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***Research Note***

# Evaluating regression model estimates of canopy fuel stratum characteristics in four crown fire-prone fuel types in western North America

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**Abstract.** Two evaluations were undertaken of the regression equations developed by M. Cruz, M. Alexander and R. Wakimoto (2003, *International Journal of Wildland Fire* **12**, 39–50) for estimating canopy fuel stratum characteristics from stand structure variables for four broad coniferous forest fuel types found in western North America. The first evaluation involved a random selection of 10 stands each from the four datasets used in the original study. These were in turn subjected to two simulated thinning regimes (i.e. 25 and 50% basal area removal). The second evaluation involved a completely independent dataset for ponderosa pine consisting of 16 stands sampled by T. Keyser and F. Smith (2010, *Forest Science* **56**, 156–165). Evaluation statistics were comparable for the thinning scenarios and independent evaluations. Mean absolute percentage errors varied between 13.8 and 41.3% for canopy base height, 5.3 and 67.9% for canopy fuel load, and 20.7 and 71% for canopy bulk density. Bias errors were negligible. The results of both evaluations clearly show that the stand-level models of Cruz *et al.* (2003) used for estimating canopy base height, canopy fuel load and canopy bulk density in the assessment of crown fire potential are, considering their simplicity, quite robust.

**Additional keywords:** average stand height, basal area, canopy base height, canopy bulk density, canopy fuel load, Douglas-fir, lodgepole pine, mixed conifer, ponderosa pine, stand density.

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## Introduction

Cruz *et al.* (2003) developed regression equations for estimating canopy base height (CBH), canopy fuel load (CFL) and canopy bulk density (CBD) for use in assessing crown fire potential in four broad coniferous forest fuel types found in western North America. Three of the types involved relatively pure stands of Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*P. contorta*). A mixed-conifer type was also identified, which consisted of several forest cover types: Engelmann spruce (*Picea engelmannii*), Engelmann spruce–subalpine fir (*Abies lasiocarpa*), white fir (*A. concolor*) and grand fir (*A. grandis*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), mountain hemlock (*T. mertensiana*)–subalpine fir, and western larch (*Larix occidentalis*)–Douglas-fir. A software application of the Cruz *et al.* (2003) regression equations has recently been developed (Alexander and Cruz 2010).

In spite of the fact that the regression equations developed by Cruz *et al.* (2003) for estimating canopy fuel stratum characteristics were never formally evaluated, several investigators have used them to assess fuels and fire potential in western North American coniferous forests (e.g. Page and Jenkins 2007*a*, 2007*b*; Whitehead *et al.* 2007; Brown *et al.* 2008; Finkral and Evans 2008; Roccaforte *et al.* 2008, 2009; Dickinson *et al.* 2009; Pierce *et al.* 2009) and in the north-eastern United States (Williams *et al.* 2008). Quite surprisingly, the equations have even been applied to Douglas-fir plantations in Spain (López-Sánchez and Rodriguez-Soalleiro 2009), which is undoubtedly a stretch in application but may be useful as a first approximation.

This paper reports on two distinct evaluations of the Cruz *et al.* (2003) regression equations. The first evaluation addresses comments made by Reinhardt *et al.* (2006) regarding the general validity of the Cruz *et al.* (2003) regression equations. They questioned whether empirical relationships such as those of Cruz *et al.* (2003) exhibit logical behaviour, especially in relation to thinning (Cruz *et al.* 2010). The second evaluation takes advantage of a recently completed canopy fuel study undertaken of ponderosa pine by Keyser and Smith (2010) in the Black Hills of South Dakota. This study provided an independent dataset for the ponderosa pine fuel type reported by Cruz *et al.* (2003).

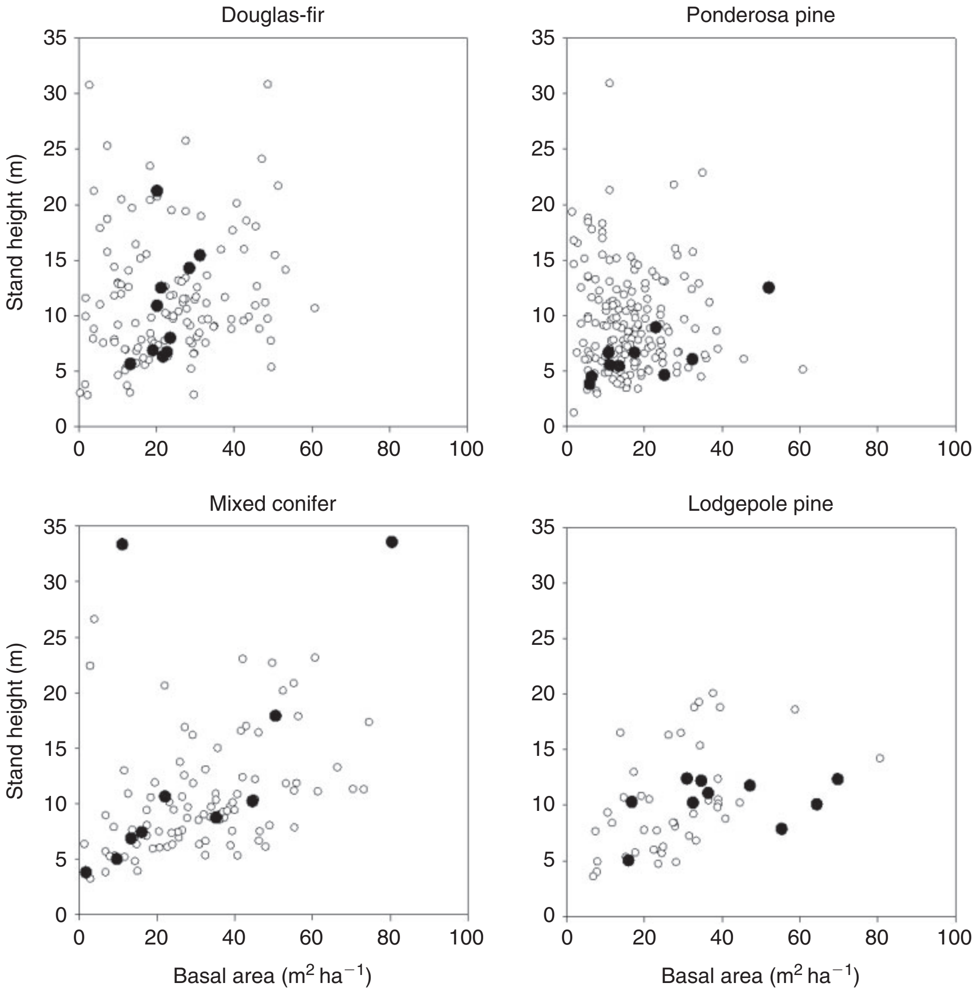

**Fig. 1.** Scatterplots of the FIA (Forest Inventory and Analysis) data associated with the development of the Cruz *et al.* (2003) regression equations for predicting canopy base height. The 10 randomly selected FIA stands in each fuel type that were used for evaluation purposes are separately identified (i.e. the slightly larger, solid data points).

## Methods

### An internal evaluation involving simulations of low thinning

The regressions developed by Cruz *et al.* (2003) were based on two primary sources of information or data. This included the database associated with the USDA Forest Service's Forest Inventory and Analysis (FIA) program (McRoberts *et al.* 2005). A subset of the FIA database consisting of 475 permanent plots located in five western US states (Colorado, Montana, Idaho, New Mexico and Arizona) and representing a wide range in stand and site conditions was selected for analysis. The CBH regression equations were derived directly from the FIA dataset with stand height and basal area selected as independent variables. The CFL and CBD regressions, with stand density and basal area as inputs, were formulated on the basis of the FIA plot data coupled with published allometric equations to calculate needle foliage weights.

Ten stands or plots were randomly selected for each forest type, i.e. Douglas-fir, lodgepole pine, ponderosa pine and mixed conifer, from the original FIA dataset (Figs 1, 2; Table 1) used in the development of the regression equations by Cruz *et al.* (2003). The values for CBH, CFL and CBD were first calculated by using the relevant regressions from Cruz *et al.* (2003) for the original stand or pretreatment case. Stand basal area was then reduced by 25 and 50%. For each reduction, the smallest diameter-at-breast height (DBH) trees were successively removed to simulate thinning from below or a 'low thinning' as discussed in a general sense by Cruz *et al.* (2010). Of the three classic types of thinning (i.e. low, crown and selection), low thinning is the one that will alter the fuel complex structure the most significantly from the standpoint of fire behaviour (i.e. increase CBH and decrease CBD) so as to reduce the likelihood of crown fire activity and thus create a more fire-resistant stand (Agee and Skinner 2005). An independent dataset was not considered necessary to evaluate the internal consistency of the Cruz *et al.* (2003) regressions with respect to simulating the effects of thinning regimes on the regression model estimates, especially in relation to the range in conditions covered by the relatively large sample sizes on which the individual equations are based. The data associated with the

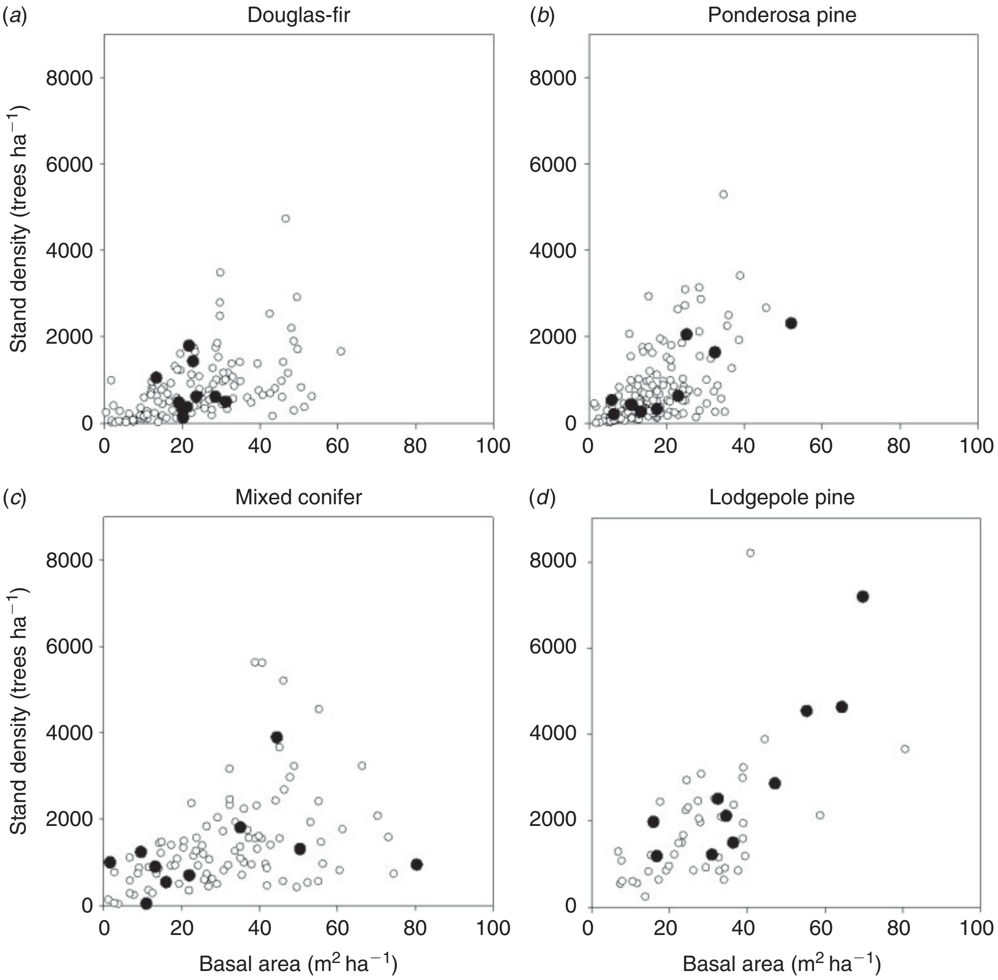

**Fig. 2.** Scatterplots of the FIA (Forest Inventory and Analysis) data associated with the development of the Cruz *et al.* (2003) regression equations for predicting canopy fuel load and canopy bulk density. The 10 randomly selected FIA stands in each fuel type that were used for evaluation purposes are separately identified (i.e. the slightly larger, solid data points).

Reinhardt *et al.* (2006) canopy fuel study was found to be unsuitable for evaluating simulated thinning regimes.

### *An independent evaluation for ponderosa pine*

Keyser and Smith (2010) destructively sampled individual tree crown fuel component weights and measured stand height, basal area and density in 16 ponderosa pine stands. From these data, we were able to calculate CBH, CFL, and CBD by using the Cruz *et al.* (2003) equations and to compare measured and predicted canopy fuel stratum characteristics. The data for mean height to the base of the live crown (i.e. CBH) and the needle foliage weight per unit area (i.e. CFL) were provided by F. W. Smith (pers. comm.). The CBD was calculated by dividing the needle foliage weight per unit area by the difference of the stand height and the mean height to live crown (i.e. the live crown length or crown depth).

### *Model performance*

The performance of each regression equation was evaluated by inspecting scatterplots and using deviation statistics used to quantify model adequacy (Willmott 1982), namely the root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MA%E) and mean bias error (MBE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \qquad (1)$$

$$\mathrm{MAE} = \frac{\sum |y_i - \hat{y}_i|}{n} \qquad (2)$$

$$\mathrm{MA\%E} = \frac{\sum \left(\frac{|y_i - \hat{y}_i|}{y_i}\right)}{n} \cdot 100 \qquad (3)$$

$$\mathrm{MBE} = \frac{\sum (\hat{y}_i - y_i)}{n} \qquad (4)$$

where $y_i$ is the observed canopy fuel stratum characteristic, and $\hat{y}_i$ is the predicted value based on the Cruz *et al.* (2003) regression equation.

**Table 1. Mean and standard deviation for stand characteristics and estimated canopy fuel load for the FIA (Forest Inventory and Analysis) dataset used by Cruz *et al.* (2003), FIA subset used in the simulated thinning regimes and Keyser and Smith (2010) canopy fuel study**

| Conifer fuel type | FIA dataset | FIA subset | Keyser and Smith (2010) |
|---|---|---|---|
| Douglas-fir | | | |
| Sample size (*n*) | 132 | 10 | |
| Average stand height (m) | 11.5 (5.6) | 10.8 (5.1) | |
| Basal area ($m^2$ $ha^{-1}$) | 23.8 (13.5) | 22.2 (4.9) | |
| Stand density (trees $ha^{-1}$) | 788 (736) | 728 (530) | |
| Canopy fuel load ($kg\,m^{-2}$) | 0.83 (0.52) | 0.70 (0.16) | |
| Ponderosa pine | | | |
| Sample size (*n*) | 190 | 10 | 16 |
| Average stand height (m) | 9.2 (4.4) | 6.5 (2.6) | 13.7 (3.6) |
| Basal area ($m^2$ $ha^{-1}$) | 16 (9.5) | 19.7 (14.2) | 26.7 (9.5) |
| Stand density (trees $ha^{-1}$) | 730 (1023) | 879 (798) | 784 (846) |
| Canopy fuel load ($kg\,m^{-2}$) | 0.61 (0.37) | 0.66 (0.52) | 0.91 (0.22) |
| Mixed conifer | | | |
| Sample size (*n*) | 101 | 10 | |
| Average stand height (m) | 10.9 (5.8) | 13.7 (11.1) | |
| Basal area ($m^2$ $ha^{-1}$) | 32 (17.5) | 28.4 (24.2) | |
| Stand density (trees $ha^{-1}$) | 1396 (1092) | 1230 (1046) | |
| Canopy fuel load ($kg\,m^{-2}$) | 1.40 (0.77) | 1.11 (0.75) | |
| Lodgepole pine | | | |
| Sample size (*n*) | 52 | 10 | |
| Average stand height (m) | 10.3 (4.3) | 10.6 (2.3) | |
| Basal area ($m^2$ $ha^{-1}$) | 29.6 (15.4) | 38.6 (18.8) | |
| Stand density (trees $ha^{-1}$) | 1955 (1513) | 2756 (1971) | |
| Canopy fuel load ($kg\,m^{-2}$) | 1.0 (0.57) | 1.29 (0.73) | |

## Results and discussion

The stand and canopy fuel stratum characteristics associated with the two simulated thinning regimes, and the original stand or pretreatment case, are summarised in Appendices 1–4. All stands showed an increase in CBH and reduction in CFL and CBD for the 25% basal area reduction thinning. Examination of the changes in canopy fuel metrics between the 25 and 50% basal area reduction thinning revealed a substantial reduction in CFL and CBD, but mixed results for CBH. The response of CBH to thinning was dependent on forest structure, namely stand density and DBH size class distribution. The increase in thinning intensity from 25 to 50% basal area generally resulted in an increase in CBH.

Following the 50% thinning, a few stands showed slight reduction or increase in CBH (e.g. stands 3 and 4 in Appendix 1 and stands 3 and 10 in Appendix 2) relative to the 25% basal area reduction thinning. This occurred in open, multicohort or multispecies stands. In the open stands where competition for light is not a limiting factor, crown depth and CBH are independent of tree height and density. Therefore, a reduction in basal area from 25 to 50% of the original situation is removing trees with both high and low CBH. In the multispecies stands, the presence of different species with distinct shade tolerances and crown architecture will influence the overall average CBH. In some situations, the smaller-diameter trees in the stand are also the ones with higher CBH. The removal of these individuals from the stand will result in a reduction in the average CBH. In multicohort stands, the 50% basal area reduction thinning can also lead to negligible changes in the CBH. This occurred in stands in which the first 25% basal area reduction thinning removed the smaller cohort trees and led to a large reduction in CBH. The second thinning affected the larger cohort trees. The removal of trees from this cohort resulted in small changes in CBH. These results highlight the fact that for a given stand structure, there is a limit with respect to the thinning density after which any further reduction in tree numbers does not result in an increase in CBH.

The comparisons between observed and predicted canopy fuel stratum characteristics derived from the Cruz *et al.* (2003) regression equations agree reasonably well, as evident from the scatterplots (Fig. 3). Mean absolute percentage errors varied between 13.8 and 41.3% for CBH, 5.3 and 67.9% for CFL, and 20.7 and 71% for CBD (Table 2). The equations predicted the various canopy fuel characteristics for the original stand condition and thinning treatments with comparable accuracy (i.e. there was no systematic decrease in accuracy or increase in bias in the simulated thinning treatments).

Evaluating predicted canopy fuel stratum characteristics against the Keyser and Smith (2010) dataset produced results similar to that of the 40 randomly selected FIA stands with regards to the CBH and CFL (Fig. 4*a–b*; Table 3). The Cruz *et al.* (2003) regression equation for ponderosa pine overpredicted CBD (Fig. 4*c*; Table 3). However, the observed and predicted CBD agreed very well when CBD was computed from the separate predictions of CFL and CBH coupled with the observed stand height (Fig. 5). One particular stand with a predicted CBD of ~0.8 $kg\,m^{-3}$ was not well modelled. This stand had a basal area of 47.2 $m^2\,ha^{-1}$ and a stand density of 3780 trees $ha^{-1}$,

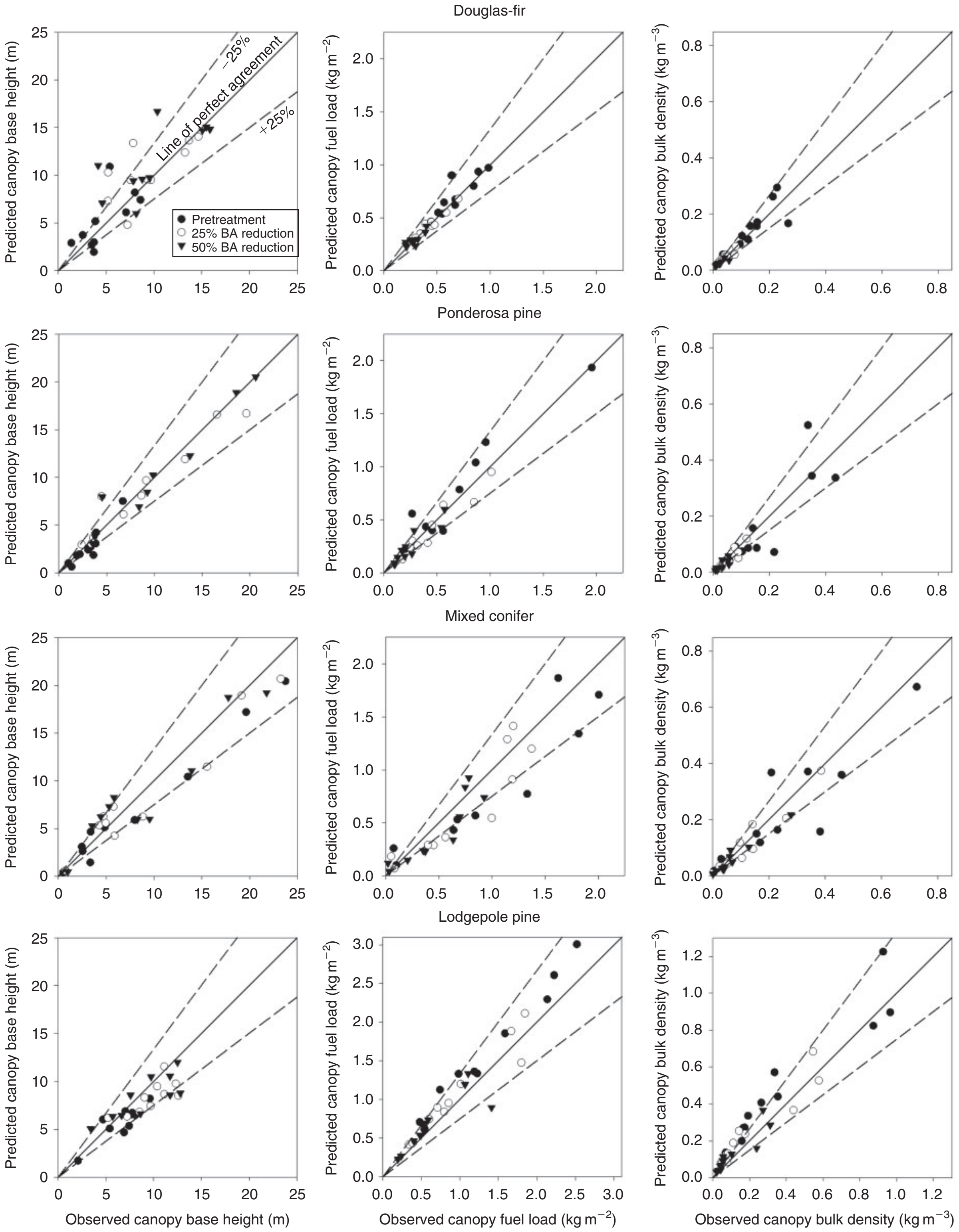

**Fig. 3.** Observed canopy fuel stratum characteristics compared with the predictions from the Cruz *et al.* (2003) regression equations for the original stand (i.e. pretreatment) and two different thinning regimes according to the proportion of basal area (BA) removed for the 10 randomly selected FIA (Forest Inventory and Analysis) stands in each of the four fuel types. The dashed lines around the line of perfect agreement indicate the ±25% error interval.

**Table 2. Statistics associated with the evaluation of the Cruz *et al.* (2003) regression equations for estimating canopy fuel stratum characteristics in relation to original or pretreatment case and the two simulated thinning regimes for the 10 randomly selected FIA (Forest Inventory and Analysis) stands for each of the four fuel types**

RMSE, root mean square error; MAE, mean absolute error; MA%E, mean absolute percentage error; MBE, mean bias error; CBH, canopy base height (m); CFL, canopy fuel load (kg m$^{-2}$); CBD, canopy bulk density (kg m$^{-3}$)

| Canopy fuel characteristic | Stand condition | RMSE | MAE | MA%E | MBE |
|---|---|---|---|---|---|
| Douglas-fir | | | | | |
| CBH | Original or pretreatment | 2.06 | 1.51 | 41.3 | 0.42 |
| | 25% basal area reduction | 2.68 | 1.90 | 28.4 | 1.07 |
| | 50% basal area reduction | 3.19 | 2.20 | 34.8 | 1.41 |
| CFL | Original or pretreatment | 0.12 | 0.08 | 12.4 | 0.05 |
| | 25% basal area reduction | 0.03 | 0.02 | 5.3 | 0.00 |
| | 50% basal area reduction | 0.24 | 0.03 | 12.3 | 0.01 |
| CBD | Original or pretreatment | 0.04 | 0.03 | 21.1 | 0.01 |
| | 25% basal area reduction | 0.01 | 0.01 | 20.7 | 0.00 |
| | 50% basal area reduction | 0.01 | 0.01 | 23.5 | 0.00 |
| Ponderosa pine | | | | | |
| CBH | Original or pretreatment | 0.77 | 0.61 | 20.2 | −0.38 |
| | 25% basal area reduction | 1.56 | 1.06 | 16.3 | −0.11 |
| | 50% basal area reduction | 1.31 | 0.87 | 13.8 | 0.00 |
| CFL | Original or pretreatment | 0.15 | 0.11 | 23.5 | 0.06 |
| | 25% basal area reduction | 0.08 | 0.06 | 14.7 | −0.04 |
| | 50% basal area reduction | 0.06 | 0.05 | 20.8 | 0.00 |
| CBD | Original or pretreatment | 0.09 | 0.06 | 30.4 | −0.02 |
| | 25% basal area reduction | 0.02 | 0.01 | 23.1 | −0.01 |
| | 50% basal area reduction | 0.01 | 0.01 | 31.8 | −0.01 |
| Mixed conifer | | | | | |
| CBH | Original or pretreatment | 1.92 | 1.52 | 22.6 | −1.07 |
| | 25% basal area reduction | 1.97 | 1.60 | 21.2 | −0.65 |
| | 50% basal area reduction | 2.24 | 2.08 | 32.6 | −0.29 |
| CFL | Original or pretreatment | 0.31 | 0.27 | 44.9 | −0.12 |
| | 25% basal area reduction | 0.22 | 0.19 | 45.6 | −0.09 |
| | 50% basal area reduction | 0.15 | 0.13 | 67.9 | −0.06 |
| CBD | Original or pretreatment | 0.10 | 0.07 | 57.1 | −0.03 |
| | 25% basal area reduction | 0.03 | 0.03 | 50.4 | −0.01 |
| | 50% basal area reduction | 0.03 | 0.02 | 71.0 | −0.01 |
| Lodgepole pine | | | | | |
| CBH | Original or pretreatment | 1.35 | 1.17 | 18.3 | −0.71 |
| | 25% basal area reduction | 1.94 | 1.60 | 18.7 | −1.08 |
| | 50% basal area reduction | 1.92 | 1.53 | 16.8 | −0.70 |
| CFL | Original or pretreatment | 0.27 | 0.24 | 24.2 | 0.24 |
| | 25% basal area reduction | 0.17 | 0.14 | 16.6 | 0.08 |
| | 50% basal area reduction | 0.19 | 0.12 | 16.9 | 0.02 |
| CBD | Original or pretreatment | 0.15 | 0.13 | 50.4 | 0.12 |
| | 25% basal area reduction | 0.07 | 0.06 | 50.8 | 0.05 |
| | 50% basal area reduction | 0.05 | 0.04 | 47.7 | 0.02 |

which is outside of the range of data used in constructing the original regression equation by Cruz *et al.* (2003) for ponderosa pine (Fig. 2*b*). Similar situations also exist with respect to some of the 40 randomly selected FIA stands (Fig. 3).

Reinhardt *et al.* (2006) evaluated the Cruz *et al.* (2003) regression models against their detailed sampling of canopy fuel stratum characteristics in five western USA conifer stands. There are, however, fundamental differences in how Reinhardt *et al.* (2006) and Cruz *et al.* (2003) compute CBH, CFL, and CBD, which preclude direct comparisons between the two studies. Cruz *et al.* (2003) defined CFL as including needle foliage only (as in Van Wagner 1977). Reinhardt *et al.* (2006), however, included needle foliage, the <0.3 cm-diameter live roundwood and the <0.6 cm-diameter dead roundwood in their measurement of CFL.

Reinhardt *et al.* (2006) also oven-dried their canopy fuel samples at 50°C for 24–48 h. Matthews (2010) has shown that low oven-drying temperatures can lead to incompletely dried samples. Oven-drying canopy fuel samples at 100–105°C for 24 h is typically required to remove all moisture in order to achieve true oven-dry biomass estimates (e.g. Buck and Hughes 1939; Ponto 1972; Brown 1978). The lower temperature used by Reinhardt *et al.* (2006) likely caused an underestimate of the moisture content and overestimate of the oven-dry weights of

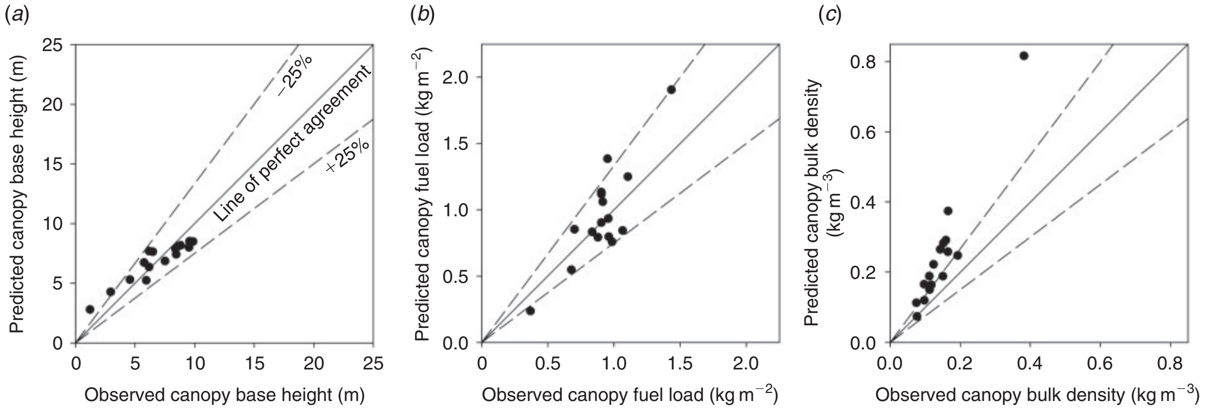

**Fig. 4.** Observed canopy fuel stratum characteristics based on the 16 stands associated with the Keyser and Smith (2010) ponderosa pine canopy fuel study in the Black Hills of South Dakota compared with the predictions from the Cruz *et al.* (2003) regression equations. The dashed lines around the line of perfect agreement indicate the ±25% error interval.

**Table 3. Statistics associated with the evaluation of the Cruz *et al.* (2003) regression equations for estimating canopy fuel stratum characteristics in relation to 16 ponderosa pine stands in the Black Hills of South Dakota (Keyser and Smith 2010)**

RMSE, root mean square error; MAE, mean absolute error; MA%E, mean absolute percentage error; MBE, mean bias error; CBH, canopy base height (m); CFL, canopy fuel load (kg m$^{-2}$); CBD, canopy bulk density (kg m$^{-3}$)

| Canopy fuel characteristic | RMSE | MAE | MA%E | MBE |
|---|---|---|---|---|
| CBH | 1.05 | 0.96 | 21.5 | 0.04 |
| CFL | 0.21 | 0.17 | 19.2 | −0.05 |
| CBD$^{A}$ | 0.14 | 0.10 | 61.0 | −0.10 |
| CBD$^{B}$ | 0.04 | 0.02 | 9.2 | 0.01 |

$^{A}$Calculated directly from Cruz *et al.* (2003) equation.
$^{B}$Calculated on basis of measured stand height and regression estimates of CFL and CBH from Cruz *et al.* (2003) equations.

the fuel samples. It is not possible to know the magnitude of the bias introduced by the low oven-drying temperature, but the tests carried out by Matthews (2010) indicate that the bias can be substantial.

Finally, Reinhardt *et al.* (2006) defined CBD as the maximum 3.0-m running mean of a vertical canopy fuel profile and CBH as the lowest point in the profile where CBD ≥ 0.012 kg m$^{-3}$. In contrast, Cruz *et al.* (2003) defined CBH as the average height to the live crown base in a stand and the CBD as the CFL (i.e. needle foliage weight per unit area) divided by the canopy depth (i.e. average stand height minus average height to live crown base). The definitions adopted by Cruz *et al.* (2003) are compatible with the canopy fuel stratum characteristics used in Van Wagner's (1977) semi-empirical crown fire initiation and propagation models whereas the values for CBH and CBD reported by Reinhardt *et al.* (2006) depart from the input specifications in Van Wagner's (1977) models (Cruz and Alexander 2010).

It is worth noting that allometric relationships can be quite variable for a given species (Green and Grigal 1978; Grigal and Kernik 1984) and are affected by stand density, genetics and edaphoclimatic conditions (Keyser and Smith 2010). The sampling of dense stands by Reinhardt *et al.* (2006), with an average basal area of 45.3 m$^2$ ha$^{-1}$, suggests that the equations derived from their measurements may be most appropriately applied in denser stands and may not be representative of more open conditions, although the limitations discussed previously still apply.

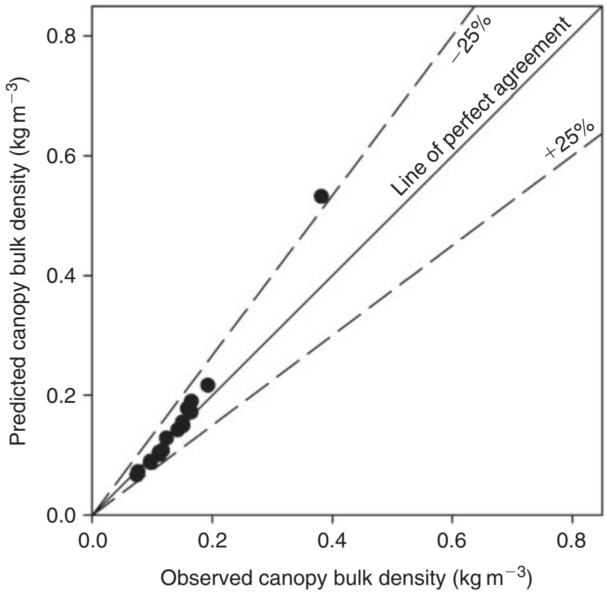

**Fig. 5.** Observed canopy bulk density based on the 16 stands associated with the Keyser and Smith (2010) ponderosa pine canopy fuel study in the Black Hills of South Dakota compared with the predictions of canopy bulk density based on measured stand height and estimates of canopy base height and canopy fuel load from the Cruz *et al.* (2003) regression equation for ponderosa pine. The dashed lines around the line of perfect agreement indicate the ±25% error interval.

## Conclusions

Given that canopy fuel stratum characteristics are very difficult to measure directly (Powell 2010), a method for making these estimates using easily acquired or readily available inputs is of great value to the environmental science and land-management communities. Considering the ever-increasing need for canopy fuel data in a wide variety of research and management applications, confirmation that previously untested models developed by Cruz *et al.* (2003) performed well should increase user confidence in them (Jakeman *et al.* 2006). However, evaluation should be an ongoing activity. The approach originally taken by Cruz *et al.* (2003) for estimating CBH, CFL and CBD could be extended to other conifer forest fuel types and geographical areas.

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**Appendix 1. Original stand and canopy fuel stratum characteristics associated with the 10 randomly selected FIA (Forest Inventory and Analysis) plots in Douglas-fir in relation to two thinning regimes**

CBH, canopy base height; CFL, canopy fuel load; CBD, canopy bulk density

| Stand number | Basal area ($m^2\ ha^{-1}$) | Stand density (trees $ha^{-1}$) | Stand height (m) | CBH (m) | CFL ($kg\ m^{-2}$) | CBD ($kg\ m^{-3}$) |
|---|---|---|---|---|---|---|
| Original stand (pretreatment) | | | | | | |
| 1 | 22.7 | 1433 | 6.7 | 3.7 | 0.64 | 0.21 |
| 2 | 20.2 | 131 | 21.2 | 5.4 | 0.55 | 0.03 |
| 3 | 28.5 | 611 | 14.3 | 8.6 | 0.89 | 0.16 |
| 4 | 31.2 | 498 | 15.4 | 8.0 | 0.98 | 0.13 |
| 5 | 21.7 | 1792 | 6.3 | 3.5 | 0.64 | 0.23 |
| 6 | 19.1 | 482 | 6.9 | 1.4 | 0.57 | 0.10 |
| 7 | 23.6 | 613 | 8.0 | 2.6 | 0.85 | 0.16 |
| 8 | 20.2 | 299 | 10.9 | 3.9 | 0.67 | 0.10 |
| 9 | 13.3 | 1051 | 5.6 | 3.7 | 0.51 | 0.27 |
| 10 | 21.2 | 376 | 12.5 | 7.1 | 0.67 | 0.12 |
| 25% basal area reduction | | | | | | |
| 1 | 17.4 | 88 | 26.4 | 13.7 | 0.39 | 0.03 |
| 2 | 14.7 | 51 | 26.1 | 7.8 | 0.34 | 0.02 |
| 3 | 21.0 | 124 | 26.8 | 14.7 | 0.59 | 0.05 |
| 4 | 23.9 | 228 | 18.4 | 9.7 | 0.70 | 0.08 |
| 5 | 16.5 | 143 | 24.2 | 13.3 | 0.44 | 0.04 |
| 6 | 13.8 | 68 | 20.7 | 5.2 | 0.34 | 0.02 |
| 7 | 17.4 | 108 | 18.9 | 7.5 | 0.45 | 0.04 |
| 8 | 15.6 | 113 | 15.1 | 5.2 | 0.45 | 0.05 |
| 9 | 9.2 | 234 | 11.1 | 7.2 | 0.30 | 0.08 |
| 10 | 15.6 | 129 | 19.2 | 9.3 | 0.48 | 0.05 |
| 50% basal area reduction | | | | | | |
| 1 | 11.0 | 43 | 28.8 | 15.1 | 0.20 | 0.01 |
| 2 | 11.0 | 23 | 32.4 | 10.4 | 0.20 | 0.01 |
| 3 | 14.4 | 67 | 29.2 | 15.5 | 0.39 | 0.03 |
| 4 | 15.6 | 110 | 19.5 | 9.5 | 0.40 | 0.04 |
| 5 | 11.0 | 62 | 29.0 | 15.9 | 0.26 | 0.02 |
| 6 | 9.2 | 38 | 22.3 | 4.2 | 0.21 | 0.01 |
| 7 | 11.9 | 46 | 19.2 | 7.9 | 0.25 | 0.02 |
| 8 | 10.1 | 60 | 15.2 | 4.6 | 0.27 | 0.03 |
| 9 | 7.3 | 136 | 13.4 | 8.2 | 0.30 | 0.06 |
| 10 | 11.0 | 78 | 19.6 | 8.8 | 0.32 | 0.03 |

**Appendix 2. Original stand and canopy fuel stratum characteristics associated with the 10 randomly selected FIA (Forest Inventory and Analysis) plots in ponderosa pine in relation to two thinning regimes**

CBH, canopy base height; CFL, canopy fuel load; CBD, canopy bulk density

| Stand number | Basal area ($m^2$ $ha^{-1}$) | Stand density (trees $ha^{-1}$) | Stand height (m) | CBH (m) | CFL (kg $m^{-2}$) | CBD (kg $m^{-3}$) |
|---|---|---|---|---|---|---|
| Original stand (pretreatment) | | | | | | |
| 1 | 10.8 | 431 | 6.7 | 3.1 | 0.56 | 0.16 |
| 2 | 11.1 | 418 | 5.5 | 1.9 | 0.45 | 0.12 |
| 3 | 6.4 | 200 | 4.5 | 1.0 | 0.20 | 0.06 |
| 4 | 52.0 | 2310 | 12.5 | 6.7 | 1.96 | 0.34 |
| 5 | 22.9 | 628 | 8.9 | 3.9 | 0.71 | 0.14 |
| 6 | 5.9 | 533 | 3.8 | 1.3 | 0.26 | 0.10 |
| 7 | 13.4 | 268 | 5.4 | 3.6 | 0.40 | 0.22 |
| 8 | 25.1 | 2051 | 4.6 | 2.2 | 0.86 | 0.35 |
| 9 | 17.4 | 322 | 6.6 | 3.3 | 0.27 | 0.08 |
| 10 | 32.4 | 1635 | 6.1 | 3.9 | 0.96 | 0.44 |
| 25% basal area reduction | | | | | | |
| 1 | 8.3 | 223 | 8.0 | 3.4 | 0.41 | 0.09 |
| 2 | 8.3 | 132 | 7.9 | 2.4 | 0.32 | 0.06 |
| 3 | 4.6 | 24 | 17.3 | 4.5 | 0.13 | 0.01 |
| 4 | 38.3 | 169 | 30.0 | 16.5 | 1.01 | 0.08 |
| 5 | 18.4 | 75 | 31.8 | 19.6 | 0.45 | 0.04 |
| 6 | 4.6 | 39 | 13.8 | 6.8 | 0.18 | 0.03 |
| 7 | 10.1 | 34 | 17.0 | 8.6 | 0.25 | 0.03 |
| 8 | 19.1 | 469 | 8.3 | 3.6 | 0.56 | 0.12 |
| 9 | 12.9 | 42 | 19.6 | 9.1 | 0.27 | 0.03 |
| 10 | 24.8 | 168 | 22.7 | 13.2 | 0.85 | 0.09 |
| 50% basal area reduction | | | | | | |
| 1 | 5.5 | 112 | 8.2 | 3.5 | 0.26 | 0.06 |
| 2 | 5.5 | 51 | 9.9 | 3.8 | 0.20 | 0.03 |
| 3 | 3.7 | 16 | 17.2 | 4.5 | 0.10 | 0.01 |
| 4 | 26.0 | 73 | 38.1 | 20.6 | 0.57 | 0.03 |
| 5 | 11.0 | 26 | 36.4 | 18.6 | 0.20 | 0.01 |
| 6 | 2.8 | 21 | 15.4 | 8.4 | 0.10 | 0.01 |
| 7 | 6.4 | 15 | 17.9 | 9.3 | 0.13 | 0.01 |
| 8 | 12.9 | 198 | 9.0 | 3.8 | 0.29 | 0.05 |
| 9 | 9.2 | 25 | 20.9 | 9.9 | 0.17 | 0.02 |
| 10 | 16.5 | 92 | 24.0 | 13.7 | 0.54 | 0.05 |

**Appendix 3. Original stand and canopy fuel stratum characteristics associated with the 10 randomly selected FIA (Forest Inventory and Analysis) plots in mixed conifer in relation to two thinning regimes**

CBH, canopy base height; CFL, canopy fuel load; CBD, canopy bulk density

| Stand number | Basal area ($m^2 ha^{-1}$) | Stand density (trees $ha^{-1}$) | Stand height (m) | CBH (m) | CFL ($kg m^{-2}$) | CBD ($kg m^{-3}$) |
|---|---|---|---|---|---|---|
| Original stand (pretreatment) | | | | | | |
| 1 | 16.1 | 532 | 7.5 | 2.5 | 0.84 | 0.17 |
| 2 | 35.1 | 1801 | 8.7 | 3.4 | 1.82 | 0.34 |
| 3 | 1.7 | 988 | 3.8 | 0.5 | 0.10 | 0.03 |
| 4 | 9.6 | 1231 | 5.0 | 3.3 | 0.64 | 0.38 |
| 5 | 80.4 | 940 | 33.6 | 23.7 | 2.05 | 0.21 |
| 6 | 13.3 | 888 | 6.9 | 2.5 | 0.67 | 0.16 |
| 7 | 22.0 | 694 | 10.6 | 4.8 | 1.33 | 0.23 |
| 8 | 11.0 | 36 | 33.3 | 19.6 | 0.07 | 0.01 |
| 9 | 44.5 | 3888 | 10.2 | 8.0 | 1.62 | 0.73 |
| 10 | 50.5 | 1299 | 17.9 | 13.5 | 2.01 | 0.46 |
| 25% basal area reduction | | | | | | |
| 1 | 11.9 | 168 | 13.5 | 4.7 | 0.56 | 0.06 |
| 2 | 26.6 | 722 | 14.2 | 5.8 | 1.19 | 0.14 |
| 3 | 1.3 | 494 | 4.1 | 0.7 | 0.08 | 0.02 |
| 4 | 7.8 | 342 | 10.2 | 5.9 | 0.45 | 0.10 |
| 5 | 60.2 | 191 | 35.6 | 23.3 | 1.20 | 0.10 |
| 6 | 9.2 | 157 | 12.1 | 4.3 | 0.40 | 0.05 |
| 7 | 16.5 | 368 | 11.9 | 5.0 | 1.00 | 0.14 |
| 8 | 8.3 | 19 | 36.7 | 19.2 | 0.05 | 0.00 |
| 9 | 33.1 | 1912 | 11.8 | 8.8 | 1.14 | 0.39 |
| 10 | 38.0 | 653 | 20.8 | 15.6 | 1.37 | 0.26 |
| 50% basal area reduction | | | | | | |
| 1 | 8.3 | 83 | 15.7 | 5.3 | 0.35 | 0.03 |
| 2 | 17.4 | 325 | 16.7 | 5.8 | 0.70 | 0.06 |
| 3 | 0.8 | 247 | 4.0 | 1.0 | 0.03 | 0.01 |
| 4 | 4.6 | 89 | 13.6 | 8.3 | 0.21 | 0.04 |
| 5 | 40.8 | 106 | 34.6 | 21.8 | 0.78 | 0.06 |
| 6 | 7.3 | 119 | 12.2 | 3.5 | 0.37 | 0.04 |
| 7 | 11.0 | 169 | 13.5 | 4.4 | 0.63 | 0.07 |
| 8 | 5.5 | 11 | 36.6 | 17.8 | 0.02 | 0.00 |
| 9 | 22.0 | 1095 | 12.2 | 9.5 | 0.75 | 0.28 |
| 10 | 24.9 | 299 | 21.1 | 13.9 | 0.93 | 0.13 |

**Appendix 4. Original stand and canopy fuel stratum characteristics associated with the 10 randomly selected FIA (Forest Inventory and Analysis) plots in lodgepole pine in relation to two thinning regimes**

CBH, canopy base height; CFL, canopy fuel load; CBD, canopy bulk density

| Stand number | Basal area ($m^2\ ha^{-1}$) | Stand density (trees $ha^{-1}$) | Stand height (m) | CBH (m) | CFL ($kg\ m^{-2}$) | CBD ($kg\ m^{-3}$) |
|---|---|---|---|---|---|---|
| Original stand (pretreatment) | | | | | | |
| 1 | 55.3 | 4542 | 7.9 | 5.4 | 2.13 | 0.87 |
| 2 | 16.7 | 1174 | 10.3 | 6.9 | 0.53 | 0.16 |
| 3 | 32.5 | 2507 | 10.2 | 7.4 | 0.98 | 0.35 |
| 4 | 36.4 | 1490 | 11.1 | 4.7 | 1.23 | 0.19 |
| 5 | 34.6 | 2108 | 12.2 | 7.7 | 1.19 | 0.26 |
| 6 | 69.7 | 7192 | 12.3 | 9.6 | 2.52 | 0.93 |
| 7 | 30.9 | 1210 | 12.4 | 8.1 | 0.74 | 0.17 |
| 8 | 47.1 | 2861 | 11.8 | 7.1 | 1.59 | 0.34 |
| 9 | 64.3 | 4632 | 10.1 | 7.8 | 2.22 | 0.96 |
| 10 | 15.9 | 1971 | 5.0 | 2.1 | 0.48 | 0.16 |
| 25% basal area reduction | | | | | | |
| 1 | 40.6 | 1576 | 11.3 | 7.2 | 1.80 | 0.44 |
| 2 | 12.9 | 372 | 17.5 | 12.6 | 0.39 | 0.08 |
| 3 | 25.7 | 777 | 18.7 | 12.3 | 0.71 | 0.11 |
| 4 | 27.5 | 392 | 21.8 | 11.1 | 0.80 | 0.07 |
| 5 | 25.7 | 1119 | 13.4 | 8.5 | 0.85 | 0.18 |
| 6 | 53.0 | 3486 | 14.5 | 11.1 | 1.84 | 0.55 |
| 7 | 23.0 | 475 | 16.3 | 9.1 | 0.60 | 0.08 |
| 8 | 34.9 | 986 | 17.5 | 10.4 | 1.01 | 0.14 |
| 9 | 49.8 | 2408 | 12.6 | 9.7 | 1.67 | 0.58 |
| 10 | 12.2 | 340 | 11.3 | 3.4 | 0.34 | 0.04 |
| 50% basal area reduction | | | | | | |
| 1 | 27.5 | 566 | 12.6 | 6.7 | 1.41 | 0.24 |
| 2 | 8.3 | 177 | 18.4 | 12.8 | 0.24 | 0.04 |
| 3 | 16.5 | 356 | 20.9 | 11.7 | 0.48 | 0.05 |
| 4 | 18.4 | 204 | 23.3 | 12.5 | 0.50 | 0.05 |
| 5 | 16.5 | 589 | 13.8 | 8.6 | 0.53 | 0.10 |
| 6 | 35.1 | 1756 | 15.8 | 11.7 | 1.11 | 0.27 |
| 7 | 15.6 | 197 | 17.4 | 7.6 | 0.40 | 0.04 |
| 8 | 23.9 | 366 | 20.2 | 9.7 | 0.59 | 0.06 |
| 9 | 33.1 | 1234 | 13.3 | 9.9 | 1.07 | 0.31 |
| 10 | 7.3 | 113 | 14.2 | 4.9 | 0.20 | 0.02 |