Project Title: Improved canopy fuel estimation procedures for conifer forests in the interior West

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Abstract

This study investigated the transportability of crown biomass allometries, the vertical distribution of fuel in crowns and the influence of these factors on canopy fire hazard evaluation using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). We conducted our analyses using data derived from almost 600 trees of seven species sampled at over 100 locations across the interior western US. Data were obtained via an extensive field sampling campaign as well as by re-analyzing a number of legacy datasets. Our results show use of non-local crown biomass allometries can cause systematic over or underestimation of foliage and branch biomass even when there is no statistical difference between the parameters of local and non-local allometries. Divergence in predictions from local and non-local allometries exceeded 100% of actual crown biomass in some cases. These results suggest local allometric models should be used where they are available. Where local models are unavailable, models developed using the widest possible range of trees should be used, because this will reduce the influence of local allometric relationships on predictions.

Crown fuel biomass was skewed upward and concentrated near the tops of crowns and canopies almost without exception, regardless of species or stand density. This is consistent with redistribution of foliage and supporting structure into favorable light environments in response to light competition in crowns and canopies. The effect was more pronounced in closed-canopy forests than in open-canopy woodlands. However, there were otherwise no systematic trends in the response of within-crown biomass distribution to stand density with respect to shade tolerance. This suggests the vertical distribution of canopy fuels can be adequately represented using 'generic' within-crown fuel distributions so long as species-specific differences in the response of crown ratio to stand density are accounted-for.

Predictions of canopy bulk density (CBD) and canopy base height (CBH) from FFE-FVS were more sensitive to fuel distribution assumptions than to choice of allometric crown biomass estimator. Relaxing the assumption of uniform vertical distribution of crown fuel increased estimates of CBD by ~20-100% and estimates of CBH by ~100-400%. In comparison, use of alternative allometries precipitated changes in CBD and CBH that were invariably < 50%. Increases in estimated CBD from FFE-FVS when non-uniform fuel distributions are used reflect better representation of the connectivity of canopy fuel than is possible using uniform fuel distributions. However, the dramatic increases we observed in CBH estimates are partially a result of the CBH estimation methodology used in FFE-FVS. Incorporating non-uniform fuel distributions in FFE-FVS will improve its utility for canopy fire hazard evaluation, but may necessitate changes to the current CBH estimation methodology.

Background and Purpose

Long-term maintenance of fuels reduction treatments is a primary goal for forest management in western conifer forests. Fire resistant structures created by stand- and landscape-level fuels treatments are not static; canopy density increases with time as trees grow and regeneration is recruited into the over-story. With this increased canopy density, active crown fire behavior again becomes likely. Accurate predictions of how canopy density changes with initial treatment and how canopy density increases with time are crucial in determining how, when, and how often fuels treatments are performed. In this work, we developed improved methods for estimating the amount and vertical distribution of canopy fuels from forest inventory data and initiated the process of integrating these estimators of canopy fuels into a widely used forest growth and fire behavior modeling framework (the Fire and Fuels Extension to the Forest Vegetation Simulator [FFE-FVS]).

The most common fuels treatment to reduce crown fire behavior in western conifer forests is thinning to reduce stand density. Thinning to low stand density is thought to reduce the amount of canopy fuel to a level that is insufficient to support crown fire. However, low-density stands usually have high basal area growth rates and rapidly increasing canopy density. Also, regeneration can be prolific in low-density stands; this creates ladder fuels and eventually increases canopy density when regeneration becomes part of the main canopy. Initial treatment effectiveness and longevity of treatment effects are evaluated using estimates of surface fuels and canopy structure in surface and canopy fire behavior models. Two types of crown fire behavior are predicted based on stand structure and weather conditions – passive or active crown fire (Scott and Reinhardt 2001). Passive crown fire occurs when there is sufficient connectivity between surface and canopy fuels to spread surface fire vertically into the main canopy at a given wind speed. The height in a canopy where there are sufficient fuels to spread flames vertically is called the canopy base height (CBH). Active crown fire occurs when there is sufficient horizontal continuity of fine fuels (e.g. foliage and small branches) at any height in the canopy to carry fire from tree to tree at a given wind speed. (A third type of crown fire behavior, conditional crown fire, is predicted when active crown fire is predicted yet fuel and weather conditions are insufficient to support passive crown fire [Rebain et al. 2010].) The density (kg m^{-3}) of needles and small branches used to determine continuity of canopy fuels is called canopy bulk density (CBD).

Estimates of the amount and vertical distribution of canopy fuel are critical to accurate estimates of the threshold wind speed where passive or active crown fire will occur. The Fire and Fuels Extension to FVS is the primary tool used by federal land managers to predict CBD. Although FFE-FVS provides a working prediction of CBD through time, the underlying assumptions and equations used to calculate and predict CBD may not accurately represent CBD or CBH. The Fire and Fuels Extension to FVS estimates crown mass from allometries based on tree inventory variables such as diameter at breast height (DBH) and height. The allometries used by FFE-FVS to predict crown mass were developed by Brown (1978) using data obtained from trees in northern Montana and Idaho. These models, therefore, may not represent the full range of variation in allometric relationships across the interior western US. Furthermore, FFE-FVS assumes fuel (foliage and half of 1-hr fuel [Bradshaw et al. 1983]) is distributed uniformly within individual crowns, which is unrealistic (Reinhardt et al. 2006; Keyser and Smith 2010).

A measure of 'effective' CBD is generated in FFE-FVS by summing the crown mass of individual trees by height intervals across the canopy to identify the point of likely crown fire spread (Scott and Reinhardt 2001). But, crown mass is not evenly distributed within individual tree crowns – rather it is distributed as a skewed normal distribution, with less mass at the top and bottom of a tree crown and most of the mass concentrated near the center of the crown. Inaccurate crown mass estimation and unrealistic vertical crown profiles may result in the underestimation of CBH and CBD in FFE-FVS and therefore produce inaccurate estimates of potential fire behavior. Keyser and Smith (2010) found using a local crown fuel biomass allometry in combination with a non-uniform vertical fuel distribution assumptions resulted in a 78% increase in estimated CBD on average over estimates from the July, 2013 production version of FFE-FVS for Black Hills ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.). Forty-seven percent of the increase came from using the local biomass allometry, while the remainder was attributable to relaxing the assumption of uniformity for vertical crown fuel distribution. This suggests predictions of likely crown fire behavior from FFE-FVS are in error, resulting in incorrect evaluations of CBD response to fuel treatments. In Keyser and Smith (2010), only two of 16 stands evaluated had CBD estimates > 0.10 kg m^{-3} (the CBD threshold for active crown fire [Keyes and O'Hara 2002]) from the July, 2013 production version of FFE-FVS. The number increased to 12 when the local allometry and non-uniform fuel distribution were used.

The above results are consistent with results from Reinhardt et al. (2006), who found that procedures for estimating CBD based on a uniform vertical distribution of canopy fuel (e.g., dividing total fuel load by canopy length) were not accurate when compared to CBD empirically determined by felled tree measurements in five dense stands across the West. This suggests that where FFE-FVS is used to design and evaluate fuels treatments, it is probable that either the amount of density reduction necessary to achieve a desired effect will be underestimated, or the longevity of effectiveness of a given treatment will be overestimated. This study thus addressed an urgent need to ascertain the degree to which allometric crown fuel mass estimators are transportable across geographic areas in the interior western US, and to characterize the vertical distribution of crown fuels for western US conifers.

Study Description and Location

In this study, we developed improved procedures for characterizing coniferous forest canopy fuels to ensure accurate predictions of potential fire behavior in response to fuel reduction treatments. By comparing crown fuel biomass allometries from different geographic areas in the interior western US, we determined whether there was a need for local crown mass equations for individual species. We also developed non-uniform vertical distributions of canopy fuels for incorporation into FFE-FVS, which vastly improved the accuracy of CBD predictions. These modifications to CBD prediction methodology will greatly improve land managers' ability to evaluate initial fuels treatment effectiveness and to plan for maintenance of fuels treatment projects into the future. This study extends the work of Keyser and Smith (2010) on Black Hills ponderosa pine to include geographic areas covering the interior western US for a set of species that includes those most important for fuels reduction treatments. We consulted with fire and fuels managers and with silviculturists to develop a list of species of highest concern for canopy fuel treatments. From this feedback, we identified ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), lodgepole pine (*P. contorta* Douglas ex Loudon), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), pinyon (*P. edulis* Engelm.) and juniper (*Juniperus scopulorum* Sarg.) as the species of major concern.

Our investigation was structured around three objectives:

Objective 1: Perform a comprehensive evaluation of existing conifer crown biomass equations that could be used in fire behavior modeling systems and develop new locally derived estimators where existing equations prove inadequate.

Our species of interest fell into two broad forest types: pinyon and juniper are short-statured trees usually found on xeric sites that typically form open canopy 'woodlands', while subalpine fir, lodgepole pine, Engelmann spruce, ponderosa pine and Douglas-fir are taller trees found on comparatively wetter sites that form closed-canopy 'forest' stands. Forest tree species represented a shade tolerance gradient. Lodgepole and ponderosa pine are considered intolerant, Douglas-fir is considered intermediate, and subalpine fir and Engelmann spruce are considered tolerant of shaded growing environments (Burns and Honkala 1990). As part of this study, we assembled an annotated bibliography of available crown biomass estimators for western US conifers (Ex, Keyser, and Smith In Review).

This work involved an extensive field sampling effort in 2011-12. Our sampling methodology closely followed Keyser and Smith (2010). We also re-analyzed previously published data from Brown (1978), Long and Smith (1988), Long and Smith (1989) and Keyser and Smith (2010). In total, our analyses of the transportability of crown fuel biomass allometries and the vertical distribution of crown fuel incorporated destructively sampled data from 566 trees in 111 places in the interior western US (Table 1, Fig. 1). In order to assess the transportability of crown biomass allometries, we assembled duplicate datasets for ponderosa pine and Douglas-fir from each of two geographic areas (Table 2). For both species, we sampled trees from a north population (northern Idaho, Montana and Wyoming), and a corresponding south population (southern Idaho, Utah, Colorado and New Mexico).

We assessed the transportability of crown biomass models by testing for statistical differences between the parameters of allometric crown biomass estimators for north and south populations of ponderosa pine and Douglas-fir (Table 2). We postulated that if allometric relationships were invariant, estimated parameters of allometric biomass models should not vary significantly between geographic areas when model form and predictor variables were held constant. Statistically significant differences in parameters indicated differences in allometric relationships between geographic areas. We also evaluated the potential for increased bias and error from transporting crown biomass allometries between geographic areas by comparing fit statistics of nonlinear models developed using data from trees from local, nonlocal and global populations. We hypothesized that if allometric relationships between tree parts did not vary between geographic areas use of nonlocal allometries should have negligible effects on estimator performance assuming the trees used to develop local and nonlocal estimators spanned similar ranges of size and stand density. These analyses are described in a draft document that will be submitted for publication as part of FFE-FVS documentation once implementation of improved CBD estimation procedures in FFE-FVS is finalized (Ex et al. (a) In Prep.).

Table 1. Summary sample data. Natural Resources Conservation Service plant codes (the first two letters of the genus plus the first two letters of the species) are used to designate species. N is # sample locations followed by # sample trees in parentheses. All other columns are means followed by minimum and maximum values in parentheses. BA is basal area and QMD is quadratic mean diameter. Diameter-based variables were obtained using dbh except where noted.

Spp.	N	BA (m^2 ha^{-1})	QMD (cm)	Dia. (cm)
ABLA[*,**]	17 (75)	48.4 (23.3, 93.8)	15.6 (8.6, 25.4)	14.5 (0.0, 40.6)
JUSC[***]	3 (15)	27.0 (16.6, 43.8)	19.6 (15.5, 23.3)	20.4 (6.3, 41.8)
PICO[*]	21 (110)	34.7 (9.1, 56.9)	9.8 (3.4, 29.3)	8.9 (0.0, 27.6)
PIED[***]	3 (15)	27.0 (16.6, 43.8)	19.6 (15.5, 23.3)	19.1 (6.2, 33.5)
PIEN[*]	14 (49)	56.2 (25.1, 101.5)	16.9 (10.0, 23.5)	16.8 (0.0, 48.8)
PIPO[*]	36 (194)	28.0 (5.8, 61.3)	25.3 (8.1, 43.7)	24.9 (0.0), 86.4)
PSME[*]	20 (108)	38.7 (11.5, 62.0)	21.3 (13.5, 34.0)	19.7 (0.0, 86.1)

[*] Brown (1978) did not include stand-level data. Stand-level summary statistics were therefore derived from four fewer lodgepole pine locations as well as eight fewer locations each for subalpine fir, Engelmann spruce, ponderosa pine, and Douglas fir.
[**] Stand-level data from two small (< 0.01 ha) inventory plots sampled by Long and Smith (1989) indicated stand density index (SDI) > 150% of maximum SDI for the species. We presumed this reflected sampling bias and excluded these data when summarizing BA as well as from subsequent analyses that incorporated these variables.
[***] Rocky Mountain juniper and twoneedle pinyon were sampled together in three stands where they co-occurred. All diameter-based variables for these species were calculated using diameter at root crown.

Objective 2: Develop statistical descriptions of non-uniform, vertical distribution of crown fuel mass to improve fire behavior prediction for coniferous species important in fuel treatments across the interior west.

We met Objective 2 by parameterizing two-parameter cumulative Weibull distributions for foliage and 1-hr fuel as described by Keyser and Smith (2010). The form of the model was:

Model 1: $y = 1 - e^{[-\left(\frac{x}{\beta}\right)^{\alpha}]}$

where y is the cumulative proportion of biomass at x, and x is depth into the crown expressed as a proportion of total crown length. The estimated shape parameter α represents the degree to which biomass is skewed upward or downward in crowns, while the estimated scale parameter β represents the degree to which biomass is concentrated in a few sections versus spread evenly throughout crowns. We developed non-uniform fuel distributions for individual trees, stands, species, and forest types (woodlands versus forests). This work is described in Ex, Smith and Keyser (In Prep.).

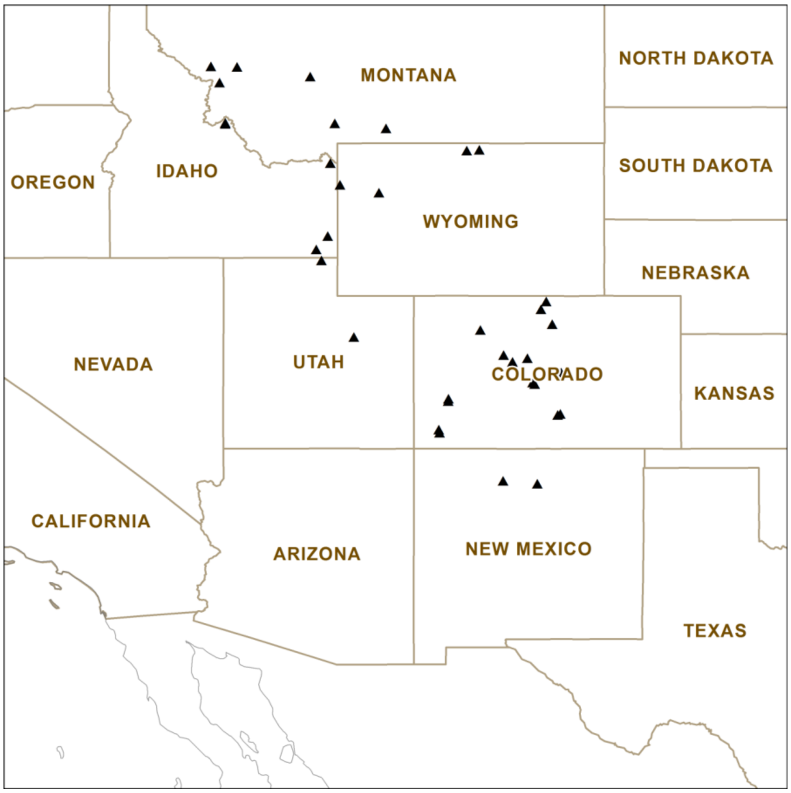

Figure 1. Map of locations where destructive sampling occurred in 2011-12.

Table 2. Summary sample data for north and south populations of Douglas-fir and ponderosa pine. Columns are as described for Table 1.

Spp.	Pop.	N	BA (m^2 ha^{-1})	QMD (cm)	Dia. (cm)
PIPO	North	6 (29)	33.1 (14.1, 61.3)	26.9 (8.1, 43.7)	26.7 (4.6, 55.4)
	South	6 (30)	26.9 (13.0, 39.6)	27.6 (14.5, 43.2)	30.4 (8.1, 54.4)
PSME	North	6 (30)	43.4 (16.9, 62.0)	21.2 (14.7, 33.6)	22.1 (6.1, 56.1)
	South	6 (30)	34.0 (11.5, 54.4)	21.3 (13.5, 34.0)	22.9 (4.3, 54.6)

Objective 3: Incorporate these crown fuel biomass distribution models into FFE-FVS and make the algorithms available to developers of other fuel and fire applications.

We developed executable versions of FFE-FVS that incorporated new biomass models and non-uniform fuel distributions. We then compared predictions of CBD and CBH from the executables with predictions from the production version of FFE-FVS to ascertain the impact of using nonlocal crown fuel biomass allometries and non-uniform fuel distributions on CBD and CBH estimation. This work is described in Ex et al. (b) (In Prep.).

Key Findings

Transportability of crown fuel biomass allometries: Local crown biomass allometries generally performed better than non-local models (Ex et al. (a) In Prep.). There were statistical differences between some, but not all, parameters of crown biomass allometries from north and south populations of ponderosa pine and Douglas-fir. However, even in cases where there were no statistical differences in model parameters between populations, using non-local allometries to estimate crown biomass usually resulted in biased estimates (Fig. 2). The degree of bias associated with non-local allometries reflects the degree of similarity between trees from local and non-local populations. The performance of global allometries, which were developed using data from both local and non-local populations of trees, was intermediate between that of local and non-local allometries.

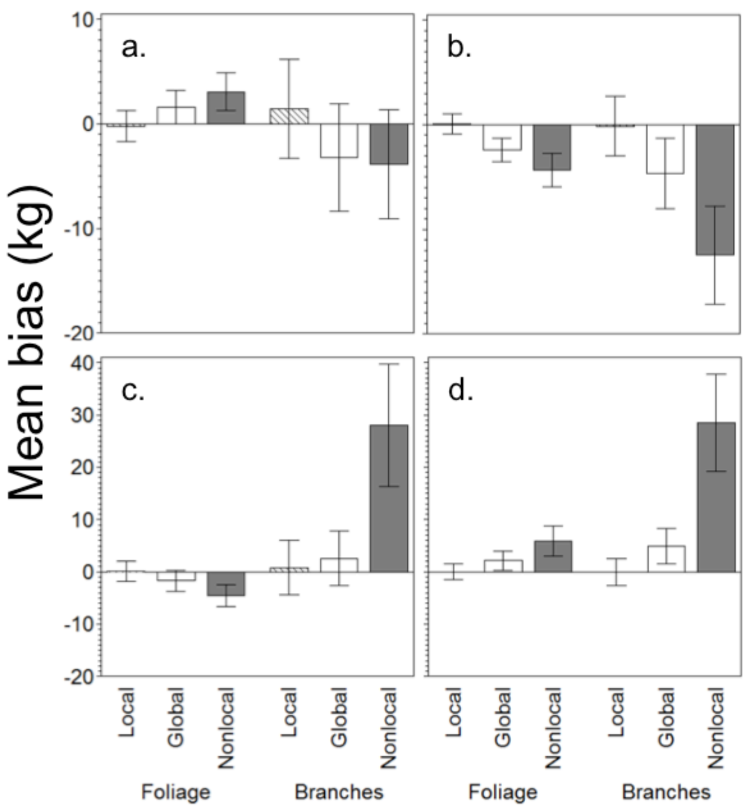

Figure 2. Prediction bias from local, nonlocal and global crown biomass allometries for sample trees from north (a: ponderosa pine, b: Douglas-fir) and south (c: ponderosa pine, d: Douglas-fir) populations. Error bars are +/- 1 standard error.

Variation in vertical crown fuel distribution: We found foliage and 1-hr fuel was nearly always skewed upward and concentrated above crown midpoints, regardless of forest type, species or stand density (Fig. 3 [Ex, Smith and Keyser In Prep.]). Crown fuel distribution was partly associated with stand-level factors (e.g. stand density), and partly associated with tree-level factors (e.g. canopy position of a given tree). On average, the characteristics of foliage and 1-hr fuel distributions varied within a given stand over about half the range of variation for species. This means attempts to characterize crown fuel distributions using inventory data are likely to meet with limited success, as distribution parameters are substantially influenced by variation in within-stand conditions that is not captured in inventory data. There were no consistent differences between species in crown fuel distribution parameters. However, fuel was generally shifted upward and more concentrated in the crowns of forest-grown species than in the crowns of woodland species (Fig. 3), which is consistent with foliage redistribution into favorable light environments in the more crowded, closed-canopy forest stands.

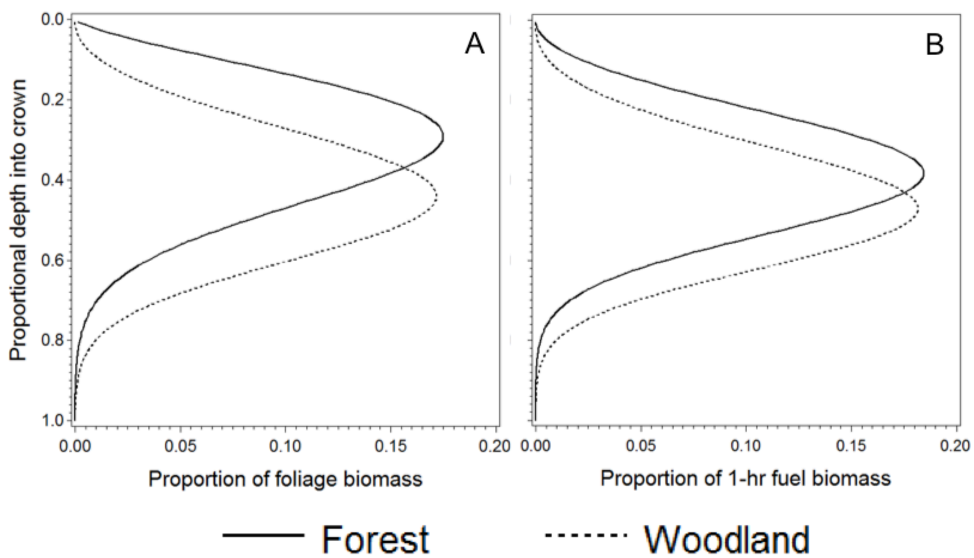

Figure 3. Typical distributions of foliage (A) and 1-hr fuel biomass (B) for forest and woodland conifer species.

Effect of species shade tolerance on crown fuel distribution response to stand density: We expected to find predictable trends with respect to shade tolerance in the relationship between crown fuel distributions and stand density. This supposition was based on the apparent mechanistic basis of crown fuel distribution characteristics in foliage redistribution as a response to light competition (Ex and Smith (a) In Prep.). Instead, we found the response of Weibull distribution parameters to stand density was the same for tolerant and intolerant tree species (Fig. 4 [Ex, Smith and Keyser In Prep.]). The implication is that the influence of shade tolerance on canopy biomass distribution is primarily expressed through species differences in the response of crown ratio to stand density, not in the response of within-crown biomass distribution.

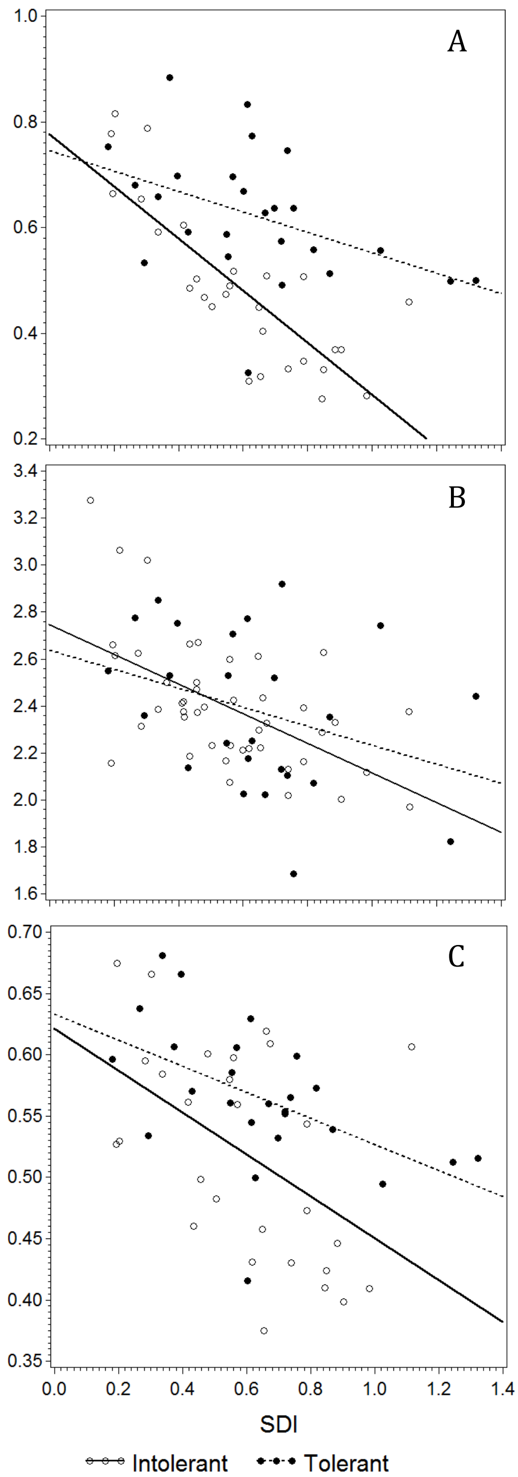

Figure 4. Relationships between crown ratio (A), α (B) and β (C) and SDI for tolerant (lodgepole pine and ponderosa pine) and intolerant (Douglas-fir, Engelmann spruce and subalpine fir) conifers. There are no statistical differences between regression lines for tolerant and intolerant species in B and C.

Impact of crown fuel allometries and fuel distribution assumptions on CBD and CBH estimation: Relaxing the uniformity assumption for crown fuel distributions led to large increases in estimated CBD and CBH for all species (Ex et al. (b) In Prep.). Average CBD increases ranged from 17% for Rocky Mountain juniper and twoneedle pinyon to 112% for subalpine fir, while average CBH increases ranged from 1.3 m (4.3 ft) for Engelmann spruce to 4.4 m (14.4 ft) for ponderosa pine. Using updated crown biomass allometries led to smaller and more variable changes in estimates of CBD and CBH than using non-uniform fuel distributions (Ex et al. (a) In Prep.). Changes in CBD ranged from -26% for Engelmann spruce to 22% for ponderosa pine, while changes in CBH ranged from -0.3 m (-1.0 ft) for ponderosa pine to 0.1 m (0.3 ft) for lodgepole pine. The combined effect of using non-uniform crown fuel distributions and updated biomass allometries was always an increase in estimated CBD and CBH because the magnitude of change from using non-uniform distributions was without exception larger than that from using updated biomass allometries. Estimates of CBD and CBH were not sensitive to distribution parameter values.

Management Implications

There is potential for large errors in estimation of crown fuel biomass from non-local allometries. This work showed that even statistically insignificant differences in the parameters of crown biomass allometries from different geographic areas can result in average differences on the order of tens of kg in predicted crown fuel biomass (Fig. 2). This translated to differences at times in excess of 100% of observed biomass for the smallest trees in our dataset, and in some cases in excess of 50% for the largest trees (Ex et al. (a) In Prep.). Allometric crown fuel estimators perform best for trees and stands that are similar to those used for model development. Systematic differences in crown characteristics (e.g. the proportion of foliage biomass relative to branch biomass) between trees from different geographic areas results in biased estimates of crown fuel biomass when allometries are used for trees that are dissimilar to those used for model development. Our results suggest local biomass allometries should be used whenever possible, as local estimators, presumably developed using data from trees similar to those for biomass will be estimated, are least prone to systematic error. When local biomass allometries are unavailable, allometries developed using as broad a sample of trees as possible are preferable to those developed from a non-local sample of trees. Using allometries developed from broad samples of trees helps minimize the effect of systematic differences between trees from different geographic areas on crown biomass estimates.

Using 'generic' upward-skewed non-uniform distributions for forest and woodland tree species substantially improves CBD prediction capability. Our finding that distribution parameters are variable within stands and not predictably related to species shade tolerance suggests there will be rapidly diminishing returns from attempts to develop distributions specific to particular species and stands that are based solely on available inventory data. However, it is notable that fuel distributions were almost without exception skewed upward in our dataset. This implies using 'generic' upward-skewed distributions for forests and woodlands is unlikely to substantially misrepresent canopy fuel distribution. Most of the effects of stand density and species shade tolerance on canopy fuel distributions was captured in the response of crown ratio to these factors (Ex, Smith, and Keyser In Prep.).

Implementing our results in FFE-FVS will likely require modification of the methodology used to estimate CBH. We observed increases in estimated CBH in excess of 1.3 m (4.3 ft) when non-uniform fuel distributions were used (Ex et al. (b) In Prep.). These results are specific to the methodology used to estimate CBH in FFE-FVS and would not affect CBH estimation if an alternative methodology were used (such as designating CBH simply as mean crown base height). Because CBH is estimated in FFE-FVS as the height at which CBD surpasses a threshold, estimated CBH strongly depends on the threshold. Using more realistic upward-skewed distributions in-effect shifts crown fuel biomass from lower to upper canopies, which increases the height at which the CBH threshold is met. Incorporating non-uniform crown fuel distributions in CBD estimation thus will likely require adjusting the CBH threshold to accommodate non-uniform fuel distributions in order to obtain realistic predictions of torching behavior from FFE-FVS.

Relationship to Other Recent Findings and Ongoing Work

This study highlighted the need for development of local crown biomass allometries as well as further research into factors that enhance transportability of allometries and mechanisms that dictate biomass distribution in crowns and canopies. Affleck, Keyes, and Goodburn (2012) note the potential applicability of existing crown biomass allometries developed for ecological or forest products investigations to fire hazard analysis. The current study will continue to increase the availability of local crown fuel biomass estimators by making available a comprehensive list of existing allometries developed mostly for non-fire purposes (Ex, Keyser, and Smith In Review) in combination with the proportions of different time lag classes of fuel for different species and size classes of trees (to be included in the final version of Ex et al. (a) In Prep.).

We used the current study as a jumping off point for an investigation into the stability of allometric models based on tree hydraulics across geographic areas (Ex and Smith (b) In Prep.). This work showed the transportability of allometric models based on the hydraulic architecture of trees is highly species-specific, and may be related to contrasting biomass allocation strategies for early vs. late seral species or species with differing tolerance to drought and shade. Continuing this line of inquiry into the effect of site-specific factors on allometric relationships will allow us to build a knowledge base with regard to allometric model characteristics that confer transportability across geographic areas.

Future Work Needed

Improved characterization of crown fuel characteristics for conifers depends on development of three parallel lines of research: investigation of factors that enhance transportability of allometries, improvement of methodologies for quantifying the amount and distribution of crown biomass, and, investigation of factors that influence the spatial distribution of biomass in crowns and canopies. Our work on transportability of hydraulically based allometries (Ex and Smith (b) In Prep.) suggests there may be better and worse strategies for development of generally applicable allometric crown biomass models depending on species' successional role and ecological strategy axes. Building a comprehensive understanding of the relationship between tree hydraulics, biomechanics, site factors, and autecology of species is essential for development of a suite of allometric models that perform well across the wide range of sites encountered in the interior western US.

Local allometries are regarded as a gold standard against which non-local models are evaluated. Improvement of the efficiency with which crown and canopy biomass can be quantified will promote development of local allometries. This will not only increase the availability of local allometries for quantification of crown and canopy fuel, but will increase the capacity to evaluate non-local allometries. Emerging technologies such as terrestrial LIDAR scanning show great potential for increasing the efficiency with which crown and canopy biomass can be quantified. Development of more efficient methodologies for quantifying crown and canopy biomass, particularly methodologies that also describe the spatial distribution of biomass, should be a priority for future research.

Increased understanding of the mechanisms that dictate the spatial distribution of fuel in crowns and canopies will increase our capability to characterize the canopy fuels complex. We contributed to this knowledge base with the current study by investigating the relationship between light availability and foliage distribution (Ex and Smith (a) In Prep.). However, other factors besides light availability are clearly influential in dictating the distribution of fuel in crowns and canopies. Assembling a comprehensive picture of how factors such as species composition, site quality and competitive environment interact to influence the canopy fuels profile is necessary to improve characterization of the canopy fuels complex.

Finally, the sensitivity of the CBH estimation methodology used by FFE-FVS to fuel distribution assumptions highlights the need for a re-evaluation of how the vertical connectivity of fuels is represented in fire behavior models. Alternative methods of specifying CBH, such as mean crown base height, may be less sensitive to fuel distribution assumptions, but are not always meaningful (such as when crown base heights are highly variable). More work is needed to develop a robust method of characterizing vertical fuel continuity in forest stands that is applicable in a wide variety of situations.

Deliverables Crosswalk Table

Proposed	Delivered	Status
Training sessions	Material will be covered in FFE-FVS training sessions once our results are incorporated in subsequent FFE-FVS releases	Pending incorporation of work into production version of FFE-FVS
Conference presentations	(1) Crown fuel profiles from inventory data for western US conifers (2) Crown fuel distribution and fire hazard for western US conifers (3) Describing crowns and canopies: light environment and shade tolerance dictate foliage distribution	(1) Association for Fire Ecology 5th International Fire Ecology and Management Congress, Dec. 2012, Portland, OR. (2) Society of American Foresters 2013 National Convention, Oct. 2013, N. Charleston, SC. (3) Society of American Foresters 2014 National Convention (upcoming), Oct. 2014, Salt Lake City, UT.
Refereed publications	(1) An empirical test of predicted trends in crown hollowing and self-pruning with respect to shade tolerance for sympatric conifer species. (2) Characterizing canopy fuels for interior western US conifer forests. (3) Effect of fuel distribution assumptions on canopy fire hazard assessment using the Fire and Fuels Extension to the Forest Vegetation Simulator.	(1) In preparation for *Trees* (2) In preparation for *The Canadian Journal of Forest Research* (3) In preparation for *The Journal of Forestry*
Non-refereeed publications	(1) An annotated bibliography of crown biomass estimators for western US conifers. (2) Revision of FFE-FVS user guide to document improved CBD and CBH estimation procedures	(1) In review for publication through the USFS Southern Research Station (2) Draft project documentation is complete, we will work with FMSC staff to update FFE-FVS documentation as new procedures are implemented in FFE-FVS

Computer software	Modification of FFE-FVS to incorporate new biomass allometries and non-uniform fuel distributions	We have worked with FMSC staff to develop stand-alone executable versions of FFE-FVS that incorporate our findings. We will continue to assist with testing and implementation into the production version of FFE-FVS

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