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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 to those estimated from stand data using several computational techniques. An allometric approach to estimating these canopy fuel characteristics was useful, but required estimates of vertical biomass distribution and site-adjustment factors in order to provide accurate estimates. Available crown fuel was estimated separately for each tree based on species, diameter and crown class. The vertical distribution of this fuel was then modeled within each tree crown based on tree height and crown base height. Summing across trees within the stand at every height resulted in an estimated vertical profile of canopy fuel that approximated the observed distribution.

Keywords: Canopy bulk density, canopy biomass, foliage, crown fire hazard, *Pinus ponderosa, Pinus contorta, Pseudotsuga menziesii, Abies concolor*, *Calocedrus decurrens*, fire behavior modeling.

Introduction

Assessing the susceptibility of forest stands to crown fire and designing silvicultural treatments to reduce crown fire susceptibility 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 requires 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 and others 2004), and canopy bulk density (Albini 1996, Cruz and others 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 and others, 2005), the Canadian Forest Fire Behavior Prediction System (CFFBPS; Forestry Canada Fire Danger Group 1992), CFIS (Crown Fire Initiation and Spread; Cruz and others 2005), FARSITE (Finney 1998), Fuel 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 can potentially use much more detailed descriptions of canopy fuels, including the vertical distribution of fuels.

Direct, non-destructive 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 digital hemispherical photographs, ACCUPAR ceptometer, and LiCor LAI 2000. Keane and others (2005) compare detailed results for each of those instruments at these study sites, so we will not compare optical instruments in this paper. This paper focuses 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: 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, co-dominant, etc.) on predicted canopy fuel load, as well as the effects of non-uniform 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 (Scott and Reinhardt 2002, 2005; Keane and others 2005) (table 1). In each of these stands we established a 10 or 15 meter 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 apart the trees branch by branch to obtain 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,
- crown position (dominant, co-dominant, *etc*.),
- tree height, and
- height to the base of the crown

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 (the ratio of the length of the branch with live foliage to total branch length),

- height above ground to branch attachment on bole,
- fresh weight

All branches were weighed for every tree whose stem was within the plot boundary. 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 to 10 percent of branches removed from each tree. The biomass of sample branches was sorted into the following classes and weighed immediately without drying:

- live foliage,
- live branchwood
- dead branchwood
- open cones,
- closed cones, and
- lichen and moss.

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

Trees on each of the five stands were sampled by removing progressively larger diameter trees, beginning with the smallest, until all trees were cut within the plot. This allowed us to quantify the effects of fuel treatment on canopy characteristics, and also to compare alternative canopy fuel estimation methods in both treated and untreated stands (Keane and others 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. For three stands with a substantial conifer understory there was an additional preliminary treatment removing all trees less than 5 cm dbh (2% to 5% of the stand basal area), simulating an understory removal treatment.

Data analysis

From the measured green weights and sub-sampled moisture contents we computed oven-dry fuel weight 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 weight by size class for every branch. We assigned this oven-dry branch fuel weight by class and component to the 1 meter 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 in the short duration 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 weight by adding 50% of the 0-6 mm diameter branch class weight to the foliage weight. In this study, because data were available in finer classes, we defined available fuel as foliage plus the 0-3 mm live and 0-6 mm 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 weight in thin (1 meter) vertical layers across all trees and dividing by the volume of that layer (plot area x layer depth) we obtained a vertical fuel profile for each stand – the most basic representation of the available canopy fuel (figure 1). We computed an effective plot-level value of canopy bulk density as the maximum of the 3 meter 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 load 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.

Effect of crown position **–** Some allometric equations exist for predicting crown fuel weight by class and component for a variety of tree species, and to some extent for trees of various crown classes (dominant, co-dominant, intermediate and suppressed) (for example, 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 from mostly large dominant and co-dominant trees. We explored the effect of crown position on biomass of canopy fuel by finding the multiplier which minimizes the sum of residuals:

$$\sum \left| obs_i - predadj_i \right|$$

where obs_i is the observed available biomass from tree i and $predadj_i$ is the predicted available biomass using Brown’s equations for dominant and co-dominant 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 co-dominant trees to trees of all crown positions. Note that if crown position has no effect on crown biomass then the multiplier would be the same for all crown positions.

Vertical distribution within a crown – Predicting vertical canopy fuel profiles from allometric equations for individual trees requires making an assumption regarding the vertical distribution of available fuel within an individual tree. Previous work has assumed 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 vertical distribution of canopy fuel using the following equation:

$$y_i=ß_1x_i+ ß_2x_i^2+ ß_3x_i^3+e_i$$

where

y_i=proportion of biomass from crown base to height i
x_i=proportion of crown at height i

The above equation was fit for each species at each study site using standard nonlinear regression techniques with the constraint that $ß_1+ ß_2+ ß_3=1$ 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 observed canopy fuel load (as described in the previous section) for each plot and sampling-level combination to estimates made using three existing or possible new methods.

Allometric equations

We predicted available canopy fuel load by estimating foliage and 0-6 mm branchwood for each tree from species and diameter using Brown's (1978) published allometric equations for dominant and co-dominant trees, adjusting for crown position by using the multipliers 1.0 for dominant trees, 0.9 for co-dominant trees, 0.6 for intermediate and .4 for suppressed trees, summing all the foliage from all trees and half the 0-6 mm branchwood, and dividing by plot area. This method is identical to that used in FMAplus (Carlton 2004), and similar to that implemented in FFE-FVS (Reinhardt and Crookston 2003).

Adjusted allometric equations

This method is identical to that described above, but with the species- and plot-specific crown class multipliers detailed above applied to predictions for each tree. The adjustment multipliers were developed using the same dataset from which we computed observed canopy fuel load; correlation of observed canopy fuel load and 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 on predicting canopy fuel load for individual trees.

Regression

Cruz and others (2003) applied equations for crown foliage (Brown 1978, Loomis and Roussopoulos 1978, Stiell 1969, Stocks 1980) to 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. Their data analysis yielded regression equations (one for each forest type) to predict 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/treatment-level combination was compared to several alternative estimates. Observed canopy bulk density was defined as the maximum 3 m running mean based on the directly measured available fuel data. We assumed that crown fire can travel through the densest layer of the crown, and the bulk density of relatively sparsely occupied spaces above and below this dense layer may not be important in predicting crown fire behavior. Estimates from seven computational methods were compared to these observed values.

Load-over-depth (three methods)

The “load-over-depth” approach simply divides canopy fuel load by canopy depth, a straight-forward approach to calculating canopy bulk density that implicitly assumes a uniform vertical distribution of available canopy fuel within a forest canopy. Canopy depth estimates can be derived several ways. In each of the following load-over-depth methods, canopy fuel load is the *observed* value from the destructive dataset – it is not estimated from equations. Therefore, comparing the load-over-depth methods with the observed 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 and others 2003). Crown length for each tree was calculated as the difference between tree height and crown base height. The mean crown length method 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) (*biomass percentile method*). In other words, the canopy base is the height below which 10 percent of the canopy fuel occurs, and stand height is the height above which 10 percent 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 (*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 – it is 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 above, this method requires a vertically resolved fuel profile. We first estimated tree crown biomass for each tree from tree species, diameter, height and crown base height and previously published allometric equations, not using 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 value of canopy bulk density for the plot was taken to be the maximum value attained by the 3 m running 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 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 above for predicting canopy fuel load without adjustment for non-uniform vertical distribution within a 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 layers. Effective canopy bulk density was then computed as the maximum 3 m running mean of those 1 m layers.

Adjusted allometric equations – This method is similar to the method described above, 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 layers, and effective canopy bulk density then taken to be the maximum 3 m running mean of those 1 m layers. Comparison with observed canopy bulk density is not statistically valid because the same dataset was used to generate the adjustments and make the comparisons. However, the results may serve to illustrate whether the technique merits further investigation and validation.

Lookup tables

We estimated canopy bulk density using the lookup table that Keane and others (1998, 1999) 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 canopy cover). 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 estimate 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 intermediate treatments medium cover, and for the last treatment we used low-cover.

Regressions

We also used regression equations developed by Cruz and others (2003) for predicting canopy bulk density from stand descriptors. In creating the predictive equations Cruz and others

(2003) applied the load-over-depth (mean crown length) method described above, 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) to predict 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 figure 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 kg/m^3 to 0.26 kg/m^3, surprisingly low considering we deliberately looked for dense stands. The Salmon (Douglas-fir/lodgepole) site had the highest observed canopy bulk density (0.26 kg/m^3), followed by the Flagstaff site (ponderosa pine). Both sites had single storied stands with simple canopy profiles. While Salmon also had the highest canopy fuel load (2.09 kg/m^2), Flagstaff had the lowest canopy fuel load of the five sites (0.93 kg/m^2). Flagstaff's high bulk density is the result of this relatively small fuel load being distributed in a narrow, compact layer. While Blodgett (mixed conifer) 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, with Ninemile having the largest bulk density near the bottom of the canopy, and Tenderfoot near the top.

Effects of the treatment levels on canopy bulk density at the five study sites are shown in figure 2 and the effect of treatment on canopy fuel load is shown in figure 3. At Ninemile, thinning from below to a residual basal area of 75% effectively reduced canopy bulk density (from 0.089 kg/m^3 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, reducing fire hazard dramatically while retaining most of the larger trees and most of the stand's basal area. At Flagstaff, 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, and this removal was ineffective in reducing the canopy bulk density substantially (from 0.166 kg/m^3 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 result in the best match between predicted and observed canopy biomass by species and site. Predicted biomass from Brown (1978) was computed from equations for dominant and co-dominant trees, thus we expected that multipliers for dominant and co-dominant trees would be near one, and progressively less for intermediate and suppressed trees. As expected, ponderosa pine, the most shade-intolerant of these species, needs more adjustment for 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 Blodgett and Ninemile. The larger adjustment factor for co-dominant than for dominant ponderosa pine at Ninemile 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 a similar pattern for all species (figure 4), with more biomass occurring in the upper portion of the crown.

Estimating canopy fuel load

Canopy fuel load was over-predicted by allometric equations (table 5), with observed values on average 0.17 kg/m^2 less than predicted. Also, average size of the deviation between predicted and observed (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 (average deviation 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 density are also shown in table 5, as well as mean error and root mean square error. Values from allometric equations and from the Cruz and others (2003) regression equations were poorly correlated with observed canopy bulk densities. As with canopy fuel load, the excellent fit of canopy bulk density predictions from adjusted allometry is expected, since the adjustments were developed from our own data. Correlations between predicted and observed values of canopy bulk density 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. Predicted values from the Cruz and others (2003) regressions and from Keane and others tables (1998, 1999) were high, overestimating canopy bulk density by an average of 0.062 and 0.070 kg/m^3 respectively. Values from allometric equations were relatively unbiased (mean deviation near zero), but poorly correlated (r=.55) with observed values.

Even using observed canopy biomass, canopy bulk density was poorly predicted by dividing biomass by the 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 the observed canopy biomass by canopy length where the canopy length is defined as the height below which 90% of the canopy biomass occurs minus the height below which 10% of the 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 90^{th} 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 Ninemile study site, for the untreated stand and the stand at 75% of original basal area, the actual canopy fuel profile (light grey lines), and the profile as computed by the alternate methods. For this multi-storied stand, approximating the canopy fuel profile as occurring between mean tree height and mean crown base height (figure 5a) 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 estimated canopy bulk density. Note that the area inside the black solid box is the same as inside the grey solid line, and represents observed total canopy fuel before treatment. Similarly, the area inside the black dashed box is the same as inside the grey dashed curve and equals observed canopy biomass after 25% of the stand basal area was removed. Figure 5b and 5c 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 use of a simple mean. Figure 5d is similar to 5a, however the canopy fuel loads are estimated by the Cruz regressions rather than using the observed loads. Figure 5e and 5f illustrate just how well the canopy fuel profile can be replicated by using allometric equations for each tree, distributing the biomass along the crown length for that same tree, and then summing across trees. The derived profile mimics the observed remarkably well, even without the adjustments for site (figure 5e), crown class and species vertical distribution relationships. If the adjustments are made (figure 5f), the allometric equations (Brown 1978) reflect the observed canopy profile extremely closely.

Discussion

Canopy bulk density is an important determinant of crown fire occurrence in fire modeling systems such as FARSITE (Finney 1998) and NEXUS (Scott 1998), and BehavePlus (Andrews and others 2005). FARSITE uses a default value of 0.2 kg/m^3 for canopy bulk density. Cruz and others (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, and 0.32 kg/m^3 for mixed conifer. Our observations suggest that these values may be high. The crown fire modeling systems were developed without specific knowledge of canopy fuel characteristics. With improved information regarding canopy fuel characteristics, existing crown fire modeling systems may need to be re-evaluated (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 fuel moistures 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 moistures, 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 a stand attribute that is very amenable to management. However, even intensive destructive sampling such as conducted here does not lead to 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 responsive to stand manipulations in a consistent way. We recommend defining canopy base height based on 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. This value was derived after examining computed canopy fuel profiles from many stands. While arbitrary, the method seems to perform consistently. Removing trees always results in canopy base height either increasing or staying 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 to 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 in an even aged stand; however, it is completely illogical in a two-storied stand. Methods that are based on empirical relationships, such as those in Cruz and others (2003), may exhibit illogical behavior. For example, in their equations, stand basal area occurs as a predictive variable with a positive coefficient, as might be expected, since denser stands typically have higher canopy base heights due to self-pruning in light-limited 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 canopy bulk density estimates, 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 in 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 amount of space occupied by the narrow tips of a few tall trees, which contribute little fuel to a crown fire.

Conclusions

The stands we sampled, deliberately chosen to be dense and prone to crown fire, had pretreatment observed canopy bulk densities ranging from 0.089 kg/m^3 to 0.257 kg/m^3 and available canopy fuel loads ranging from 0.91 kg/m^2 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 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 accurate predictions. Additional individual-tree based sampling to determine multipliers by species, crown class and probably eco-region will greatly improve our confidence in allometric predictions.

Better estimates of canopy fuel properties will make it possible to better use models of crown fire occurrence and behavior, assess 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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Table 1. Locations and pre-treatment characteristics of study sites.

Study site	Forest type	Location	Aspect	Elevation (m)	Basal Area (m2/ha)	Quadratic mean diameter at breast height (cm)	Density of trees > 10 cm (trees/ha)	Stand height (m)
Blodgett	Sierra Nevada mixed conifer (white fir[1], incense cedar[2], ponderosa pine[3], Douglas-fir[4])	Blodgett Forest Research Station, California	NNE	1300	46.8	35.1	325	34
Flagstaff	ponderosa pine	Coconino National Forest, Arizona	S	2308	69	18.8	2067	15
Ninemile	ponderosa pine/Douglas-fir	Lolo National Forest, Montana	NNE	1050	30.5	17.9	481	22
Salmon	Douglas-fir/ lodgepole pine[5]	Salmon-Challis National Forest, Idaho	SE	2300	37.7	15.2	1209	17
Tenderfoot	lodgepole pine	Lewis and Clark National Forest, Montana	NE	2290	42.7	15.5	1145	19

[1] *Abies concolor*
[2] *Calocedrus decurrens*
[3] *Pinus ponderosa*
[4] *Psuedotsuga menzeisii*
[5] *Pinus contorta*

Table 2. Canopy and stand characteristics by study site and treatment level. CBD is canopy bulk density, kg/m^3, CBH is canopy base height, m, and CFL is available canopy fuel load, kg/m^2.

Site	Treatment	Basal Area (m^2/ha)	CBD (kg/m^3)	CBH (m)	CFL (kg/m^2)	Canopy Cover (%)
Ninemile	Untreated	30.42	.089	0	1.40	Missing
	Understory removed	29.71	.086	1	1.33	59
	75% original basal area	23.31	.055	5	0.76	50
	50% original basal area	16.60	.037	11	0.40	30
	25% original basal area	9.23	.022	12	0.24	19
Salmon	Untreated	36.26	.257	1	2.09	70
	75% original basal area	27.24	.222	2	1.69	59
	50% original basal area	18.84	.153	3	1.19	47
	25% original basal area	8.16	.069	5	0.55	24
Flagstaff	Untreated	69.02	.166	5	0.93	69
	75% original basal area	53.21	.147	6	0.80	52
	50% original basal area	35.89	.104	7	0.54	42
	25% original basal area	17.79	.057	9	0.27	23
Blodgett	Untreated	46.77	.101	2	1.72	74
	Understory removed	45.82	.101	4	1.67	74
	75% original basal area	34.34	.081	10	1.27	60
	50% original basal area	24.21	.056	10	0.93	44
	25% original basal area	12.73	.027	15	0.44	27
Tenderfoot	Untreated	42.69	.112	2	1.00	52
	Understory removed	38.64	.111	5	0.91	60
	75% original basal area	32.66	.093	5	0.78	52
	50% original basal area	21.06	.060	6	0.51	40
	25% original basal area	7.87	.028	10	0.21	24

Table 3. Adjustment factors to correct biomass predictions for crown class. Number of trees are shown in parentheses.

Species	Study site	N	Dominant	Co-dominant	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)
Ponderosa pine	Ninemile	33	0.45 (2)	0.65 (8)	0.3 (8)	0.15 (15)
Ponderosa pine	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)
Douglas-fir	Salmon	46	(0)	1.1(20)	0.5 (12)	0.45 (14)
Douglas-fir	Blodgett	1	(0)	(0)	1.0 (1)	(0)
Lodgepole pine	Tenderfoot	67	0.6 (7)	0.55 (21)	0.55 (11)	0.3 (28)
Lodgepole pine	Salmon	15	(0)	1.25 (8)	0.75 (5)	0.1 (2)

Table 4. Species-specific equations for modeling the vertical distribution of crown fuel. N is the number of trees, n the number of vertical segments used to develop the equations. y is cumulative proportion of crown biomass, x is fractional crown length.

Species	Study Site	Sample size	Fuel Component	Equation	R^2
Douglas-fir:	Blodgett	N=1,n=8	Foliage	$\hat{y}=3.2606x^2-2.2606x^3$	.994
			Total	$\hat{y}=3.5170x^2-2.5170x^3$	.989
			Available	$\hat{y}=3.3724x^2-2.3724x^3$	.994
	Ninemile	N=22,n=255	Foliage	$\hat{y}=2.7821x^2-1.7821x^3$	.963
			Total	$\hat{y}=.0687x+2.9938x^2-2.0625x^3$	.962
			Available	$\hat{y}=2.9398x^2-1.9398x^3$	.963
	Salmon	N=22,n=255	Foliage	$\hat{y}=1.7767x^2-7767x^3$	.913
			Total	$\hat{y}=2.6094x^2-1.6094x^3$	.933
			Available	$\hat{y}=1.9489x^2-.9489x^3$	.927
Ponderosa pine	Blodgett	N=2,n=49	Foliage	$\hat{y}=3.0112x^2-2.0112x^3$	.997
			Total	$\hat{y}=-3.3710x^2-2.3710x^3$	.997
			Available	$\hat{y}=3.0609x^2-2.0609x^3$	.996
	Flagstaff	N=47,n=308	Foliage	$\hat{y}=.102x+2.837x^2-1.939x^3$	.915
			Total	$\hat{y}=.2912x+2.6671x^2-1.9584x^3$	.917
			Available	$\hat{y}=.1251x+2.8072x^2-1.9322x^3$	.907
	Ninemile	N=15,n=185	Foliage	$\hat{y}=2.3330x^2-1.3330x^3$	.869
			Total	$\hat{y}=2.6720x^2-1.6720x^3$	.854
			Available	$\hat{y}=2.3637x^2-1.3637x^3$	.873
Lodgepole pine	Salmon	N=11,n=111	Foliage	$\hat{y}=2.0369x^2-1.0369x^3$	.949
			Total	$\hat{y}=2.4727x^2-1.4727x^3$	.946
			Available	$\hat{y}=2.2132x^2-1.2132x^3$	.950
	Tender-foot	N=44, n=486	Foliage	$\hat{y}=1.3375x^2-.3375x^3$	.918
			Total	$\hat{y}=1.7209x^2-.7209x^3$	.920
			Available	$\hat{y}=1.4657x^2-.4657x^3$	.924
White fir:	Blodgett	N=12,n=216	Foliage	$\hat{y}=.8975x^2-.1025x^3$	.910
			Total	$\hat{y}=2.2345x^2-1.2345x^3$	.921
			Available	$\hat{y}=.9428x^2+.0572x^3$	.914
Incense Cedar:	Blodgett	N=9,n=104	Foliage	$\hat{y}=2.5251x^2-1.5251x^3$	.963
			Total	$\hat{y}=2.6202x^2-1.6202x^3$	.949
			Available	$\hat{y}=2.5395x^2-1.5395x^3$	.964

Table 5. Correlations between observed and predicted canopy fuel load and canopy bulk density.

Canopy Fuel Load, kg/m2			
Method	correlation	Bias = Mean(O-P)	Precision = $\sqrt{\frac{\sum(O-P)^2}{n}}$
Allometric equations[1]	0.297	-0.1716	0.7015
Cruz regressions[2]	0.385	0.0286	0.5586
Adjusted allometric eq [3,4]	0.985	0.0726	0.1123
Canopy Bulk Density, kg/m3			
Load over depth			
Mean[5]	0.700	-0.0362	0.0829
Biomass percentile[5]	0.987	0.0019	0.0099
Height percentile[5]	0.966	0.0172	0.0247
Keane lookup tables[6]	0.549	-0.0704	0.0885
Allometric equations[1]	0.546	-0.0152	0.0888
Cruz regressions[2]	0.616	-0.0618	0.1366
Adjusted allometric eq[3,4]	0.996	0.0102	0.0123

n=23
1 Allometric equations are from Brown, J.K. 1978 as implemented in Carlton, D 2004.
2 Cruz, M. G. and others, 2003
3 Allometric equations are from Brown, J.K. 1978 adjusted as described in methods above.
4 Adjustments were developed from this data set, therefore correlations are expected to be high.
5 These values reflect observed fuel loads divided by different measures of canopy depth.
6 Keane and others, 1998, 1999

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

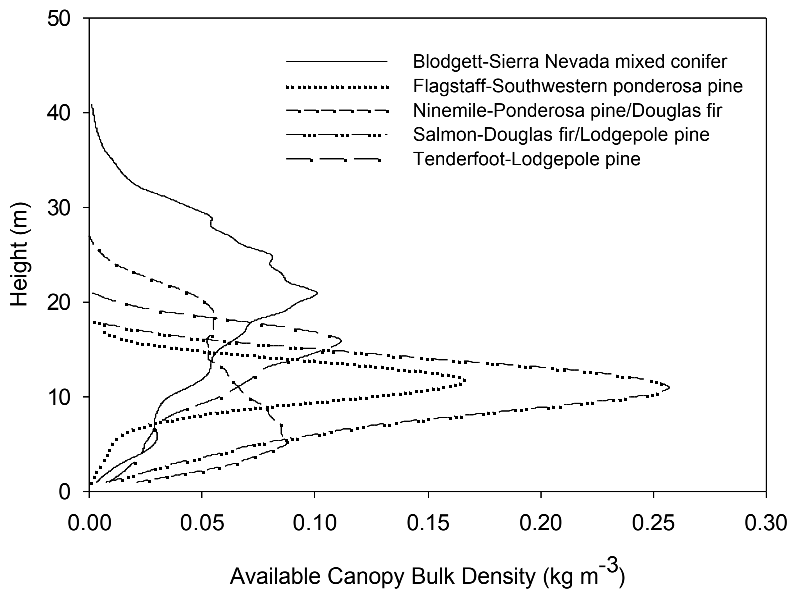


Figure 2. Canopy fuel profiles before and after treatment on the five study sites.

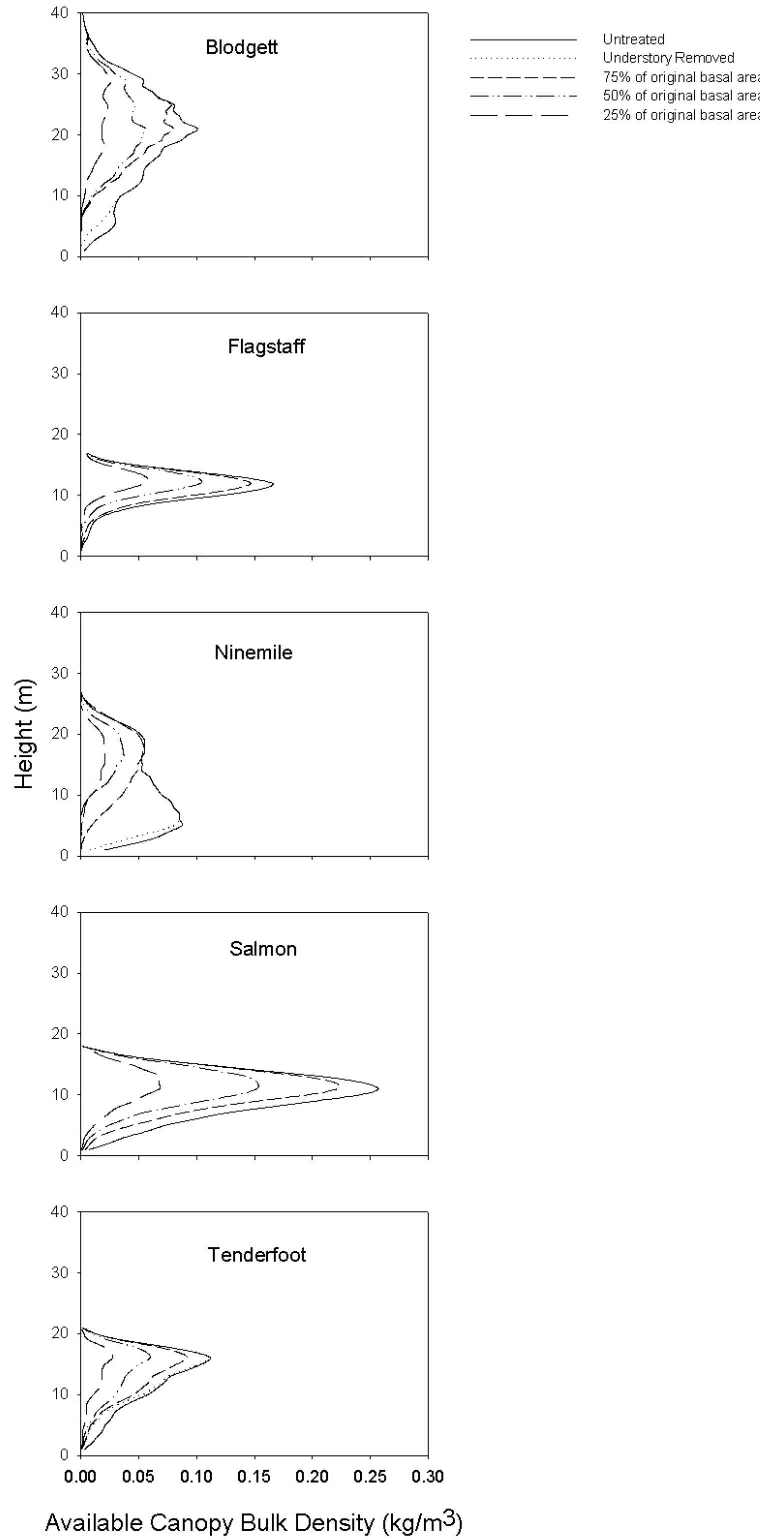


Figure 3. Canopy fuel load (kg/m2) by study site by treatment. Loads include foliage, 0-3mm live branchwood, and 0-6 mm dead branchwood. Quartiles refer to the residual percent basal area after treatment.

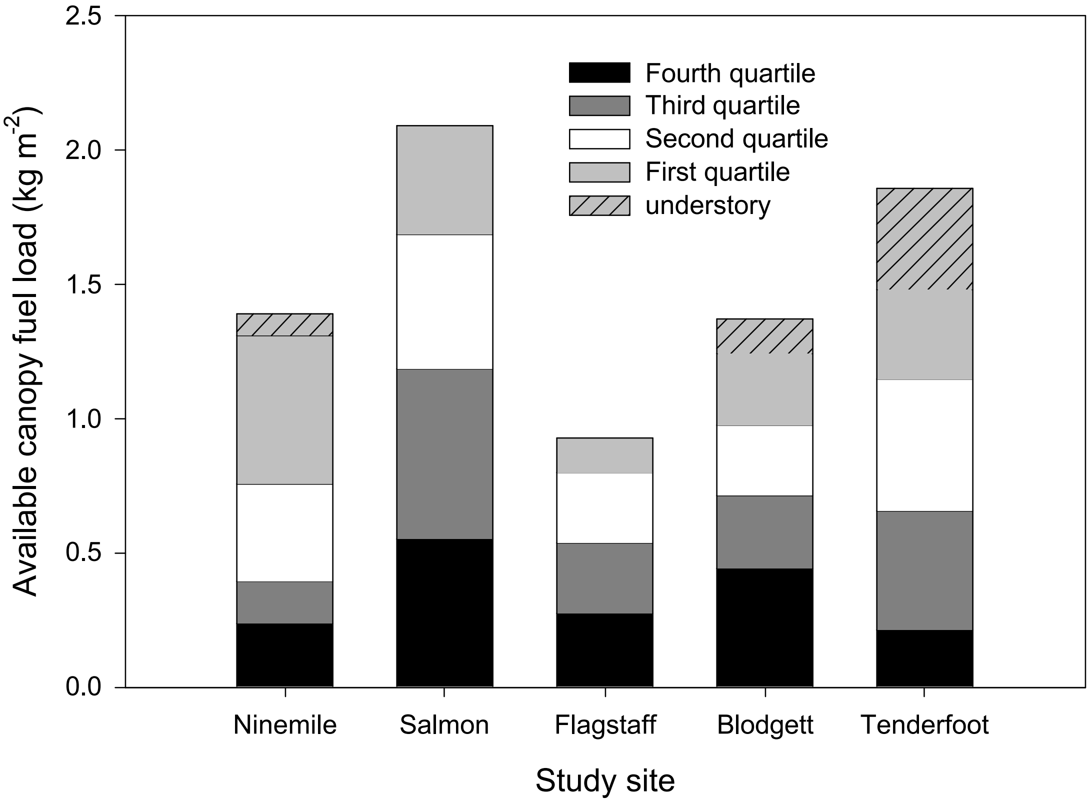


Figure 4. Cumulative proportion of crown biomass by fractional crown length by species.

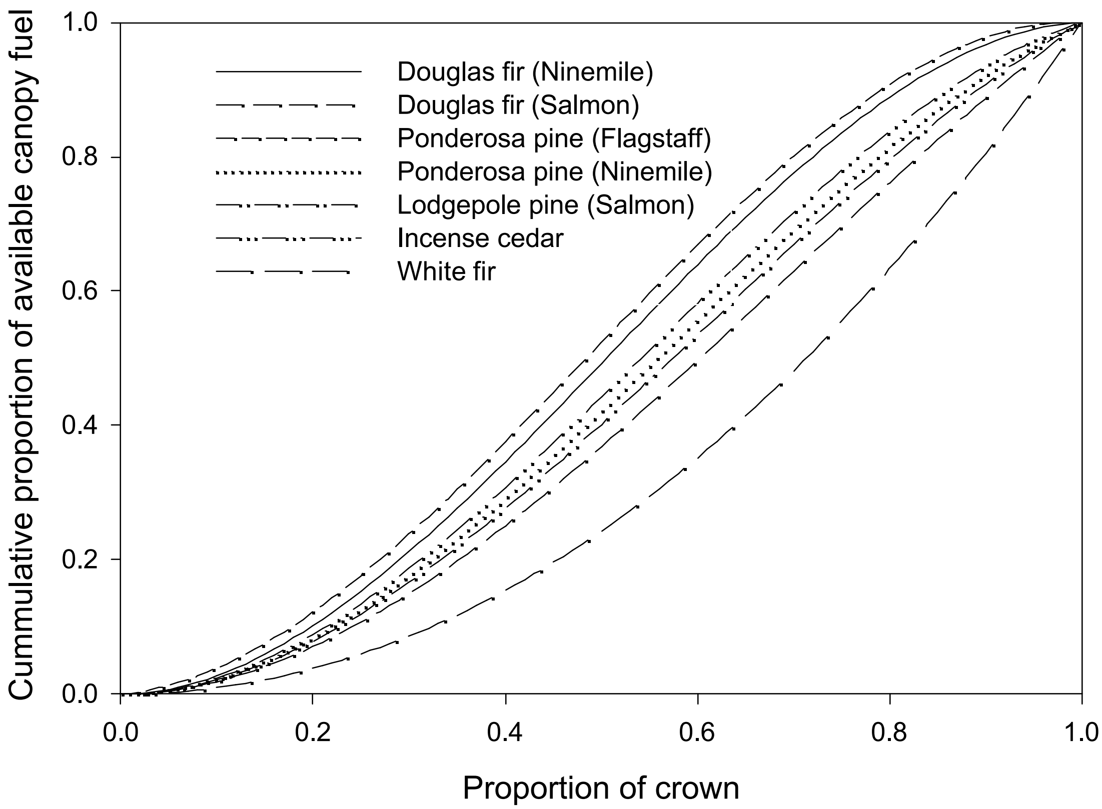
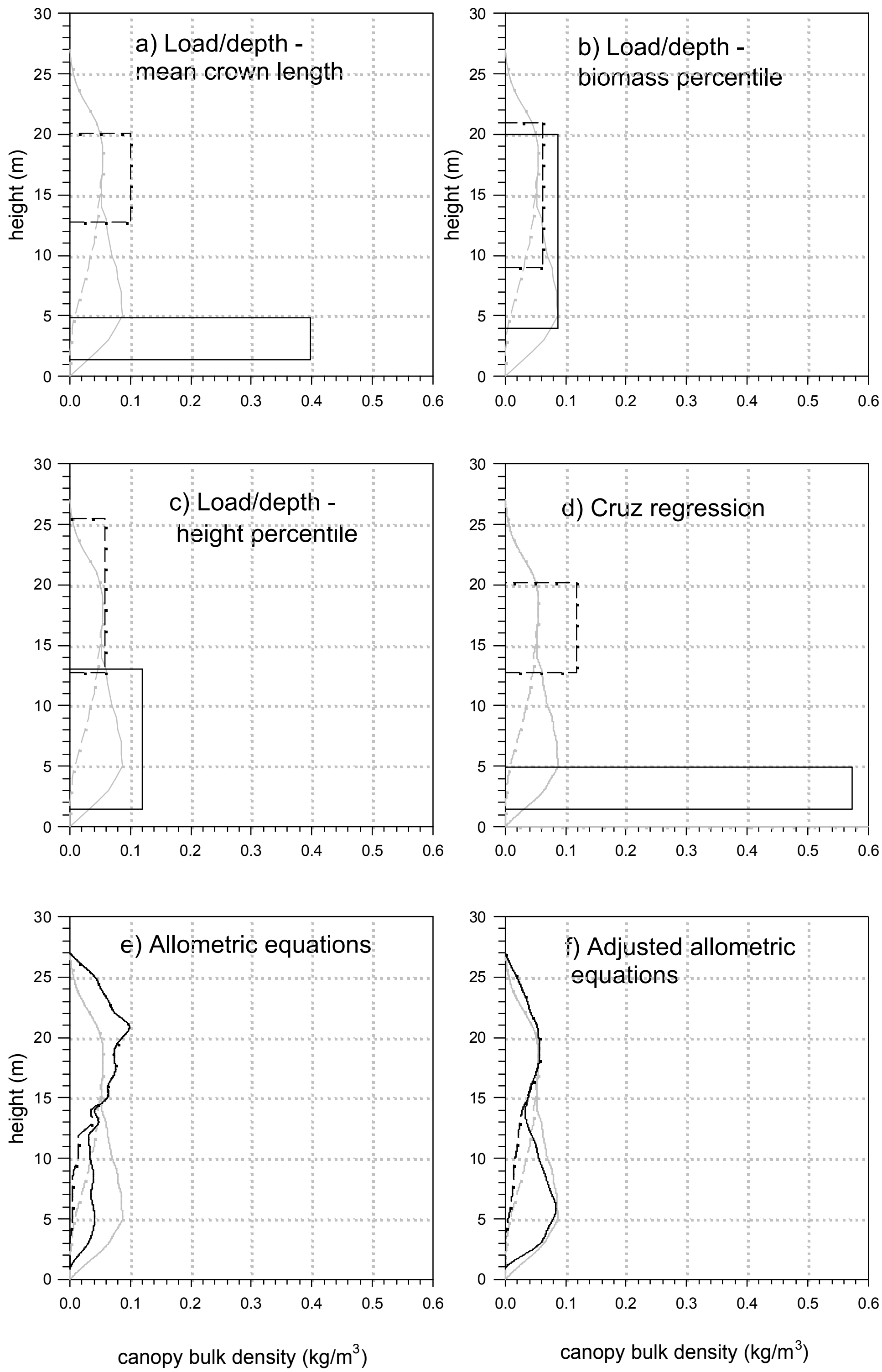


Figure 5. Observed canopy fuel profile at the Ninemile study site compared to simulated canopy profiles as modeled implicitly by four methods and explicitly by two methods. The grey solid lines show the observed canopy fuel profile at Ninemile before treatment (solid lines) and after 25% of the stand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


a) Load/depth - mean crown length
b) Load/depth - biomass percentile
c) Load/depth - height percentile
d) Cruz regression
e) Allometric equations
f) Adjusted allometric equations
height (m)
canopy bulk density (kg/m3)
0
5
10
15
20
25
30
0.0
0.1
0.2
0.3
0.4
0.5
0.6