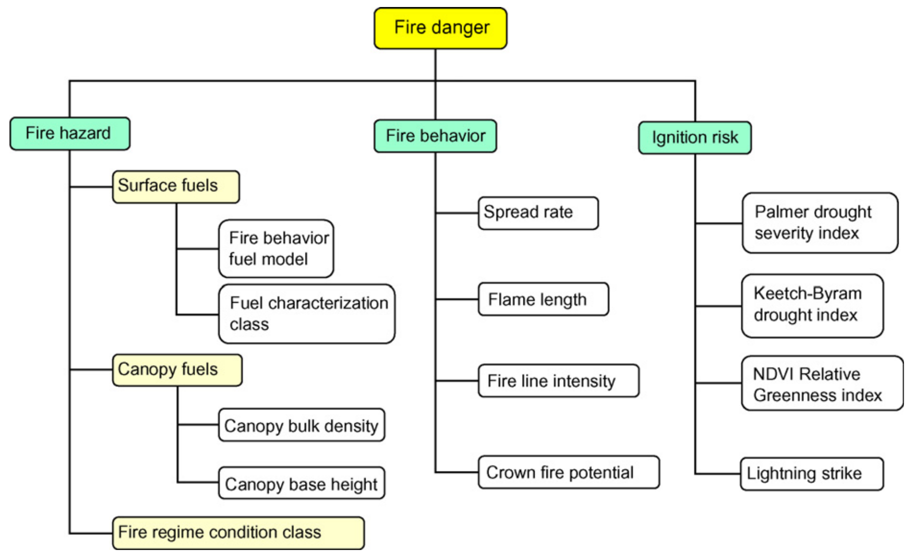

Fig. 3. Dendrogram showing how the overall fire danger topic is organized and evaluated. The complete evaluation of fire danger is made up of three parts—evaluation of fire hazard, fire behavior, and ignition risk, which are primary topics. Under each of these three primary topics are secondary and elementary topics. Under hazard are the topics surface fuels, canopy fuels, and fire regime. Under behavior are the elementary topics spread rate, flame length, fireline intensity, and crown fire potential. Under ignition risk are the secondary topics fire weather and ignition potential.

If *CBDaggregation* is $\geq$93 (i.e., $\geq$93% of the maximum value of aggregation), then there is no evidence for low aggregation of high CBD values, else
Observed values of *CBDaggregation* fall within the open interval (76, 93), and evaluate to partial support for the proposition, based on a linear interpolation between 76 and 93. The open interval (76, 93) represents the median 80% range of the data.

2.5.2. Primary topic—fire behavior

Evaluation of fire behavior depends on the *union* of topics addressing spread rate, flame length, fireline intensity, and crown fire potential (Table 1), each of which is an elementary topic that directly evaluates data (Tables 1 and 2). The spread rate topic evaluates the proposition that likelihood of spread rate of surface fire >8.0 kph within the subwatershed is low. The flame length topic evaluates the proposition that likelihood of flame length >1.2 m within the watershed is low. The fireline intensity topic evaluates the proposition that likelihood of fireline intensity >400 kW m^{-1} within the watershed is low. The crown fire potential topic evaluates the proposition that likelihood of crown fire spread potential >7 within the watershed is low. This metric is an index based on crown fire ignition and spread potentials (Keane et al., 2004) and represents the ratio of crown fire to surface fire behavior based on Rothermel (1972, 1991) surface and crown fire algorithms.

None of the fire behavior elementary topics are entirely independent of the other topics; rather, one or more of these topics is used in the calculation of the others. For example, flame length influences the spread rate calculation, and fireline intensity influences flame length. In fact, fireline intensity is double weighted in our model because of the equivalence of flame length and fireline intensity (Chandler et al., 1983). We used both in the model because intensity relates best to fire effects and flame length is easily observed and often asked for. Each selected elementary topic is used here to provide a more comprehensive picture of expected fire behavior. While complete independence among the topics would be desirable, there is no set of fire behavior attributes with such independence, and there is also no independent set that provides a comprehensive picture of expected fire behavior.

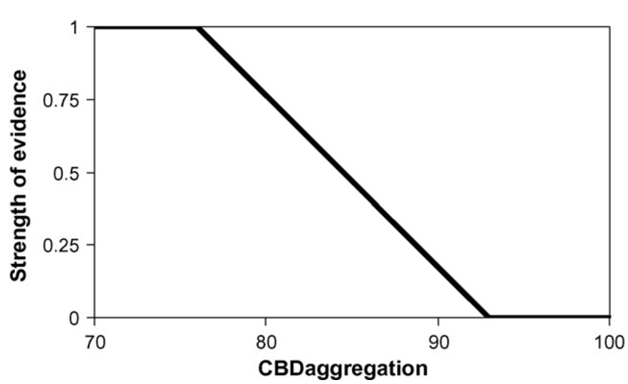

Fig. 4. The fuzzy membership function used to evaluate strength of evidence for the proposition of low canopy bulk density. The proposition is fully satisfied when the observed value of *CBDaggregation* $\leq$ 76, and there is no evidence for the proposition if *CBDaggregation* $\geq$ 93 (Table 2). Observed values of *CBDaggregation* that fall within the open interval (76, 93) evaluate to partial support for the proposition, based on linear interpolation between 76 and 93.

2.5.3. Primary topic—ignition risk

Evaluation of ignition risk depends on the *union* of four elementary topics—Palmer drought severity index (Palmer, 1965), the Keetch-Byram drought index (Keane et al., 2004), the AVHRR-NDVI relative greenness index (Keane et al., 2004), and lightning strike probability (Tables 1 and 2). First, the probability of a summer Palmer drought severity index value <−2 is evaluated. A value of −2 corresponds to moderate drought in the Palmer rating system. This elementary topic is included because it allows consideration of the effects of long-term drought on vegetation and fuels. Second, the probability of a Keetch-Byram drought index value >400 is evaluated. The topic considers the short-term effects of precipitation and temperature on duff, litter, and soil moisture in the top 20 cm. An index value of 400 corresponds to a deficit of 10 cm of water in the top 20 cm; Burgan (1993) suggested that severe fire behavior often occurs when the KBDI exceeds this value.

The AVHRR-NDVI relative greenness value on Julian day 152 (1 June 2004) is then considered as a topic that indirectly represents fuel condition by incorporating vegetation drying or curing in a measure of relative greenness. June 1 is used to represent the height of the growing season in the study area; the greenest values indicate lesser chance for fire ignition. Future versions of this modeling system would include dates to capture the span of the fire season of each unique map zone.

Finally, lightning strike probability is evaluated, which we base on actual strikes triangulated and recorded over 15 years (1990–2004). The probability of human-caused ignitions is also important but omitted in this implementation. We constructed a logic module for evaluating the likelihood of human-caused ignitions, but it is not implemented in this version because wall-to-wall human ignition density data were unavailable for map zone 16. In a future version, we will incorporate a direct evaluation based on recorded human-ignition densities, or an indirect measure of likelihood involving road density maps and maps of human congregation sites.

2.6. Priorities for fuels treatment

A decision model for determining priorities of subwatersheds for fuels treatment was graphically designed with Criterium DecisionPlus (InfoHarvest, Inc., Seattle, WA), which uses both the analytic hierarchy process (AHP, Saaty, 1992) and the Simple Multi-Attribute Rating Technique (SMART, Kamenetzky, 1982) to support planning activities such as priority setting, alternative selection, and resource allocation. We used a decision model structure that was nearly identical to that of the logic model (Fig. 3). In the context of decision models based on the AHP, the concept of topics is replaced by criteria. Thus, in the decision model for fuels treatment, the first level of the model contained the three criteria, fire hazard, wildfire behavior, and ignition risk. However, for purposes of setting treatment priorities for subwatersheds, we also added a fourth criterion, percentage of subwatershed area classified as wildland–urban interface (WUI), to illustrate expanding the scope of analysis to include additional logistical factors that can influence decisions about priorities. Note that numerous other criteria and subcriteria could be included to account for other logistical considerations that might influence decisions about treatment priorities.

Weights for each criterion at the first level of the decision model were derived from the standard pair-wise comparison procedure of the AHP (Saaty, 1992), in which a decision maker is asked to judge the relative importance of one criterion versus each of the others. We provided the judgments on relative importance for our example application. Weights for sets of subcriteria under each criterion (the second level of the decision model) were derived in the same manner. For purposes of subsequent discussion, criteria at the lowest level of an AHP model are commonly referred to as attributes of a decision alternative, and these attributes correspond to the elementary topics of the logic model (Table 1).

A SMART utility function was specified for each attribute of a subwatershed, and this function represented the mirror image of the fuzzy membership function of its corresponding elementary topic; i.e., the fuzzy parameters defining no support and full support (Table 2) were now used to define utility values of 1 (full utility) and 0 (no utility), respectively, on the SMART utility scale of [0,1]. Note, however, that the WUI criterion is both a primary (first level) criterion of the decision model and an attribute of a subwatershed for which there is no corresponding elementary topic in the logic model. In this case, the critical values corresponding to full and no utility were separately specified as 67 and 0%, respectively, and represent the maximum and minimum of observed WUI percentages.

2.7. Analysis

Fire danger evaluation (Table 1) for all subwatersheds in the study area (Fig. 1) was performed with the NetWeaver® logic engine (Miller and Saunders, 2002) in EMDS (Reynolds et al., 2003). Continuous data related to recent burns in map zone 16 were not available, and were not implemented in this version of the fire danger model. This component should be added as data become available. Priority setting for fuels treatments among subwatersheds was performed with Priority Analyst, an engine for running Criterium DecisionPlus models in EMDS.

3. Results

We describe results in terms of the strength of evidence in support of the overarching proposition of low fire danger, or of subordinate propositions under fire danger. Recall that all propositions take the null form; for example, low strength of evidence based on the underlying evaluation implies that the proposition of low fire danger has poor support.

3.1. Fire danger

There were pronounced differences in fire danger between subwatersheds in the northern and southern portions of the study area (Fig. 5). Support for the proposition of low fire danger was generally moderate in the north and low in the south, which also contained small pockets of very low support. Dangerous wildfire conditions were largely driven by conditions conducive to severe fire behavior. Fig. 6 shows the partial products of the entire evaluation process; from viewing this composite, it is possible to see the various contributions to overall fire danger. We summarize the results of the partial products immediately below.

3.1.1. Fire hazard

Throughout much of the northern half of map zone 16, evaluation of fire hazard showed moderate to full support for the proposition of low fire hazard. The outstanding exception was the northern peninsula of subwatersheds extending to the east, where most of the subwatersheds showed low support for the proposition (Fig. 6). Likewise, in much of the northern half of the map zone, evaluation of fire regime condition class showed moderate to full support for the proposition of low departure of vegetation and fuel conditions from historical ranges. The southern half was mixed in its support but with a considerable number of subwatersheds showing low, very low, and no support.

The canopy fuels evaluation was composed of the partial evaluations of canopy bulk density and canopy base height. In general, the canopy fuels evaluation showed subwatersheds displaying conditions favorable to severe wildfire in both the northern and southern portions of the map zone. Evaluation of canopy base height showed conditions conducive to severe wildfire in the northern peninsula of subwatersheds extending to the east and especially in the southern subwatersheds. Evaluation of canopy bulk density showed conditions favorable to severe wildfire throughout the map zone, but most especially in the northern peninsula of subwatersheds extending to the east.

The surface fuels evaluation was composed of the partial evaluations of fire behavior fuel model and fuel loading. In general, the surface fuels evaluation showed subwatersheds displaying conditions favoring severe wildfire in both the northern and southern portions of the map zone, but most especially in the northern peninsula of subwatersheds extending to the east (Fig. 6). Here, fuels were dominated by shrub types with grassland-savanna fuel types also common. Evaluation of fire behavior fuel model showed that with the exception of the northernmost peninsula of subwatersheds extending to the east, the northern half of the map zone showed moderate to full support for the proposition that expected fire behavior would be low. In the subwatersheds of the south-eastern portion of the map zone, the evaluation suggested that expected wildfire behavior would be severe. The evaluation of

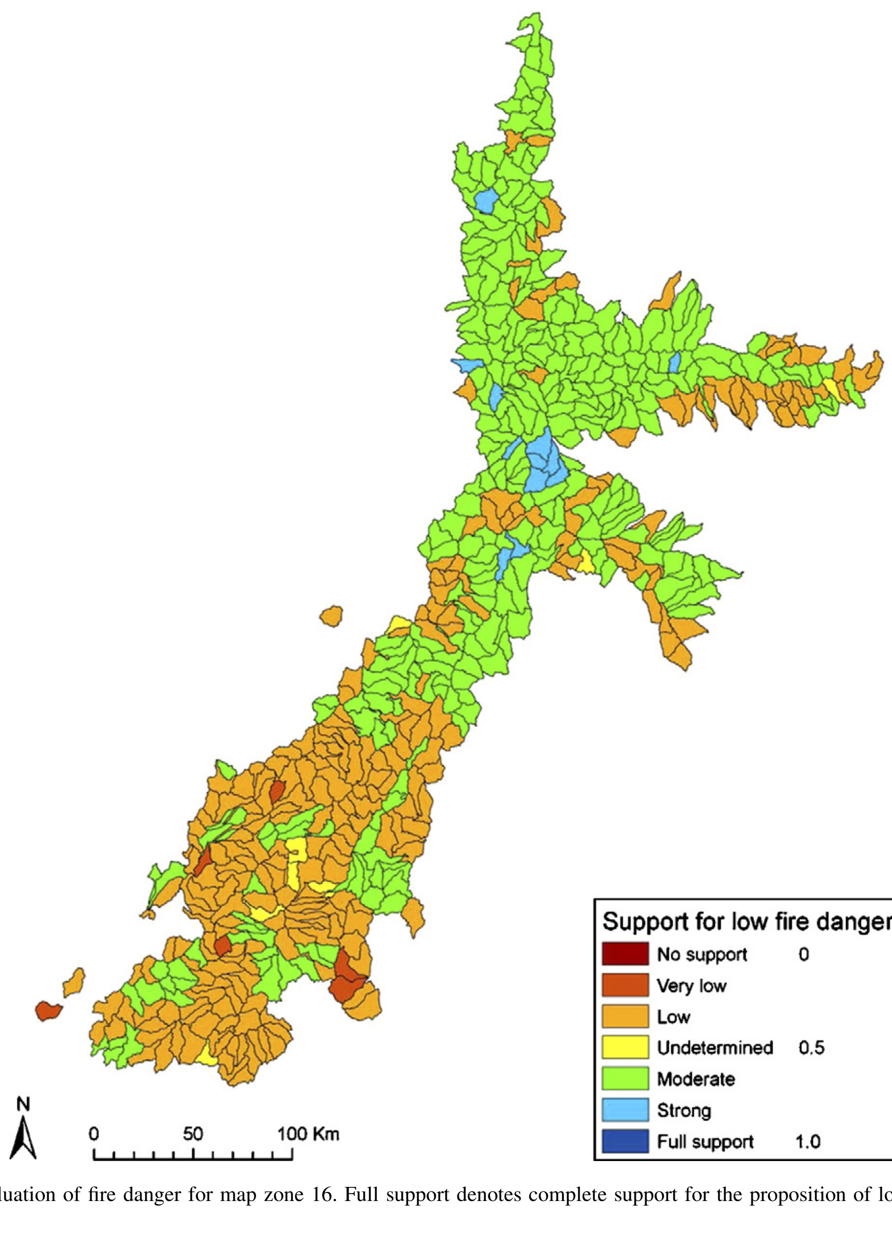

Fig. 5. Evaluation of fire danger for map zone 16. Full support denotes complete support for the proposition of low fire danger.

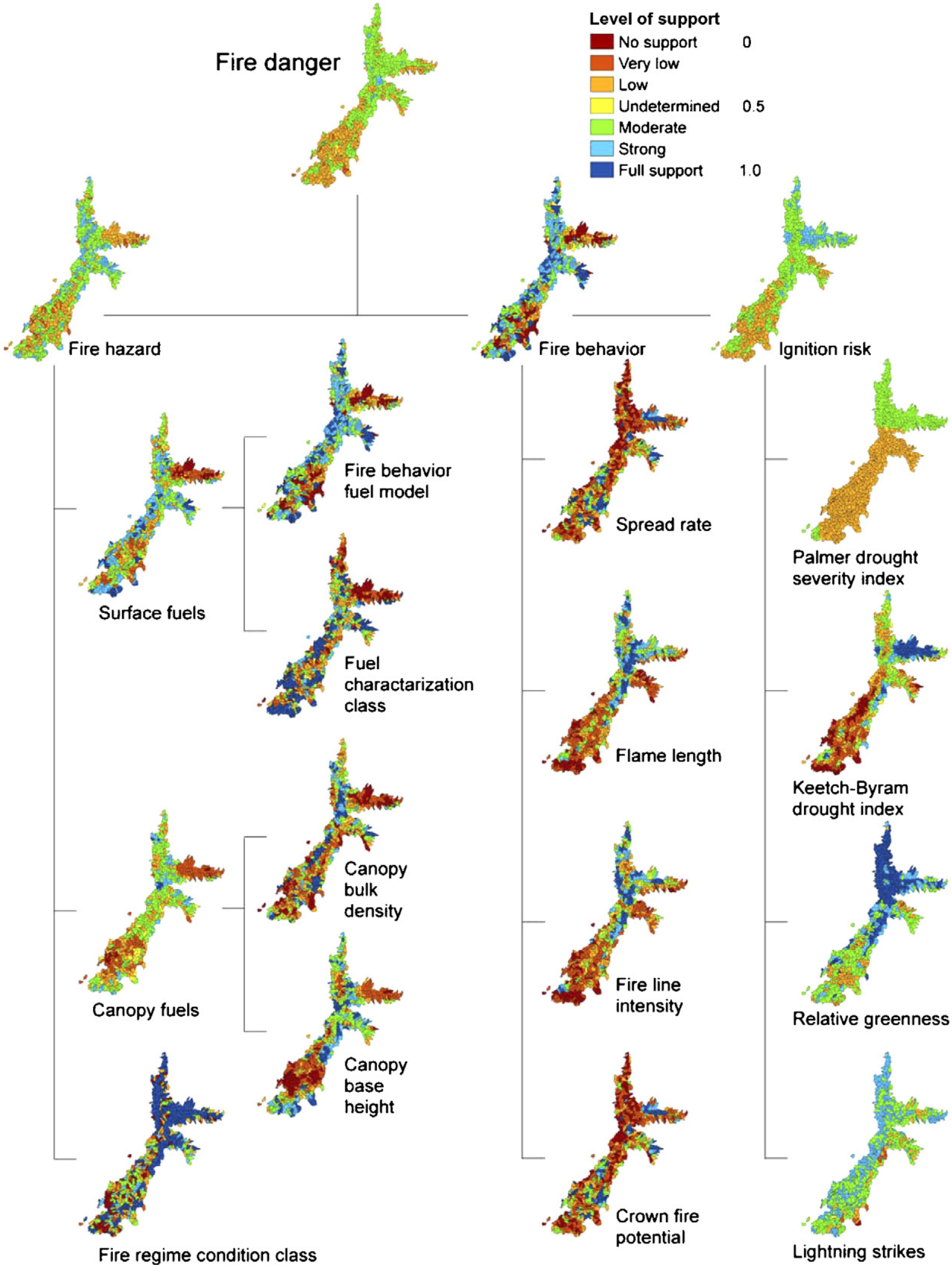

Fig. 6. Composite of all partial product evaluations leading to the full evaluation of fire danger (Fig. 5) for map zone 16.

fuel characterization class showed highly mixed results throughout the map zone, with the exception of the northern-most peninsula of subwatersheds extending to the east where surface fuels were conducive to severe wildfire.

3.1.2. Fire behavior

The fire behavior evaluation consisted of the partial product evaluations of fire spread rate, flame length, fireline intensity, and crown fire potential (Table 1, Fig. 6). Throughout the map zone, there was low to very low support for the proposition that expected wildfire behavior would be low.

The evaluation of wildfire spread rate showed that expected spread rate of surface fires would be high under 90th percentile conditions especially in the central and northern sectors. In the flame length evaluation, the likelihood of high flame length was high in the southern half of the map zone and in the southernmost peninsula of subwatersheds extending to the east in the northern sector. The evaluation of fireline intensity produced results similar to those of the flame length evaluation, and crown fire potential results were similar to those of the spread rate evaluation (Fig. 6).

3.1.3. Ignition risk

The ignition risk evaluation consisted of the partial product evaluations of the Palmer Drought Severity Index, the Keetch-Byram Drought Index, NDVI-relative greenness, and the relative number of cloud-to-ground lightning strikes. Throughout the southern half of the map zone, there was low support for the proposition that likelihood of wildfire ignition is low. In general, higher overall ignition risk was driven by the tendency for more severe annual summer drought and lower relative greenness in the southern portion of map zone 16, and moderate to full support for relatively fewer lightning strikes in the northern and central sectors of the map zone.

3.2. Priorities for fuels treatment

The map for fuels treatment priorities (Fig. 7A) took into account most of the same factors as used to produce the map for fire danger and its components (Fig. 6), but with weighting of criteria and subcriteria by a fire ecologist, and also considering the influence of wildland–urban interface (Fig. 7B). Ideally, when developing operational decision models for management, derivation of weights would be performed by a panel of managers and scientists. Indeed, we emphasize the importance of such collaborative development in our conclusions. Here, for illustration purposes, and considering a simple decision model in which three of the four decision criteria are more technical in nature, development of weights by a fire ecologist seemed appropriate.

The majority of subwatersheds with a priority rating of high or very high occurred in the southern two-thirds of the map zone (Fig. 7A). The map of treatment priorities (Fig. 7A) was strongly conditioned by the presence of wildland–urban interface in a subwatershed because of the emphasis placed on this criterion in the decision model. Normalized weights on primary criteria, derived from the pair-wise comparison process, were wildland–urban interface, 0.50; fire behavior, 0.27; fire hazard, 0.15; and ignition risk, 0.08. A more detailed view of a small region in Fig. 7 (Fig. 8) shows the correspondence between wildland–urban interface and decision scores for fuels treatment for subwatersheds. Notice that all subwatersheds with wildland–urban interface $\geq$16.64% (Fig. 8B) were classified as very high priority (Fig. 8B). Model output from the Priority Analyst (Fig. 9) shows how the four primary decision criteria contribute to the overall decision score for a sampling of 10 subwatersheds. The three highest ranked subwatersheds (Fig. 9) are also labeled in Fig. 8B. Notice that the three highest ranked cases could be distinguished from the next seven cases by the level of influence of the wildland–urban interface. Furthermore, although the relative contribution of fire

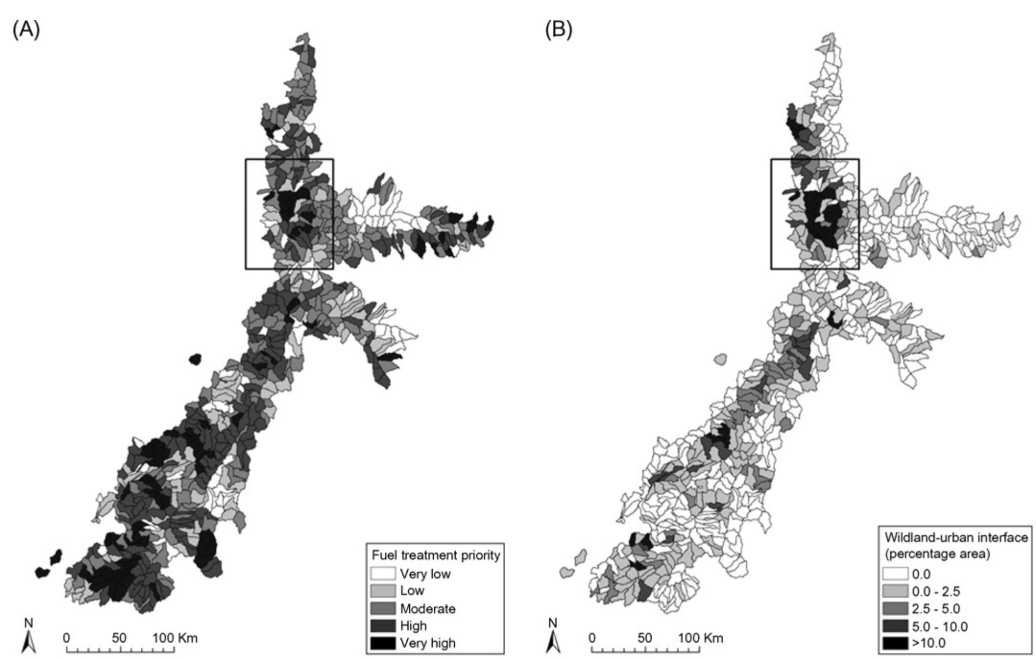

Fig. 7. Priorities for fuels treatment in subwatersheds of map zone 16. (A) Priorities of subwatersheds. This map, which reflects the influence of both weighting decision criteria and consideration of proximity to the wildland–urban interface, should be compared with Fig. 5. (B) Percentage of wildland–urban interface in each subwatershed. Both maps are symbolized using a natural breaks algorithm in ArcMap to define the classes in the legend. Bounding boxes in A and B indicate corresponding detailed views in Fig. 8.

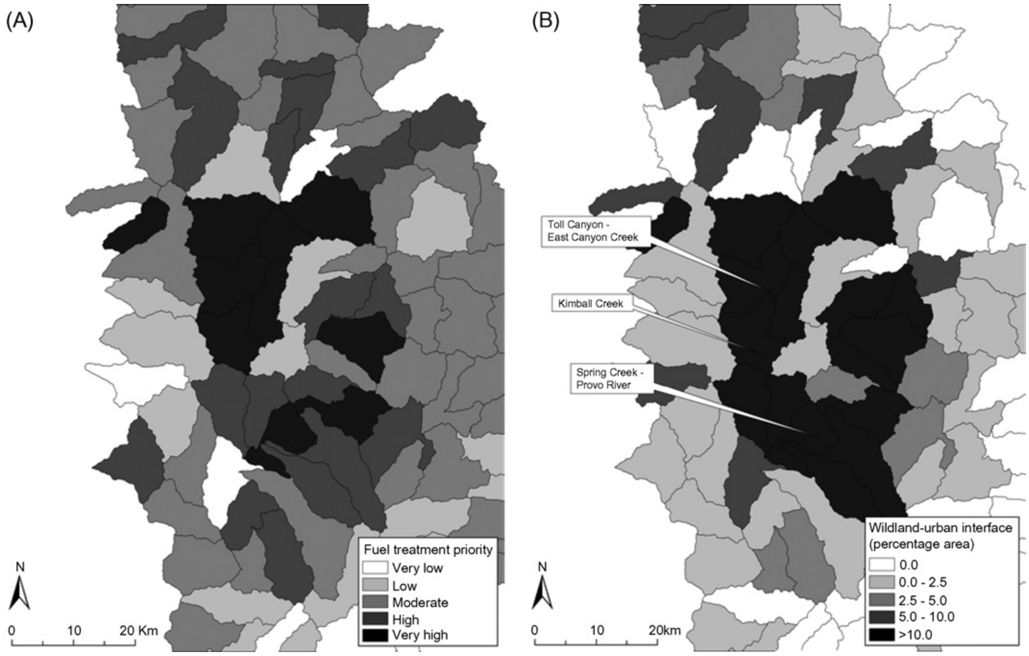

Fig. 8. Detailed views of example subregions from Fig. 7. (A) Detailed view of priorities of subwatersheds from bounding box in Fig. 7A. (B) Detailed view of percentage wildland–urban interface in each subwatershed from bounding box in Fig. 7B. Both maps are symbolized using a natural breaks algorithm in ArcMap to define the classes in the legend.

behavior was fairly consistent across the top 10 cases, the contributions of fire hazard and ignition risk were relatively low among the top three.

4. Discussion

The relative nature of our evaluation of fire danger has at least three important implications. First, the observed data value for each elementary topic in the logic model and for each attribute in the decision model was evaluated against reference conditions that were defined by the data themselves (Table 2). As a result, basic evaluations at the lowest level of each model were relatively objective. A second consequence of defining reference conditions in this manner was that the models were maximally sensitive to the data, thus assuring a high level of discrimination among outcomes over the set of subwatersheds in map zone 16. Finally, this method of deriving reference conditions means that the values used depended on the spatial extent of the assessment area. For example, reference conditions appropriate to an assessment of the entire southwestern US would be at least somewhat broader than those for map zone 16 alone.

Evaluation outcomes and their underlying premises are affected by the scale of input data, whether they are at a relatively fine (e.g., 30- to 90-m pixels) patch scale or, in the case of the PDSI data used here, the continental scale. For map zone 16, evaluating the likelihood that a subwatershed experienced drought in the past 20 years was derived from a 2.5° continental scale grid of reconstructed PDSI (Fig. 10). Although there was wide variation in the probability of experiencing a long term drought (PDSI < -2) for the continental US (0–37%, Fig. 10), map zone 16 exhibited a

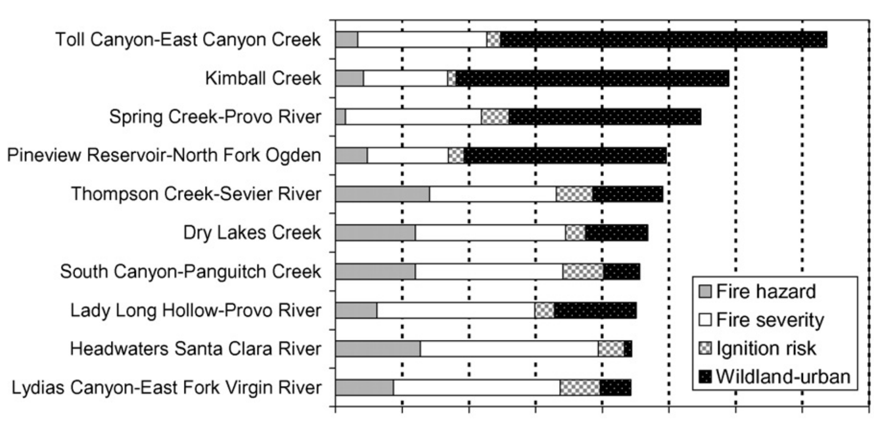

Fig. 9. Contributions of primary decision criteria to decision scores for priority of fuels treatment in subwatersheds of map zone 16.

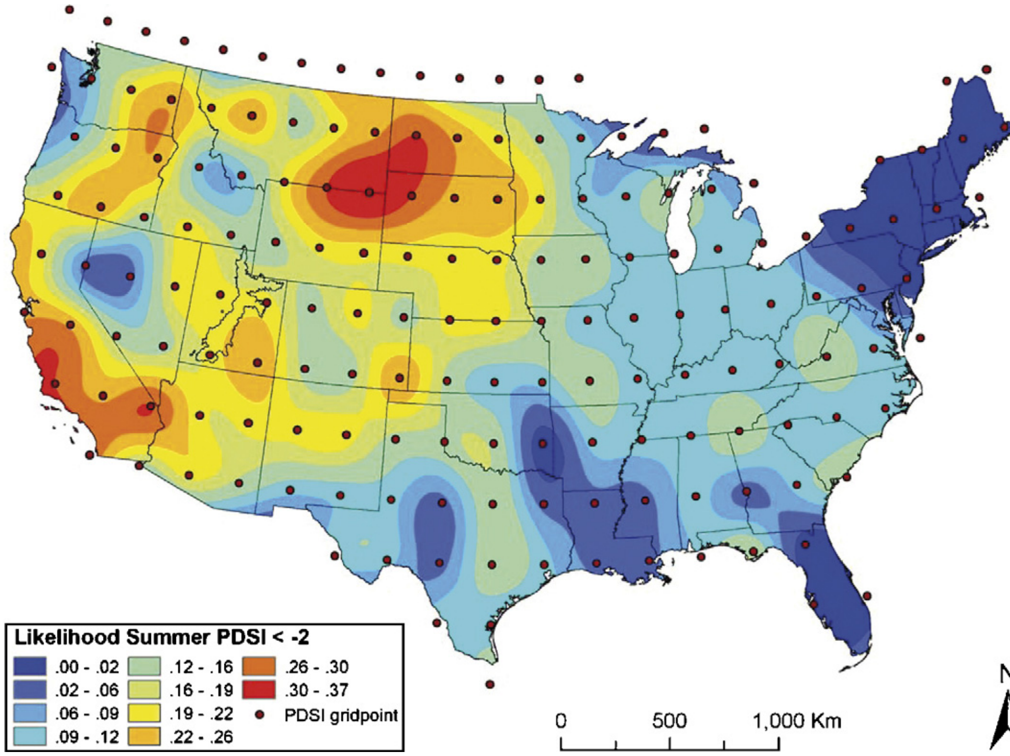

Fig. 10. Grid points of the Palmer Drought Severity Index (PDSI), and drought map for the average of 20 years (1971–1990) (adapted from Cook et al., 2004).

relatively narrow range of probabilities from 14 to 23%; or about 25% of the continental scale variation. Thus, one might be concerned that the contribution of long-term drought to the evaluation of ignition risk at the scale of a map zone may be neutral, as if adding a constant. This was not the case. Fig. 11A and B illustrate the influence of including continental scale drought data in the map zone evaluation of fire danger. Differences can be seen among subwatersheds within evaluations of fire danger (Fig. 11A) and ignition risk (Fig. 11B) when comparing the same evaluations with and without PDSI. For map zone 16, PDSI does provide information on long-term drought that is beneficial to managers.

In addition to considering the scale of input data, the contributions of topics at each level to overall fire danger should be considered when interpreting an evaluation. For example, 10 subwatersheds that share a similar overall result for evaluation of fire danger (i.e., moderate support, 0.56, for the proposition of low fire danger) are shown in Fig. 12, but they differed by evaluation result at the primary topic and lower levels. Use of the *union* operator in the design of the knowledge base made it possible for relatively high fire hazard within a subwatershed to be offset by relatively low predicted fire behavior in the event of a wildfire (e.g., see subwatershed 224, Fig. 12). Similarly, subwatershed 339 (Fig. 12) displayed evidence for low fire behavior but high ignition risk. An important strength of the logic model is that the full range of variability is expressed among subwatersheds at the level of an elementary topic, and each elementary topic contributes to evaluations of secondary and primary topics within a subwatershed and among subwatersheds. Thus, it is important to keep in mind that variability of support for a subwatershed at the elementary topic level in the hierarchy should be considered when interpreting a primary or secondary topic level evaluation result for any subwatershed, and among subwatersheds.

The present study illustrates application of EMDS for evaluating wildland fire danger and prioritizing vegetation and forest fuels treatments at the spatial extent of a USGS map zone. When the national LANDFIRE mapping effort (www.landfire.gov) provides full coverage for the continental US (CONUS), it will be technically feasible to conduct an analysis of fire danger for all subwatersheds in the CONUS in the same manner as we have illustrated here. Moreover, it is a relatively simple matter, given such a base analysis, to summarize such watershed-scale evaluations to various intermediate broader scales such as States, geographic regions, Forest boundaries, or Forest Planning zones as a basic input to broad-scale planning and resource allocation.

At the other extreme, the present study provides a starting point for finer-scale planning. We have examined the evidence for fire danger in subwatersheds of map zone 16, but this information, by itself, is not necessarily sufficient for fuels treatment planning. As shown above, subwatersheds that exhibit a similar moderate level of fire danger do not necessarily share the same evaluation results for primary topics (Fig. 12). Thus variability of support for propositions within a subwatershed at the level in the logic model where data are evaluated should be considered when interpreting an evaluation result among subwatersheds at the level of the primary or secondary topics.

To that end, subwatersheds in the worst condition with respect to fuels may not be the best candidates for fuels treatment. In particular, additional strategic or logistical factors

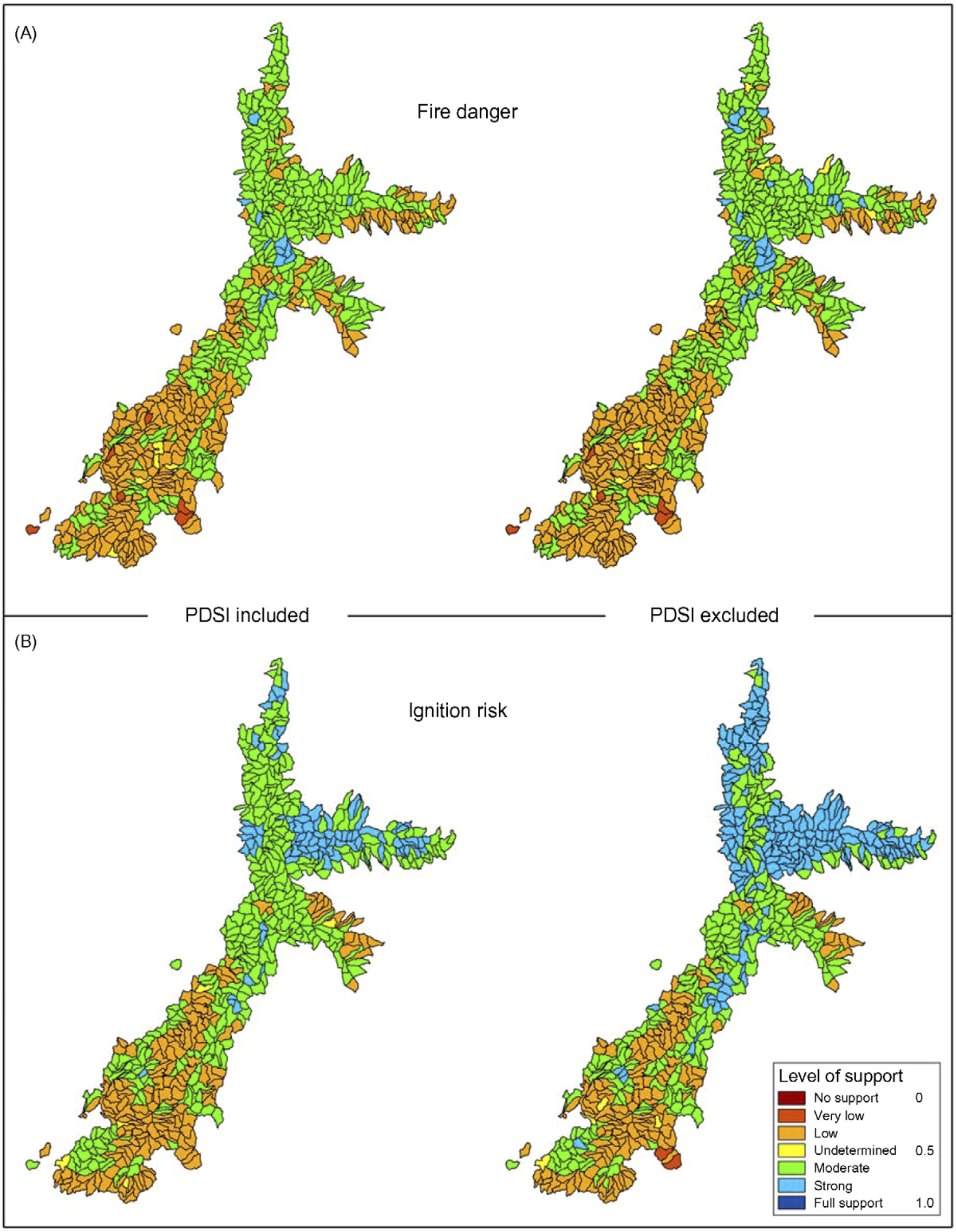

Fig. 11. Comparison of (A) overall fire danger and (B) ignition risk evaluations with and without the Palmer Drought Severity Index (PDSI) elementary topic evaluation.

such as proximity to population centers, presence of endangered species, slope steepness, and road access all might be taken into account in selection of specific watersheds within a management area for fuel treatment. Such an approach was illustrated by Reynolds and Hessburg (2005) using the Priority Analyst component of EMDS, which uses a decision engine for such purposes. In that study, they considered the compositional and structural integrity of forests along with contemporary fire risks, and the technical and economic feasibility of restoration. Carefully designed decision models can not only assist with a more circumspect approach to selection of individual treatment units, but can also show which of several treatment options may be most suitable in a given unit, thus also providing support for the tactical level of planning.

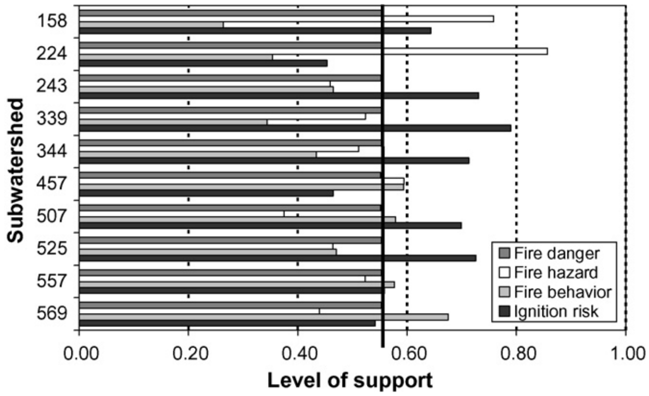

Fig. 12. Comparison of 10 subwatersheds in map zone 16, each of which displayed moderate support (strength of evidence = 0.56 in the interval [0,1]) for the proposition of low fire danger. Note that level of support varies considerably by primary topic (fire hazard, fire behavior, ignition risk).

Similarly, evaluation of treatment priorities related to fire danger is not necessarily limited to fuel and fire characteristics; it can also incorporate human impacts, and social or economic, or other value considerations. One such consideration, when evaluating the context of fire danger, may be the pattern of wildland–urban interface in the study area (Fig. 7B). Readers might fairly ask, ‘‘Given that the structures of the logic model for danger evaluation and the decision model for treatment priorities are so similar in this example, why bother with two separate models?’’ First, and perhaps most obviously, the two models produce very different interpretations of the data (compare fire danger in Fig. 5 with treatment priority in Fig. 7A). The logic model is a relatively objective interpretation of fire danger, given that parameters used to interpret observations (Table 2) were derived from field data, and given that the logic is presented in a relatively pure form insofar as all topics (with the exception of fireline intensity and flame length) are equally weighted. Although weights can easily be applied to topics in a logic model, they also add an additional level of subjectivity that is more effectively managed within the context of decision models, such as those based on the analytic hierarchy process, for example, that are more specifically designed to deal with such issues (Reynolds and Hessburg, 2005). Logic models also offer the opportunity to synthesize and summarize potentially complex information, thus simplifying the structure of a decision model. In this study, for example, the decision model used summarized information about the topics under fire hazard that would otherwise have been difficult to adequately represent in an intrinsically linear decision model (see, for example, the description of the CBD topic in Section 2.5.1).

Finally, the two types of models are very complementary in the sense that the logic model focuses on the question, ‘‘What have I got?’’, whereas the decision model focuses on the question, ‘‘Now that I know what I have, what should I do about it?’’ Notice that logistical issues are not pertinent to the first question, but they may be extremely important for the second. An important consequence of separating the overall modeling problem into these two complementary phases is that each phase is rendered conceptually simpler. The logic model evaluates and keeps separate the status of the components of each ecological system under evaluation; in this case, the components of wildland fire danger of each subwatershed in the map zone. The decision model takes the ecological status of each ecosystem and places it in one or more social contexts that are designed to further inform decision-making. The decisions will be based only partially on the ecological status information. They will also be based on social context and human values, in this case, proximity to and amount of wildland–urban interface, which captures a measure of the potential risk of fire damage to people and their structures. After priorities have been derived by the decision model concerning what to do about the existing fire danger conditions, the decision-maker can look back at the decision and see the relative contributions of the ecological states and their social context(s) to the overall decision. This transparent model design and structure aids in decision explanation and it allows decision makers to consider in the sense of scenario planning, the effects of alternative weightings of important decision criteria.

As Box (1979) noted, ‘‘All models are wrong; some are useful.’’ Thus, as with any model intended to support significant management decisions, our model of fire danger requires both verification and validation because all models are necessarily simplifications of reality. The present model has, in fact, been substantially verified in the sense that it performs as expected based on our own analyses, and has been vetted in several meetings over the past year involving substantial numbers of prominent fire managers and fire scientists who agree that the representation of fire danger is reasonable. In contrast to verification, validation is a more rigorous process in which model accuracy is objectively evaluated by comparing predicted and actual outcomes, ideally with statistical procedures. Readers unfamiliar with logic-based models may wonder if validation is even possible. However, models based on logic are no better or worse in this respect than their probabilistic counterparts. Although a detailed discussion of this assertion is beyond the scope of this report, it may be sufficient to note that metrics expressing strength of evidence have commonly been treated as subjective probabilities (Zadeh, 1968). Finally, model validation was not feasible within the temporal scope of our study. Realistically, even a preliminary validation in this context would require 5–10 years. If the model for fire danger were to be adopted as a tool to support strategic planning for fuels treatment, then we certainly recommend that explicit provisions for validation be an integral part of any ongoing assessment process designed to support it.

5. Conclusions

Given the widespread increase in danger of wildland fire throughout the western US over the past 70 years or more, the sustainability of western forest ecosystems is clearly at stake. Decision support systems such as EMDS can play a role in assisting with restoration to improve or maintain their sustainability. Issues surrounding decisions about fuels management are complex and often require abstraction, but logic and decision models are well suited to representing the inherent complexities and abstractness of the problem, thus rendering the analytical problem more manageable. This particular application of EMDS also is an example of how decision support systems can not only be used as tools for technical specialists and decision makers, but as tools for communicating clearly and effectively with the general public who understandably have a strong interest in the topic of wildfire and want to understand, and be involved in, any proposed solution. Both logic and decision models are ''good at explaining themselves'' in relatively intuitive terms, and thus provide a basis for an effective public dialog.

Finally, there is an important interdependency between science, policy, and decision support systems. Although logic models are sometimes used for prediction, they are fundamentally concerned with interpretation (Reynolds et al., 2003a); what does the information mean? Meaning can be highly normative or subjective, and usually falls somewhere in between the two extremes. As a result, virtually all interpretation embeds some degree of subjectivity; that is, values and policy are inextricable aspects of logic and decision models. The practical implication is that successful application of most decision support systems to real-world situations ultimately depends on a close collaboration between the scientific community that brings its facts to the table, and the policy makers that need to reach decisions based on that information and additional social and economic considerations. Decision support systems provide a conspicuous advantage in this context—detailed documentation of a decision-making process. With ongoing monitoring and evaluation, lessons learned can be readily incorporated into decision models providing increasing effectiveness to decision-making and an explicit vehicle for adapting management.

Acknowledgments

This research was supported by the Managing Disturbances Program of the Pacific Northwest Research Station (RWU-4577), and by the National LANDFIRE Prototype Project, USDA Forest Service. Mark Twery, Rich Lasko, Norm Johnson, and three anonymous reviewers provided helpful reviews of an earlier draft.

References

Agee, J.K., 1998. The landscape ecology of western forest fire regimes. Northwest Sci. 72, 24–34.

Agee, J.K., 2003. Historical range of variability in eastern Cascades forests, Washington, USA. Landsc. Ecol. 18, 725–740.

Albini, F.A., 1976. Estimating wildfire behavior and effects. General Technical Report INT-30, United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 92 p.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122, United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Box, G.E., 1979. Robustness in the strategy of scientific model building. In: Launer, R., Wilkinson, G. (Eds.), Robustness in Statistics. Academic Press, New York, pp. 210–236.

Burgan, R.E., 1988. 1988 Revisions to the 1978 national fire-danger rating system. Research Paper RP-SE-273. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, 39 p.

Burgan, R.E., Hartford, R.A., 1993. Monitoring vegetation greenness with satellite data. General Technical Report INT-297. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Burgan, R.E., 1993. A method to initialize the Keetch-Byram Drought Index. West. J. Appl. Forest. 8, 109–115.

Burkett, V.R., Wilcox, D.A., Stottlemeyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., Doyle, T., 2005. Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. Ecol. Complex. 2, 357–394.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., Williams, D., 1983. Fire in Forestry. Volume 1: Forest Fire Behavior and Effects. John Wiley & Sons, 450 p.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the Western United States. Science 306 (5698), 1015–1018.

DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. Fire's Effect on Ecosystems. John Wiley and Sons, New York, NY, USA.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The national fire-danger rating system—1978. General Technical Report INT-39. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 63 p.

Ferry, G.W., Clark, R.G., Montgomery, R.E., Mutch, R.W. Leenhouts, W.P., Zimmerman, G.T., 1995. Altered fire regimes within fire-adapted ecosystems. United States Department of the Interior—National Biological Service, Washington, DC.

GAO, 2002. Severe wildland fires: leadership and accountability needed to reduce risks to communities and resources. Report to Congressional Requesters GAO-02-259, United States General Accounting Office, Washington, DC.

GAO, 2003. Additional actions required to better identify and prioritize lands needing fuels reduction. Report to Congressional Requesters GAO-03-805, United States General Accounting Office, Washington, DC.

GAO, 2004. Forest Service and BLM need better information and a systematic approach for assessing risks of environmental effects. GAO-04-705, United States General Accounting Office, Washington, DC.

Hann, W.J., 2004. Mapping fire regime condition class: a method for watershed and project scale analysis. In: Engstrom, R.T., Galley, K.E.M., De Groot, W.J. (Eds.), Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temprate, Boreal, and Montane Ecosystems. Tall Timbers Research Station, Tallahassee, FL.

Hardy, C.C., 2005. Wildland fire hazard and risk: problems, definitions, and context. Forest Ecol. Manage. 211, 73–82.

Hessburg, P.F., Agee, J.K., 2003. An environmental narrative of Inland Northwest US forests, 1800–2000. Forest Ecol. Manage. 178, 23–59.

Hessburg, P.F., Agee, J.K., Franklin, J.F., 2005. Dry mixed conifer forests of the Inland Northwest, USA: contrasting the landscape ecology of the presettlement and modern eras. Forest Ecol. Manage. 211 (1), 117–139.

Keane, R.E., Garner, J.L., Schmidt, K.M., Long, D.G., Menakis, J.P., Finney, M.A., 1998. Development of input data layers for the FARSITE fire growth model for the Selway-Bitterroot Wilderness Complex, USA. General Technical Report RMRS-GTR-3, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Keane, R.E., Mincemoyer, S.A., Schmidt, K.M., Long, D.G., Garner, J.L., 2000. Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico. General Technical Report RMRS-GTR-46-CD, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Keane, R.E., Rollins, M., Parsons, R., 2004. Developing the spatial programs and models needed for the implementation of the LANDFIRE Project. In: Proceedings of the 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress. http://ams.confex.com/ams/FIRE2003/5FIRE/abstracts/66069.html.

Keane, R.E., Frescino, T.L., Reeves, M.C., Long, J., 2007. Mapping wildland fuels across large regions. In: Rollins, M.G., Frame, C. (Eds.), The LANDFIRE

Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management. General Technical Report RMRS-GTR-175. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Kamenetzky, R., 1982. The relationship between the analytical hierarchy process and the additive value function. Decision Sci. 13, 702–716.

Kolb, P.F., Adams, D.L., McDonald, G.I., 1998. Impacts of fire exclusion on forest dynamics and processes in central Idaho. Tall Timbers Fire Ecol. Conf. 20, 911–923.

McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E., 2002. FRAGSTATS 3.0: spatial pattern analysis program for categorical maps. University of Massachusetts, Amherst.

Miller, B.J., Saunders, M.C., 2002. The NetWeaver Reference Manual. Pennsylvania State University, College Park, PA, 61 p.

NWCG, 1996. Glossary of wildland fire terminology. PMS 205 NFES 1832, National Interagency Fire Center, Boise, ID.

NWCG, 2005. Glossary of wildland fire terminology. PMS 205 NFES 1832, National Interagency Fire Center, Boise, ID.

Ottmar, R.D., Sandberg, D.V., Prichard, S.J., Riccardi, C.L., 2004. Fuel characterization class systems. In: Proceedings of the 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress. http://ams.confex.com/ams/FIRE2003/5FIRE/abstracts/66069.html.

Palmer, W.C., 1965. Meteorological drought. Research Paper 45, U.S. Weather Bureau, Washington, DC (Available through National Oceanic and Atmospheric Administration, Library and Information Services Division, Washington, DC 20852), 58 p.

Pickett, S.T.A., White, P.S., 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, San Diego, CA, USA.

Reynolds, K.M., Hessburg, P.F., 2005. Decision support for integrated landscape evaluation and restoration planning. Forest Ecol. Manage. 207, 263–278.

Reynolds, K.M., Rodriguez, S., Bevans, K., 2003. User Guide for the Ecosystem Management Decision Support System, Version 3.0. Environmental Systems Research Institute, Redlands, CA, 82 p.

Rollins, M.G., Keane, R.E., Zhu, Z., 2006. An overview of the LANDFIRE Prototype Project. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, 840 p.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuel. Research Paper INT-115, United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires. General Technical Report INT-143, United States Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Research Paper INT-438, United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT, USA.

Saaty, T.L., 1992. Multicriteria Decision Making: The Analytical Hierarchy Process. RWS Publications, Pittsburgh, PA.

Sandberg, D.V., Ottmar, R.D., Cushon, G.H., 2001. Characterizing fuels in the 21st century. Int. J. Wildland Fire 10, 381–387.

Schmidt, K.M., Menakis, J.P., Hardy, C.C., Hann, W.J., Bunnell, D.L., 2002. Development of coarse-scale spatial data for wildland fire and fuel management. General Technical Report RMRS-GTR-87. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 41 p (+CD).

Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The interaction of fire, fuels, and climate across the Rocky Mountain forests. Bioscience 54 (7), 661–676.

Scott, J.H., 1999. NEXUS: a system for assessing crown fire hazard. Fire Manage. Notes 59 (2), 20–24.

Scott, J.H., Burgan, R.E., 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, 72 p.

Scott, J.H., Reinhardt, E.D., 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Research Paper RMRS-RP-29, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Scott, J.H., Reinhardt, E.D., 2002. Estimating canopy fuels in conifer forests. Fire Manage. Today 62, 45–50.

Seaber, P.R., Kapinos, P.F., Knapp, G.L., 1987. Hydrologic unit maps. United States Geological Survey, Washington, DC, United States. Water-Supply Paper 2294.

Turner, M.G., 1989. Landscape ecology: the effect of pattern on process. Annu. Rev. Ecol. Syst. 20, 171–197.

Turner, M.G., Gardner, R.H., O'Neill, R.V., 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York, NY, USA.

U.S. Government, 2003. Healthy Forests Restoration Act of 2003. 108th Congress, 1st Session. House of Representatives Report 108-386, pp. 1–48.

White, M.A., Thornton, P.E., Running, S.W., 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochem. Cycl. 11, 217–234.

Whitlock, C., Knox, M.A., 2002. Prehistoric burning in the Pacific Northwest. In: Vale, T.R. (Ed.), Fire, Native Peoples, and the Natural Landscape. Island Press, Washington, DC.

Zadeh, L.A., 1968. Probability measures of fuzzy events. J. Math. Anal. Applic. 23, 421–427.