Effects of Alternative Treatments on Canopy Fuel Characteristics in Five Conifer Stands[1]

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Abstract

A detailed study of canopy fuel characteristics in five different forest types provided a unique dataset for simulating the effects of various stand manipulation treatments on canopy fuels. Low thinning, low thinning with commercial dbh limit, and crown thinning had similar effects on canopy bulk density (*CBD*) and canopy fuel load (*CFL*), but only the strict low thinning significantly affected canopy base height (*CBH*). In four of five sampled stands, *CBD* and *CFL* responded linearly to increasing treatment intensity in those three thinning treatments. The ponderosa-pine/Douglas-fir stand, with its significant understory component, showed little change in *CBD* with the commercial limit and crown thinning treatments. The diameter-limit harvest exhibited little consistency among sites and, hence, it is not a good silvicultural tool for creating canopy fuel reduction prescriptions. Due to fire-induced mortality, crown scorch (from prescribed fire) was more effective than mechanical pruning (to an equivalent height) at modifying canopy fuel characteristics. At achievable scorch and pruning heights, neither treatment had a significant effect on *CBD* or *CFL*.

Introduction

Silviculturists are frequently asked to manipulate stand structure to meet fire and fuel management objectives, including mitigation of crown fire potential. As summarized by Graham et al. (2004), effective strategies for reducing crown fire occurrence and severity include reducing surface fuels (Biswell 1960, Pollet and Omi 2002), increasing canopy base height (Agee 2002, Schmidt and Wakimoto 1988), and reducing canopy bulk density (Agee 1996, Scott 1998).

The wide variety of available treatment types and intensities, coupled with a wide array of initial stand structures, makes development of a single, uniformly effective treatment impractical (Graham et al. 1999). This paper summarizes detailed canopy biomass measurements in various ways to simulate of the effects of several possible silvicultural treatments (thinning, pruning, and prescribed fire) on canopy fuel characteristics.

Method

Scott and Reinhardt (2002, 2005) measured individual-tree and plot-level canopy fuel characteristics in five coniferous stands in the western U.S., each in a different forest type:

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- ponderosa pine/Douglas-fir (PPDF)
- ponderosa pine (PP)
- Douglas-fir (DF)
- lodgepole pine (LP)
- Sierra Nevada mixed conifer (SNMC)

The previous canopy fuel study publications report only stand-level summaries. For this analysis, we utilized unpublished tree-level summaries gathered during the same field study. We used the following tree characteristics data to simulate various treatments at each site:

- Species
- Diameter at breast height
- Canopy fuel mass by 1-m height increments
- Number of trees per acre represented by each sample tree

In addition, crown ratio and crown class (crown position) were used in the simulation of crown thinning.

Canopy fuel mass is the oven-dry mass of fuel available to burn in the flaming phase of a crown fire. Only very fine fuel is consumed in the short duration of a crown fire. Van Wagner (1977) assumed foliage was the only available canopy fuel component when computing mass flow rate on an experimental fire. Fine branches may also be consumed in the flaming portion of a crown fire. Others add a portion of the fine branch mass to the foliage (Brown and Bradshaw 1994, Brown and Reinhardt 1991, Call and Albini 1997). In this analysis, canopy fuel is assumed to include the foliage, 0 to 3 mm diameter live branchwood, and 0 to 6 mm diameter dead branchwood. Canopy fuel mass by 1m height layer for each tree was estimated by (1) removing and measuring individual branches in 1m height increments, (2) sorting, drying, and weighing a sub-sample of those branches, (3) developing regression equations for estimating branch biomass by size class and component, and (4) applying those regressions to every measured branch (Scott and Reinhardt 2005). Vertical profiles of canopy fuel mass in each 1m height layer (canopy bulk density) illustrate differences in initial stand condition among the five sites (*fig. 1*).

All study plots were fixed-radius (either 10 or 15m radius), so the number of trees per acre represented by each sample tree in the plot is simply the inverse of plot area.

Canopy Characteristics

Three plot-level canopy fuel characteristics were estimated from the dataset: canopy fuel load, canopy bulk density, and canopy base height.

Canopy fuel load (*CFL*) is the canopy fuel mass per unit ground area. We estimated *CFL* by dividing the sum of canopy fuel mass over all trees (all height increments) by the horizontal plot area. Canopy fuel load is not currently used to predict the occurrence of crown fire, but is used to predict the intensity of a crown fire in some fire behavior simulation systems (for example, Finney 1998, Scott 1999).

Canopy bulk density (*CBD*) is the canopy fuel mass per unit canopy volume (Scott and Reinhardt 2001). In this analysis, *CBD* is estimated as the maximum 3m deep running mean from the *CBD* profile (Scott and Reinhardt 2005). Canopy bulk density is important in modeling the occurrence of active crown fires (Wan Wagner

1977), and, in some fire models, crown fire spread rate (Albini 1996, Butler et al. 2004, Cruz et al. 2005).

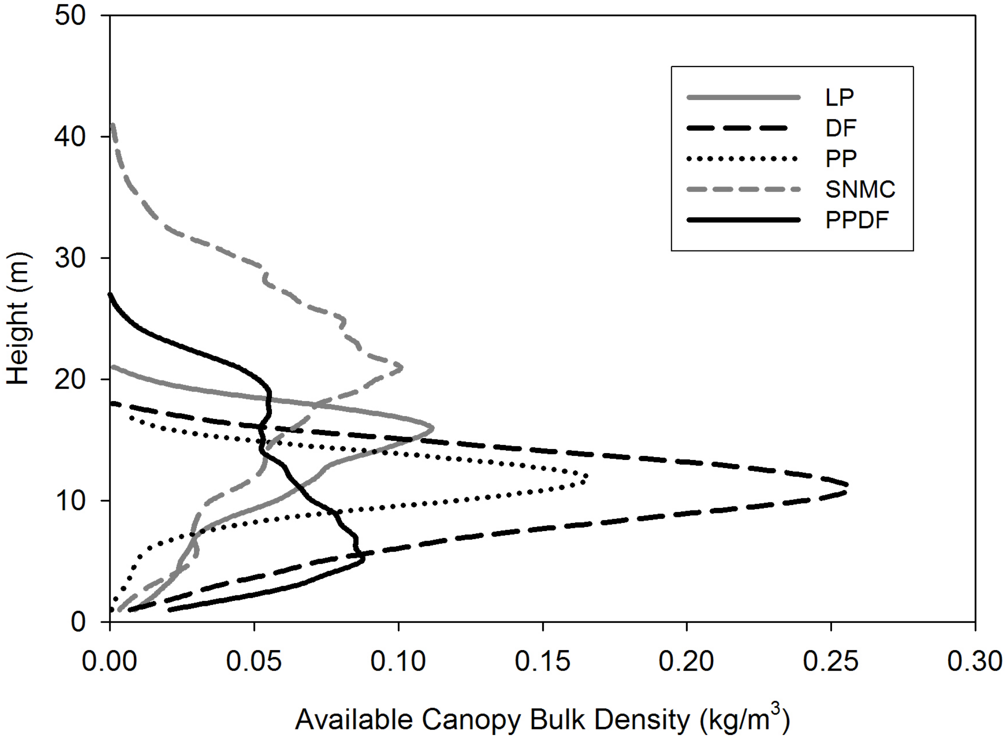

Figure 1—Pre-treatment vertical canopy fuel profiles (3-m running mean) for five conifer stands. Available canopy bulk density (*CBD*) includes the mass of foliage, 0 to 6 mm diameter dead branch material, and 0 to 3 mm live branch material. A single effective value of *CBD* for each stand is defined as the maximum 3-m running mean. Canopy base height is defined as the height at which *CBD* exceeds 0.011 kg/m^3. Canopy fuel load is represented by the area “under” (to the left of) each curve. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine.

Canopy base height (*CBH*) is defined here as the lowest height above the ground at which there is sufficient available canopy fuel to propagate fire vertically through the canopy (Scott and Reinhardt 2001). Using a method adapted from Sando and Wick (1972), *CBH* is calculated as the lowest height above the ground at which at least 0.011 kg/m^3 of available canopy fuel was present (Reinhardt and Crookston 2003), using a 3m deep running mean to smooth observed values. Canopy base height is important in modeling the transition from surface fire to some kind of crown fire (Cruz et al. 2004, Van Wagner 1977).

Alternative Silvicultural Treatments

Six silvicultural treatments were simulated in each of the five stands:

- Low thinning to a target residual basal area (BA)
- Low thinning to a target residual BA, with a commercial dbh limit
- Crown thinning (high thinning) to a target residual BA

- Diameter-limit cutting to specified dbh
- Mechanical pruning
- Scorch from prescribed fire with resulting mortality

Low thinning is removal of trees from the lower crown classes to favor those in the upper crown classes. We simulated low thinning by removing trees strictly by dbh, with no consideration for crown class, crown ratio, or spacing. The first low thinning treatment is applied to all trees in the plot without regard for a tree's commercial value, thus, all small trees, regardless of commercial value, are removed. In the second low thinning treatment, we applied a commercial (merchantable) diameter limit (dbh below which the direct costs of harvesting exceeds the commercial value of merchantable material). We varied commercial limit among stands to reflect differences in species composition and associated markets: 10" dbh in the SNMC stand, 7" dbh in the PPDF, DF, and PP stands, and 5" dbh in the LP stand. Removal of all merchantable trees from a stand is an "economic clearcut", not a thinning. We simulate the full range of treatment intensity for academic curiosity, not because it is a suggested or common practice.

Crown thinning is the removal of trees from the dominant and codominant crown classes in order to favor the *best* trees of those same classes. We simulated a crown thinning by removing dominant and codominant trees in order of increasing live crown ratio. That is, dominant and codominant trees with low live crown ratios (poor quality) were removed first. A commercial limit was not applied to the crown thinning, because even poor quality dominant and codominant trees are usually of merchantable size. We simulated crown thinning through to its endpoint--removal of *all* dominant and co-dominant trees--even though the result (leaving only suppressed and intermediate trees) is not a crown thinning at all.

Diameter-limit cutting is the removal of all trees below a specified dbh. (Diameter-limit cutting can also be applied as the removal of trees *above* a specified dbh, and often is restricted to removal of only merchantable trees.) We simulated diameter-limit cutting by removing all trees *smaller* than a specified dbh, without regard for a commercial limit.

Pruning is the removal of live or dead branches from a standing tree. In timber applications, pruning is done to improve wood quality; in urban forest applications, pruning is done to improve aesthetics or tree health; in wildland fire applications, pruning is done to separate surface and canopy fuels (increase *CBH*). We simulated pruning by progressively removing from the dataset the canopy fuel mass in the lowest layers of the canopy fuel profile, but otherwise we left the trees in the treelist. No regard was given to leaving a minimum crown length on pruned trees--each tree is pruned until its crown is gone. Using the *CBD* calculation method used in this analysis, pruning can only affect canopy bulk density if pruning height exceeds the height of maximum bulk density (Scott and Reinhardt 2005). The fuel mass of any given branch was assigned to the 1m layer in which it is attached to the bole, with no accounting for branch angle. Because most branches near the bottom of the crown tend to angle downward, this analysis tends to over-predict the effect of pruning on *CBH*, especially in open stands containing large-crowned trees with branches near the ground. All five of the stands used here were closed-canopy, so this potential for over-prediction is minimized.

Crown scorch is needle death due to convective heat above a wildland fire. Height of crown scorch is a function of in-stand wind speed and intensity of the surface fire (Van Wagner 1973). By controlling fireline intensity in relation to in-stand wind speed, prescribed fire managers can control scorch height. Scorched branches are assumed to contribute to canopy fuel mass. In reality, several months to a few years may pass before scorched foliage and fine branches fall to the ground and are no longer available for a crown fire. However, the time period during which we may overestimate the effects of scorch on canopy fuels corresponds to a period of little potential for surface fire. Scorch from prescribed fire was simulated by progressively removing from the dataset the biomass in the lowest layers of the canopy fuel profile, just as we did for mechanical pruning. In addition, we simulated fire-caused tree mortality by computing the probability of tree mortality based on scorch height in relation to tree height, crown length, and bark thickness (Ryan and Reinhardt 1988).

The equations for predicting tree mortality are logistic. The result they give is a probability of mortality. To use the probability of mortality in our analysis, we simulated mortality in a manner similar to that used in FFE-FVS (Reinhardt and Crookston 2003). Canopy fuel mass for each tree (at each 1m height layer) was reduced by the tree's probability of mortality. The resulting simulations represent the expected value of canopy fuel.

Results and discussion

Results are presented as a series of charts that show the effect of treatment intensity on canopy characteristics for each of the three canopy fuel characteristics. Each figure displays results for all five sample stands and all three canopy fuel characteristics; there is one figure for each treatment.

Low Thinning to Target Residual Basal Area

Canopy bulk density (*CBD*) was linearly related to residual basal area (*fig. 2a*). In fact, despite the wide range of initial stand structure and composition, four of the five sites exhibited similar *CBD* at a given level of residual basal area. For example, with 100 ft^2/ac of basal area remaining after removing trees from below, *CBD* at all but the DF site ranged from 0.06 to 0.07 kg/m^3. *CBD* is strongly linearly related to residual BA, even at the DF site, but the value of *CBD* was much different (*CBD* at the DF site was 0.18 kg/m^3 with 100 ft^2/ac of basal area remaining). The reason for this difference is not clear, but the dominance of Douglas-fir is likely a contributing factor. The fine branching and shade tolerance of Douglas-fir apparently contributed to higher canopy fuel mass per unit canopy volume.

Most stands showed an initial period during which reduction of BA from below had no effect on *CBD*. This occurred because the small trees, which were removed first, had little or no fuel mass in the critical dense canopy layer that determines *CBD*. The PPDF stand, however, exhibited a rapid initial drop in *CBD* with BA, because the critical canopy layer occurred in the predominantly Douglas-fir under- and middle-stories, whereas in the other stands it occurred higher in the canopy (*fig. 1*).

Canopy fuel load (*CFL*) also responded linearly to residual basal area, but, unlike with *CBD*, there was no other similarity in relationship among sites (*fig. 2b*). With 100 ft^2/ac of basal area remaining after removing trees from below, *CFL* varied almost four-fold, from 0.4 to 1.4 kg/m^2. The steepest initial drop in *CFL* with BA again occurred in the PPDF stand. This steep drop corresponded to removal of the under- and middle stories of this stand; slight reduction in BA in such a canopy layer had a significant effect on available canopy fuel.

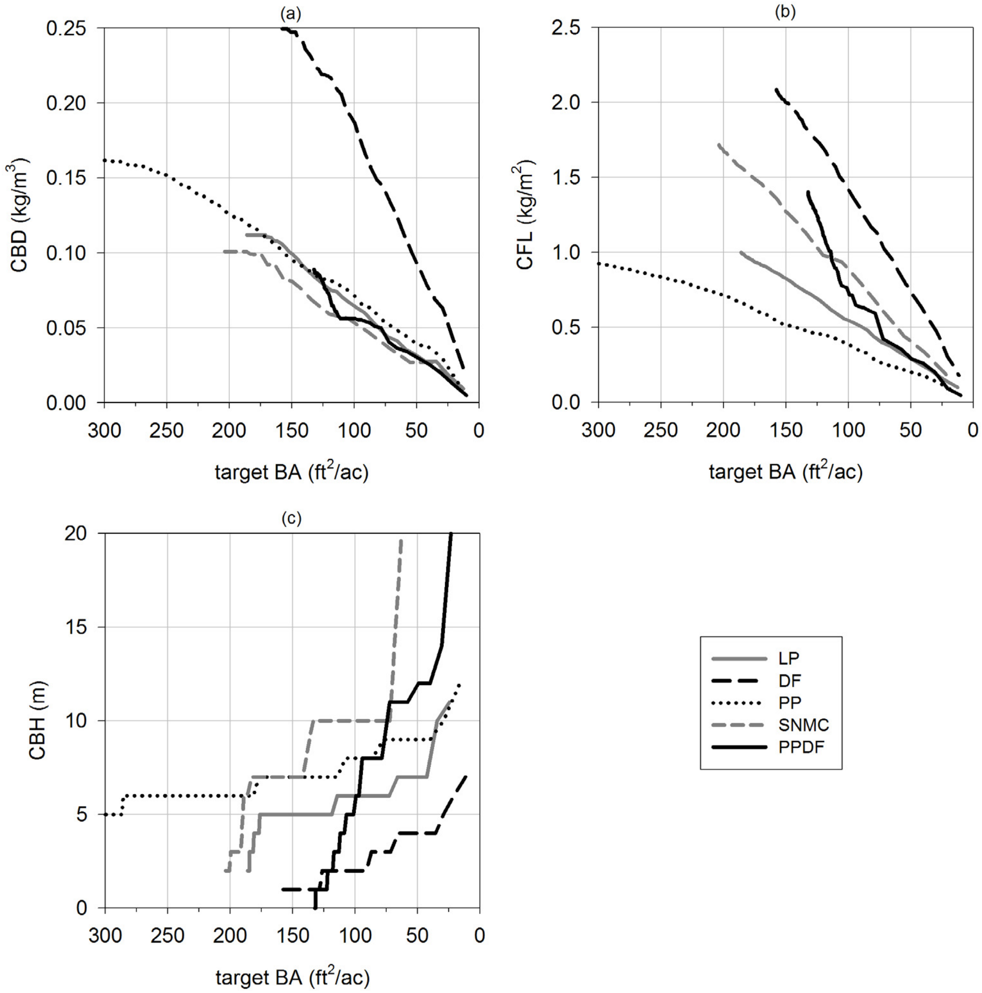

Figure 2—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to a variable-intensity **low thinning**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine.

The relationship between canopy base height (*CBH*) and low thinning residual BA bears none of the consistency of that for *CBD* and *CFL* (*fig. 2c*). First, *CBH* appeared as a step function, because the method we used only estimates *CBH* to the nearest meter. When *CBD* in the critical 1m layer fell below the critical value (0.011 kg/m^3), *CBH* changed abruptly to a higher layer. Nonetheless, meaningful trends emerged. The stands containing a shade-tolerant understory (PPDF and SNMC) showed an initial strong increase in *CBH* with decreasing residual BA, because removal of the understory in those stands greatly increased *CBH*. Once the understory was removed, *CBH* was determined mostly by the overstory, and the response of *CBH* was flat with decreasing residual BA until many overstory trees were removed. The PPDF stand, because it is multi-storied, showed consistent increase in *CBH* with decreasing residual BA. The PP stand, a single-cohort without an understory of any kind, showed almost no change in *CBH* with even large reductions in BA from below.

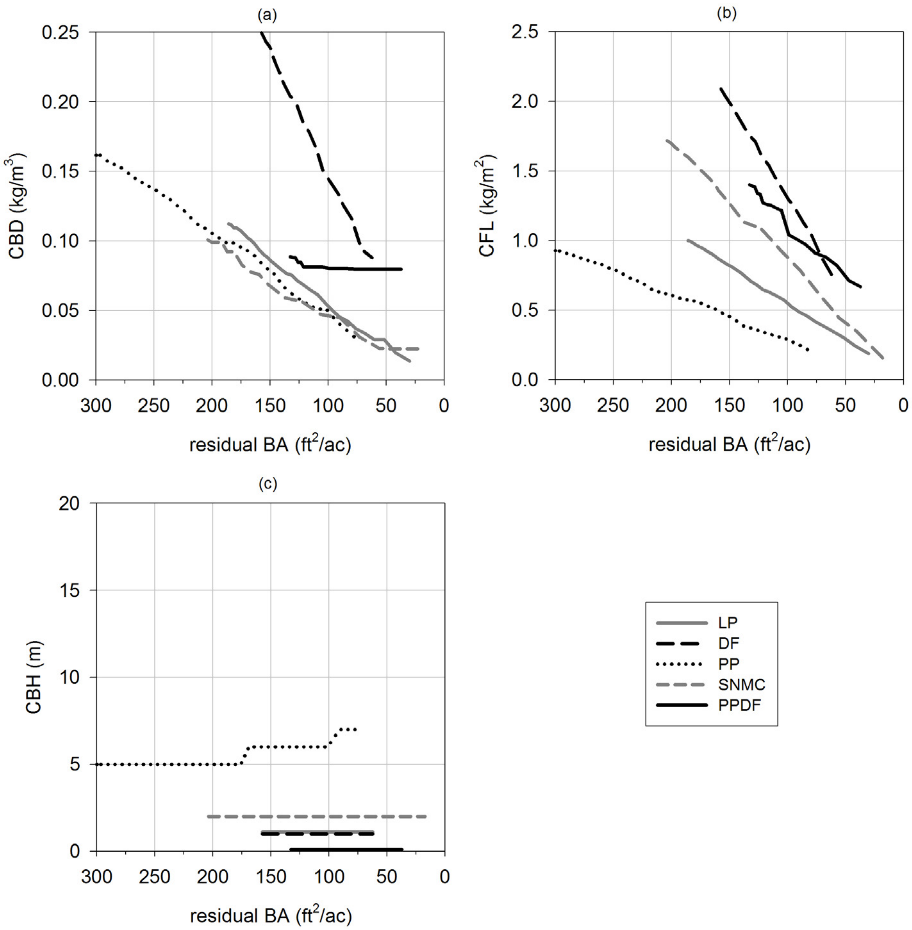

Figure 3—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to a variable-intensity **low thinning with commercial limit**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine. Commercial d.b.h. limit varied among stands to reflect local conditions: 10” dbh in the SNMC stand, 7” dbh in the PPDF, DF, and PP stands, and 5” in the LP stand. Trees smaller in diameter than the commercial limit were retained.

Low thinning to target residual basal area, with commercial limit

The line for each stand begins at the BA and canopy fuel characteristic corresponding to the initial condition, and ends at the BA and canopy fuel characteristic corresponding to removal of all merchantable trees. In four of the five stands, applying a commercial limit did not significantly change the response of *CBD* to residual BA. All showed linear response and similar slope as the strict low thinning (*fig. 3a*). In the PPDF stand, however, *CBD* was nearly unchanged, even after the entire overstory was removed, because the critical dense layer occurred in the layer comprised of the sub-merchantable trees.

Response of *CFL* to residual BA was similar with and without the commercial limit in all stands. The biggest change again occurred in the PPDF stand, whose response to BA was less steep with the addition of the commercial limit. This occurred because the non-commercial trees are composed almost exclusively of

Douglas-fir, whereas the commercial-sized trees are a mixture of Douglas-fir and ponderosa pine. The foliage and fine branching of Douglas-fir apparently give it a higher canopy fuel mass per unit of BA than ponderosa pine.

The largest effect of adding a commercial limit to the low thinning occurred for *CBH*. Almost no amount of thinning increased *CBH* if the non-commercial trees were left (*fig. 3c*). In fact, four of the five stands showed no change in *CBH* even after all merchantable trees were removed, because those trees had enough canopy fuel mass to maintain the critical density that determines *CBH*. Removing larger trees did not remove canopy fuel mass from the low canopy layers. Only the PP stand showed any increase in *CBH* with this treatment, but less so than without the commercial limit.

Crown Thinning

Crown thinning had a similar effect on *CBD* as the low thinning with commercial limit—a linear response of *CBD* with respect to residual BA in all but the PPDF stand, which exhibited no change in *CBD* even with removal of all dominant and co-dominant trees (*fig. 4a*). Just as for the commercial low thinning treatment, this result occurred because the critical dense canopy layers occurred in the Douglas-fir under- and middle-stories, which was composed of suppressed and intermediate crown classes, and because the dominant and codominant trees did not have significant canopy fuel mass in those critical layers.

Crown thinning also had a similar effect on *CFL* as low thinning with commercial limit--only the PPDF stand was different than strict low thinning. With a strict low thinning, the PPDF stand exhibited strong sensitivity of *CFL* to initial reduction in BA (*fig. 4b*), because the smallest trees in the stand contained a large proportion of the total canopy fuel mass. In contrast, crown thinning removed the larger trees from the stand--primarily ponderosa pine--which contained a smaller portion of the total *CFL* than the small understory trees. Therefore, the response of *CFL* to BA reduction in the crown thinning was initially weak, and strengthened only as trees with longer crowns--Douglas-fir in the PPDF stand--were eventually removed.

As with low thinning with a commercial limit, crown thinning had very little effect on *CBH* (*fig. 4c*). In the DF, SNMC, and PPDF stands, CBH did not change even after all dominant and codominant trees were removed. In the PP and LP stands, CBH increased only after nearly all of the dominant and codominant trees had been removed, and then only slightly.

Diameter Limit Cutting

Results of the diameter-limit cutting simulation showed none of the consistency of low thinning in its effect on *CBD* (*fig. 5a*). In contrast to low and crown thinning, diameter-limit cutting did not show a linear relationship between maximum dbh of harvested tree and *CBD*. All sites except PPDF showed no reduction in *CBD* until trees greater than about 5 in. dbh had been removed. In contrast, *CBD* was reduced with removal of even small diameter trees in the PPDF stand, because those trees contributed to the critical dense layers of the canopy. Once *CBD* began to drop in relation to diameter, it did so quickly in all but the PPDF and SNMC sites, for which reducing *CBD* required removal of the large-diameter overstory trees.

Results of the diameter-limit cutting simulations on *CFL* were also quite different than low and crown thinning, showing no clear linear trends or consistencies

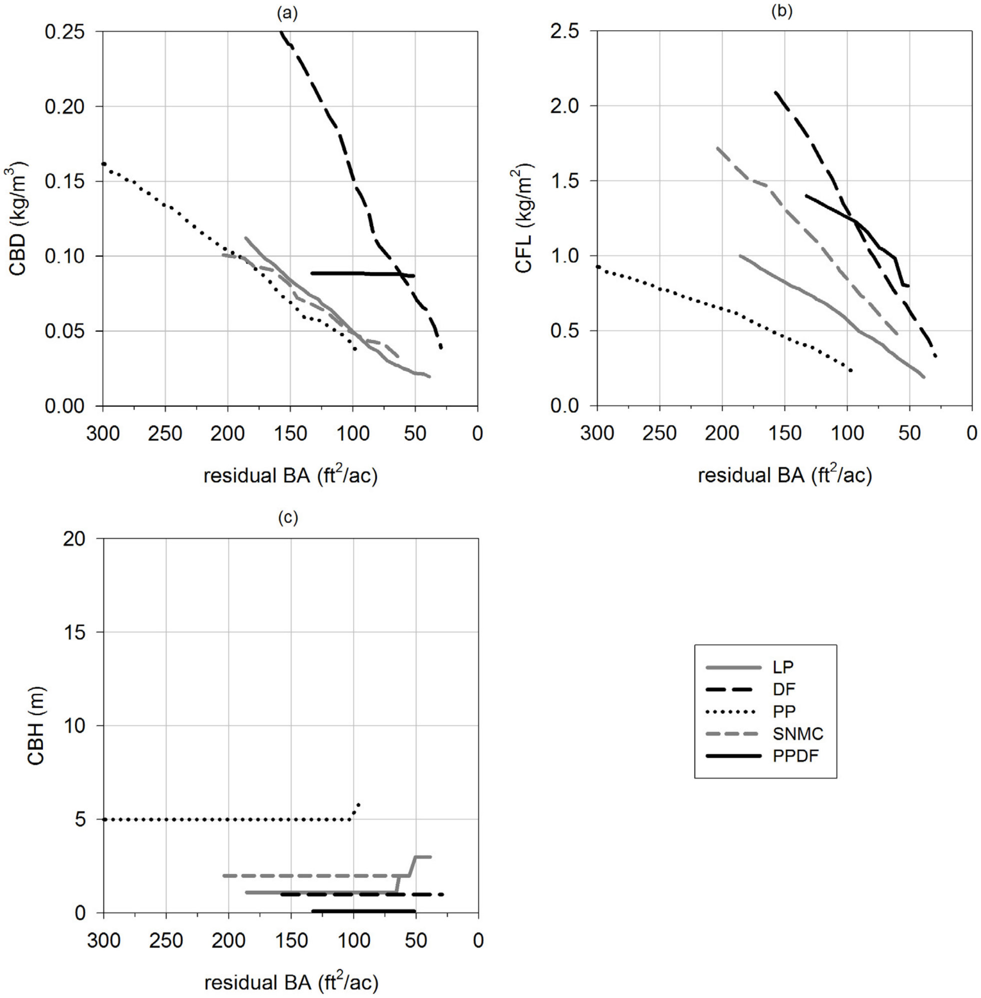

Figure 4—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to a variable-intensity **crown thinning**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine. Crown thinning is removal of trees in the dominant and codominant crown classes in order to favor the best trees of those same classes.

(*fig. 5b*). Just as for *CBD*, *CFL* dropped most quickly in the PPDF stand, indicating the influence of small diameter trees at that site and their significant contribution to *CFL*. Other sites showed little effect of removing small-diameter trees, because at those sites the small trees did not contain a significant fraction of the total canopy fuel mass in the stand.

The effect of diameter limit on *CBH* displayed more apparent consistency than low thinning--as the diameter limit increased, so too did the resulting *CBH* (*fig. 5c*). Nonetheless, the wide range of *CBH* at a given diameter limit makes generalization impractical. At a diameter limit of 5 inches dbh, *CBH* varied from 1 to 6m among the sites; at 10 inches dbh, *CBH* ranged from 4 to 8 m; at 15 inches, *CBH* ranged from 8 to 12m.

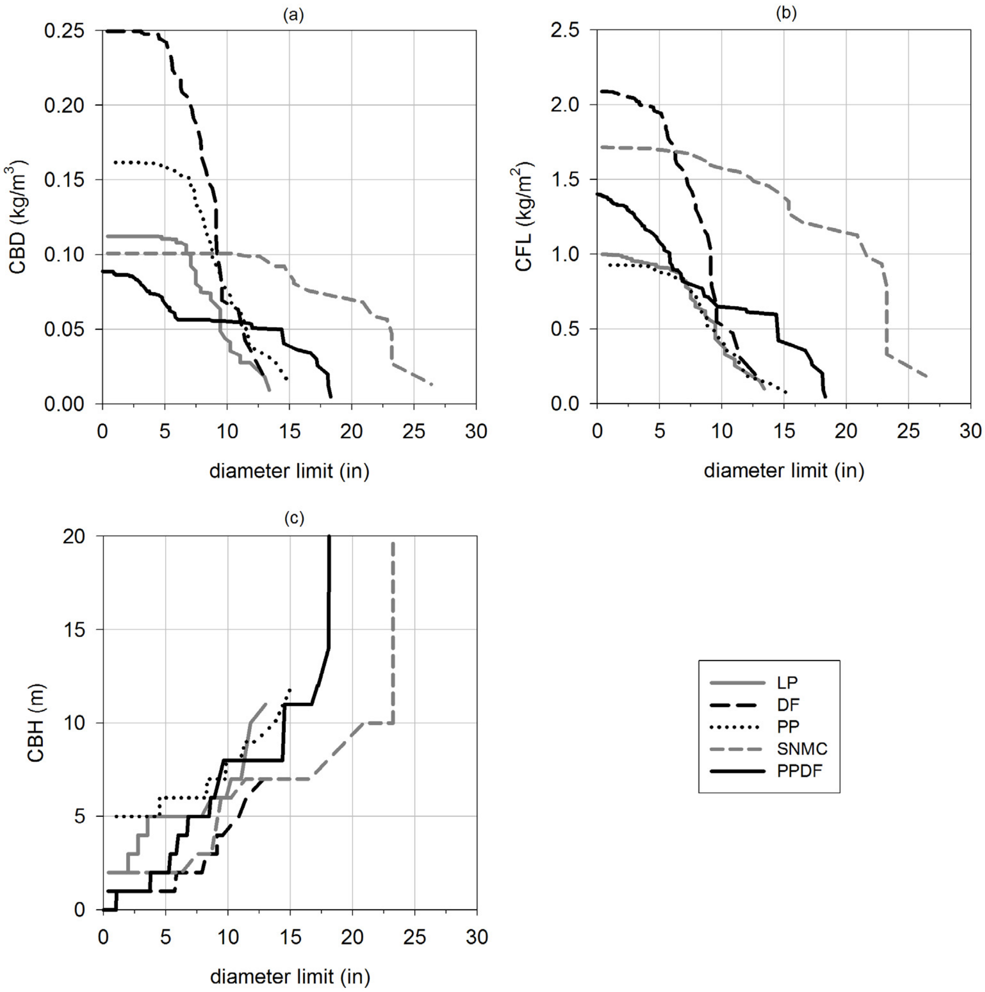

Figure 5—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to a variable-intensity **diameter-limit harvest**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine. All trees less than the diameter limit were removed.

Mechanical Pruning

Pruning to a prescribed height had predictably little effect on *CBD* (*fig. 6a*). Pruning did not have an effect on *CBD* unless pruning height approached the critical dense layers of the canopy. Therefore, the PPDF site, for which the densest canopy layers occurred nearest the ground due to the Douglas-fir under- and middle-stories, showed the earliest effect of pruning on *CBD* (that is, at the lowest pruning height values). Pruning heights above 3m are impractical to apply to all trees in a stand, therefore, mechanical pruning has no practical effect on *CBD*.

Any amount of pruning removes fuel mass from the canopy. However, the lowest layers of the canopy do not generally contain a significant portion of the total canopy fuel load (*fig. 6b*), the exception being stands with significant understories. For example, the greatest reduction in *CFL* at a pruning height of 3m occurs at the PPDF site because of its significant Douglas-fir understory.

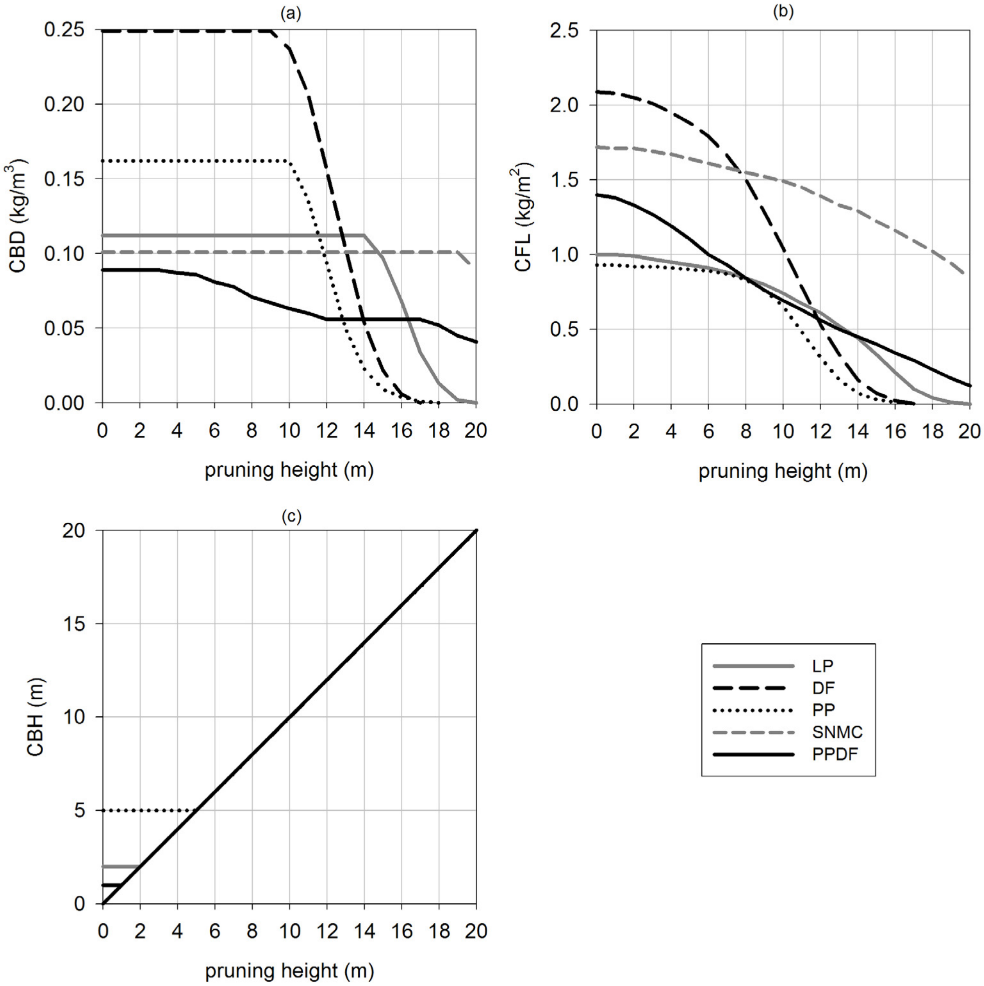

Figure 6—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to a variable-intensity **mechanical pruning**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine.

The effect of pruning on *CBH* was quite predictable (*fig. 6c*). Because pruning by definition removes all available canopy fuel below the pruning height, *CBH* must always be greater than or equal to pruning height. Pruning had no effect if *CBH* already exceeded pruning height. For example, initial *CBH* in the PP stand was 5m because the high stand density caused crowns to recede and prevented understory trees from establishing, so that there was not enough canopy fuel to meet the 0.011 kg/m^3 *CBH* threshold until that height. Pruning to heights below 5m therefore had no effect on *CBH* in the PP stand, while pruning to heights above 5m increased *CBH* directly.

Scorch from Prescribed Fire with Resulting Mortality

The effect of scorch height on canopy fuel characteristics is expected to be similar to that of mechanical pruning, but with one important difference: crown scorch and related fire influences of the fire can cause tree death, leading to a further reduction of canopy. If there were no resulting mortality, scorch and pruning would have the same effect as simulated in this analysis. The difference between the crown scorch and mechanical pruning simulations is entirely due to mortality.

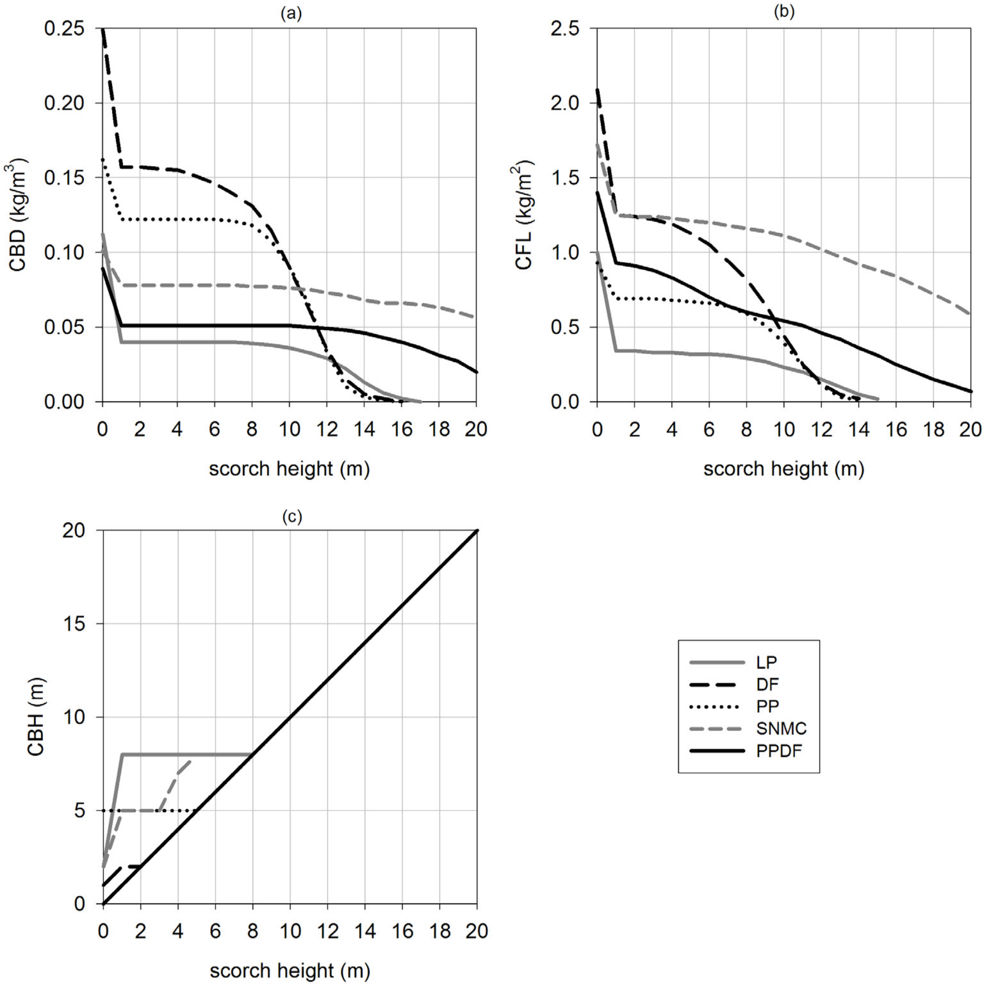

Figure 7— Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to various heights of **crown scorch**. Stands are labeled: LP = lodgepole pine; DF = Douglas-fir; PP = ponderosa pine; SNMC = Sierra Nevada Mixed Conifer; PPDF = ponderosa pine. Response includes scorch-induced mortality.

All stands exhibited a drop in *CBD* with crown scorch height of just 1m, followed by a range (up to about 8m scorch height) in which increasing scorch height did not significantly reduce *CBD* (*fig. 7a*). This pattern is a direct result of the probability of mortality equations used in the analysis, which predict non-zero probability of mortality. Even if a tree experiences a fire that does not scorch its crown, then there is a small increase in probability of mortality as scorch height increases. In the PPDF stand, fire-caused mortality causes a drop in *CBD* even with little crown scorch, because of high probability of mortality in the Douglas-fir under- and middle-stories. However, *CBD* then changes little with increasing scorch height because the remaining trees are not as susceptible to fire-caused mortality. The PP and SNMC sites show the least difference between mechanical pruning and scorch (aside from the initial drop), indicating their structure and composition resists fire-caused mortality.

Again, all stands exhibited an initial drop in *CFL* with a crown scorch height of just 1m, corresponding to mortality of the most susceptible trees in each stand. The initial drop was again smallest in the PP and SNMC sites due to their relatively resistant structure and composition.

The differences in effect on *CBH* between scorch and pruning were generally minor (*fig. 7c*). The exception to that rule is the SNMC site, where even 1m of scorch caused enough mortality to raise *CBH* to 8m. However, increasing scorch height to 8m had no additional effect because the remaining trees were more resistant to fire-caused mortality. The PPDF and SNMC sites show "blips" in the response of *CBH* to scorch height at higher levels of crown scorch. These deviations are minor, and correspond to levels of scorch that cause mortality in trees that, in addition to the biomass removed through scorch alone, reduce *CBD* in the layer(s) just above scorch height enough that the 0.011 kg/m^3 cannot be met.

Conclusion

This paper reports an analysis of a limited but accurate canopy fuel mass dataset. A similar analysis could be performed on a more extensive dataset that includes hundreds of stands in a given forest type. However, such an analysis would require making *estimates* of canopy fuel mass using allometric equations. Because such equations were generally built for dominant and co-dominant trees, some of the trends seen in this dataset might be masked by poor estimates of canopy fuel mass in sub-dominant trees. Improved individual-tree canopy fuel mass and available-fuel prediction models would greatly improve our ability to estimate stand-level canopy fuel characteristics.

In the single cohort stands, low thinning, low thinning with a commercial limit, and crown thinning all had a similar effect on *CBD* and *CFL*: reducing BA reduced *CBD* and *CFL* proportionally (*fig. 8*). This result means that reducing BA by some fraction of the initial condition would reduce *CBD* and *CFL* by roughly the same fraction, *regardless of how the BA was reduced*. That is, a tree's contribution to *CFL* (and therefore *CBD*) is proportional to its contribution to BA. This result is consistent with allometry that relates canopy biomass to the square of dbh (Brown 1978). The exception to this proportionality rule is the PPDF stand, whose strong understory of Douglas-fir resulted in a bi-modal canopy fuel profile that was unique among the study stands. In the PPDF stand, commercial thinning with a commercial limit and crown thinning were resulted in drastically different *CBD* values than the strict low thinning, because it was the dense understory layer that dominated the *CBD* estimates. The rule of proportionality, therefore, only applies to the uni-modal stands in the study.

In stands without an understory, the initial reduction of BA has little effect on reducing *CBD* or *CFL* because the small trees removed first in a low thinning have little biomass, and what biomass they do have occurs below the layers of maximum density. In contrast, *CBD* and *CFL* may be reduced with only small reductions in BA in stands with a substantial under- or middle-story, because in those stands, the layers of maximum density occur lower in the canopy.

The proportionality rule described above does not apply to *CBH*--whether the small trees in a stand remain or are removed has a significant effect on *CBH*. In fact, *CBH* remained essentially unchanged in the crown thinning and low thinning with commercial limit treatments, whereas a strict low thinning increased *CBH* significantly.

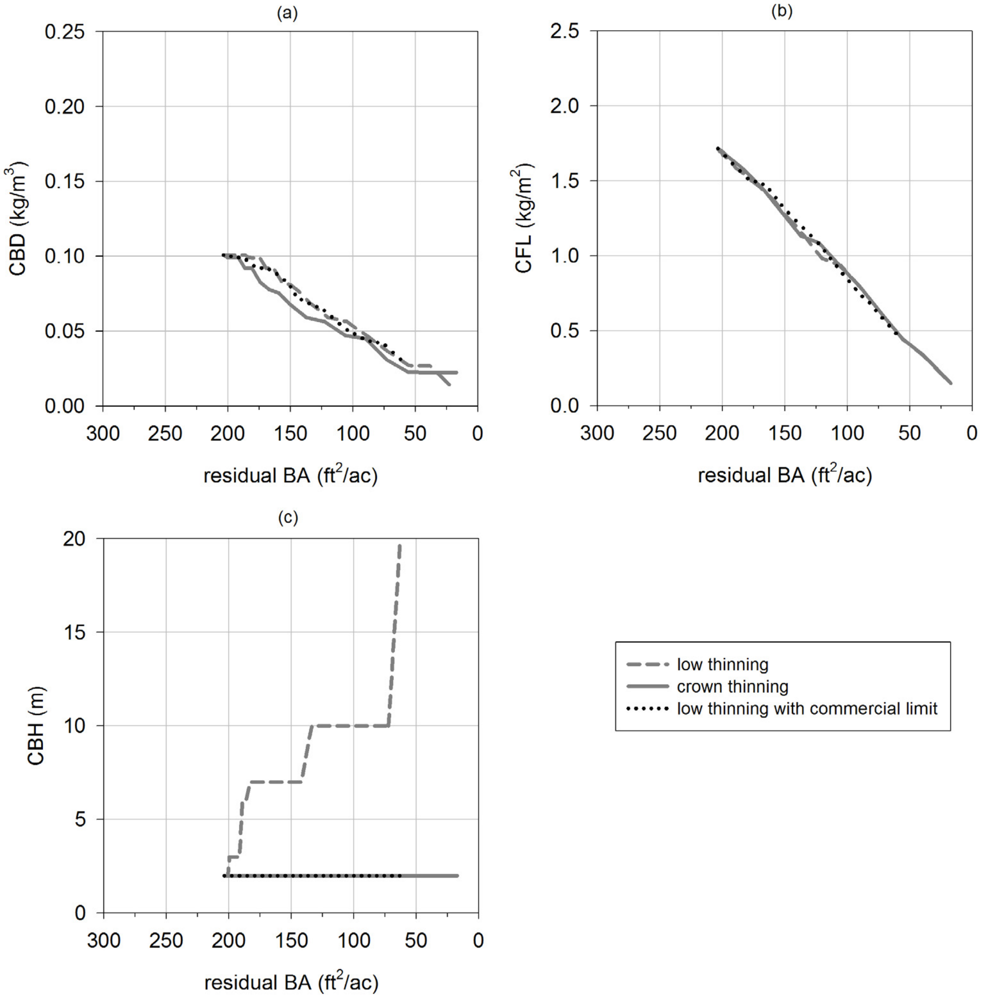

Figure 8—Response of (a) canopy bulk density (*CBD*), (b) canopy fuel load (*CFL*), and (c) canopy base height (*CBH*) to variable-intensity low thinning, low thinning with commercial limit, and crown thinning in the Sierra Nevada Mixed Conifer stand.

Due to the wide range of initial stand structures among stands, removing trees to a prescribed diameter limit has no predictable effects on canopy characteristics. Diameter-limit cutting is a convenient marking guideline but a poor prescription variable. Therefore, a canopy fuel treatment analysis should not specify a diameter-limit harvest. However, a low thinning can be marked as a diameter-limit cut if stand-specific structure is taken into account.

Mechanical pruning has little effect on *CBD* and *CFL* in the practical range of manual application (up to about 3m). The layers of maximum bulk density occur higher in the canopy, so little of the total canopy fuel load occurs within reach of mechanical pruning. Pruning can only affect *CBD* if pruning height reaches into the layers of maximum density, which is practically not possible if pruning is accomplished manually. Pruning has a predictable (linear) effect on *CBH:* it is always raised to pruning height unless it already exceeds pruning height.

Scorch from a prescribed fire has two effects on canopy fuel. First, scorch simulates the mechanical pruning by removing available fuel from scorched branches. Second, fire-caused mortality may further affect canopy fuel characteristics by removing available fuel from the canopy above the scorch height. Because fire-caused mortality is a function of species and tree diameter, the strength of this secondary effect depends in part on initial stand structure and composition.

Although we cannot draw general conclusions regarding the effects of these treatments on potential fire behavior, we can make inferences regarding their effects on canopy fuels. Stands with shade-tolerant understories, like the PPDF stand in this study, must be treated differently than single-cohort stands. Canopy base height will often be very near the ground, and will usually result directly from the contribution of the understory rather than the overstory. Therefore, any treatment that does not remove or drastically reduce this canopy layer (for example, crown thinning and commercial thinning) cannot raise *CBH*. Also, this understory layer may often contain the dense canopy layers that determine *CBD*, as the PPDF stand did. In that case, crown and commercial thinning will not decrease *CBD*. Low thinning (including removal of non-commercial trees) and prescribed burning would both be effective at reducing *CBD* and raising *CBH* in such stands. Crown and commercial thinning could be effective if coupled with a prescribed fire aimed at removal of the understory through fire-caused mortality.

More silvicultural tools may be appropriate for management of canopy fuels in single-cohort stands. Crown thinning and commercial low thinning are both effective at reducing *CBD* and *CFL* in these stands, but do not reduce *CBH*. Crown and commercial low thinning are less costly than strict low thinning, so more land area could be treated for the same investment, a potential advantage over strict low thinning. The lack of increase in *CBH* may be tolerable if *CBH* is already high enough, or if the thinning is combined with either prescribed burning or mechanical pruning to raise *CBH*.

This analysis focuses on effects of alternative treatments on canopy fuels, not their effects on fire potential. Each treatment may also affect (positively or negatively) other factors affecting potential fire behavior, including surface fuel characteristics, dead surface fuel moisture content, and wind adjustment factor (ratio of eye-level wind speed to 20-ft wind speed). Thinning a forest canopy generally results in lower dead surface fuel moisture and increased eye-level wind speed. Also, activity fuel from thinning or pruning may result in increased fuel load, unless mitigated as an integral part of the treatment. These side-effects of canopy fuel treatments must be considered when determining the overall effect of a treatment on potential fire behavior. Also, this analysis does not address the potential cost efficiency of each treatment. Because funding for fuel treatment is limited, land managers would presumably choose treatments that offer the most benefit for their cost. Quantifying the net cost of fuel treatment is a relatively simple task. Quantifying the benefit, however, is a much more difficult and abstract endeavor. Clearly, this analysis of the effects of alternative treatments on canopy fuel characteristics is but a small first step toward that goal.

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