Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements

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Abstract: Assessment of crown fire potential requires quantification of canopy fuels. In this study, canopy fuels were measured destructively on plots in five Interior West conifer stands. Observed canopy bulk density, canopy fuel load, and vertical profiles of canopy fuels are compared with those estimated from stand data using several computational techniques. An allometric approach to estimating these canopy fuel characteristics was useful, but, for accuracy, estimates of vertical biomass distribution and site-adjustment factors were required. Available crown fuel was estimated separately for each tree according to species, diameter, and crown class. The vertical distribution of this fuel was then modeled within each tree crown on the basis of tree height and crown base height. Summing across trees within the stand at every height yielded an estimated vertical profile of canopy fuel that approximated the observed distribution.

Résumé : L'évaluation du risque de feu de cimes exige la quantification des combustibles de la canopée. Dans cette étude, les combustibles de la canopée ont été mesurés de façon destructive dans des parcelles établies dans cinq peuplements de conifères de l'Ouest situés à l'intérieur des terres. Les valeurs observées de la densité apparente de la canopée, de la charge de combustible de la canopée et des profiles verticaux de combustible de la canopée sont comparées à celles qui ont été estimées à partir de données de peuplement à l'aide de plusieurs méthodes de calcul. Une approche allométrique pour estimer ces caractéristiques des combustibles de la canopée était utile mais nécessitait une estimation de la distribution verticale de biomasse et des facteurs d'ajustement qui tiennent compte du site pour fournir des estimations justes. Le combustible disponible dans la cime a été évalué séparément pour chaque arbre sur la base de l'espèce, du diamètre et de la classe de cime. La distribution verticale de ce combustible a ensuite été modélisée dans la cime de chaque arbre sur la base de la hauteur de l'arbre et de la hauteur de la base de la cime. La sommation de tous les arbres dans le peuplement à toutes les hauteurs a produit une estimation du profile verticale de combustible de la canopée qui correspondait approximativement à la distribution observée.

[Traduit par la Rédaction]

Introduction

Assessing the susceptibility of forest stands to crown fire and designing silvicultural treatments to reduce susceptibility to crown fire have become priorities for many land-management agencies. Canopy fuel characteristics are important factors affecting crown-fire occurrence and behavior, so any assessment of crown-fire hazard and comparison of fuel treatment alternatives require repeatable, meaningful estimates of canopy characteristics.

Research has identified several canopy fuel characteristics that affect the incidence and subsequent behavior of crown fire: canopy base height (Alexander 1988; Van Wagner 1977), canopy fuel load (Rothermel 1991), foliar moisture content (Alexander 1998; Van Wagner 1977; Cruz et al. 2004), and canopy bulk density (Albini 1996; Cruz et al. 2005; Van Wagner 1977). In addition, canopy cover and stand height indirectly affect crown-fire incidence through their effects on surface fire behavior by influencing wind reduction and dead fuel moisture content.

A number of fire-modeling systems commonly used by fire researchers and managers require estimates of one or more canopy fuel characteristics for modeling crown fire. BehavePlus® (Andrews et al. 2005), the Canadian forest fire behavior prediction system (CFFBPS; Forestry Canada Fire Danger Group 1992), Crown fire initiation and spread (CFIS; Cruz et al. 2005), FARSITE (Finney 1998), Fuels management analyst™ (Carlton 2004), NEXUS (Scott 1999; Scott and Reinhardt 2001), and the Fire and fuels extension to the forest vegetation simulator (FFE-FVS; Reinhardt and Crookston 2003) all rely on estimates of canopy fuel characteristics. Albini's (1996) radiation-driven crown fire spread model and Linn's (1997) FIRETEC/HIGRAD physical model potentially use much more detailed descriptions of canopy fuels, including their vertical distribution.

Direct, nondestructive measurement of many canopy fuel characteristics is not possible, therefore a variety of indirect methods have been developed. Several optical sensors are available for estimating canopy bulk density, including

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Table 1. Locations and pretreatment characteristics of study sites.

Study site	Forest type	Location	Aspect	Elevation (m)	Basal area (m^2/ha)	Quadratic mean DBH (cm)	Density of trees >10 cm diameter (no./ha)	Stand height (m)
Blodgett	Sierra Nevada mixed conifer[a]	Blodgett Forest Research Station, California	NNE	1300	46.8	35.1	325	34
Flagstaff	Ponderosa pine	Coconino National Forest (NF), Arizona	S	2308	69	18.8	2067	15
Ninemile	Ponderosa pine / Douglas- fir	Lolo NF, Montana	NNE	1050	30.5	17.9	481	22
Salmon	Douglas-fir / lodgepole pine[b]	Salmon-Challis NF, Idaho	SE	2300	37.7	15.2	1209	17
Tenderfoot	Lodgepole pine	Lewis and Clark NF, Montana	NE	2290	42.7	15.5	1145	19

[a]White fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), and Douglas-fir (*Pseudotsuga menziesii*).
[b]*Pinus contorta*.

digital hemispherical photographs, AccuPAR™ ceptometers, and Li-Cor® LAI-2000. Keane et al. (2005) compare detailed results for each of those instruments at these study sites, so we will not compare optical instruments in this paper, focusing instead on alternative estimates based on stand data. We compare several indirect methods for estimating canopy fuel load and canopy bulk density with values derived from destructively measured plots. The indirect measures rely on measurements commonly available to forest managers: number of trees per acre by species, diameter, height, crown class, and crown base height. We illustrate the utility of describing the vertical canopy fuel profile when designing fuel treatments. In addition, we explore the effect of a tree's position within the canopy (dominant, codominant, etc.) on predicted canopy fuel load, as well as the effects of nonuniform vertical distribution of fuel within a single crown on plot-level canopy fuel profiles.

Direct measurement of canopy fuel profiles

We destructively measured canopy fuels in five conifer stands in conifer forest types important to land managers in the western USA (Keane et al. 2005; Scott and Reinhardt 2002, 2005) (Table 1). In each of these stands we established a 10 or 15 m radius circular plot (depending on tree density), deliberately selecting plots in dense, crown-fire-prone areas, inventoried all trees within the plot, including understory trees at least 0.3 m (1 ft) tall, and then took the trees apart branch by branch to determine biomass by size class and component (live or dead). We chose dense stands that local land managers judged to be of high crown-fire potential.

Field sampling procedure

The inventory of each plot included tree measurements that can be used to relate to crown fuel load and its distribution within the canopy, including for each tree:

- Species
- Diameter at breast height (DBH)
- Crown position (dominant, codominant, etc.)
- Tree height
- Crown base height

Tree-level summaries of biomass, including foliage and live and dead branch material by diameter size class, were compiled by aggregating biomass for every branch on a tree. Every branch on every tree was cut from the bole and the following branch characteristics were measured:

- Basal diameter
- Length
- live foliage ratio (ratio of the length of the branch with live foliage to total branch length)
- Height above ground to branch attachment on the bole
- Fresh mass

All branches from every tree whose stem was within the plot boundary were weighed. We assumed that biomass of branches outside the plot boundary from trees within the plot was offset by biomass from branches inside the plot boundary from trees outside the plot.

Biomass by size class and component was measured on a systematic sample of 5%–10% of branches removed from each tree. The biomass of sample branches was sorted into

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the following classes and weighed immediately without drying:

- Live foliage
- Live branchwood
- Dead branchwood
- Open cones
- Closed cones
- Lichen and moss

Live and dead branchwood was further sorted by size class (diameter outside bark) using breakpoints of 3, 6, 10, and 25 mm. Subsamples of the sorted material were oven-dried at 50 °C for at least 24 h but not more than 48 h to determine dry mass and moisture content.

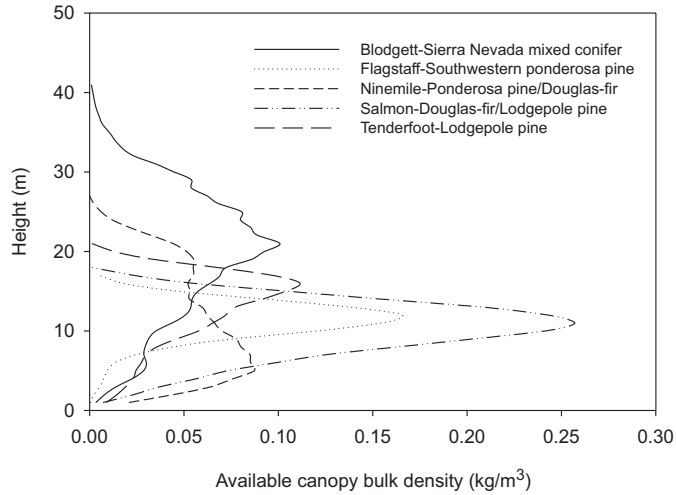
Trees in each of the five stands were sampled by removing the smallest trees and then progressively larger diameter trees, until all trees within the plot were cut. This allowed us to quantify the effects of fuel treatment on canopy characteristics, and also to compare alternative canopy fuel estimation methods in treated and untreated stands (Keane et al. 2005). We used four levels of sampling (pretreatment and successive removal of 25%, 50%, and 75% of the initial stand basal area) for each stand. Three stands with a substantial conifer understory received an additional preliminary treatment that consisted of removing all trees less than 5 cm DBH (2%–5% of stand basal area), simulating an understory-removal treatment.

Data analysis

From the measured green masses and subsampled moisture contents we computed oven-dry fuel mass for each fuel component for the sample branches. We used these data to develop species-specific regression equations, which we then applied to the unsorted branches, estimating oven-dry mass by size class for every branch. We assigned this oven-dry branch fuel mass by class and component to the 1 m height class associated with each branch. Not all canopy biomass is available to the flaming front of a crown fire; only the finest fuel particles burn during the short period of a crown fire (Call and Albini 1997). Available canopy fuel is generally assumed to include the foliage plus some fraction of the live and dead branchwood. Brown and Reinhardt (1991) suggested estimating available canopy fuel mass by adding 50% of the 0–6 mm diameter branch class mass to the foliage mass. In this study, because data were available for the finer classes, we defined available fuel as foliage plus the 0–3 mm diameter live and 0–6 mm diameter dead branchwood classes. To date there is little observational or theoretical evidence to support *any* assumption regarding which biomass classes are available in a crown fire; field and laboratory study is clearly needed.

By summing available fuel masses in thin (1 m) vertical layers across all trees and dividing by the volume of that layer (plot area × layer depth) we obtained a vertical fuel profile for each stand — the most basic representation of available canopy fuel (Fig. 1). We computed an effective plot-level value of canopy bulk density as the maximum of the 3 m running mean of this vertical distribution (Scott and Reinhardt 2005). The running mean smoothes the profile and makes it less sensitive to sampling anomalies. We computed canopy fuel load as the sum of available fuel loads over all trees and height classes on a plot; canopy fuel load is represented as the area inside the curve of the available-fuel profile.

Fig. 1. Observed profiles of canopy fuel before treatment on the five study sites.



Effect of crown position

Some allometric equations exist for predicting crown fuel mass by size class and component for a variety of tree species, and to some extent for trees of various crown classes (dominant, codominant, intermediate, and suppressed) (for example, see Brown 1978). Equations are generally based on tree species, diameter, and height. Because many widely used equations were intended to be used for predicting post-harvest residue rather than available canopy fuel, the data used in developing crown-biomass equations were obtained from mostly large dominant and codominant trees. We explored the effect of crown position on biomass of canopy fuel by finding the multiplier that minimizes the sum of residuals

$$\sum \left| \text{obs}_i - \text{pred-adj}_i \right|$$

where obs_i is the observed available biomass from tree i and pred-adj_i is the predicted available biomass using Brown's equations for dominant and codominant trees and a tree multiplier to account for crown position. The multiplier was determined for each crown position within each species at each study site. This simple approach allowed us to extend the use of allometric equations developed for dominant and codominant trees to trees of all crown positions. Note that if crown position has no effect on crown biomass then the multiplier is the same for all crown positions.

Vertical distribution within a crown

Predicting the vertical profile of canopy fuel at a stand level from individual tree measurements and allometry requires an assumption regarding the vertical distribution of fuel within each tree's crown. In previous work it has been assumed that available fuel is uniformly distributed within a tree's crown (Reinhardt and Crookston 2003; Scott and Reinhardt 2001). We used height-class data to predict the vertical distribution of canopy fuel using the following equation

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$$y_i = \beta_1 x_i + \beta_2 x_i^2 + \beta_3 x_i^3 + e_i$$

where y_i is the proportion of biomass from the base of the crown to height i and x_i is the proportion of the crown at height i.

The above equation was fit for each species at each study site using standard nonlinear regression techniques with the constraints that $\beta_1 + \beta_2 + \beta_3 = 1$ and also the predicted proportion of biomass is never less than zero. These constraints forced the equation through the origin and 1,1, i.e., none of the biomass occurs below the base of the crown and all of it occurs below the top of the crown.

Indirect methods for estimating canopy fuel load

We compared the observed canopy fuel load (as described in the previous section) for each plot and sampling-level combination with estimates made using three existing or possible new methods.

Allometric equations

We predicted available canopy fuel load by estimating foliage and 0–6 mm diameter branchwood for each tree from species and diameter using Brown's (1978) published allometric equations for dominant and codominant trees, adjusting for crown position by using the multipliers 1.0 for dominant trees, 0.9 for codominant trees, 0.6 for intermediate trees, and 0.4 for suppressed trees, summing values for all the foliage from all trees and half the 0–6 mm diameter branchwood and dividing by the plot area. This method is identical with that used in FMAplus® (Carlton 2004) and similar to that implemented in the Fire and Fuels Extension to the Forest Vegetation Simulator FFE-FVS (Reinhardt and Crookston 2003).

Adjusted allometric equations

This method is identical with that described in the previous paragraph, but with the species- and plot-specific crown-class multipliers applied to predictions for each tree. The adjustment multipliers were developed using the same data set from which we computed observed canopy fuel load; correlation of observed canopy fuel load with that predicted with this method is therefore expected to be higher than with the unadjusted equations. However, comparison of correlation coefficients between the adjusted and unadjusted estimates may shed light on the importance of crown position for predicting canopy fuel load for individual trees.

Regression

Cruz et al. (2003) applied equations for crown foliage (Brown 1978; Loomis and Roussopoulos 1978; Stiell 1969; Stocks 1980) to USDA Forest Service Forest Inventory and Analysis (FIA) plots in four forest types in the western United States (Douglas-fir, ponderosa pine, lodgepole pine, and mixed conifer) to estimate canopy fuel load at each plot. The potential contribution of fine live and dead branches was not included in the canopy fuel load estimates. Analysis of their data yielded regression equations (one for each forest type) for predicting canopy fuel load from common stand descriptors (stem density and basal area). We applied their equations to our plot data.

Indirect methods for estimating canopy bulk density

Observed canopy bulk density for each plot and treatment-level combination was compared with several alternative estimates. Observed canopy bulk density was defined as the maximum 3 m running mean based on direct measurements of available fuel. We assumed that crown fire can travel through the densest layer of the crown, and that taking the bulk density of relatively sparsely occupied spaces above and below this dense layer into account may not be important in predicting crown fire behavior. Estimates obtained using seven computational methods were compared with these observed values.

Load over depth (three methods)

The "load-over-depth" approach simply divides canopy fuel load by canopy depth, a straightforward approach to calculating canopy bulk density that implicitly assumes a uniform vertical distribution of available canopy fuel within a forest canopy. Estimates of canopy depth can be derived in several ways. In each of the following load-over-depth methods, canopy fuel load is the *observed* value from the destructive data set — it is not estimated from equations. Therefore, comparing the load-over-depth and observational methods is really comparing different ways of estimating canopy depth. The load-over-depth methods, as calculated here, are heavily informed by the field data.

We compared three different ways of estimating canopy depth. First, we estimated canopy depth as the *mean crown length* over all trees on the plot (Cruz et al. 2003). Crown length for each tree was calculated as the difference between tree height and crown base height. Mean crown length is mathematically equivalent to the difference between mean tree height and mean crown base height. Second, we estimated canopy depth as the difference between heights below which 90% and 10% of available canopy biomass occurs (Albini 1996): the *biomass-percentile method*. In other words, the base of the canopy is the height below which 10% of the canopy fuel occurs, and stand height is the height above which 10% of the canopy fuel occurs. Finally, we estimated canopy depth as the difference between the 90th percentile tree height and the median crown base height: the *height-percentile method*. Unlike the biomass percentile method, this method does not require construction of a canopy fuel profile.

Maximum running mean (two methods)

The maximum running mean approach yields an effective value of canopy bulk density to use for fire modeling — the highest canopy bulk density found in any 3 m deep canopy layer. It is not necessary to estimate canopy depth using this approach; however, like the biomass-percentile method described in the previous paragraph, this method requires a vertically resolved fuel profile. We first estimated crown biomass for each tree from species, diameter, height, and crown base height and previously published allometric equations, not from our destructively sampled biomass data. We summed estimates of available canopy fuel across all trees in 1 m vertical layers to compute canopy bulk density in each layer. We then smoothed these values with a 3 m running mean; the effective canopy bulk density for the plot was taken to be the maximum value attained by the 3 m running

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Table 2. Canopy and stand characteristics by study site and treatment level.

Site and treatment	Basal area (m^2/ha)	Canopy bulk density (kg/m^3)	Canopy base height (m)	Available canopy fuel load (kg/m^2)	Canopy cover (%)
Ninemile					
Untreated	30.42	0.089	0	1.40	Missing
Understory removed	29.71	0.086	1	1.33	59
75% of original basal area	23.31	0.055	5	0.76	50
50% of original basal area	16.60	0.037	11	0.40	30
25% of original basal area	9.23	0.022	12	0.24	19
Salmon					
Untreated	36.26	0.257	1	2.09	70
75% of original basal area	27.24	0.222	2	1.69	59
50% of original basal area	18.84	0.153	3	1.19	47
25% of original basal area	8.16	0.069	5	0.55	24
Flagstaff					
Untreated	69.02	0.166	5	0.93	69
75% of original basal area	53.21	0.147	6	0.80	52
50% of original basal area	35.89	0.104	7	0.54	42
25% of original basal area	17.79	0.057	9	0.27	23
Blodgett					
Untreated	46.77	0.101	2	1.72	74
Understory removed	45.82	0.101	4	1.67	74
75% of original basal area	34.34	0.081	10	1.27	60
50% of original basal area	24.21	0.056	10	0.93	44
25% of original basal area	12.73	0.027	15	0.44	27
Tenderfoot					
Untreated	42.69	0.112	2	1.00	52
Understory removed	38.64	0.111	5	0.91	60
75% of original basal area	32.66	0.093	5	0.78	52
50% of original basal area	21.06	0.060	6	0.51	40
25% of original basal area	7.87	0.028	10	0.21	24

mean throughout the canopy. In these methods, available canopy fuel was estimated from allometric equations (Brown 1978). We compared two methods of estimating available canopy fuel; both assume that available canopy fuel is the foliage plus 50% of the 0–6 mm diameter live branchwood.

Allometric equations

With this method we applied Brown (1978) equations to our tree data as described previously for predicting canopy fuel load without adjustment for nonuniform vertical distribution within the crown. Predicted available crown fuel was assumed to be uniformly distributed from the base of the crown to the top of each tree. Available fuel was then summed across all trees in the plot in 1 m vertical layers. Effective canopy bulk density was then computed as the maximum 3 m running mean of these 1 m layers.

Adjusted allometric equations

This method is similar to the method described in the previous paragraph, but the available fuel estimates for each tree were modified by species- and plot-specific crown-class multipliers. Further, we applied species- and plot-specific equations for the cumulative vertical distribution of canopy fuel within a tree crown rather than assuming a uniform vertical distribution. Adjusted available fuel for each tree in the plot was then summed in 1 m vertical layers, and effective canopy bulk density then taken to be the maximum 3 m running mean of these 1 m layers. Comparison with observed canopy bulk density is not statistically valid because the same data set was used to generate the adjustments and make the comparisons. However, the results may serve to illustrate whether or not the technique merits further investigation and validation.

Lookup tables

We estimated canopy bulk density using the lookup table that Keane et al. (1998, 2000) used to create a spatial data layer for use in FARSITE (Finney 1998). They populated the lookup table for combinations of forest type, structural stage (seedling/sapling or pole/medium/large), and canopy-cover class (low, medium, or high). For each cover type they assigned a canopy bulk density for the high-cover class pole/medium/large structural stage, then reduced that value by 30% to obtain an estimate of the canopy bulk density of the medium-cover class and by 70% for the low-cover class. For the seedling/sapling structural stage they assigned a canopy bulk density value for the low-cover class, then increased that value by 15% for the medium-cover class (there was no value for high-cover seedling/sapling stands). These reference values were compiled from a limited research study that did not involve destructive sampling. For our untreated stands we used the values for high cover, for the in-

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termediate treatments those for medium cover, and for the last treatment those for low cover.

Regressions

We also used regression equations developed by Cruz et al. (2003) for predicting canopy bulk density from stand descriptors. In creating the predictive equations, Cruz et al. (2003) applied the load-over-depth (mean crown length) method described previously, together with published allometric equations, to compute canopy bulk density for a set of FIA plots in four forest types (Douglas-fir, ponderosa pine, lodgepole pine, and mixed conifer). Available canopy fuel load included foliage only. Their data analysis yielded regression equations (one for each forest type) for predicting canopy bulk density from common stand descriptors (stem density and basal area).

Results

Measurement of canopy fuels in five conifer stands

Observed canopy fuel profiles for the five study sites before treatment are shown in Fig. 1. Canopy fuel characteristics for the five sites at the different treatment levels are summarized in Table 2. Observed canopy bulk densities for untreated stands ranged from 0.09 to 0.26 kg/m^3, surprisingly low considering that we looked for dense stands. The Salmon (Douglas-fir / lodgepole pine) site had the highest observed canopy bulk density (0.26 kg/m^3), followed by the Flagstaff (southwestern ponderosa pine) site. Both sites had single-storied stands with simple canopy profiles. While the Salmon (Douglas-fir / lodgepole pine) site also had the highest canopy fuel load of the five sites (2.09 kg/m^2), the Flagstaff site had the lowest (0.93 kg/m^2). The Flagstaff site's high bulk density is the result of this relatively small fuel load being distributed in a narrow, compact layer. While the Blodgett (Sierra Nevada mixed conifer) site had a high canopy fuel load (1.72 kg/m^2), the fuel was distributed over a much larger vertical area, resulting in a relatively low bulk density of 0.10 kg/m^3. The Ninemile (ponderosa pine / Douglas-fir) and Tenderfoot (lodgepole pine) sites are interesting in the asymmetry of their canopy profiles, the largest bulk density being near the bottom of the canopy at the Ninemile site and near the top at the Tenderfoot site.

The effects of the different treatment levels on canopy bulk density at the five study sites are shown in Fig. 2 and the effect of treatment on canopy fuel load is shown in Fig. 3. At the Ninemile site, thinning from below to a residual basal area of 75% effectively reduced canopy bulk density (from 0.089 to 0.055 kg/m^3) and shifted the canopy profile upwards, removing fuels from the bottom of the canopy profile. Stands with a canopy profile of this type are very amenable to restoration thinning from below, thus reducing fire hazard dramatically while retaining most of the larger trees and most of the stand's basal area. At the Flagstaff site, where the stand was a uniform single story composed of trees that varied little in size, removal of 25% of the basal area left the shape of the canopy profile almost unchanged; this removal was ineffective in reducing the canopy bulk density substantially (from 0.166 to 0.147 kg/m^3).

Crown class was an important determinant of tree biomass and thus, indirectly, of canopy fuel characteristics. Table 3 shows the multipliers that yield the best match between predicted and observed canopy biomasses by species and site. Using Brown (1978), predicted biomass was computed from equations for dominant and codominant trees, thus we expected that multipliers for dominant and codominant trees would be near 1, and progressively less for intermediate and suppressed trees. As expected, ponderosa pine, the most shade-intolerant of these species, needs more adjustment for the effects of suppression than more shade-tolerant species. While sample sizes were small or missing for some species / crown class combinations, there were regional differences in these relationships. The multipliers for southwestern ponderosa pine in Flagstaff were much smaller across crown classes than for ponderosa pine at the Blodgett and Ninemile sites. The larger adjustment factor for codominant than for

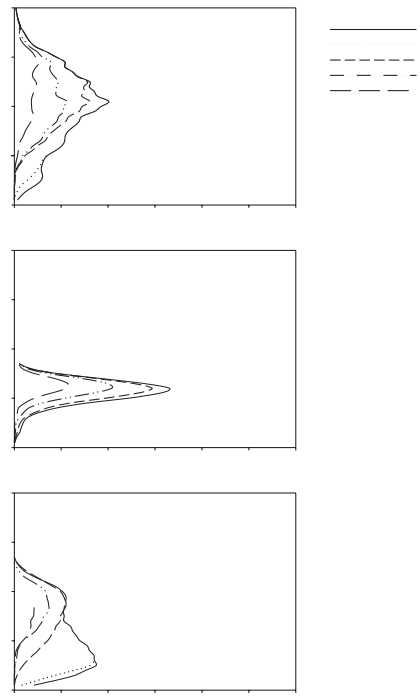

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Fig. 3. Canopy fuel load at each study site by treatment. Loads include foliage, 0–3 mm diameter live branchwood, and 0–6 mm diameter dead branchwood. Quartiles refer to the residual % basal area after treatment.

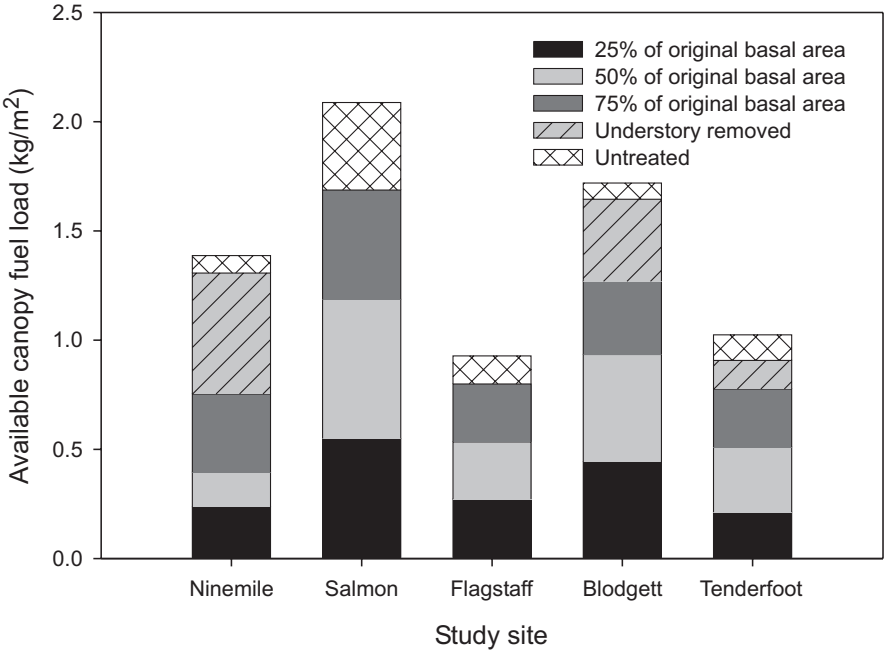

Table 3. Adjustment factors used to correct biomass predictions of crown class.

			Crown class			
	Study site	N	Dominant	Codominant	Intermediate	Suppressed
White fir	Blodgett	18	1.05 (3)	0.8 (5)	0.35 (3)	0.3 (7)
Ponderosa pine	Flagstaff	77	0.45 (10)	0.2 (29)	0.15 (24)	0.1 (14)
	Ninemile	33	0.45 (2)	0.65 (8)	0.3 (8)	0.15 (15)
	Blodgett	2	1.55 (2)	(0)	(0)	(0)
Incense cedar	Blodgett	16	(0)	1.1 (2)	0.75 (8)	0.4 (6)
Douglas-fir	Ninemile	169	(0)	2.0 (2)	1.25 (39)	1.05(128)
	Salmon	46	(0)	1.1(20)	0.5 (12)	0.45 (14)
	Blodgett	1	(0)	(0)	1.0 (1)	(0)
Lodgepole pine	Tenderfoot	67	0.6 (7)	0.55 (21)	0.55 (11)	0.3 (28)
	Salmon	15	(0)	1.25 (8)	0.75 (5)	0.1 (2)

Note: Numbers in parentheses are numbers of trees.

dominant ponderosa pine at the Ninemile site is probably a data anomaly due to inadequate sample size.

The vertical distribution of biomass in individual tree crowns had an important effect on the vertical distribution of fuels in the canopy as a whole. Species-specific equations for modeling the vertical distribution of crown fuel (Table 4) show similar patterns for all species (Fig. 4), with more biomass occurring in the upper portion of the crown.

Estimating canopy fuel load

Canopy fuel load was overpredicted by the allometric equations (Table 5), observed values being, on average, 0.17 kg/m^2 less than predicted values. Also, the average deviation between predicted and observed values (root mean square error) was very large (0.70 kg/m^2), and the correlation between predicted and observed values was low for the allometric technique. The predictions from regression equations were unbiased (the average deviation was near zero), but had large errors (0.56 kg/m^2), and the correlation between predicted and observed values was still low. Because the adjusted-allometry method used adjustments based on this study, there is naturally a high correlation between predicted and observed values. More importantly, the error of the predictions is much reduced (0.11 kg/m^2), indicating the promise of using adjusted regression equations to predict canopy fuel load.

Estimating canopy bulk density

Correlations between observed and predicted canopy bulk densities are also shown in Table 5, as well as mean error and root mean square error. Values from allometric equations and from Cruz et al.'s (2003) regression equations were poorly correlated with observed canopy bulk densities. As with canopy fuel load, the excellent fit of canopy bulk densities predicted from adjusted allometry is expected, since the adjustments were developed from our own data. Correlations

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Table 4. Species-specific equations for modeling the vertical distribution of crown fuel.

Tree species and study site	Sample size[a]	Fuel component	Equation[b]	R^2
Douglas-fir				
Blodgett	$N = 1$, $n = 8$	Foliage	$\hat{y} = 3.2606x^2 - 2.2606x^3$	0.994
		Total	$\hat{y} = 3.5170x^2 - 2.5170x^3$	0.989
		Available	$\hat{y} = 3.3724x^2 - 2.3724x^3$	0.994
Ninemile	$N = 22$, $n = 255$	Foliage	$\hat{y} = 2.7821x^2 - 1.7821x^3$	0.963
		Total	$\hat{y} = 0.0687x + 2.9938x^2 - 2.0625x^3$	0.962
		Available	$\hat{y} = 2.9398x^2 - 1.9398x^3$	0.963
Salmon	$N = 22$, $n = 255$	Foliage	$\hat{y} = 1.7767x^2 - 0.7767x^3$	0.913
		Total	$\hat{y} = 2.6094x^2 - 1.6094x^3$	0.933
		Available	$\hat{y} = 1.9489x^2 - 0.9489x^3$	0.927
Ponderosa pine				
Blodgett	$N = 2$, $n = 49$	Foliage	$\hat{y} = 3.0112x^2 - 2.0112x^3$	0.997
		Total	$\hat{y} = -3.3710x^2 - 2.3710x^3$	0.997
		Available	$\hat{y} = 3.0609x^2 - 2.0609x^3$	0.996
Flagstaff	$N = 47$, $n = 308$	Foliage	$\hat{y} = 0.102x + 2.837x^2 - 1.939x^3$	0.915
		Total	$\hat{y} = 0.2912x + 2.6671x^2 - 1.9584x^3$	0.917
		Available	$\hat{y} = 0.1251x + 2.8072x^2 - 1.9322x^3$	0.907
Ninemile	$N = 15$, $n = 185$	Foliage	$\hat{y} = 2.3330x^2 - 1.3330x^3$	0.869
		Total	$\hat{y} = 2.6720x^2 - 1.6720x^3$	0.854
		Available	$\hat{y} = 2.3637x^2 - 1.3637x^3$	0.873
Lodgepole pine				
Salmon	$N = 11$, $n = 111$	Foliage	$\hat{y} = 2.0369x^2 - 1.0369x^3$	0.949
		Total	$\hat{y} = 2.4727x^2 - 1.4727x^3$	0.946
		Available	$\hat{y} = 2.2132x^2 - 1.2132x^3$	0.950
Tenderfoot	$N = 44$, $n = 486$	Foliage	$\hat{y} = 1.3375x^2 - 0.3375x^3$	0.918
		Total	$\hat{y} = 1.7209x^2 - 0.7209x^3$	0.920
		Available	$\hat{y} = 1.4657x^2 - 0.4657x^3$	0.924
White fir				
Blodgett	$N = 12$, $n = 216$	Foliage	$\hat{y} = 0.8975x^2 - 0.1025x^3$	0.910
		Total	$\hat{y} = 2.2345x^2 - 1.2345x^3$	0.921
		Available	$\hat{y} = 0.9428x^2 + 0.0572x^3$	0.914
Incense cedar				
Blodgett	$N = 9$, $n = 104$	Foliage	$\hat{y} = 2.5251x^2 - 1.5251x^3$	0.963
		Total	$\hat{y} = 2.6202x^2 - 1.6202x^3$	0.949
		Available	$\hat{y} = 2.5395x^2 - 1.5395x^3$	0.964

[a] N is the number of trees and n the number of vertical segments used to develop the equations.
[b] y is the cumulative proportion of crown biomass and x is the fractional crown length.

between predicted and observed canopy bulk densities varied from 0.55 to 0.99 for the seven methods tested. Again, four of these methods were not independent of the observed data, so they present a "best case" measure of performance. Values predicted from Cruz et al.'s (2003) regressions and from Keane et al.'s (1998, 2000) tables were high, overestimating canopy bulk density by, on average, 0.062 and 0.070 kg/m^3, respectively. Values derived from allometric equations were relatively unbiased (the mean deviation was near zero) but poorly correlated ($r = 0.55$) with observed values.

Even using observed canopy biomass, canopy bulk density was poorly predicted by dividing biomass by average crown length. Average crown length is probably not a useful indicator of canopy volume in any but the simplest, single-storied stand. In contrast, dividing observed canopy biomass by canopy length, where canopy length is defined as the height below which 90% of canopy biomass occurs minus the height below which 10% of canopy biomass occurs (Albini 1996), was an extremely accurate method of estimating canopy bulk density, and even using a more easily determined proxy for that canopy length, the height of the 90th percentile tall tree minus the height of the median crown base height was an effective method of estimating canopy bulk density.

Figure 5 illustrates, for the untreated stand and the stand at 75% of original basal area at the Ninemile site, the actual canopy fuel profile (grey lines) and the profile as computed using the alternative methods. For this multistoried stand, the assumption that the canopy fuel profile occurs between mean tree height and mean crown base height (Fig. 5*a*) is clearly misleading. The large number of small trees in the untreated stand causes the crown profile to be narrow and low to the ground, and artificially inflates the estimated canopy bulk density. Note that the area inside the box with a solid black outline in Fig. 5*a* is the same as that inside the solid grey curve and represents observed total canopy fuel before treatment. Similarly, the area inside the box with a

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Fig. 4. Cumulative proportion of crown biomass by fractional crown length for each tree species.

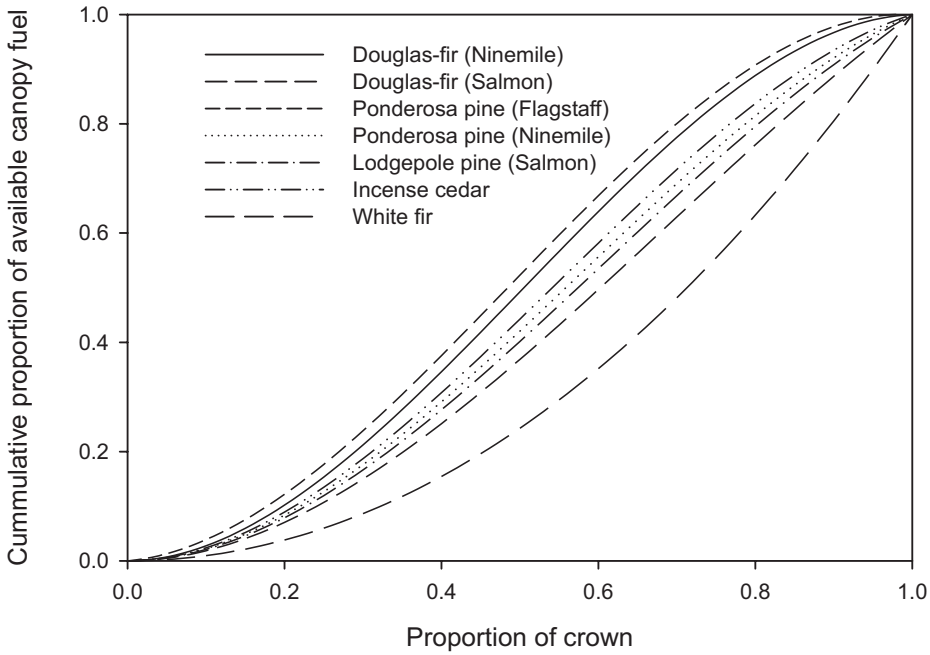

Table 5. Correlations between observed and predicted canopy fuel load and canopy bulk density (n = 23).

Method	Correlation	Bias = mean (observed – predicted)	Precision = $\sqrt{\frac{\sum (O-P)^2}{n}}$
Canopy fuel load (kg/m^2)			
Allometric equations[a]	0.297	–0.1716	0.7015
Regressions[b]	0.385	0.0286	0.5586
Adjusted allometric equations[c]	0.985	0.0726	0.1123
Canopy bulk density (kg/m^3)			
Load- over-depth			
Mean[d]	0.700	–0.0362	0.0829
Biomass percentile[d]	0.987	0.0019	0.0099
Height percentile[d]	0.966	0.0172	0.0247
Lookup tables[e]	0.549	–0.0704	0.0885
Allometric equations[a]	0.546	–0.0152	0.0888
Regressions[b]	0.616	–0.0618	0.1366
Adjusted allometric equations[c]	0.996	0.0102	0.0123

[a]From Brown (1978) as implemented in Carlton (2004).
[b]Cruz et al. (2003).
[c]Allometric equations are from Brown (1978) adjusted as described in the methods above. Adjustments were developed from this data set, therefore correlations are expected to be high.
[d]Values reflect observed fuel loads divided by different measures of canopy depth.
[e]Keane et al. (1998, 2000).

black broken outline is the same as that inside the broken grey curve and equals observed canopy biomass after 25% of the stand basal area was removed. Figures 5*b* and 5*c* are computed similarly, but using the different estimates of canopy length based on different approximations of stand height and canopy base height. Both these methods are far more successful than using a simple mean. Figure 5*d* is similar to Fig. 5*a*; however, the canopy fuel loads are estimated by Cruz et al's (2003) regressions rather than using the observed loads. Figures 5*e* and 5*f* illustrate just how well the canopy fuel profile can be replicated using allometric equations for each tree, distributing the biomass along the crown length for the same tree, and then summing across trees. The derived profile mimics the observed profile remarkably well, even without the adjustments for site (Fig. 5*e*), crown class, and species vertical distribution relationships. If the adjustments are made (Fig. 5*f*), the allometric equations (Brown 1978) reflect the observed canopy profile extremely closely.

Discussion

Canopy bulk density is an important determinant of

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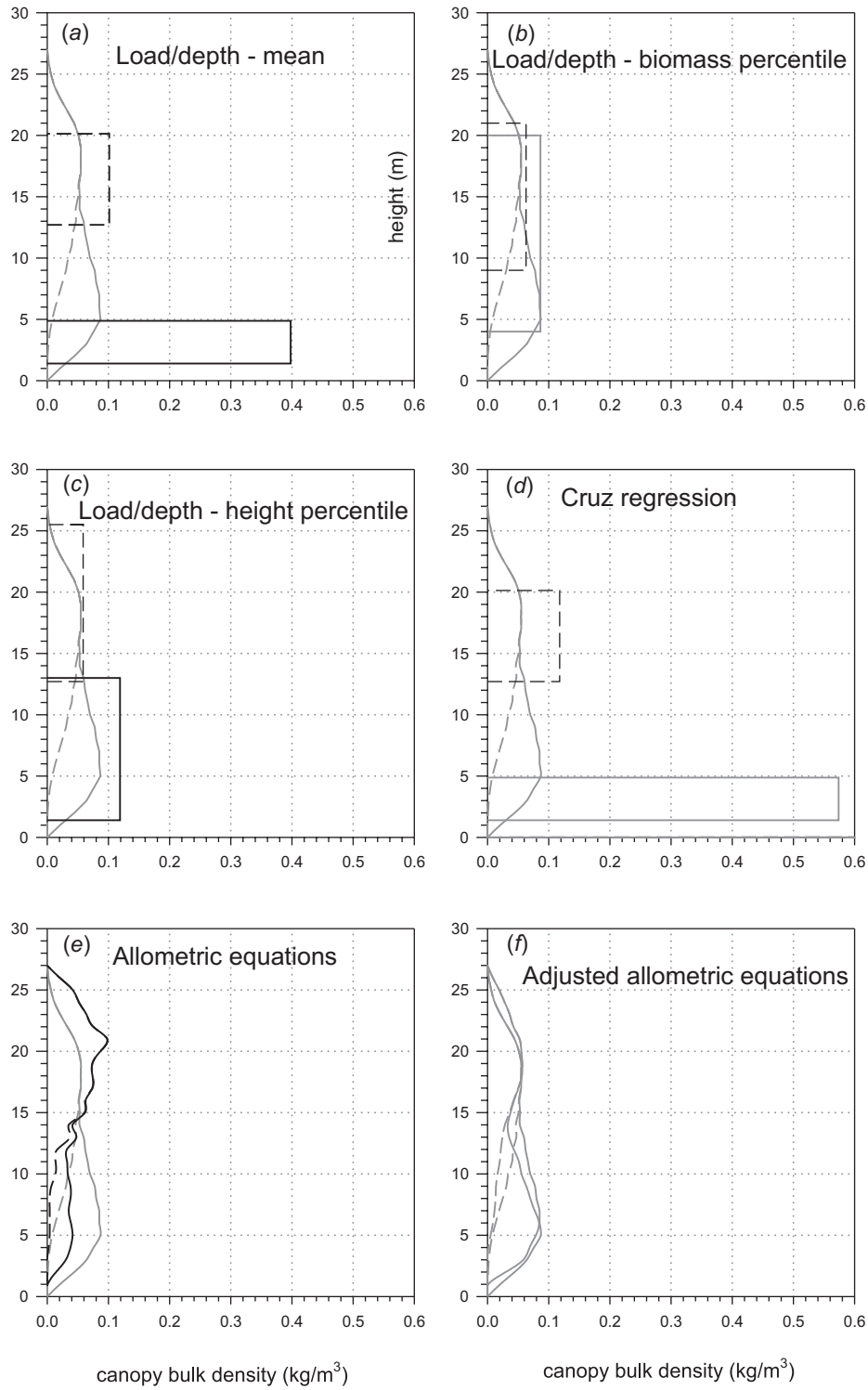
Fig. 5. Observed canopy fuel profile at the Ninemile study site compared with simulated canopy profiles modeled implicitly by four methods and explicitly by two methods. The grey lines show the observed canopy fuel profile at the Ninemile site before treatment (solid line) and after 25% of the stand basal area was removed (broken line). The black lines represent canopy profile before treatment (solid line) and after 25% of the stand basal area was removed (broken line) computed as observed canopy fuel load divided by mean crown length (*a*), observed canopy fuel load divided by the difference between the height below which 90% of canopy biomass occurs and the height below which 10% of canopy biomass occurs (*b*), observed canopy fuel load divided by the difference between the 90th percentile tree height and the median crown base height (*c*), the canopy fuel load predicted by Cruz et al.'s (2003) regression equations divided by mean crown length (*d*), the allometric approach (*e*), and the allometric approach adjusted for site factors, crown class, and vertical distribution (*f*).



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crown-fire occurrence in fire-modeling systems such as FARSITE (Finney 1998), NEXUS (Scott 1998), and BehavePlus (Andrews et al. 2005). FARSITE uses a default value of 0.2 kg/m^3 for canopy bulk density. Cruz et al. (2003) report a mean derived canopy bulk density of 0.18 kg/m^3 for ponderosa pine and Douglas-fir stands, 0.28 kg/m^3 for lodgepole pine stands, and 0.32 kg/m^3 for mixed conifer stands. Our observations suggest that these values may be high. The crown fire modeling systems were developed without specific knowledge of canopy fuel characteristics. As information regarding canopy fuel characteristics improves, existing crown fire modeling systems may need to be reevaluated (Scott 2006).

Canopy fuel loads are of interest to managers because of their contribution to crown-fire intensity. Also, if left untreated, canopy fuels become surface "activity" fuels following thinning, and may contribute substantially to surface fire behavior. In many cases thinning alone could actually increase the crown-fire hazard because, while canopy fuels are reduced, surface fire intensity may increase enough to initiate crown-fire behavior, even in the treated stand, under more moderate weather conditions (Agee and Skinner 2005; Stephens and Moghaddas 2005). Since thinned stands are more open, surface wind speeds are greater and fuels drier than under closed canopies (van Wagtendonk 1996; Scott and Reinhardt 2001). Therefore, when planning thinning treatments for fuel hazard reduction, the impact on canopy fuels, surface fuels, surface fuel moisture, and midflame wind speed must all be taken into account.

Modeling the vertical canopy bulk density profile of a stand as we did here not only provides a method for estimating canopy bulk density as a stand attribute, it also lends insight into fuel-treatment options to mitigate crown-fire hazard in the stand. For example, the Ninemile site, where maximum canopy bulk density occurs low in the canopy profile, is especially amenable to a light thinning from below, while the Salmon and Flagstaff sites, with their dense, single-storied structure, required heavier thinning to substantially impact canopy fuels.

Canopy base height is also an important predictor of crown-fire behavior, and is a stand attribute that is very amenable to management. However, even intensive destructive sampling such as that conducted here does not yield an "observed" canopy base height. Canopy base height has to be defined, preferably in a way that is meaningful when assessing crown-fire hazard and is responsive to stand manipulations in a consistent way. We recommend defining canopy base height on the basis of a minimum amount of canopy bulk density, as in Sando and Wick (1972). We have used this method widely, implementing it in the FFE-FVS, using a threshold value of 0.012 kg/m^3, which was derived from canopy fuel profiles that were computed after many stands were examined. Though arbitrary, the method seems to perform consistently. Removing trees always causes the canopy base height either to increase or stay the same, as it should. The method fails, however, when canopy bulk density never exceeds the threshold value. Very open stands, no matter if the crowns reach the ground, have an undefined canopy base height. Other methods of defining canopy base height have serious logical problems. Using the average of crown base heights is an obvious approach for an even-aged stand; however, it is completely illogical for a two-storied stand. Methods that are based on empirical relationships, such as those in Cruz et al. (2003), may exhibit illogical behavior. For example, in those authors' equations, stand basal area is a predictive variable with a positive coefficient, as might be expected, since denser stands typically have higher canopy base heights, owing to self-pruning in limited-light conditions. However, those equations predict that thinning (i.e., reducing basal area) will decrease canopy base height, an illogical result.

Similarly, stand height is implicitly a part of many estimates of canopy bulk density, and is subject to similar concerns. If stand height were computed as a simple average of tree heights, the removal of an understory layer of short trees would increase estimated stand height, another illogical result. Therefore, we recommend computing stand height by a method analogous to our computation of canopy base height: the highest point at which canopy bulk density exceeds 0.012 kg/m^3. This excludes from the canopy volume the large space occupied by the narrow tips of a few tall trees, which contribute little fuel to a crown fire.

Conclusions

The stands we sampled, chosen because they were dense and prone to crown fire, had observed pretreatment canopy bulk densities ranging from 0.089 to 0.257 kg/m^3 and available canopy fuel loads ranging from 0.91 to 2.09 kg/m^2. We expect that few stands in similar forest types will have substantially larger canopy bulk densities and fuel loads than those observed here.

An allometric approach to estimating canopy fuel load, canopy bulk density, and canopy fuel profiles has promise; however, site-specific adjustment factors were necessary for making accurate predictions. Additional individual-tree-based sampling to determine multipliers by species, crown class, and probably ecoregion will greatly improve our confidence in allometric predictions.

More accurate estimates of canopy fuel properties will make it possible to better use models of crown-fire occurrence and behavior, assess the effects of treatments on crown-fire potential, map canopy fuels consistently across administrative boundaries and ecological types, and model fire behavior for landscape-scale planning processes.

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