# Biomass of Coniferous Understory Trees in Crater Lake National Park, Oregon

by

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Fall 1981
CPSU/UW 82-1

# PREFACE

Biomass by diameter size classes of five understory coniferous tree species in southern Oregon was estimated using regression equations. Species included white fir *(Abies concolor)*, Shasta red fir *(Abies magnifica* var. *shastensis)*, lodgepole pine *(Pinus contorta)*, ponderosa pine *(Pinus ponderosa)*, and mountain hemlock *(Tsuga mertensiana)*. Trees ranged up to 3 m tall and were selected from "open" and "dense" overstory classes. Estimates of biomass, segregated into foliar, 0-0.63 cm live, 0.64-2.53 cm live, 2.54-7.61 cm live, 7.62-20.32 cm live, 0-0.63 cm dead, and 0.64-2.53 cm dead diameter size classes, were made using as independent variables groundline diameter, total height, diameter$^2$ x ht, and basal area. Coefficients of determination ($R^2$) were high, exceeding 95 percent for total biomass in every case. Coefficients of determination tended to be lower as diameter size class increased. Tree age was predicted much less precisely than biomass. A simplified procedure using tree height to predict biomass is presented for management application.

The author thanks the staff of Crater Lake National Park, particularly Dan Sholly and Mark Forbes, for coordinating space and field assistance on this project. The following people provided field and laboratory assistance: R. Scott Berg, Roberta Chapman, John Davis, Shannon Downey, Lora Isberg, and Robert Wagner. Major assistance in data analysis was provided by Robert Flewelling. Production of the publication was coordinated by Nadyne Snyder.

# BIOMASS OF CONIFEROUS UNDERSTORY TREES IN CRATER LAKE NATIONAL PARK, OREGON

Forest fuel inventories have traditionally concentrated on dead and down fuels because these are the predominant classes of available fuel in most prescribed fires and many wildfires. However, low intensity prescribed fires can create as well as consume fuels, primarily by causing mortality of understory trees. The biomass and fuel size class distribution of understory trees are not well documented, although dead fuels created in initial fires can significantly affect the fire behavior of reburns. This report investigates the biomass of five common understory trees in southern Oregon. The study objectives were to: 1) determine biomass of several species of understory trees by diameter size classes; and 2) relate the measured biomass values to easily measured tree characteristics.

## MATERIALS AND METHODS

The study area was within Crater Lake National Park, located within the southern Cascade Range in Oregon (Figure 1). Sample elevations ranged from 1400 to 1900 m. Five of the most common understory tree species that would be affected by prescribed or prescribed natural fires were chosen for analysis: white fir *(Abies concolor* (Gord. & Glend) Lindl.*)*, Shasta red fir *(Abies magnifica* Murr. var. *shastensis* Lemm*)*, ponderosa pine *(Pinus ponderosa* Dougl.*)* lodgepole pine *(Pinus contorta* Dougl. var. *murryana* Grev. & Balf.*)*, and mountain hemlock *(Tsuga mertensiana* (Bong.) Carr.*)*.

Species, height class, and overstory class were controlled in the experimental design. For each of the five species, three height classes were defined: 0-1 m, 1-2 m, and 2-3 m. Subjectively chosen "open" and "closed" overstory classes were also defined, as a factor that might influence biomass of a given height class of a species through nutrient, light, and moisture competition. Five replications of each species within a given overstory density and height class were collected, for a total of 30 trees per species and 150 trees overall.

White fir trees were sampled from *Abies concolor* habitat types dominated by ponderosa pine and white fir. Lodgepole pine and Shasta red fir were sampled from the upper boundary of *Abies concolor* habitat types into *Tsuga mertensiana* habitat types. Lodgepole pine is clearly a seral component of these communities; Shasta red fir has been described as both seral and climax in this area (Franklin and Dyrness, 1973). Mountain hemlock was sampled from *Tsuga mertensiana* habitat types and ponderosa pine was collected in *Pinus ponderosa* habitat types.

Within a given sample location, open and closed canopy areas were located and trees were chosen to fit into the selected height classes. A selected tree

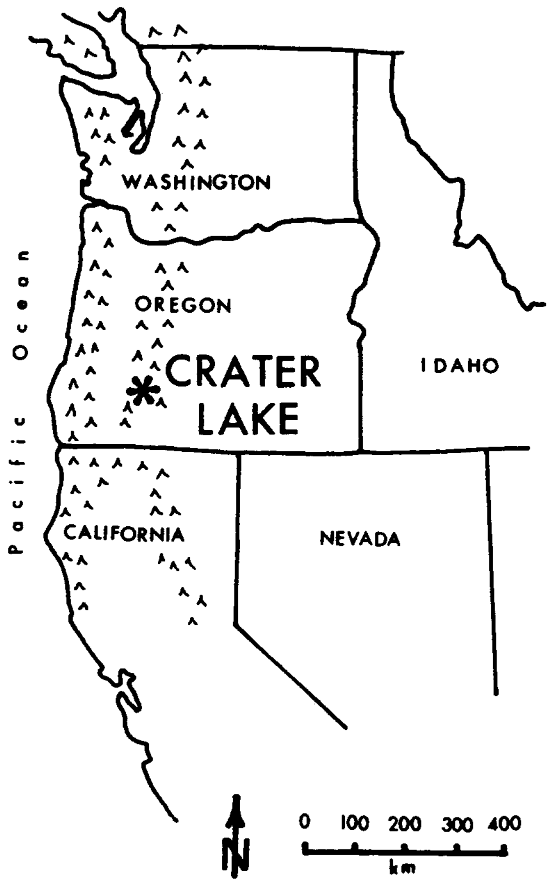


Figure 1. Crater Lake National Park, Oregon.

was excised and basal diameter (to 0.1 cm) and height (to 0.1 m) were measured. Basal area was measured with a 10 factor metric prism from the stump of the excised tree to provide later quantification of the overstory classification. The excised tree was then segregated into the following diameter size classes:

Live fuels: foliage; 0-0.63 cm; 0.64-2.53 cm; 2.54-7.61 cm; and 7.62-20.32 cm

Dead fuels: 0-0.63 cm; 0.64-2.53 cm

The size classes correspond to fuel moisture timelag classes in the National Fire-Danger Rating System (Deeming _et al._, 1977). Although live fuels were segregated into these fuel moisture timelag size classes, they do not, as live fuels, exhibit the timelags which apply to the moisture relations of dead fuels only. Samples were bagged and carried to the laboratory for dry weight determination; no subsampling was attempted.

Most fuel size class segregation was completed in the field, but some needle segregation was completed in the laboratory. Samples were oven-dried at 65 degrees C for a minimum of 48 hours; the larger fuel sizes (up to 9.5 cm diameter) were dried for at least 120 hours after being air-dried for at least 60 days. The basal section of each tree was aged using a dissecting scope.

The analysis was conducted in two phases. The first phase was designed to test the significance of species, height class, and overstory class on the dependent variable, oven-dry biomass. A balanced, three-way ANOVA with 5 replications per cell was employed for three dependent variable combinations: live foliar biomass, all live fuel, and total biomass. These results were then used to see which species could be lumped for biomass prediction regressions and which independent variables might best be used in the regressions. Logarithm transformations (base 10) were made to meet the ANOVA assumptions, as unequal variances existed in the untransformed data. Orthogonal contrasts were computed to differentiate the species' main effects. Results are significant at alpha $\leq$ 0.05.

Linear regression analyses for biomass prediction were done using a combination of additive, multiplicative, and natural logarithmic transformations to normalize the data and correct for nonhomogeneous variance. These transformations are listed with the individual equations. Dependent variables (Y) were biomass of individual or combined fuel classes, and age; independent variables (X) included ground diameter, total height, a combination of diameter and height, and point estimates of basal area (BA). All intercept (a) values listed for ln-ln equations were adjusted for logarithmic bias (Baskerville, 1972) by adding the correction term ($S^2_{Y \cdot X}/2$). The general forms of the biomass equations are:

$$\ln Y = a + b \ln X$$

$$\ln Y = a + b_1 \ln X_1 + b_2 \ln X_2$$

# RESULTS

The aboveground biomass for the five species, segregated by overstory density, height class, and diameter size class is shown in Table 1. Foliage was separated from other live 0-0.63 cm diameter fuels because of its different chemical composition affecting combustion, and a higher probability of detachment from the other classes of fuel after crown scorching by fire. Foliar biomass averaged about one-third of total live aboveground biomass, with higher proportions in small trees and lower proportions in the 2-3 m height class. Attached dead fuels on these live trees usually comprised less than 10 percent of total aboveground biomass. There were only small quantities of live fuels in the greater-than-7.6 cm diameter size class and small amounts of dead fuels exceeding 0.64 cm diameter. Average physical dimensions, stand basal area, and age of sample trees are shown in Table 2.

## Analyses of Variance

The three way complete analysis of variance for foliar biomass indicated that the main effects were all significant, as well as the species-overstory density interaction. Orthogonal contrasts defined in advance of analysis showed that white fir foliar biomass exceeded that of red fir, and the two fir species foliar biomass exceeded that of the two pines. There were no differences between the two pines or between red fir and mountain hemlock. Trees grown in open stands had significantly more foliar biomass than trees grown under dense canopies. As expected, taller trees had more foliar biomass than shorter ones. The significance of the species-overstory interaction suggests that the foliar biomass of some species reacts differently to a change in stand density. Foliar biomass of the pines and firs increased with decreasing stand basal area. Foliar biomass of mountain hemlock was relatively stable over a wide range of stand basal area.

The sum of all live fuel classes showed significant biomass differences between density and height classes, but not between species; no interactions were significant. The total of all fuel classes had significant biomass differences for all three main effects. Orthogonal contrasts on the species main effect indicated that the total aboveground biomass of the two fir species combined exceeded that of the two pine species combined.

## Biomass Regressions

The analyses of variance indicated that aboveground biomass for a given species was affected by height and the subjective "open" and "dense" overstory density class. Other work has suggested that groundline diameter is a useful biomass predictor (Edwards and McNab, 1979). Diameter at breast height was not used here because roughly half of the trees were below that height. The independent variables chosen for biomass regressions were natural logarithms of: tree height times 10 (nearest 0.1 m); groundline diameter times 10 (nearest 0.1 cm); the square of groundline diameter times 10 multiplied by the height times 10; and basal area of stand plus one in $m^2$/ha.

The dependent biomass variables were also transformed to natural logarithms after 1 g was added to each value to avoid zeros in the data. The five biomass categories for each species were:

(live foliage + 1)

(all live fuels between 0-0.63 cm + 1)

(live fuels between 0.64-2.53 cm + 1)

(live fuels between 2.54-20.32 cm + 1)

(total aboveground biomass + 1)

Regressions were individually calculated for "dense" and "open" overstory classes, and for combined overstory classes when basal area was added as a second independent variable. Segregation by overstory class was not done for mountain hemlock because of the analysis of variance results. Equations for each fuel class are presented in Tables 3-7. The single independent variable with the best goodness-of-fit is displayed, along with the multiple regression where basal area has been added. As with most regressions, the use of very low values of the independent variable may give unrealistic values of biomass.

Foliar biomass (Table 3) is best predicted by groundline diameter. Mountain hemlock is the only species where height consistently provided a better fit to the data. The close relationship between foliar biomass and basal diameter is consistent with the findings of Grier and Waring (1974); they found a high correlation between foliage mass of conifers and sapwood basal area. For the trees sampled here, most of the wood is sapwood, so that groundline diameter can be considered an index of sapwood diameter.

When foliar biomass is combined with other live fuels in the 0-0.63 cm diameter size class (Table 4), groundline diameter is again the best prediction in the majority of cases; only mountain hemlock is better predicted by height. The volumetric variable, diameter$^2$ times height, is the best predictor in 7 of the 20 equations.

The live fuel biomass in the 0.64-2.53 cm diameter class is best predicted by volume or height (Table 5). These fuels are larger branch or upper stem components, so that height of the tree should be a good predictor of the biomass of this size class.

The biomass of the 2.54-20.32 cm diameter size class is best predicted by groundline diameter (Table 6). There were some zero values in these categories for the smaller trees, so that goodness-of-fit values were considerably lower than for the other fuel classes. For the larger trees, the basal section is included in this class, so groundline diameter is expected to be the best predictor of the largest sizes of biomass.

Total aboveground biomass is best predicted by an index of volume (Table 7). Only for mountain hemlock is height a best predictor. In all cases, goodness-of-fit exceeded 95 percent; less than 5 percent of variance was unexplained by the equation.

Application of the best-fit equation will provide the most precise estimation of biomass, but for many purposes the procedure will be cumbersome, requiring measurement of height, basal diameter, or both. Because height (or height class) is most easily measured, a listing of biomass equations using height as the independent variable is provided in Table 8.

The goodness-of-fit by species for open and dense overstory group equations tended to encompass the fit obtained by pooling the data within species and using stand basal area as a second independent variable. For some species, there was little difference between the separate and pooled $R^2$ values. Where a wide range in goodness-of-fit existed between equations for open-grown and dense understory-grown trees, the pooled data tended to average the fit with the addition of a point estimate of basal area. For example, the foliar biomass $R^2$ for dense understory grown lodgepole pine was 0.70; using a pooled data set and stand basal area increased the $R^2$ to 0.85. Conversely, using the pooled equation for open grown lodgepole decreased $R^2$ from 0.95 to 0.85.

## Age Regressions

Similar regression techniques were employed to predict age of trees from physical dimensions. Age data were not transformed, and basal area was used untransformed and with a natural logarithm transformation. Using thirteen different groups of tree ages segregated by species and overstory density (Table 9), the same combinations of independent variables used for biomass estimation were regressed on the age data.

The fit of the equation is generally much lower than for the biomass equations. The range of $R^2$ for the several equations calculated for each combination of species and density (Table 7) was 0.20-0.96; only four groups had $R^2$ exceeding 0.80. Equations for the best set of variables for each group are shown on the right side of the table.

It is apparent that the age of small understory trees in this study can be only generally estimated from commonly measured physical dimensions. Trees in the 0-3 m height range growing under dense canopies were more precisely aged than open grown trees, which is surprising given the stagnation and erratic growth often associated with understory trees in dense forests. However, the equations are of marginal utility even for local application, and extrapolation to other areas is not recommended.

# DISCUSSION

There are relatively few studies comparing the biomass of the selected understory conifer trees, and few comparisons can be drawn. The only directly comparable equations are those from Brown (1978); total aboveground biomass as a function of height was presented for dominant ponderosa pine, grand fir *(Abies grandis* (Dougl.) Forbes*)*, and lodgepole pine in the Rocky

Mountains. Grand fir is closely related to white fir and the two are difficult to distinguish in Oregon. Graphical comparison (Figures 2, 3, 4) shows the biomass of the Rocky Mountain trees to be intermediate between "open" and "dense" grown southern Cascade trees. The equations may thus represent a broader range of habitats than the sample locations indicate. The most comprehensive set of biomass equations for Pacific Northwest plants (Gholz et al., 1979) uses pooled data sets or data from areas outside Oregon and Washington, but note that care must be taken to evalate the applicability of an equation to a specific site separated from the sample site. The caution also applies to the equations in this study.

Biomass of trees is often estimated using sample trees that are open-grown dominants. Using Brown's (1978) data for small trees grown in shaded environments would overestimate total biomass by a factor of 2 to 5 (Figure 2). Knowledge of the specific microsite as well as the general habitat will enable more precise biomass prediction.

The biomass equations show generally decreasing goodness-of-fit as fuel size classes become larger. Over the same series of size classes reported here, Brown (1976) found coefficients of determination for biomass and branch diameter regressions to decrease from 0.93 to 0.82, for eleven western conifers including lodgepole and ponderosa pine. In both studies there were fewer observations in the larger size classes. The shade tolerant species in this study (white fir, Shasta red fir, mountain hemlock) tended to have higher foliar biomass than shade intolerant species (lodgepole pine, ponderosa pine), which is also true of most of the species that Brown (1976) studied, except ponderosa pine.

Prediction of age from size characteristics is difficult, even for the relatively small ranges in size included in this study. Oliver (1981) has reviewed the relation of tree age to stand architecture and concluded that a narrow range of tree ages can display the vertical and diameter distribution normally associated with all-age forests. Conversely, stems of similar height and diameter may represent significantly different ages.

Relative shade tolerance of species can be estimated by comparing the foliar biomass of trees grown in shaded and open environments. The average foliar biomass by species in dense overstory and open overstory conditions, and the ratio of dense to open foliar biomass, is shown in Table 10. Mountain hemlock has a ratio approaching 1.0, suggesting it is able to maintain leaf area quite well in shade. Shasta red fir has a much lower ratio, followed by white fir, ponderosa pine, and lodgepole pine. This ranking differs slightly from the rankings of Minore (1979) who reviewed autecological characteristics of northwestern tree species (Table 10, right column). The rankings of the two fir species and the two pine species are reversed.

The ratio of Shasta red fir is almost twice that of white fir, yet from Minore's ranking it is less shade tolerant and should maintain relatively less leaf area in the shade than in the open. The successional patterns of Shasta red fir are not well documented. It has been described as climax in some areas and seral to white fir or to mountain hemlock elsewhere (Franklin and Dyrness, 1973). In the locations at Crater Lake where it was sampled,

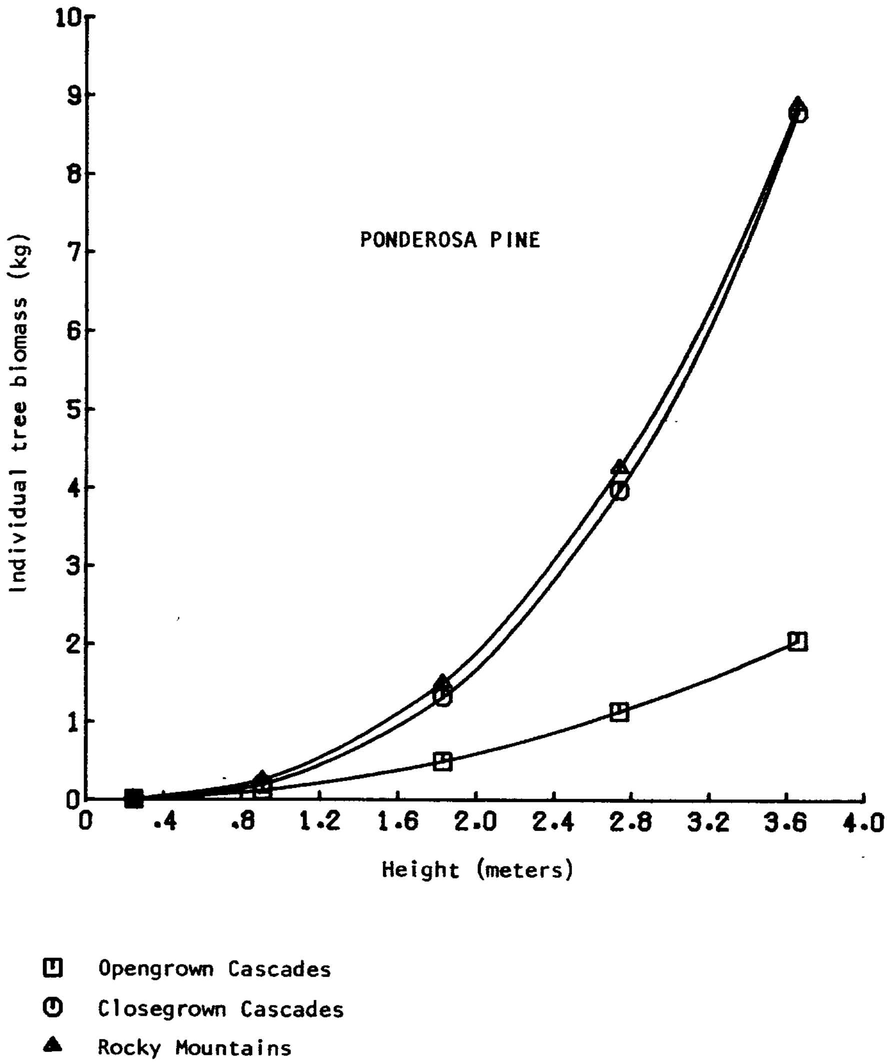


Figure 2. Tree biomass vs. height - ponderosa pine.

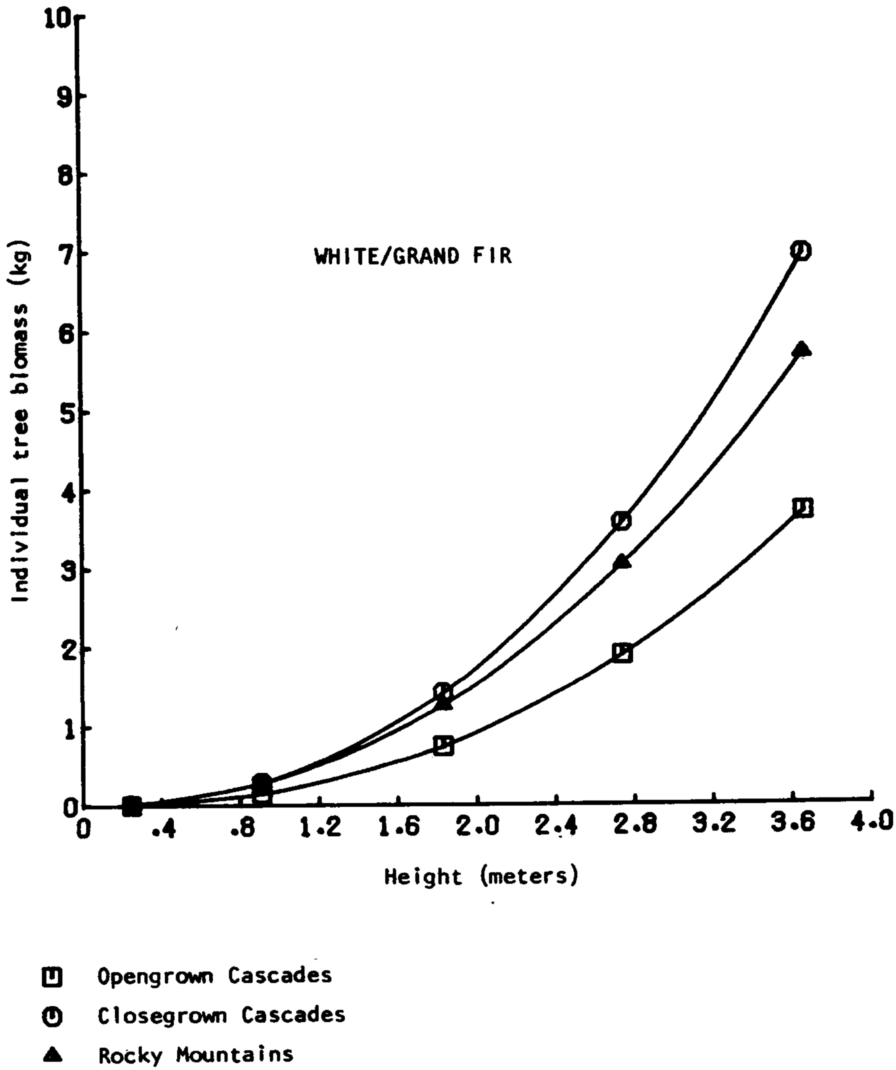


Figure 3. Tree biomass vs. height - white/grand fir.

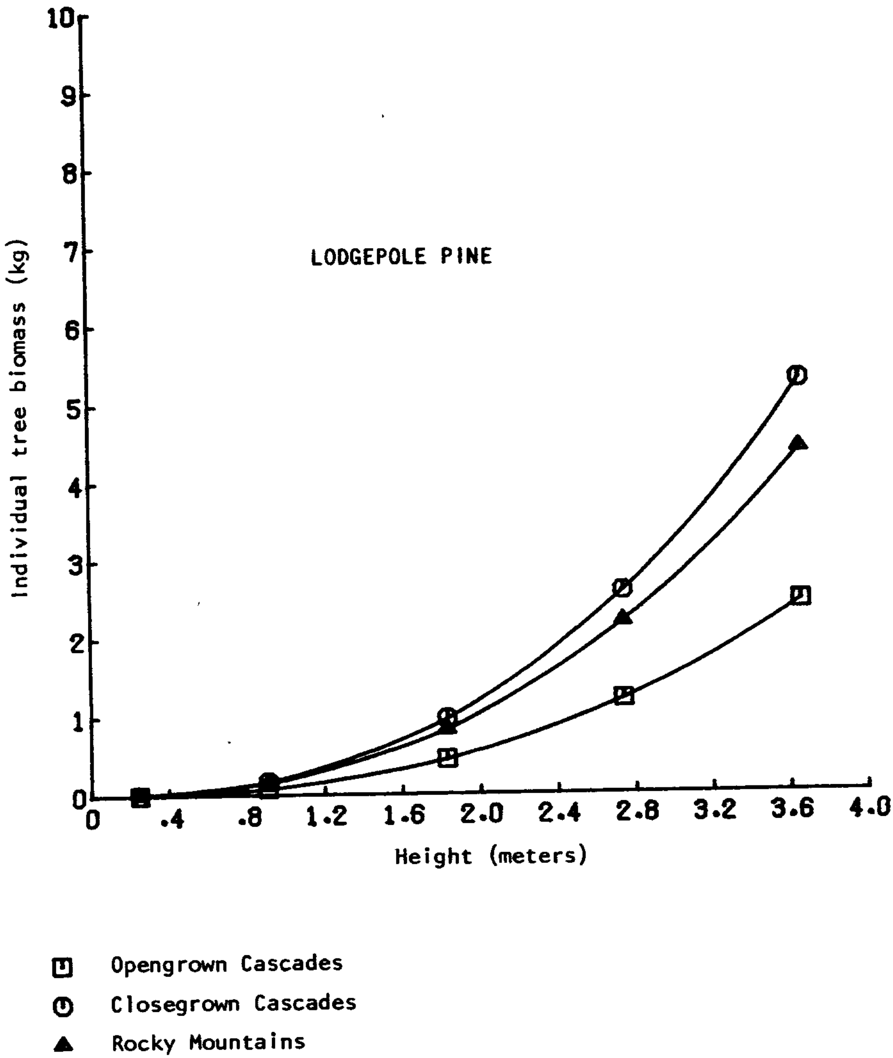


Figure 4. Tree biomass vs. height - lodgepole pine.

Shasta red fir appears to have moderately high shade tolerance based on its ability to maintain leaf area under shade. This also suggests, due to a partial association of shade tolerance and climax status, that Shasta red fir may be a climax dominant in this area.

The ratio reversal of ponderosa and lodgepole pine foliar biomass is probably due to the specific sampling locations. The lodgepole pine samples were collected in a stand where it is seral to mountain hemlock, while the ponderosa pine samples were collected in a climax stand of ponderosa pine. For similar basal areas where overstories were dense, the hemlock stand appeared to provide much more shade, reducing the foliar biomass of shaded understory lodgepole pine and also the foliar biomass ratio. Had ponderosa pine samples been collected in stands where white fir is climax, a similar reduction in foliar biomass of the pine might have occurred. The ratios of ponderosa pine and lodgepole pine are, therefore, not directly comparable, and the foliar biomass ratio reversal is not of major significance.

The white fir foliar biomass ratio is only slightly above that of ponderosa pine when both are sampled from areas where they are climax dominants. This suggests that white fir, commonly observed to grow in doghair thickets in mixed conifer forest understories, may be less shade tolerant than it often is assumed to be. In Montana, where grand fir appears to have an ecological role similar to white fir, most understory trees from 1-4 m tall are between 40-120 years old (Antos and Habeck, 1981). They are able to survive, but grow very slowly; new establishment is limited to openings in the stand. Similar age structures were found in this study (Table 2). Much of the white fir reproduction seems to have originated in a period of several decades after fire suppression became effective and stands were relatively open. Since the time of understory closure, light and moisture competition have all but eliminated further tree establishment.

## MANAGEMENT APPLICATIONS

In many management applications, the degree of precision from a best-fit equation may be less useful than a more easily applied equation with only a good fit. Because height class is the easiest and quickest measure, it is the tree characteristic used below to estimate understory tree biomass, even though for most species studied it gives a good but not best fit to the biomass data.

The methodological scheme outlined below is but one of several ways that biomass estimation may be approached. It is one of the broadest and least precise methods but is also fairly simple to apply. It can be integrated with measures of dead and down fuel (Brown, 1974) and litter or duff depth/mass regressions (Agee, 1973) to provide estimates of available fuel and created fuel from prescribed fires.

Field Sampling

In this example, 20 plots in mixed conifer forest comprise the sample. It will usually be better to sample a larger number due to variability in understory tree density. Each square fixed plot is 3 m on a side. Basal area of the stand is estimated with a prism from the center of the fixed 9 $m^2$ plot; however, the prism sampling is not constrained by the fixed-plot boundaries. Understory trees are tallied by a grouped species (pines or firs) and by 1 m height classes within each plot. The data are shown in Table 11.

Biomass Estimation

The biomass is estimated by the height-biomass regressions using the combined pine and combined fir equations by overstory density class (Table 8). The procedure involves: 1) separating plots into "open" or "dense" overstories; 2) summing the number of pines and firs by height class in each overstory class; 3) calculating an average tree biomass within each category identified under (2); and 4) computing average biomass per unit area.

1. *Separation of plots.* The criteria for open and dense overstories is basal area of the stand. In this study areas classed as "open" tended to have basal areas below 45 $m^2$/ha, and "dense" stands had basal areas above 45 $m^2$/ha. Therefore, the sample data here was segregated using this criterion; 11 plots were classed as "open" and 9 were "dense."

2. *Summing the data.* The data grouped by species and height class are shown in Table 12.

3. *Computing an average tree biomass by category.* These are 12 categories shown in Table 12, and it is necessary to calculate an average tree biomass for each category. This can then be multiplied by the number of trees in each category to compute total biomass. The equations to be used are at the bottom of Table 8: both pines dense, both pines open, both firs dense, and both firs open. A sample calculation for the 0-1 m height class, dense overstory, both firs equation is shown below:

Equation: $\ln Y = -0.0628 + 2.3576 \ln(X2)$

where $Y$ = biomass (g) + 1

$X2$ = tree height times 10

In this example the mean of the height class, 0.5 m, is used to represent the average height of the trees tallied in this category.

Then,

$$h = 0.5 \text{ m}$$

$$(X2) = 5$$

$$\ln(X2) = 1.6094$$

and,

$$\ln(Y) = -0.0628 + 2.3576\ (1.6094)$$
$$\ln(Y) = 3.7315$$
$$Y = 41.74$$

so biomass is equal to 40.74 g for the average 0-1 m height class tree. Similar calculations are done for each category, resulting in the average per tree biomass shown in Table 13.

4. *Computing average biomass per unit area.* The total biomass on "open and "dense" plots is obtained by multiplying the figure in Table 12 by the equivalent category figures in Table 13.

For this example, total biomass is shown in Table 14. This must be converted to an area basis by dividing by the area of all plots within that overstory class. In this example, there were 11 "open" plots and 9 "dense" plots. Because each plot is 9 $m^2$, total area in "open" plots is 99 $m^2$ and total area in "dense" plots is 81 $m^2$. When the totals shown in Table 14 are divided by these figures, the average biomass per unit area is 872 $g/m^2$ for "open" areas and 417 $g/m^2$ for "dense" areas. A weighted average for the entire area can be calculated if the chosen plots represent the actual proportions of the area in "open" and "dense" overstories: $872(.55) + 417(.45) = 667\ g/m^2$.

This figure can then be used as an estimate of the total biomass. On a first burn, very little understory tree biomass will be consumed, but can be considered a biomass transfer from live to dead fuel, depending on scorch height and damage to roots.

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Table 1. Aboveground oven-dry biomass (g) by diameter size class.

| Species | Overstory Density* | Height Class** | Foliage | Other Live 0-0.63cm Fuel | Live 0.64-2.54cm Fuel | Live 2.54-7.61cm Fuel |
|---|---|---|---|---|---|---|
| White Fir | D | 1 | 4.5 | 4.4 | 11.5 | 0 |
| | O | 1 | 34.3 | 12.8 | 24.4 | 0 |
| | D | 2 | 88.3 | 64.5 | 132.7 | 80.9 |
| | O | 2 | 331.4 | 163.5 | 90.0 | 243.8 |
| | D | 3 | 256.5 | 171.4 | 151.5 | 1048.7 |
| | O | 3 | 743.3 | 369.6 | 199.3 | 1481.0 |
| Shasta Red fir | D | 1 | 32.4 | 13.1 | 34.6 | 0 |
| | O | 1 | 49.0 | 25.9 | 48.5 | 11.6 |
| | D | 2 | 158.0 | 82.8 | 170.1 | 158.7 |
| | O | 2 | 272.8 | 153.3 | 136.0 | 250.0 |
| | D | 3 | 295.9 | 166.6 | 206.2 | 1301.7 |
| | O | 3 | 534.7 | 265.2 | 286.1 | 1656.2 |
| Lodgepole Pine | D | 1 | 8.7 | 8.1 | 13.5 | 0 |
| | O | 1 | 20.4 | 8.3 | 16.9 | 0 |
| | D | 2 | 39.4 | 35.4 | 196.1 | 59.7 |
| | O | 2 | 127.6 | 94.0 | 123.2 | 170.9 |
| | D | 3 | 48.0 | 84.3 | 304.5 | 383.2 |
| | O | 3 | 465.4 | 283.6 | 179.2 | 1430.7 |
| Ponderosa Pine | D | 1 | 4.6 | 5.9 | 8.0 | 0 |
| | O | 1 | 14.7 | 7.9 | 20.6 | 0 |
| | D | 2 | 49.6 | 35.4 | 137.6 | 97.6 |
| | O | 2 | 171.6 | 69.9 | 144.5 | 393.5 |
| | D | 3 | 99.5 | 79.4 | 236.5 | 503.3 |
| | O | 3 | 438.9 | 154.2 | 273.0 | 1421.3 |
| Mountain Hemlock | D | 1 | 32.4 | 11.0 | 20.9 | 0 |
| | O | 1 | 15.3 | 8.8 | 9.4 | 0 |
| | D | 2 | 118.7 | 91.7 | 150.5 | 109.7 |
| | O | 2 | 143.0 | 138.7 | 158.9 | 127.3 |
| | D | 3 | 423.9 | 267.1 | 204.5 | 1172.6 |
| | O | 3 | 421.5 | 290.7 | 292.6 | 884.6 |

Table 1. continued.

| | Live 7.62-20.32cm Fuel | All Live Fuel | Dead 0-0.63cm Fuel | Dead 0.64-2.53cm Fuel | All Fuel |
|---|---|---|---|---|---|
| | 0 | 20.4 | 4.0 | 0 | 24.4 |
| | 0 | 71.5 | 0.7 | 0 | 72.2 |
| White Fir | 0 | 366.4 | 45.1 | 0 | 411.6 |
| | 0 | 828.8 | 18.5 | 0 | 847.3 |
| | 0 | 1628.2 | 103.8 | 6.0 | 1738.0 |
| | 86.4 | 2879.3 | 124.0 | 7.5 | 3010.8 |
| | 0 | 80.0 | 4.5 | 0 | 84.6 |
| | 0 | 135.0 | 7.5 | 0 | 142.5 |
| Shasta Red fir | 0 | 569.5 | 39.6 | 0 | 609.1 |
| | 0 | 812.1 | 27.5 | 0 | 839.6 |
| | 0 | 1970.4 | 94.4 | 11.9 | 2076.7 |
| | 1054.0 | 3796.2 | 148.7 | 29.9 | 3974.8 |
| | 0 | 30.4 | 0.6 | 0 | 30.9 |
| | 0 | 45.7 | 0.1 | 0 | 45.8 |
| Lodgepole Pine | 0 | 330.6 | 11.3 | 0 | 341.9 |
| | 0 | 515.8 | 21.2 | 1.3 | 538.3 |
| | 0 | 819.9 | 36.8 | 0 | 856.7 |
| | 0 | 2358.9 | 100.7 | 0 | 2459.6 |
| | 0 | 18.5 | 2.5 | 0 | 21.1 |
| | 0 | 43.2 | 0.1 | 0 | 43.3 |
| Ponderosa Pine | 0 | 320.2 | 13.7 | 0 | 333.9 |
| | 0 | 779.5 | 12.1 | 4.1 | 795.7 |
| | 76.7 | 995.5 | 57.8 | 11.7 | 1065.0 |
| | 0 | 2287.4 | 103.5 | 28.0 | 2418.9 |
| | 0 | 64.3 | 1.6 | 0 | 66.0 |
| | 0 | 33.5 | 3.6 | 0 | 37.1 |
| Mountain Hemlock | 0 | 470.4 | 23.9 | 0 | 494.6 |
| | 0 | 568.0 | 20.0 | 0 | 588.0 |
| | 0 | 2068.2 | 63.9 | 4.3 | 2136.3 |
| | 0 | 1889.4 | 56.9 | 0 | 1946.3 |

*D = dense overstory, generally exceeding 45 $m^2$/ha basal area;
O = open understory, basal area generally below 45 $m^2$/ha.

**height class 1 = 0-1 m; height class 2 = 1-2 m; height class 3 = 2-3 m.

Table 2. Average groundline diameter, height, stand basal area, and age of sample trees.

| Species | Overstory Density | Height Class* | Groundline Diameter (cm) | Total Height (m) | Stand Basal Area ($m^2$/ha) | Age (Yrs.) |
|---|---|---|---|---|---|---|
| White Fir | Dense | 1 | 0.82 | 0.48 | 51 | 10.8 |
| | Open | 1 | 1.02 | 0.50 | 27 | 15.6 |
| | Dense | 2 | 2.74 | 1.38 | 87 | 34.8 |
| | Open | 2 | 3.68 | 1.46 | 9 | 35.2 |
| | Dense | 3 | 4.64 | 2.56 | 78 | 67.5 |
| | Open | 3 | 6.42 | 2.56 | 28 | 79.8 |
| Shasta Red Fir | Dense | 1 | 1.34 | 0.52 | 81 | 37.4 |
| | Open | 1 | 1.90 | 0.52 | 16 | 25.5 |
| | Dense | 2 | 3.16 | 1.44 | 84 | 78.0 |
| | Open | 2 | 4.06 | 1.48 | 12 | 25.2 |
| | Dense | 3 | 5.64 | 2.52 | 70 | 78.4 |
| | Open | 3 | 7.20 | 2.52 | 26 | 80.8 |
| Lodgepole Pine | Dense | 1 | 0.86 | 0.58 | 54 | 29.6 |
| | Open | 1 | 1.08 | 0.56 | 0 | 9.6 |
| | Dense | 2 | 2.46 | 1.50 | 42 | 53.2 |
| | Open | 2 | 3.34 | 1.50 | 18 | 42.0 |
| | Dense | 3 | 3.18 | 2.54 | 88 | 66.0 |
| | Open | 3 | 5.88 | 2.48 | 28 | 53.8 |
| Ponderosa Pine | Dense | 1 | 0.98 | 0.52 | 63 | 22.4 |
| | Open | 1 | 1.26 | 0.56 | 18 | 27.0 |
| | Dense | 2 | 3.12 | 1.58 | 48 | 53.6 |
| | Open | 2 | 4.84 | 1.44 | 21 | 61.8 |
| | Dense | 3 | 4.86 | 2.52 | 104 | 65.8 |
| | Open | 3 | 7.92 | 2.42 | 14 | 60.0 |
| Mountain Hemlock | Dense | 1 | 1.40 | 0.68 | 67 | 27.6 |
| | Open | 1 | 1.90 | 0.50 | 16 | 23.0 |
| | Dense | 2 | 3.22 | 1.50 | 88 | 66.0 |
| | Open | 2 | 3.86 | 1.46 | 10 | 41.4 |
| | Dense | 3 | 5.50 | 2.46 | 92 | 68.4 |
| | Open | 3 | 5.58 | 2.52 | 28 | 41.8 |

Table 3. Best-fit equations for dry, aboveground foliar biomass (g)

| Species | Overstory Density | $R^2$ | N | $S^2Y\text{-}X$ | Equation* |
|---|---|---|---|---|---|
| White fir | Dense | 0.88 | 15 | 0.4090 | $\ln Y = -1.4059 + 1.802 \ln(X1)$ |
| | Open | 0.98 | 15 | 0.1044 | $\ln Y = -0.9338 + 0.6610 \ln(X3)$ |
| | Combined | 0.92 | 30 | 0.3121 | $\ln Y = -0.8159 + 1.9174 \ln(X1) -0.1969 \ln(X4)$ |
| Shasta Red fir | Dense | 0.96 | 15 | 0.0881 | $\ln Y = -1.1925 + 0.6316 \ln(X3)$ |
| | Open | 0.96 | 15 | 0.1027 | $\ln Y = -0.9356 + 0.6263 \ln(X3)$ |
| | Combined | 0.97 | 30 | 0.0926 | $\ln Y = -0.7453 + 0.6292 \ln(X3) -0.0921 \ln(X4)$ |
| Lodgepole pine | Dense | 0.70 | 15 | 0.5512 | $\ln Y = -1.1430 + 1.5001 \ln(X1)$ |
| | Open | 0.95 | 15 | 0.1709 | $\ln Y = -1.8756 + 1.9529 \ln(X1)$ |
| | Combined | 0.85 | 30 | 0.4836 | $\ln Y = -1.6996 + 1.9757 \ln(X1) -0.1647 \ln(X4)$ |
| Ponderosa pine | Dense | 0.93 | 15 | 0.1903 | $\ln Y = -2.1674 + 1.7412 \ln(X1)$ |
| | Open | 0.97 | 15 | 0.1052 | $\ln Y = -2.2205 + 1.8997 \ln(X1)$ |
| | Combined | 0.94 | 30 | 0.1867 | $\ln Y = -1.9329 + 1.8768 \ln(X1) -0.1261 \ln(X4)$ |
| Mountain hemlock | Combined | 0.91 | 30 | 0.2284 | $\ln Y = -0.0344 + 1.8572 \ln(X2)$ |
| | Combined | 0.91 | 30 | 0.2368 | $\ln Y = 0.0177 + 1.8584 \ln(X2) -0.0044 \ln(X4)$ |
| Both firs | Dense | 0.91 | 30 | 0.2491 | $\ln Y = -1.5660 + 1.8522 \ln(X1)$ |
| | Open | 0.95 | 30 | 0.1742 | $\ln Y = 0.6212 + 1.8299 \ln(X2)$ |
| | Combined | 0.93 | 60 | 0.2317 | $\ln Y = -0.4056 + 0.6336 \ln(X3) -0.1803 \ln(X4)$ |
| Both pines | Dense | 0.83 | 30 | 0.3571 | $\ln Y = -1.6677 + 1.6274 \ln(X1)$ |
| | Open | 0.94 | 30 | 0.1827 | $\ln Y = -1.5530 + 0.6554 \ln(X3)$ |
| | Combined | 0.89 | 60 | 0.3400 | $\ln Y = -1.6770 + 1.8927 \ln(X1) -0.1557 \ln(X4)$ |

*Y = foliar biomass + 1(g)
X1 = groundline diameter (cm) x 10
X2 = height (m) x 10
X3 = (groundline diameter x 10)$^2$ x (height x 10)
X4 = basal area + 1 ($m^2$/ha)

Table 4. Best-fit equations for dry, aboveground foliar plus other 0-0.63 cm dia. live fuel (g).

| Species | Overstory Density | $R^2$ | N | $S^2Y\text{-}X$ | Equation* |
|---|---|---|---|---|---|
| White fir | Dense | 0.92 | 15 | 0.2806 | $\ln Y = -1.1206 + 1.8632 \ln(X1)$ |
| | Open | 0.98 | 15 | 0.1048 | $\ln Y = -0.5980 + 0.6664 \ln(X3)$ |
| | Combined | 0.95 | 30 | 0.2186 | $\ln Y = -0.6538 + 1.9485 \ln(X1) -0.1531 \ln(X4)$ |
| Shasta Red fir | Dense | 0.97 | 15 | 0.0790 | $\ln Y = -0.9657 + 0.6498 \ln(X3)$ |
| | Open | 0.96 | 15 | 0.1266 | $\ln Y = -0.5501 + 0.6297 \ln(X3)$ |
| | Combined | 0.96 | 30 | 0.0986 | $\ln Y = -0.3983 + 0.6392 \ln(X3) -0.1022 \ln(X4)$ |
| Lodgepole pine | Dense | 0.86 | 15 | 0.2945 | $\ln Y = -1.1991 + 1.7578 \ln(X1)$ |
| | Open | 0.97 | 15 | 0.1224 | $\ln Y = -1.8140 + 2.0641 \ln(X1)$ |
| | Combined | 0.92 | 30 | 0.2441 | $\ln Y = -1.6403 + 2.0347 \ln(X1) -0.0698 \ln(X4)$ |
| Ponderosa pine | Dense | 0.97 | 15 | 0.0698 | $\ln Y = -1.2711 + 1.6484 \ln(X1)$ |
| | Open | 0.98 | 15 | 0.0718 | $\ln Y = -1.4306 + 1.7854 \ln(X1)$ |
| | Combined | 0.97 | 30 | 0.0718 | $\ln Y = -1.0737 + 1.7458 \ln(X1) -0.1096 \ln(X4)$ |
| Mountain hemlock | Combined | 0.93 | 30 | 0.1804 | $\ln Y = 0.3408 + 1.9085 \ln(X2)$ |
| | Combined | 0.93 | 30 | 0.1862 | $\ln Y = 0.4207 + 1.9153 \ln(X2) -0.0266 \ln(X4)$ |
| Both firs | Dense | 0.94 | 30 | 0.1794 | $\ln Y = -1.2748 + 1.8960 \ln(X1)$ |
| | Open | 0.96 | 30 | 0.1343 | $\ln Y = -0.5387 + 0.6446 \ln(X3)$ |
| | Combined | 0.95 | 60 | 0.1669 | $\ln Y = -0.1458 + 0.6430 \ln(X3) -0.1624 \ln(X4)$ |
| Both pines | Dense | 0.90 | 30 | 0.1925 | $\ln Y = -1.1237 + 1.6655 \ln(X1)$ |
| | Open | 0.96 | 30 | 0.1397 | $\ln Y = -1.1456 + 0.6551 \ln(X3)$ |
| | Combined | 0.93 | 60 | 0.2088 | $\ln Y = -1.3152 + 1.8365 \ln(X1) -0.0034 \ln(X4)$ |

*Y = biomass of +1(g) of foliar plus other 0-0.63 cm dia. live fuel
X1 = groundline diameter (cm) x 10
X2 = height (m) x 10
X3 = (groundline diameter x 10)$^2$ x (height x 10)
X4 = basal area + 1 ($m^2$/ha)

Table 5. Best-fit equations for dry, aboveground fuels in the 0.64-2.53 cm live size class (g).

| Species | Overstory Density | $R^2$ | N | $S^2$Y-X | Equation* |
|---|---|---|---|---|---|
| White fir | Dense | 0.85 | 15 | 0.6280 | lnY = -1.4619 + 0.6553 ln(X3) |
| | Open | 0.91 | 15 | 0.3128 | lnY = -0.2419 + 1.7685 ln(X2) |
| | Combined | 0.88 | 30 | 0.4481 | lnY = -1.9916 + 0.6201 ln(X3) +0.1801 ln(X4) |
| Shasta Red fir | Dense | 0.83 | 15 | 0.4574 | lnY = 0.1287 + 1.8007 ln(X2) |
| | Open | 0.92 | 15 | 0.2244 | lnY = -1.0064 + 0.5857 ln(X3) |
| | Combined | 0.87 | 30 | 0.3429 | lnY = -1.1025 + 0.5966 ln(X3) +0.0373 ln(X4) |
| Lodgepole pine | Dense | 0.91 | 15 | 0.3899 | lnY = -2.8615 + 0.8746 ln(X3) |
| | Open | 0.86 | 15 | 0.4346 | lnY = -1.1390 + 0.5916 ln(X3) |
| | Combined | 0.85 | 30 | 0.5366 | lnY = -0.7199 + 2.1259 ln(X2) -0.0776 ln(X4) |
| Ponderosa pine | Dense | 0.88 | 15 | 0.5367 | lnY = -2.0746 + 0.7206 ln(X3) |
| | Open | 0.94 | 15 | 0.2170 | lnY = -1.9169 + 0.6563 ln(X3) |
| | Combined | 0.90 | 30 | 0.3674 | lnY = -2.3241 + 0.6838 ln(X3) +0.1077 ln(X4) |
| Mountain hemlock | Combined | 0.87 | 30 | 0.4127 | lnY = -0.9592 + 2.1287 ln(X2) |
| | Combined | 0.88 | 30 | 0.4255 | lnY = -0.8200 + 2.1402 ln(X2) -0.0452 ln(X4) |
| Both firs | Dense | 0.84 | 30 | 0.5245 | lnY = -1.3115 + 0.6425 ln(X3) |
| | Open | 0.90 | 30 | 0.2881 | lnY = -1.1824 + 0.5932 ln(X3) |
| | Combined | 0.87 | 60 | 0.3955 | lnY = -1.6560 + 0.6159 ln(X3) +0.1189 ln(X4) |
| Both pines | Dense | 0.86 | 30 | 0.5566 | lnY = -2.2365 + 0.7739 ln(X3) |
| | Open | 0.90 | 30 | 0.3110 | lnY = -1.5073 + 0.6219 ln(X3) |
| | Combined | 0.85 | 60 | 0.5136 | lnY = -1.8212 + 0.6696 ln(X3) +0.0690 ln(X4) |

*Y = biomass + 1(g) of live fuels in the 0.64-2.53 cm size class
X1 = groundline diameter (cm) x 10
X2 = height (m) x 10
X3 = (groundline diameter x 10)$^2$ x (height x 10)
X4 = basal area +1 ($m^2$/ha)

Table 6. Best-fit equations for dry, aboveground fuels in the 2.54-7.61 cm live size class (g).

| Species | Overstory Density | $R^2$ | N | $S^2Y \cdot X$ | Equations* |
|---|---|---|---|---|---|
| White fir | Dense | 0.56 | 15 | 5.3936 | $\ln Y = -1.8387 + 0.8949 \ln(X3)$ |
| | Open | 0.80 | 15 | 2.5124 | $\ln Y = -4.9236 + 3.0621 \ln(X1)$ |
| | Combined | 0.69 | 30 | 3.7706 | $\ln Y = -2.9430 + 2.8710 \ln(X1) - 0.2245 \ln(X4)$ |
| Shasta Red fir | Dense | 0.70 | 15 | 3.6883 | $\ln Y = -5.6218 + 1.1923 \ln(X3)$ |
| | Open | 0.81 | 15 | 2.0740 | $\ln Y = -6.5053 + 3.4284 \ln(X1)$ |
| | Combined | 0.75 | 30 | 2.9204 | $\ln Y = -4.4731 + 1.1481 \ln(X3) - 0.2160 \ln(X4)$ |
| Lodgepole pine | Dense | 0.37 | 15 | 5.6280 | $\ln Y = 0.5723 + 2.4263 \ln(X1)$ |
| | Open | 0.73 | 15 | 3.2293 | $\ln Y = -5.2901 + 3.2112 \ln(X1)$ |
| | Combined | 0.59 | 30 | 4.4233 | $\ln Y = -4.3113 + 2.9321 \ln(X1) - 0.0906 \ln(X4)$ |
| Ponderosa pine | Dense | 0.73 | 15 | 2.3982 | $\ln Y = -3.2806 + 2.8555 \ln(X1)$ |
| | Open | 0.88 | 15 | 1.3892 | $\ln Y = -6.6104 + 3.2844 \ln(X1)$ |
| | Combined | 0.81 | 30 | 1.8648 | $\ln Y = -5.7242 + 3.0710 \ln(X1) + 0.0625 \ln(X4)$ |
| Mountain hemlock | Combined | 0.68 | 30 | 3.2595 | $\ln Y = -6.3957 + 1.2310 \ln(X3)$ |
| | Combined | 0.72 | 30 | 3.0195 | $\ln Y = -8.3353 + 1.2252 \ln(X3) + 0.5309 \ln(X4)$ |
| Both firs | Dense | 0.62 | 30 | 4.3898 | $\ln Y = -3.4685 + 1.0103 \ln(X3)$ |
| | Open | 0.80 | 30 | 2.1590 | $\ln Y = -4.5345 + 3.2033 \ln(X1)$ |
| | Combined | 0.71 | 60 | 3.2672 | $\ln Y = -4.3219 + 3.1064 \ln(X1) - 0.1562 \ln(X4)$ |
| | Dense | 0.56 | 30 | 3.8685 | $\ln Y = -3.7091 + 2.7412 \ln(X1)$ |
| | Open | 0.78 | 30 | 2.3790 | $\ln Y = -5.1521 + 1.1117 \ln(X3)$ |
| | Combined | 0.71 | 60 | 2.9925 | $\ln Y = -5.1953 + 3.0304 \ln(X1) - 0.0855 \ln(X4)$ |

*Y = biomass of +1(g) live fuels in the 2.54-7.61 cm size class
X1 = groundline diameter (cm) x 10
X2 = height (m) x 10
X3 = (groundline diameter x 10)$^2$ x (height x 10)
X4 = basal area + 1 ($m^2$/ha)

Table 7. Best-fit equations for dry, aboveground total biomass (g).

| Species | Overstory Density | $R^2$ | N | $S^2Y\text{-}X$ | Equation* |
|---|---|---|---|---|---|
| White fir | Dense | 0.98 | 15 | 0.1291 | $\ln Y = -1.2188 + 0.7848 \ln(X3)$ |
| | Open | 0.98 | 15 | 0.1040 | $\ln Y = -1.0132 + 0.7761 \ln(X3)$ |
| | Combined | 0.98 | 30 | 0.1169 | $\ln Y = -1.0350 + 0.7822 \ln(X3) -0.0281 \ln(X4)$ |
| Shasta Red fir | Dense | 0.99 | 15 | 0.0156 | $\ln Y = -1.6864 + 0.8303 \ln(X3)$ |
| | Open | 0.98 | 15 | 0.0795 | $\ln Y = -1.2089 + 0.7909 \ln(X3)$ |
| | Combined | 0.99 | 30 | 0.0500 | $\ln Y = -1.4393 + 0.8107 \ln(X3) -0.0036 \ln(X4)$ |
| Lodgepole pine | Dense | 0.98 | 15 | 0.0684 | $\ln Y = -2.2009 + 0.8765 \ln(X3)$ |
| | Open | 0.98 | 15 | 0.0855 | $\ln Y = -1.8768 + 0.8424 \ln(X3)$ |
| | Combined | 0.98 | 30 | 0.0751 | $\ln Y = -2.0426 + 0.8531 \ln(X3) +0.0178 \ln(X4)$ |
| Ponderosa pine | Dense | 0.97 | 15 | 0.1521 | $\ln Y = -1.5846 + 0.7712 \ln(X3)$ |
| | Open | 0.99 | 15 | 0.0597 | $\ln Y = -1.9806 + 0.8219 \ln(X3)$ |
| | Combined | 0.98 | 30 | 0.1088 | $\ln Y = -1.7169 + 0.7994 \ln(X3) -0.0243 \ln(X4)$ |
| Mountain hemlock | Combined | 0.95 | 30 | 0.1743 | $\ln Y = -0.0045 + 2.3321 \ln(X2)$ |
| | Combined | 0.95 | 30 | 0.1806 | $\ln Y = -0.0358 + 2.3290 \ln(X2) +0.0119 \ln(X4)$ |
| Both firs | Dense | 0.98 | 30 | 0.0707 | $\ln Y = -1.3745 + 0.8034 \ln(X3)$ |
| | Open | 0.98 | 30 | 0.0862 | $\ln Y = -1.0937 + 0.7816 \ln(X3)$ |
| | Combined | 0.98 | 60 | 0.0808 | $\ln Y = -1.1990 + 0.7935 \ln(X3) -0.0182 \ln(X4)$ |
| Both pines | Dense | 0.96 | 30 | 0.1447 | $\ln Y = -1.7636 + 0.8094 \ln(X3)$ |
| | Open | 0.98 | 30 | 0.0890 | $\ln Y = -1.8680 + 0.8262 \ln(X3)$ |
| | Combined | 0.97 | 60 | 0.1167 | $\ln Y = -1.8363 + 0.8209 \ln(X3) -0.0013 \ln(X4)$ |

*Y = total aboveground biomass + 1(g)
X1 = groundline diameter (cm) x 10
X2 = height (m) x 10
X3 = $(\text{groundline diameter} \times 10)^2 \times (\text{height} \times 10)$
X4 = basal area + 1 ($m^2$/ha)

Table 8. Equations for dry, aboveground total biomass (g) using only height (m) as an independent variable.

| Species | Overstory Density | R | N | $S^2$Y-X | Equation* |
|---|---|---|---|---|---|
| White fir | Dense | 0.97 | 15 | 0.1878 | lnY = -0.1084 + 2.3128 ln(X2) |
| | Open | 0.96 | 15 | 0.2137 | lnY = 0.5927 + 2.2926 ln(X2) |
| | Combined | 0.96 | 30 | 0.2243 | lnY = 0.3702 + 2.3536 ln(X2) -0.0062 ln(X4) |
| Shasta Red fir | Dense | 0.97 | 15 | 0.1160 | lnY = -0.0344 + 2.4005 ln(X2) |
| | Open | 0.96 | 15 | 0.1733 | lnY = 1.1758 + 2.1375 ln(X2) |
| | Combined | 0.96 | 30 | 0.1635 | lnY = 1.2914 + 2.2550 ln(X2) -0.2389 ln(X4) |
| Lodgepole pine | Dense | 0.95 | 15 | 0.2227 | lnY = -1.0415 + 2.4574 ln(X2) |
| | Open | 0.96 | 15 | 0.2323 | lnY = -0.2727 + 2.4567 ln(X2) |
| | Combined | 0.93 | 30 | 0.3284 | lnY = -0.3125 + 2.5697 ln(X2) -0.1430 ln(X4) |
| Ponderosa pine | Dense | 0.89 | 15 | 0.5019 | lnY = 0.2672 + 2.0537 ln(X2) |
| | Open | 0.94 | 15 | 0.3123 | lnY = -0.7982 + 2.7449 ln(X2) |
| | Combined | 0.87 | 30 | 0.6096 | lnY = 0.2767 + 2.3301 ln(X2) + 0.0986 ln(X4) |
| Mountain hemlock | Combined | 0.95 | 30 | 0.1743 | lnY = -0.0045 + 2.3321 ln(X2) |
| | Combined | 0.95 | 30 | 0.1806 | lnY = -0.0358 + 2.3290 ln(X2) +0.0119 ln(X4) |
| Both firs | Dense | 0.96 | 30 | 0.1703 | lnY = -0.0628 + 2.3576 ln(X2) |
| | Open | 0.96 | 30 | 0.2154 | lnY = 0.8240 + 2.2220 ln(X2) |
| | Combined | 0.95 | 60 | 0.2199 | lnY = 1.0780 + 2.2908 ln(X2) -0.1968 ln(X4) |
| Both pines | Dense | 0.91 | 30 | 0.3725 | lnY = -0.2733 + 2.2143 ln(X2) |
| | Open | 0.94 | 30 | 0.2725 | lnY = -0.4785 + 2.5783 ln(X2) |
| | Combined | 0.90 | 60 | 0.4644 | lnY = -0.0803 + 2.4261 ln(X2) -0.0977 ln(X4) |

*Y = total biomass + 1(g)
X2 = height (m) x 10

Table 9. Age predictions from size characteristics: ranges of goodness-of-fit and parameters of best-fit equations.

| Species | Overstory Density | Range of $R^2$ | Best-fit Equation |
|---|---|---|---|
| White fir | Dense | 0.51-0.54 | $Y = -27.41 + 20.42 \ln(X1)$ |
| White fir | Open | 0.59-0.74 | $Y = -55.72 + 8.71 \ln(X3) + 7.86 \ln(X5)$ |
| Shasta red fir | Dense | 0.49-0.60 | $Y = 115.66 + 8.27 \ln(X3) - 28.99 \ln(X5)$ |
| Shasta red fir | Open | 0.21-0.48 | $Y = -131.86 + 13.47 \ln(X3) + 2.24 (X4)$ |
| Lodgepole pine | Dense | 0.78-0.84 | $Y = -17.75 + 7.75 \ln(X3) + 0.77 \ln(X5)$ |
| Lodgepole pine | Open | 0.43-0.81 | $Y = 4.70 + 0.77 \ln(X3) + 13.37 \ln(X5)$ |
| Ponderosa pine | Dense | 0.83-0.96 | $Y = -26.25 + 23.49 \ln(X1)$ |
| Ponderosa pine | Open | 0.58-0.72 | $Y = -21.25 + 6.66 \ln(X3) + 0.41 (X4)$ |
| Mountain hemlock | Combo | 0.34-0.66 | $Y = -23.81 + 5.93 \ln(X3) + 0.28 (X4)$ |
| Both firs | Dense | 0.44-0.53 | $Y = -32.61 + 26.58 \ln(X1)$ |
| Both firs | Open | 0.33-0.48 | $Y = -61.08 + 9.18 \ln(X3) + 1.00(X4)$ |
| Both pines | Dense | 0.80-0.87 | $Y = -18.71 + 7.57 \ln(X3) + 0.68 \ln(X5)$ |
| Both pines | Open | 0.47-0.69 | $Y = -21.00 + 5.20 \ln(X3) + 7.23 \ln(X5)$ |

Y = age (years)
X1 = groundline diameter (cm) x 10
X2 = total height (m) x 10
X3 = (groundline diameter x 10)$^2$ x (height x 10)
X4 = basal area ($m^2$/ha)
X5 = basal area + 1 ($m^2$/ha)

Table 10. Average foliar biomass (g) per tree by overstory density: ratios and ranks of shade tolerance.

| Species | Dense Overstory | Open Overstory | Ratio | Ratio Rank* | Relative Shade Tolerance (Minore, 1979)* |
|---|---|---|---|---|---|
| White fir | 116.4 | 369.7 | 0.31 | 3 | 2 |
| Shasta red fir | 162.1 | 285.5 | 0.57 | 2 | 3 |
| Lodgepole pine | 32.0 | 204.5 | 0.16 | 5 | 4 |
| Ponderosa pine | 51.2 | 208.4 | 0.25 | 4 | 5 |
| Mountain hemlock | 191.7 | 193.2 | 0.99 | 1 | 1 |

Table 11. Hypothetical field data collected for understory tree biomass estimation.

| Plot No. | Basal Area ($m^2$/ha) | Height Class 0-1m Pine | Height Class 0-1m Fir | Height Class 1-2m Pine | Height Class 1-2m Fir | Height Class 2-3m Pine | Height Class 2-3m Fir |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 1 | 3 | 0 | 1 | 1 | 1 |
| 2 | 60 | 0 | 2 | 0 | 0 | 2 | 0 |
| 3 | 60 | 0 | 2 | 0 | 3 | 0 | 3 |
| 4 | 0 | 2 | 1 | 0 | 0 | 1 | 2 |
| 5 | 40 | 0 | 4 | 0 | 2 | 0 | 1 |
| 6 | 90 | 0 | 3 | 0 | 0 | 2 | 1 |
| 7 | 10 | 2 | 2 | 0 | 6 | 0 | 0 |
| 8 | 20 | 0 | 1 | 0 | 2 | 3 | 3 |
| 9 | 90 | 0 | 2 | 0 | 1 | 0 | 0 |
| 10 | 60 | 0 | 3 | 0 | 3 | 0 | 0 |
| 11 | 30 | 1 | 3 | 0 | 2 | 0 | 0 |
| 12 | 25 | 0 | 2 | 0 | 1 | 1 | 2 |
| 13 | 80 | 0 | 2 | 0 | 3 | 0 | 1 |
| 14 | 90 | 1 | 3 | 0 | 2 | 0 | 3 |
| 15 | 50 | 0 | 1 | 0 | 2 | 2 | 2 |
| 16 | 60 | 0 | 4 | 1 | 1 | 0 | 0 |
| 17 | 40 | 0 | 3 | 0 | 3 | 1 | 2 |
| 18 | 10 | 2 | 0 | 0 | 4 | 0 | 1 |
| 19 | 20 | 2 | 1 | 0 | 0 | 0 | 1 |
| 20 | 0 | 1 | 2 | 0 | 1 | 1 | 3 |
| | | 12 | 44 | 1 | 37 | 14 | 26 |

Table 12. Summary of trees by overstory class, species and height class.

| Height Class | "Open" (below 45 $m^2/ha$) | | "Dense" (above 45 $m^2/ha$) | |
|---|---|---|---|---|
| | Pine | Fir | Pine | Fir |
| 0-1 m | 11 | 22 | 1 | 22 |
| 1-2 m | 0 | 22 | 1 | 15 |
| 2-3 m | 8 | 15 | 6 | 10 |

Table 13. Average per tree biomass (g) by category.

| Height Class | Open | | Dense | |
|---|---|---|---|---|
| | Pine | Fir | Pine | Fir |
| 0-1 m | 38 | 80 | 26 | 41 |
| 1-2 m | 666 | 935 | 305 | 556 |
| 2-3 m | 2490 | 2910 | 947 | 1854 |

Table 14. Total understory tree biomass (g) by open and dense overstory class.

| Height Class | Open | | Dense | |
|---|---|---|---|---|
| | Pine | Fir | Pine | Fir |
| 0-1 m | 418 | 1760 | 26 | 902 |
| 1-2 m | 0 | 20570 | 305 | 8340 |
| 2-3 m | 19920 | 43650 | 5682 | 18540 |
| Total | 86318 | | 33795 | |

Table 15. Common conversion factors used for biomass and fuel estimation.

| To Convert From | To | Multiply By |
|---|---|---|
| feet (ft) | meters (m) | 0.3048 |
| square feet ($ft^2$) | square meters ($m^2$) | 0.0929 |
| square meters ($m^2$) | acres (ac) | 0.000247 |
| hectares (ha) | acres (ac) | 2.47 |
| grams per sq. meter ($g/m^2$) | pounds per acre (lbs/ac) | 8.92 |
| grams per sq. meter ($g/m^2$) | tons per acre (T/ac) | 0.0045 |
| kilograms per sq. meter ($kg/m^2$) | pounds per acre (lbs/ac) | 8917 |
| kilograms per sq. meter ($kg/m^2$) | tons per acre (T/ac) | 4.458 |

Conversion in the other direction is accomplished by dividing by the factor in the right column.