Appendix A:
Fire Climbing in the forest: a semi-qualitative semi quantitative approach to assessing ladder fuel hazards

Title: Fire climbing in the forest: a semi-qualitative, semi-quantitative 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-severity, low-intensity fires into severe, catastrophic fires. Attempts at assessing ladder fuels have been either expensive and spatially-limited quantified approaches, or unrepeatable and variable expert opinion efforts. We have developed a mixed semi-quantitative, semi-qualitative approach using a flowchart that systematizes observations and constrains judgments and decision making. 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 due to 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 (USA), 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.

Key Words

Fire ecology; fire behavior; ladder fuels; fire hazard

1. Introduction

Many forest fires spread along the ground, only occasionally climbing up into the canopy (Agee, 1993; Pyne et al., 1996). Under most fire conditions, forest canopies are unable to sustain fire due to a low effective fuel load (kg dry mass/m^3) and large gaps between fuels (Agee, 1993; Pyne et al., 1996; Agee, 1998). An arrangement of fuel—woody material or vegetative matter—is typically required to convey flames from ground and surface fuels to the low, mid and high aerial fuels of the canopy. These low aerial 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. 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, catastrophic canopy fires.

Ladder fuels are often 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; Stephens and Moghaddas, 2005b; Stephens and Fule, in press) 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, in press). 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 (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. While a quantified fullmeasurement approach might be the most repeatable and precise, it is also likely to be quite expensive, slow and difficult to apply across a large area.

Due to the difficulty of quantitatively measuring fuel ladders managers have generally relied upon a second approach: expert opinion. Experienced or trained technicians visually 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 semi-quantitative, semi-qualitative approach that utilizes element of both prior approaches. We utilize 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. Necessarily, 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 success of a fuel ladder for conducting fire depends on burn-time conditions as well as the fuel structure itself. Only the fuel structure can be assessed in the field prior to 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*.), for example, 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 non-linear effect due to its effect on air flow and fuel pre-heating.

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 it requires the technician make judgments. Also, it is rapid and adapted to local conditions. As with quantitative assessments, we systematize observations and constrain 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 flowchart 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.

2. 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. The system has been developed, however, in a mixed conifer forest in the Plumas National Forest located in the northern Sierra Nevada, California (USA). The climate is Mediterranean with a predominance of winter precipitation totaling about 1600mm per year. Elevation of the forest varies from approximately 1000-1500m.

Vegetation is primarily Sierra Nevadan mixed conifer forest, a mix of conifers and several hardwoods: white fir (Abies concolor), Douglas-fir (Pseudotsuga menziesii), sugar pine (Pinus lambertiana), ponderosa pine (P. ponderosa), Jeffrey pine (P. jeffreyi), 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 (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 three ways. First, several hundred 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). Second, field technicians on the Small Bird research module of the PLAS collected data at their field locations across the Plumas National Forest. Third, the PLAS vegetation crew collected data at research sites coordinated by the California Spotted Owl, Small Mammal, and Vegetation Plot modules. As a result, plot locations are dispersed across a wide range of slopes, elevations, aspects and forest types and conditions.

Any method for determining ladder fuel hazards must have a defined area of observation. For our purposes, plots were deemed to be 12.6m in radius (1/20th ha) and were divided into four quadrants. Independent observations were made in each quadrant.

Ladder Fuel Hazard Assessment Flowchart Method

The LaFHA flowchart 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. A single tree in a field is not considered a forest as 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 "non-forest" and give it a rating of E indicating no canopy for fire to reach.

If there is any forest covering part of the plot, the technician must then consider each quadrant one at a time. In this step two, the technician determines whether low aerial fuels are clumped in sufficient volume 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 square meters (2m x 2m) with gaps of less than 50cm. If the fuel is particularly dense, or tall and brushy, a clump may cover a small area. A particularly dense clump may cover as little as $2m^2$ on the forest floor, for example.

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 2m are present. This number could be modified for other fire regimes.

In the fourth step, the technician records the rating to which the flowchart has led. Category A is high risk, with clumped aerial fuels leading to a continuous ladder. Categories B and C are moderate risk for different reasons. B has clumped fuels but the ladder, if present, is discontinuous. Flames would get off the ground but they wouldn't 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, so represent low fire laddering risk. The technician records measurements of height to lower live crown (HTLCB, or a large mass of clumped dead fuel on the tree) and the maximum gap in the best ladder in the quadrant. These data are used later to verify the classification (an A rating cannot have a gap of more than 2m, for example) and should be useful for evaluations of actual fire behavior. Potential values are shown in the flowchart itself.

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

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 flowchart 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 might be as short as several hours, and others took continued supervision over the course of a week.

3. Results

Almost four thousand (3824) observations were made over the course of three summers (2003-5) 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 non-forest sites comprised the remaining 35% (Table 2).

4. Discussion

The data indicate that category A sites are clearly at high risk of passive crown fire torching as low aerial fuels are clumped, the live crown extends to within 0.65m of the ground, on average, and the maximum gap in the best fuel ladder is less than a meter (0.93m). 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. D sites have no clumping of low aerial fuels and have high height to live crowns (mean 4.7m) and large gaps in the ladder (mean 4.93m). Category E sites have, by definition, no risk of laddering as 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. During extreme fire weather, however, the presence of these ladder fuels could produce flame lengths long enough to move 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 not present to carry fire higher. This structure is probably more resistant to passive crown fire 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 5m and the gap in the canopy above is 3m, then the largest gap from the ground to the upper canopy is still 5m. In other words, the height to live crown is a gap to consider, as well. This happened frequently and so 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 flowchart.

Occasionally, technicians would record values impossible for a category. An "A," for example, cannot have a maximum gap of greater than 2m by definition. So, if a technician quantified an "A" as having a gap of 4m 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 post-treatment or post-fire 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. While 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, for example, does a C site have as much ladder fuel risk as an A because its slope is much steeper: 20°, 30°, 45°, or 60°? Further, what is the difference between a category C with ponderosa pine (<u>Pinus ponderosa</u>) and a category C with white fir (<u>Abies concolor</u>)? 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 have not yet been verified with real fire behavior. It is our intent to evaluate areas with LaFHA ratings prior to 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. Such verification will make the system 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.

5. Conclusion

The LaFHA approach has advantages in that it is rapid and can be applied extensively across an area. Due to the flowchart that systematizes and constrains judgments and decision-making, the results are mostly consistent and repeatable. The quantitative measures taken allow for analysis of the ratings and their values. All of these represent advantages over traditional expert opinion approaches. In comparison to quantified methods, it is much more rapid and cost-effective compared to detailed field measurements conducted across a broad spatial area.

We anticipate that this approach may be used by managers to characterize pre- and post-fuels 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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Tables used in text

Table 1: Practical definitions for LaFHA flowchart decisions. These definitions are provided with Figure 1 to provide clarity for field technicians. They 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.

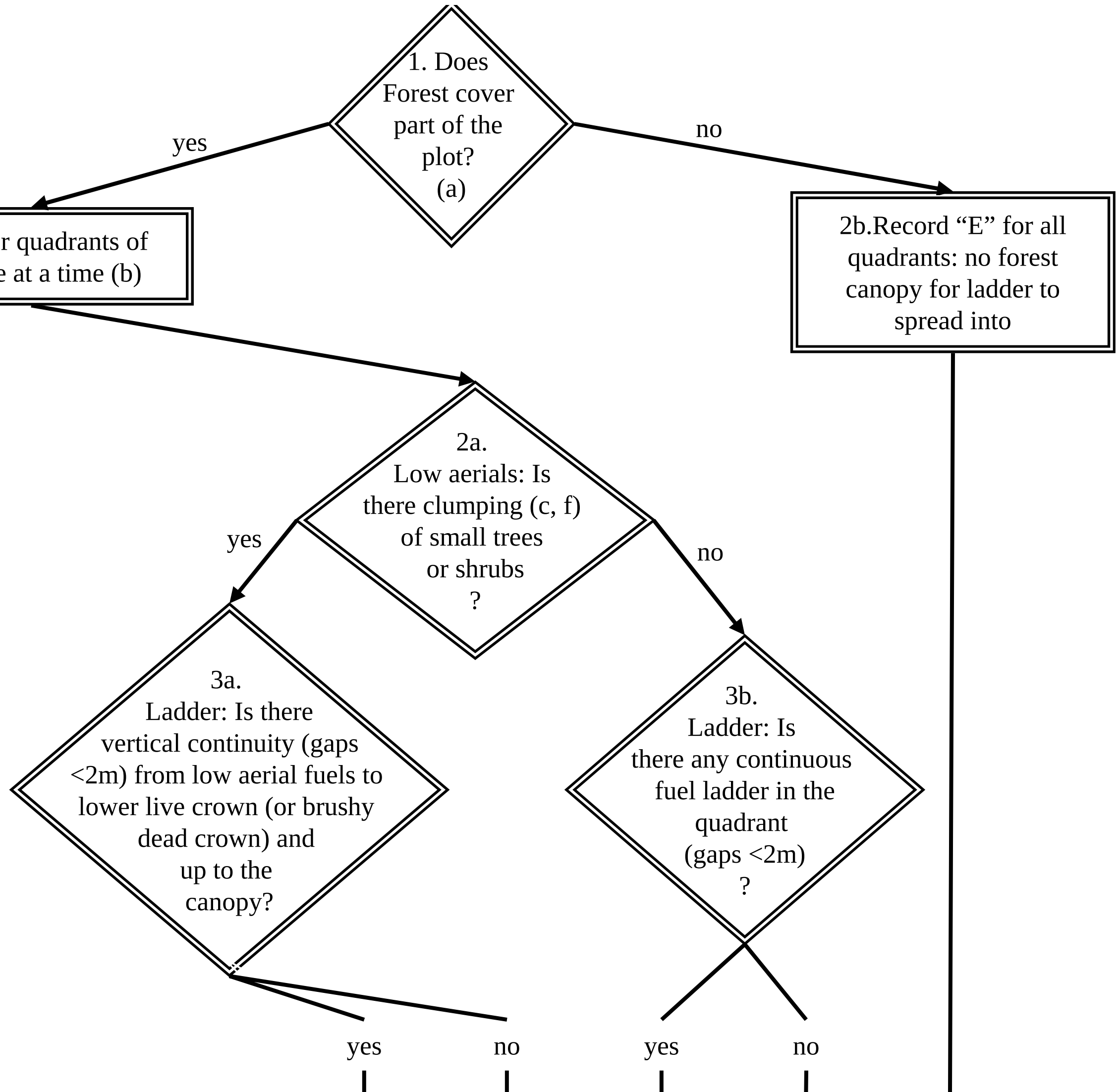
Flowchart Reference	Feature	Description
a	Forest & shrub fields	A single tree in a field is not a forest. A single tree extending over part of the plot that is near other trees is part of a forest. Even though shrub fields are "clumped" as low aerial fuels there may not be any canopy to which to spread 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 square meters (2m x 2m) with gaps of less than 50cm. If it is particularly dense, or tall and brushy, a clump may cover a smaller area. A particularly dense clump may cover as little as $2m^2$ on the forest floor, for example. 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 flowchart page).
e	HTLCB	Height to live crown base: 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. In order 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.

Table 2: Data from ladder fuel hazard assessments in mixed conifer forests of the northern Sierra Nevada. Data from all observations are shown in the column indicating

Rating	Count	Percent of plots in this category		Height to live crown base, or dense dead aerial fuels (excluding E sites)		Maximum gap in best ladder in quadrant (excluding E sites)	
		Including category E	Excluding category E	Mean (m)	st. dev.	Mean (m)	st. dev.
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)	1362	35.0	35.6	4.70	3.01	4.93	2.92
E (no forest)	72	1.8	n/a				
Total with E	3896	100.0	n/a				
Total without E	3824	n/a	100.0				

Figures used in text

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



4. For each quadrant, record risk category, height to crown base, & size of gap in fuel ladder (notes d-h). Possible value ranges are shown in “()”:

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

5. Repeat for each quadrant

6. Final risk rating calculated later in lab. Factors considered may include a) the rating of all four quadrants, b) slope (non-linear rise in risk with increase in slope), & c) vegetation type.