Fire Climbing in the Forest: A Semiqualitative, Semiquantitative Approach to Assessing Ladder Fuel Hazards

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ABSTRACT

Ladder fuels carry fire from the forest floor to the canopy and thereby may turn low-intensity fires into severe canopy fires. Attempts at assessing ladder fuels have been either expensive and spatially limited quantified approaches or unrepeatable and variable expert opinion strategies. We have developed a mixed semiquantitative, semiqualitative approach using a flow chart that systematizes observations and constrains judgments and decisionmaking. The ladder fuel hazard assessment (LaFHA) approach leads to ladder hazard ratings and some quantified observed data; it can be repeated across a very large area at relatively low cost and, because of the systematic and constrained approach, produces results that are mostly consistent and repeatable. Key attributes assessed are clumping of low aerial fuels, height to live crown base, and maximum gaps in vertical fuel ladders. Three field seasons of testing and implementing the LaFHA approach resulted in almost 4,000 observations. For the study area in the northern Sierra Nevada, California, more than a quarter of sites were rated high hazard and about 40% more were moderate risk. Data are presented on heights to live crown base and maximum gaps for each of the rated hazard categories.

Keywords: fire ecology, fire behavior, ladder fuels, fire hazard

Many forest fires spread along the ground, only occasionally climbing up into the canopy (Kilgore and Sando 1975, Agee 1993, Pyne et al. 1996). Under most fire conditions, forest canopies are unable to sustain fire because of a low effective fuel load (dry mass in kilograms per cubic meter) and large gaps between fuels (Agee 1993, 1998, Pyne et al. 1996). An arrangement of fuel—woody material or vegetative matter—typically is required to convey flames from ground and surface fuels to the low, middle, and high aerial fuels of the canopy (Sando and Wick 1972, Kilgore and Sando 1975, Call and Albini 1997). Brush and seedlings typically comprise the low aerial fuels; saplings other small trees form midaerial fuels. These low and midaerial fuels are called ladder fuels for the function they serve in forest fires; fire climbs up the aerial fuel matrix as a person might climb a ladder (Kilgore and Sando 1975, Cruz et al. 2003). The hazard of ladder fuels is that they can change the nature of the fire itself. A fire climbing from the forest floor up to the canopy may turn low-severity, low-intensity fires into severe canopy fires.

Ladder fuels often are discussed conceptually (Agee 1993, MacCleery 1995, Stephens 1998, Meyer and Pierce 2003, Brown et al. 2004, Sturtevant et al. 2004, Thacker 2004, Peterson et al. 2005, Stephens and Moghaddas 2005a, 2005b, Stephens and Fule 2005) but descriptions of actual measurements are less common (Ottmar et al. 1998, Scott and Reinhardt 2001, Pye et al. 2003, Stephens and Moghaddas 2005a, 2005b, Stephens and Fule 2005). Early descriptions provided information about the vertical distribution of aerial fuels but did not characterize individual ladders (Sando and Wick 1972, Kilgore and Sando 1975). Cruz et al. (2003) describes several definitions of ladder fuels as being somewhat useful but too vague for quantification (Ottmar et al. 1998).

Attempts to characterize or rank ladder fuel hazards typically use one of two approaches. Quantitative efforts entail measuring a number of physical attributes in a forest (Kilgore and Sando 1975, Pye et al. 2003). Such measurements are challenging to conduct on a broad spatial scale because so many different measurements must be made; there are many different kinds of fuel and vegetation structures that can act as ladders from the ground to the canopy. Although a quantified full-measurement approach might be the most repeatable and precise, it also is likely to be quite expensive, slow, and difficult to apply across a large area.

Recent progress has been made using laser light detecting and ranging (LIDAR) technology. The technology may be deployed from satellites, airplanes, or on the ground. Ground-based approaches have been shown to be very promising at providing three-dimensional models of forest vegetation but are expensive and intensive to implement (Hopkinson et al. 2004). In addition, detecting forest fuels with ground-based LIDAR technology is years away from implementation because automated extraction of vegetation data and production of fuels measurements still are not available. Aerial use of LIDAR also is promising for producing stand-level canopy fuels data but remains very limited in application (Andersen et al. 2005).

Because of the difficulty and high cost of quantitatively measuring fuel ladders managers generally have relied on a second approach: expert opinion. Experienced or trained technicians visually

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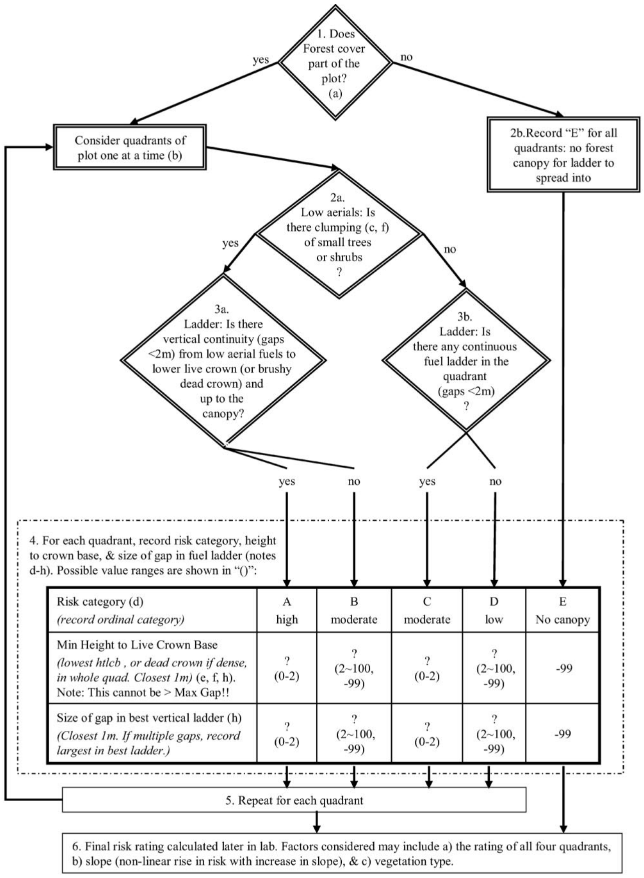

Risk category (d) *(record ordinal category)*	A high	B moderate	C moderate	D low	E No canopy
Min Height to Live Crown Base *(lowest htlcb , or dead crown if dense, in whole quad. Closest 1m)* (e, f, h). Note: This cannot be > Max Gap!!	? (0-2)	? (2~100, -99)	? (0-2)	? (2~100, -99)	-99
Size of gap in best vertical ladder (h) *(Closest 1m. If multiple gaps, record largest in best ladder.)*	? (0-2)	? (2~100, -99)	? (0-2)	? (2~100, -99)	-99

Figure 1. LaFHA flow chart. A trained technician uses this flow chart to categorize ladder fuel hazards at a site and record relevant data at each observation point. Reference letters in the flow chart correspond with definitions in Table 1.

assess the conditions in an area and provide a rating or evaluation of risk. This approach is useful in that it is rapid, adapted to local conditions, and easy to apply across a large area. Unfortunately, it also has the drawbacks of being inconsistent and hard to repeat. Two "experts" may rank similar fuel structures differently or even inconsistently with themselves at different times such as in successive years.

We have attempted to devise a semiquantitative, semiqualitative approach that uses elements of both prior approaches. We use a flow chart that guides trained technicians to rate ladder fuel hazards (LaFHAs) at a site. The flow chart helps ensure consistency in site evaluation by systematizing the approach while constraining the range of possible outcomes. Of necessity, this requires technicians to use their judgment to an extent. The approach attempts to limit the range of possible outcomes, however, by providing a limited set of evaluation criteria.

The ability of a fuel ladder to spread fire depends on burn-time conditions as well as the fuel structure itself. Only the fuel structure can be assessed in the field before the fire event and it is what we are attempting to measure. Ladder fuels are a function of several factors: vegetation type—sparse oak (*Quercus spp.*), e.g., would generate less flame length than dense dry fir (*Abies spp.*) branches; clumping of low aerial fuels; vertical continuity of fuels from the ground to the canopy; and slope, which has a nonlinear effect due to its effect on air flow and fuel preheating.

The LaFHA approach combines attributes of two general approaches. As with expert opinion approaches, we require a technician to visually identify key attributes of the fuel structure and require the technician to make judgments. Also, this approach is rapid and adapted to local conditions. As with quantitative assessments, this approach systematizes observations and constrains both the range of data taken and the types of judgments that can be made by the technicians. The results are mostly repeatable and quantified, as a result. The LaFHA flow chart guides technicians to identify clumping and vertical continuity of fuels. Vegetation type and slope are recorded and may be used to modify ratings at a later time in a systematic fashion covering the entire study area.

Methods

Field Site and Plot Locations

The LaFHA method is designed to work in a variety of forested environments, from dense low scrubs of young bishop pine (*Pinus muricata*) to tall redwoods (*Sequoia sempervirens*) with few ladder fuels. However, the system has been developed in a mixed conifer forest in the Plumas National Forest located in the northern Sierra Nevada, California. The climate is Mediterranean with a predominance of winter precipitation totaling about 1,600 mm/year. Elevation of the forest varies from approximately 1,000 to 1,500 m.

Vegetation on this landscape is primarily Sierra Nevadan mixed conifer forest (Schoenherr 1992, Barbour and Major 1995), a mix of conifers and several hardwoods: white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), incense-cedar (*Calocedrus decurrens*), and California black oak (*Quercus kelloggii*). Montane chaparral and some grasslands are interspersed with the forest (Schoenherr 1992, Barbour and Major 1995). Tree density varies by fire and timber management activity, elevation, slope, aspect, and edaphic conditions. The typical fire regime is frequent, low-severity fire with patches of high-severity canopy fire with fire return intervals of 10–30 years (Caprio and Swetnam 1995, McKelvey et al. 1996, Sierra Nevada Ecosystem Project 1996, Skinner and Chang 1996, Stephens and Collins 2004).

Site locations were determined two ways. First, almost a thousand plots locations were assigned based on a random stratification of the landscape using slope, elevation, aspect, and vegetation type to create unique strata. Vegetation data were derived from a coverage provided by the Plumas-Lassen Administrative Study (PLAS). Four hundred ninety-three of the plots were visited. A number were excluded because of steep slopes, poor access, and private property boundaries. Second, field technicians on the Small Bird research module of the PLAS collected data at their field locations across the Plumas National Forest. Their plots were nonrandom plots strung in chains of 12 stretching out from a network of forest roads. Because they visited thousands of locations throughout the forest, their data are likely to be relatively representative of the overall conditions of the forest. As a result of these two extensive sampling efforts, plot locations are dispersed across a wide range of slopes, elevations, aspects, and forest types and conditions. Although each of these research teams collected a variety of data, the protocols for LaFHA observations were the same (with one exception, described in the following section).

LaFHA Flow Chart Method

Any method for determining ladder fuel hazards must have a defined area of observation. For our purposes, plots were 12.6 m in radius (0.05 ha) and were divided into four quadrants. Independent

Table 1. Practical definitions for LaFHA flowchart decisions.

Flow chart reference	Feature	Description
a	Forest and shrub fields	A single tree in a field is not a forest. A single tree extending over part of the plot that is near other trees is part of a forest. Even though shrub fields are "clumped" as low aerial fuels there may not be any canopy to which to spread fire. In that case, the rating should be E (if all quadrants lack forest) or D if one to three quadrants lack trees. Follow the flow chart.
b	Division of plots	Quickly divide plots into four quadrants. Use trees for reference and proceed in an arc, sweeping one direction until you return to the starting point. Be sure to consider the entire quadrant. Walk around if necessary.
c	Clumping	Defined as shrub or small trees covering an area of at least 4 m^2 (2×2 m) with gaps of less than 50 cm. If it is particularly dense or tall and brushy a clump may cover a smaller area. For example, a particularly dense clump may cover as little as 2 m^2 on the forest floor. Branchy dead fuel or stems may be included in the assessment. Remember to ask yourself, "is this a dense clump of potential fuel?"
d	Rating categories	Ratings are given letters (A–E) instead of numbers to prevent confusion: categories are not of interval or ratio quality (e.g., "Is category 4 twice as risky as category 2?" Probably not). Also, final ratings depend on additional information (see step 4 at bottom of flow chart page).
e	HTLCB	HTLCB: The live crown base is the lowest extent of the live canopy. Note, if the crowns of small trees are completely separate from the overhead canopy do not consider them. If they touch, or are close to touching, do consider them.
f	Dead crown	Include dead branches in consideration of a tree's crown if they are particularly branchy or brushy. This will almost never happen in pines, but is common in white fir and Douglas-fir. If the branches radiate laterally and are well spaced (common with incense-cedar), do not consider them to be part of the ladder fuel matrix. To be considered part of a ladder, the branches should be dense and mostly vertical (pointing or arching down). Lichens, moss, and needles increase the fuel hazard. Consider this in your assessment.
g	Ground and surface fuels	Do not adjust your assessment of the risk category by the presence or absence of ground or surface fuels (litter and duff with branches and cones mixed in). Consider only clumping and the presence of ladder fuels.
h	Canopy or no canopy?	Consider only conifer and oak tree species as part of the canopy. Do not consider shrubs to have a canopy for this analysis. If there is no higher canopy, then record the gap as −999. This is important to distinguish from empty fields, which may mean a datum was or was not recorded. A −999 value indicates that data were recorded and that the gap was infinite because there was no crown.

These definitions are provided to field technicians along with Figure 1 to provide clarity. Technicians are encouraged to refer to these definitions often to ensure consistency in evaluating ladder fuel hazards. Reference letters in Figure 1 correspond with the letters in the first column.

observations were made in each quadrant, for a total of four per plot. Because the bird crews rely on fast, ocular estimates (relevees) we did not require them to actually measure the 12.6-m edge of plots. They were asked to estimate this given periodic calibration with measuring tapes.

The LaFHA flow chart method involves six steps (Figure 1) and a number of definitions (Table 1). First, the technician is required to judge whether the site has forest covering part of the plot (any part of the four quadrants). A single tree in a field is not considered a forest because it does not have a canopy linked to other trees. A single tree extending over part of the plot that is near other trees is part of a forest. If no forest is present, the technician may declare the whole plot "nonforest" and give it a rating of E indicating no canopy for fire to reach.

Second, if there is any forest covering part of the plot, the technician must then consider each quadrant one at a time. In this step, the technician determines whether low aerial fuels are clumped in sufficient volume in the quadrant to produce flames that could reach up off the forest floor. Low aerial fuels typically are shrubs, short trees, low-hanging branches, draped pine needles, and other fuels arrayed in the air just above the ground. We define clumping as shrubs or small trees covering an area of at least four m^2 (2×2 m) with gaps inside the clump of less than 50 cm. If the fuel is particularly dense or tall and brushy, a clump may cover a small area. For example, a particularly dense clump of leafy fuel may cover as little as 2 m^2 on the forest floor.

After determining whether fuels are clumped, the technician proceeds to the third step: assessing the continuity of the fuel ladder from the ground to the canopy (steps 3a and 3b, Figure 1). Ladders are considered continuous if vertical gaps of less than 2 m are present (based on personal experience with fire modeling). This 2-m gap criterion could be modified for other fire regimes.

In the fourth step, the technician records the rating to which the flow chart has led. Category A is high risk, with clumped aerial fuels leading to a continuous ladder (Figure 2). Categories B and C are moderate risk for different reasons. Category B has clumped fuels but the ladder, if present, is discontinuous. Flames would get off the ground but they would not have a good ladder to climb. Sites rated C have no clumping of low aerial fuels, but if flames were to get off the ground and reach the lower canopy a ladder would conduct flames higher. Category D sites have no clumping and no ladder and therefore represent low fire laddering risk. The technician records measurements of height to lower live crown base (HTLCB; Table 1, d) or a large mass of clumped dead fuel on the tree (Table 1, e), and the maximum gap in the best ladder in the quadrant. In the literature there are many definitions of the lower extent of the canopy (Scott and Reinhardt 2001, Andersen et al. 2005). Rather than use a strict quantitative criterion, which would require measurement, we ask the technician to interpret the vertical continuity of the canopy and discount lower dead branches and isolated limbs with leaves.

The recorded data are used later to verify the classification (e.g., an A rating can not have a gap of more than 2 m) and should be useful for evaluations of actual fire behavior. Potential values are shown in the flow chart itself.

Step 5 is to repeat the process for the next quadrant. Finally, step 6 may involve processing data after collection: modification of ratings with additional factors such as slope, vegetation type, and aggregate values from the four quadrants of each plot.

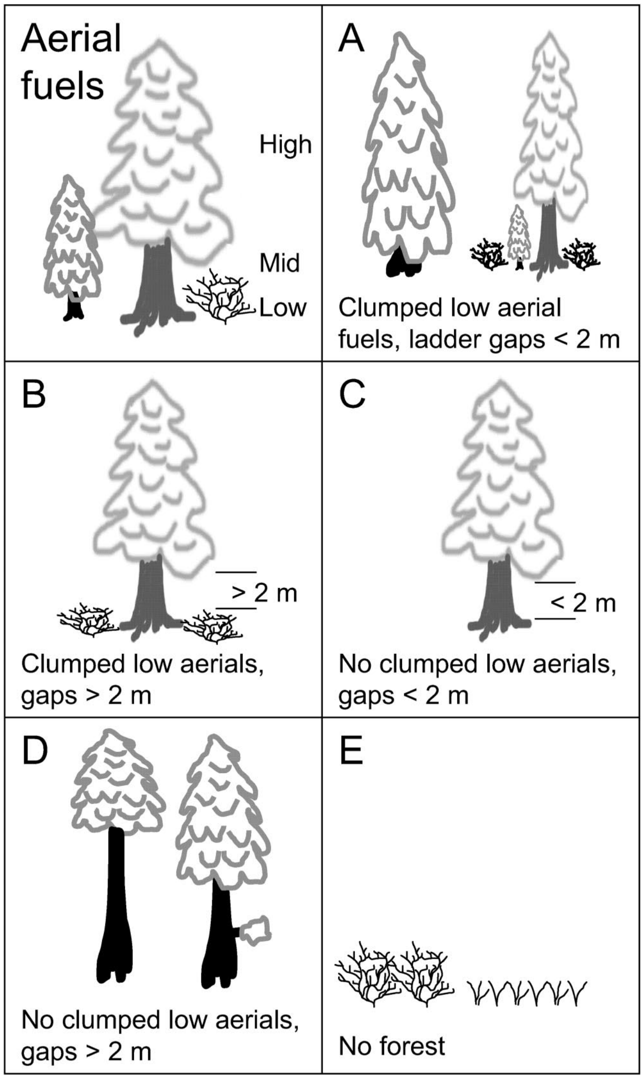

Figure 2. LaFHA rating categories from A to E. The first box depicts low, middle, and high aerial fuels. Boxes A to E show fuels in the form of trees, brush, and grass. Gaps of more or less than 2 m are shown.

Training

Training was conducted by the authors on most occasions and by experienced field technicians who had worked with the authors for some time. Feedback from the training sessions and the field crews has resulted in a number of improvements in the flow chart and its definitions (see Discussion). Ideally, in an area, the same individual or groups of individuals would conduct training to make assessments as consistent as possible.

The amount of training time varied depending on the field technicians involved. Key factors include degree of previous experience with fire assessments and fuel measurements, knowledge of local area and vegetation, and basic understanding of fire behavior. As a result of these differences, some training sessions were as short as an hour and others took continued supervision over the course of a week. As the approach has become refined and the flow chart and definitions have become more precise, it has become easier for those who have been trained to become trainers themselves.

Results

Almost 4,000 (3,824) observations were made over the course of three summers (2003–2005) in the Plumas National Forest. Just over a quarter of the observations indicated sites had a high risk of conducting fire to the canopy, while just under 40% were in the moderate range. Low risk sites (D) and nonforest sites comprised the remaining 35% (Table 2).

The data in Table 2 indicate that category A sites are clearly at high risk of fire spreading from the ground to the canopy: low aerial fuels are clumped, the live crown extends to within 0.65 m of the ground, on average, and the maximum gap in the best fuel ladder is less than a meter (0.93 m). Such conditions are conducive to fire spreading vertically.

At the opposite end of the spectrum, ratings D and E clearly represent low ladder fuel risk sites. Category D sites have no clumping of low aerial fuels and have high height to live crowns (mean, 4.7 m) and large gaps in the ladder (mean, 4.93 m). Category E sites have, by definition, no risk of laddering because there is no forest into which fire may spread.

Key functional differences occur in the moderate range between categories B (clumping on ground, no clear ladder) and C (no clumping, but good ladder). The actual risk of fire crowning in these two scenarios probably depends on fire conditions: in the absence of strong winds, there is probably little chance of a fire reaching the canopy in a category C site because there are simply few low aerial fuels to get flames up off the ground. Ground and surface fuels are unlikely to produce flame lengths sufficient to send fire up to the crown without a clump of low aerial fuels. During extreme fire weather, however, the presence of these ladder fuels could produce flame lengths long enough to convey fire into the overstory.

In contrast, areas rated with the moderate B rating could produce moderate flame lengths under many conditions, but the ladder is

Table 2. Data from LaFHA in mixed conifer forests of the northern Sierra Nevada.

		Percent of plots in this category		HTLCB or dense dead aerial fuels (excluding E sites)		Maximum gap in best ladder in quadrant (excluding E sites)	
Rating	Count	All plots: including category E	Forest only: excluding category E	Mean (m)	SD	Mean (m)	SD
A (high)	986	25.3	25.8	0.65	0.76	0.93	0.77
B (moderate)	579	14.9	15.1	4.83	3.45	5.58	3.24
C (moderate)	897	23.0	23.5	0.89	0.75	1.17	0.73
D (low)	1,362	35.0	35.6	4.70	3.01	4.93	2.92
E (no forest)	72	1.8	N/A				
Total with E (all)	3,896	100.0	N/A				
Total without E (forest only)	3,824	N/A	100.0				

not present to carry fire higher. This structure probably is more resistant to torching than category C areas.

Issues in the Field

Data returned by field crews did need to be examined and sometimes corrected. For example, some technicians would record a larger HTLCB than maximum gap. This is not possible—if the height to the lower live crown is 5 m and the gap in the canopy above is 3 m, then the largest gap from the ground to the upper canopy is still 5 m. In other words, the height to live crown is a gap to consider, as well. This happened frequently; therefore, maximum gap values were changed to the HTLCB values if they were less than HTLCB. A long-term solution is to cover this more thoroughly in training. Also, a definition to this effect has been added directly to the flow chart since the last data collection.

Occasionally, technicians would record values impossible for a category. An "A," e.g., can not have a maximum gap of greater than 2 m by definition. Therefore, if a technician quantified an "A" as having a gap of 4 m, then the correct classification should have been a "B." These values were changed for the statistical analysis, as well. This was always well covered in training and so the solution has been to add explicit "possible values" ranges in the flow chart.

Ratings Analysis

Overall, the system of categories seems useful for managers in pre- and posttreatment or postfire settings. The biggest difficulties at this stage are in modifying the results with additional information and in verifying the actual ratings categories themselves. Combining the four evaluations from each site into a single value and modifying ratings based on slope and vegetation are made difficult by the nature of the ratings themselves. Ratings are ordinal: they have order (A represents higher risk than B) but the relationship is of an unknown (and variable) quanta. Although ratio and interval data have distinct relationships between values (4 is twice as much as 2; 32° F is 8° degrees colder than 40° F), ordinal data may not be modified mathematically. At what point, e.g., does a C site have as much ladder fuel risk as an A site because its slope is much steeper: 20°, 30°, 45°, or 60°? In addition, what is the difference between a category C with ponderosa pine and a category C with white fir? Is the white fir 15 or 70% more likely to conduct fire, and under what conditions?

A second limitation of these ordinal ratings is that they still have not been verified with real fire behavior. It is our intent to evaluate areas with LaFHA ratings before prescribed fire (or possibly a wildfire), and then analyze the relationship between the assessed ladder fueling risks and the actual fire behavior under known conditions. Although some prescribed fires, especially on parklands, may target occasional torching and escapement of fire to the canopy (to simulate natural fire conditions), most will not. As a result, we may attempt to perform LaFHA analyses safely ahead of the flaming front of a wildfire.

Fire simulation can provide an additional verification (van Wagtendonk 1996) but only with the collection of additional data. Using the LaFHA approach we can collect many data across a large area; the tradeoff is that we collect a limited amount of data at any one site. As a result, the data we would need to run most simulations have not been collected. One solution might be to overlap a LaFHA inventory with a more thorough quantified approach in a test area and then model the quantified data; then, the results could be correlated with those results with our more focused assessments of ladder fuel hazards using a model-like Forest Vegetation Simulator (Scott and Reinhardt 2001).

Such field and modeling verification will make the LaFHA approach more powerful and useful. We hope that such testing over time will allow us to overcome some of the difficulties of working with ordinal data so that the ratings may be modified with slope and vegetation-type information. If validated, the model could prove to be a useful part of the national Fuel Characteristic Classification System (Greenough 2001).

Conclusion

The LaFHA approach has advantages in that it is rapid and can be applied extensively across an area with a low budget and little hardware. Because of the flow chart that systematizes and constrains judgments and decisionmaking, the results are mostly consistent and repeatable. The quantitative measures taken allow for analysis of the ratings and their values. All these represent advantages over traditional expert opinion approaches. In comparison to quantified methods, it is much more rapid and cost-effective when applied across a broad spatial area. Technologies such as LIDAR may soon provide the advantage of continuous data on canopy fuels (Hopkinson et al. 2004, Andersen et al. 2005). However, there will always be a need for rapid, local, inexpensive, and low-technological approaches to assessing risk.

We anticipate that this approach may be used by managers to characterize pre- and postfuel treatment conditions to describe change in ladder fuel conditions. Verification of the ratings with real fire events may allow the data to act as input into landscape fire behavior and risk models, and we hope that the flexibility of this system will allow it to be applied across a range of forest types.

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