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ANALYSIS OF ALGORITHMS FOR PREDICTING CANOPY FUEL

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1. ABSTRACT

We compared observed canopy fuel characteristics with those predicted by existing biomass algorithms. We specifically examined the accuracy of the biomass equations developed by Brown (1978. We used destructively sampled data obtained at 5 different study areas. We compared predicted and observed quantities of foliage and crown biomass for individual trees in our study sites for ponderosa pine, Douglas fir, and lodgepole pine. In addition, we observed the appropriateness of using similar species to predict canopy fuel characteristics when the actual species is not accounted for using Brown's equations. For example, we used western red cedar in place of incense cedar and grand fir instead of white fir. We also evaluated the importance of tree dominance as a predictor of crown biomass. Adjustments were made to Brown's equations in order to improve the predictability of the equations for future use. We also compared plot totals to assess the usefulness of the method for predicting stand level canopy fuel characteristics.

2. INTRODUCTION

Estimates of canopy fuel characteristics – loading and spatial distribution – are important for fuel and fire managers to assess crown fire hazard and to predict fire behavior. The most widely used method for estimating canopy fuel characteristics is to apply existing allometric equations that predict a tree's crown biomass to a tree list or a stand table (Scott and Reinhardt 2001, Reinhardt and Crookston in press, Agee 1996, Cruz and others 2003). Brown (1978) proposed equations for predicting crown weights given certain characteristics of a tree such as diameter (d.b.h.), tree height, crown length, crown ratio, and crown weight. The objective of this paper is to compare crown and foliage weights predicted by Brown's equations to values that were obtained through destructive sampling in 5 study areas.

3. STUDY SITES

We chose study sites in 5 forest types (table 1.) Sites were selected that were judged by local managers to be prone to crown fire – dense, often multi-storied stands.

4. METHODS

We sampled all trees in a circular plot 10-15m in diameter (.08-.17 acres) (Scott and Reinhardt 2002). Every branch on every tree was weighed. All material from a sample of 5 to 10% of the branches was sorted by size class (foliage, 0-3mm, 3-6mm, 6-10mm, 10-25mm, 25mm+ branchwood), and a subsample of the sorted material was oven-dried to determine dry weight. From these measurements, regression analysis was used to estimate the crown weight by component for every branch and then for the entire tree.

Brown's equations were used to predict total live crown biomass and the proportion of that biomass that is foliage. Although Brown offered a few different equations to predict biomass for each species, this paper focuses on the equations with d.b.h. as a predictor variable. Brown's equations for dominant and co-dominant trees were used, and then predicted values adjusted with a series of multipliers: for dominant trees 1.00, co-dominants .8, intermediates .6, and suppressed .4. These values are referred to as the "default multipliers". For the purpose of the analysis we consider the

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estimates made from the destructive method the observed values and use these observed values to compare to the predicted values obtained through Brown's equations. Model performance was compared graphically and by evaluating percent error of the predictions. Alternative regression equations were developed from our data. Residual analysis was used to check model assumptions for the regression equations.

A further objective of this study was to examine the adequacy of the crown class multipliers. Each tree in the study area was determined to be either a dominant, co-dominant, intermediate or suppressed tree. Each crown class was assigned a multiplier as described above to adjust the predicted total live biomass calculated using Brown's equation. The predicted total live biomass obtained using Brown's equation and the multiplier was compared to our observed biomass to assess the multipliers for accuracy, and the multipliers were modified to minimize the average error rate.

Finally, area estimates of canopy fuels were compared. It is these area estimates that are of greatest importance to fuel and fire managers.

5. RESULTS

Figure 1 shows the observed total live biomass of individual trees plotted against the predicted biomass obtained using Brown's equations with the default multipliers. Brown's equation uses d.b.h. as a predictor variable. Visual inspection of the graphs reveals that Brown's equations predict total live biomass quite well for lodgepole pine and most of the white fir. Brown's equations under-predict the total live biomass for the majority of the incense cedar trees (using the equation for western red cedar) and the majority of the Douglas-fir trees, especially the larger trees, in our study areas. For the ponderosa pine trees in our study areas, Brown's equation over-predicts total live biomass for most of the trees, however, it under-predicts total live biomass for the 4 largest ponderosa trees.

Foliage is the most flammable portion of the crown biomass. In Brown's paper, equations were given to predict the proportion of foliage for a tree given diameter as a predictive variable. This equation was used along with the equation for total live branch biomass to predict the biomass of foliage for a given tree. Figure 2 shows the predicted foliage obtained using Brown's equations versus the observed foliage biomass. These graphs are similar to the graphs for total live branch biomass. Again, Brown's equation appears to be doing a good job of predicting foliage biomass for lodgepole pine and white fir. It over-predicts the foliage biomass for the majority of the trees for ponderosa pine and under-predicts foliage biomass for the majority of Douglas-fir and incense-cedar trees.

Figure 3 shows Brown's equation along with the curve fitted from our data for predicting proportion of foliage from d.b.h. For white fir and incense cedar (again, species not sampled in Brown's work), Brown's curve appears to be missing the observed data altogether, over-predicting the observed proportion. Also, for lodgepole pine, Brown's equation over-predicts the proportion of foliage for most of the observations. For both ponderosa pine and Douglas-fir, there is not as strong a relationship between proportion of foliage and dbh as the other species. Both the fitted curve and Brown's equation are rather flat indicating that the proportion of foliage does not change much with respect to changes in d.b.h for these two species.

Regression equations for predicting biomass were calculated for each species. The resulting regression equations are reported in table 2. Regressions for Douglas-fir trees were fit separately for Salmon and Tenderfoot. Since these equations will presumably be used for predictions, variables were only left in the equations if they had a p-value less than .01. The variables considered were d.b.h and transformations of d.b.h and indicator variables for tree dominance. Tree dominance was a significant predictor of biomass for ponderosa pine and lodgepole pine. Table 3 gives Brown's equations that were used for this analysis and the R^2 value reported by Brown. Brown reported equations for calculating the predicted proportion of foliage for a given tree. Our analysis revealed that the predicting foliage biomass directly was more successful that predicting total biomass and estimating the proportion that was foliage, especially for ponderosa pine and Douglas-fir. However, when applying predictive equations broadly, there may be logical advantages in predicting foliage as a proportion of total biomass.

Crown class was an important determinant of crown biomass for lodgepole and ponderosa pine, the most intolerant of the species studied (table 2). Graphs of the total live biomass for each crown class individually can be viewed in figure 4.

On average, the default multipliers seem to be doing an adequate job of adjusting the predicted total live biomass for Brown's equations.

However, patterns exist within each species. For example, Brown’s equation under-predicts the biomass for Douglas-fir and over-predicts total live biomass for all classes for ponderosa pine. These observations agree with the results from figure 1 and figure 2. Adjustments to the multipliers were made separately for each species. After adjusting the multiplier in increments of .05, the optimal multiplier was selected to minimize the average error rate for each species between the Brown’s predicted biomass and the observed biomass.

Table 4 summarizes the multipliers that best accounted for crown class. For lodgepole pine, the multipliers for the suppressed and intermediate trees were adequate and, therefore, only slight adjustments were made to these multipliers. For the co-dominant size class, a multiplier of .9 was the best. For ponderosa pine, multipliers of .55, .25, .15 and .15 were the best. Finally, for Douglas-fir trees, to improve the predictions of Brown’s equation, the multipliers for suppressed trees should be .6. For co-dominant and intermediate trees a multiplier of 1.00 should be used. Figure 5 shows scatterplots of observed total live biomass and predicted total live biomass with the original multipliers and then the adjusted multipliers. The adjustments of the multipliers improved the predictability of Brown’s equation for our data for Douglas-fir, smaller ponderosa pine and incense cedar.

Table 5 summarizes the results of the individual tree analysis by species. The average error rate was calculated for each individual species comparing the observed values to the predicted values calculated using the three different methods: Brown’s equations with default multipliers, Brown’s equations with adjusted multipliers, and the regression equations fitted to our data. Adjusting the multipliers improves the predictions for total live biomass, however, the predictions for foliage are not improved using this method. Comparing Brown’s equations to our regression equations, Brown’s equations have similar error rates for lodgepole pine and Douglas-fir. For the other three species, the new regression equations are an improvement over Brown’s equations. In particular, the new equation does a much better job of predicting biomass for ponderosa pine than Brown’s equations.

Table 6 shows the observed and predicted foliage and canopy biomass by site. Brown’s equations performed extremely well in predicting stand crown biomass for the Ninemile and Tenderfoot study areas. Our regression equations predict the observed biomass very accurately for Flagstaff, Salmon, and Tenderfoot. The crown biomass at Flagstaff was greatly over-predicted by Brown’s equations, indicating that they are inappropriate for this extremely dense Southwestern ponderosa pine. The Blodgett study site, with its complex stand structure and mix of species, was relatively poorly predicted all methods.

6. CONCLUSIONS

Brown’s equations have been widely used and incorporated into various software packages for predicting and assessing canopy fuels. We tested these equations in five study areas. In these study areas, Brown’s equation did an good job of predicting total live biomass and foliage biomass for lodgepole pine and Douglas-fir. Brown’s equation tended to over-predict total live biomass and foliage biomass for ponderosa pine and under-predicted biomass for incense cedar. Crown class multipliers are recommended for each of the tree species we sampled to adjust predicted biomass depending on a tree’s crown class. At a stand level, Brown’s algorithms provided excellent predictions of canopy biomass for the Ninemile and Tenderfoot study sites, and poor predictions for the Flagstaff study site. Accuracy of predictions at Blodgett and Salmon was intermediate.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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Table 1. *Description of study areas.*

Name	Location	Forest type	Species	Basal area (ft^2/ac)
Ninemile	Lolo National Forest, MT	Ponderosa pine/Douglas-fir	Ponderosa pine Douglas-fir Total	98.7 33.9 132.6
Salmon	Salmon-Challis National Forest, ID	Douglas-fir	Douglas-fir Lodgepole pine Total	127.2 36.9 164.1
Flagstaff	Coconino National Forest, AZ	Ponderosa pine	Ponderosa pine Total	300 300
Blodgett	Blodgett Forest Research Sation,CA	Sierra Nevada mixed conifer	White fir Incense cedar Ponderosa pine Douglas-fir Total	99.1 64.2 38.6 1.7 203.6
Tenderfoot	Tenderfoot Experimental Forest, Lewis and Clark National Forest, MT	Lodgepole pine	Lodgepole pine Subalpine fir Total	185.8 0.04 185.8

Table 2. *Regression equations for each species with R^2 reported. For all equations d represents dbh and s is an indicator variable equaling one when the tree is suppressed and 0 otherwise. Similarly, i is an indicator variable for intermediate trees and c is an indicator variable for co-dominant trees. After residual analysis it was determined that the Douglas-fir equations were best fit separately for the Salmon study area and the Ninemile study area. The predicted biomass is in pounds and d.b.h. is in inches.*

Species		Regression equation	R^2
White fir	Total	$\text{biomass}=\exp(-.335+.463d-.0091d^2)$	.966
	Foliage	$\text{biomass}=\exp(-.390+.458d-.0098d^2)$	.958
Lodgepole pine	Total	$\text{biomass}=\exp(-.127+1.507\ln(d)+.202(\ln(d))^2-.666s)$	.959
	Foliage	$\text{biomass}=\exp(-773+1.666\ln(d)-.933s)$	.915
Ponderosa pine	Total	$\text{biomass}=\exp(-569+.612d-.0127d^2-.389c-.424i-.651s)$	.942
	Foliage	$\text{biomass}=\exp(-2.179+.629d-.014d^2-.568s)$	.927
Incense cedar	Total	$\text{biomass}=\exp(-.029+.605d-.0143d^2)$	.943
	Foliage	$\text{biomass}=\exp(-.797+.578d-.0141d^2)$	.909
Douglas-fir (Ninemile)	Total	$\text{biomass}=\exp(-1.13+1.710d-.170d^2+.060d^3)$	.906
	Foliage	$\text{biomass}=\exp(-2.182+1.987d-.221d^2+.0082d^3)$	.907
Douglas-fir (Salmon)	Total	$\text{biomass}=\exp(-.502+.912d-.036d^2)$	.944
	Foliage	$\text{biomass}=\exp(-1.128+.816d-.030d^2)$	.927

Table 3. *Brown's equations used for analysis with reported R^2. Brown reported the equations for live crown weight along with equations for proportion of foliage.*

Species		Regression equation	R^2
Grand fir	Total	$\text{biomass}=\exp(1.3094+1.6076\ln(d))$	.95
	Foliage	$\text{prop}=1/(1.15+.0416d)$	.94
Lodgepole pine	Total	$\text{biomass}=\exp(.1224+1.882\ln(d))$	.88
	Foliage	$\text{prop}=.493-.0117d$	.76
Ponderosa pine	Total	$\text{biomass}=\exp(.268+2.074\ln(d))$	.95
	Foliage	$\text{prop}=.558\exp(-.0475d)$	.89
Western redcedar	Total	$\text{biomass}=\exp(.8815+1.6389\ln(d))$	.96
	Foliage	$\text{prop}=.617\exp(-.0233d)$	.98
Douglas-fir	Total	$\text{biomass}=\exp(1.1368+1.5819\ln(d))$	.93
	Foliage	$\text{prop}=.484\exp(-.021d)$	.95

Table 4. *Adjusted tree class multipliers by species. The original multipliers were .8 for co-dominant trees, .6 for intermediate trees, and .4 for suppressed trees, for all species.*

Species	N	Dominant	Co-dominant	Intermediate	Suppressed
White-fir	18	1.00	.70	.35	.55
Lodgepole pine	82	.80	.90	.60	.35
Ponderosa pine	112	.55	.25	.15	.15
Incense cedar	16	1.00	1.00	.95	.40
Douglas-fir	216	1.00	1.00	1.00	.60

Table 5. *The error rates calculated as (Observed Biomass-Expected Biomass)/Observed Biomass for 1) Brown's predictive equations with default multipliers, 2) Brown's equations using the adjusted crown class multiplier, and 3) the fitted equations.*

Species		Brown's equations with default multipliers	Brown's equations with adjusted multipliers	Fitted equations
White fir	Total	-0.151	-0.094	-0.096
	Foliage	-0.352	-0.334	-0.106
Lodgepole pine	Total	-0.070	-0.032	-0.081
	Foliage	-0.205	-0.365	-0.167
Ponderosa pine	Total	-2.056	-1.755	-0.113
	Foliage	-3.390	-3.251	-0.173
Incense cedar	Total	0.217	0.014	-0.118
	Foliage	0.168	-0.365	-0.179
Douglas-fir	Total	0.236	-0.164	-0.205
	Foliage	0.164	-0.272	-0.162

Table 6. *Comparision of observed versus predicted values for each study site separately. The predicted values were calculated using 1)Brown's equations with original multipliers, 2) Brown's equations with the adjustment multipliers, and 3) the fitted equations.*

Study Site		Observed biomass (tons/acre)	Predicted biomass using Brown's equations with default multipliers (tons/acre)	Predicted biomass with adjusted multipliers (tons/acre)	Predicted biomass using fitted regression equations (tons/acre)
Ninemile	Total	15.82	14.22	12.33	13.85
	Foliage	4.93	4.27	4.06	5.21
Blodgett	Total	22.18	18.71	16.75	19.48
	Foliage	6.52	5.71	5.93	5.55
Flagstaff	Total	6.48	14.85	10.33	6.08
	Foliage	1.75	5.30	3.76	1.76
Salmon	Total	8.30	5.92	7.56	7.52
	Foliage	3.15	2.34	2.79	2.80
Tenderfoot	Total	5.40	5.11	5.06	5.59
	Foliage	1.50	1.50	1.96	1.56

Figure 1.

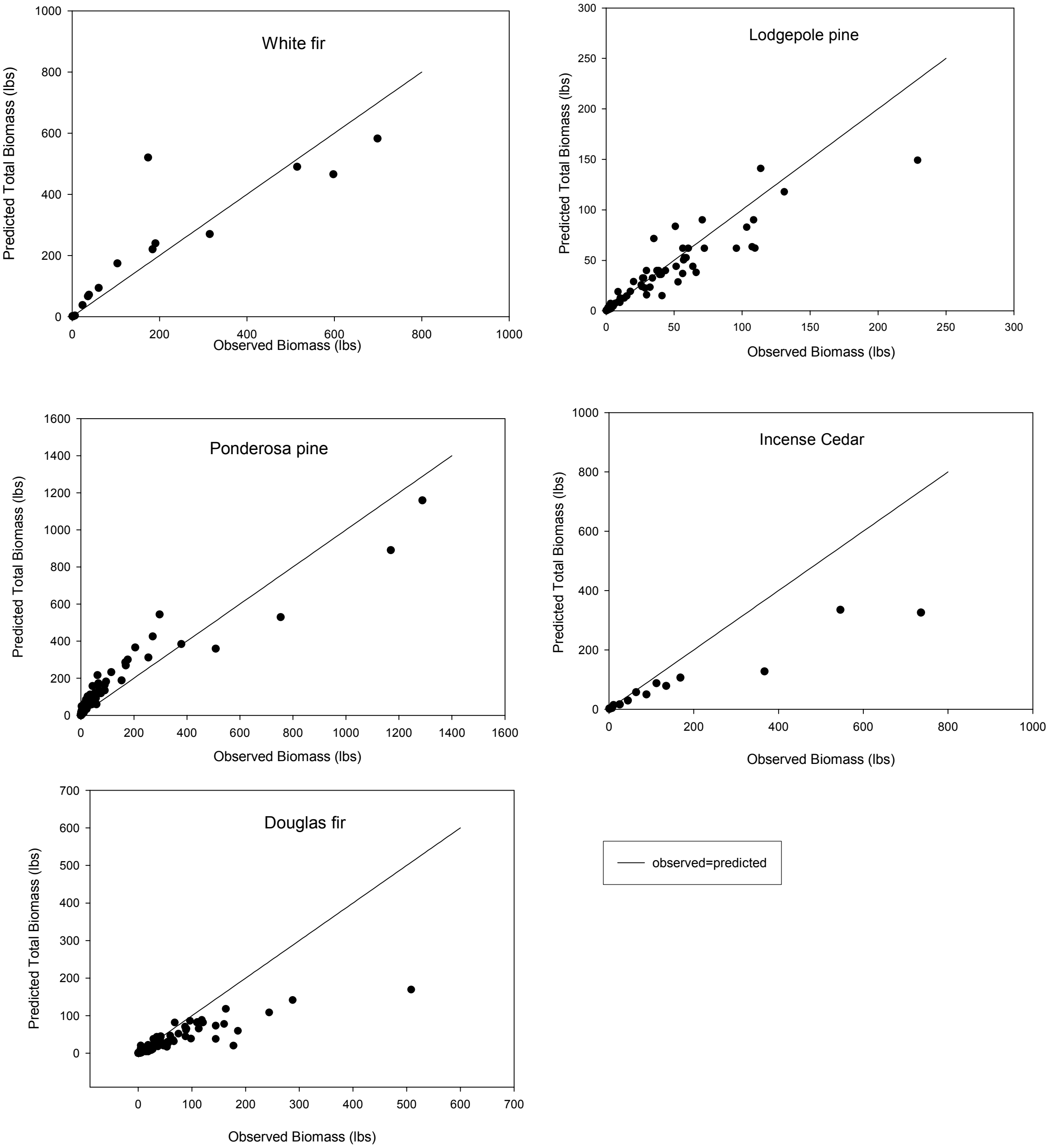

Figure 1: Scatterplots of predicted total live biomass versus observed total live biomass for each species.

Figure 2.

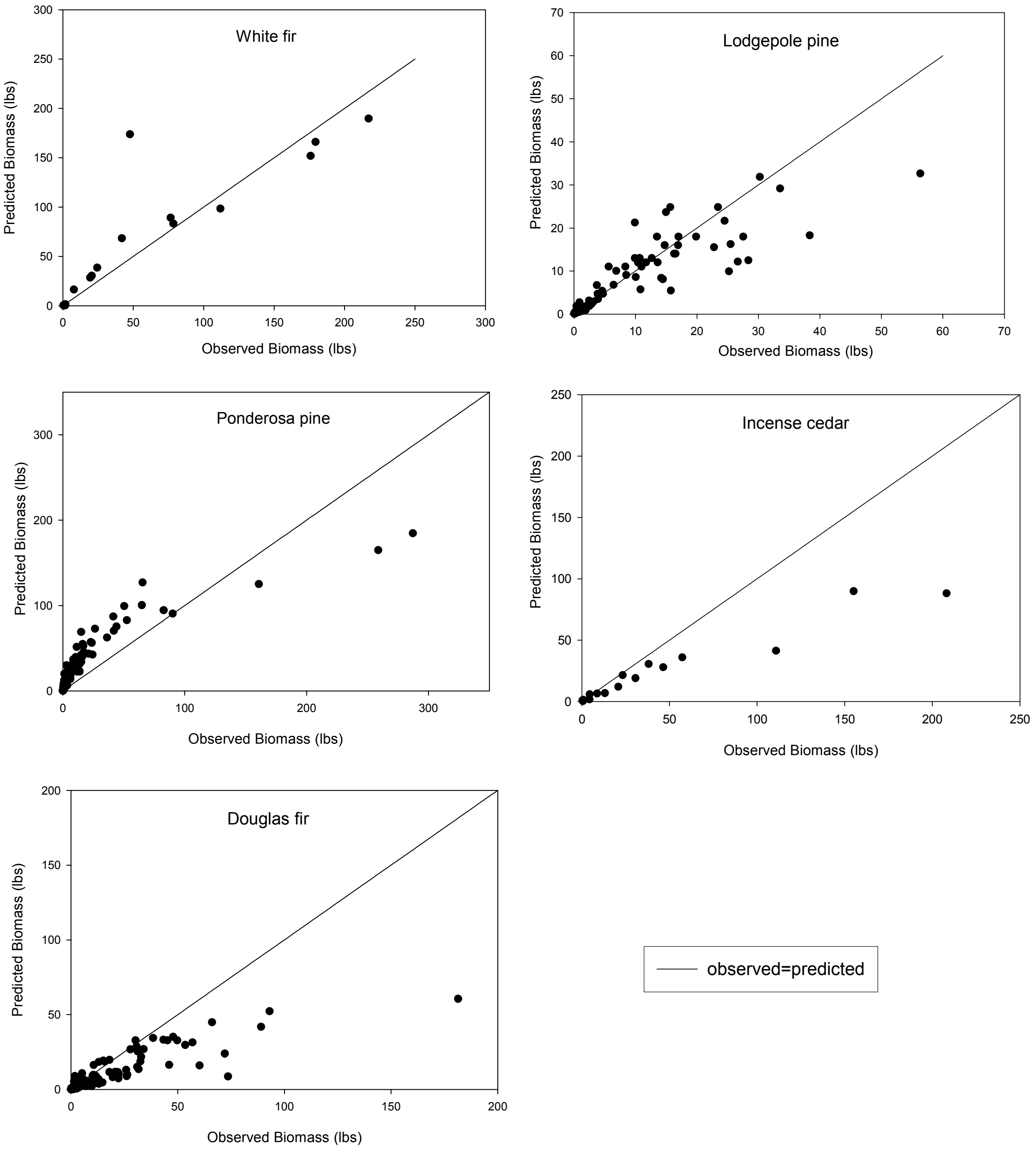

Figure 2: Scatterplots of the predicted foliage calculated using Brown's equations versus the observed biomass.

Figure 3.

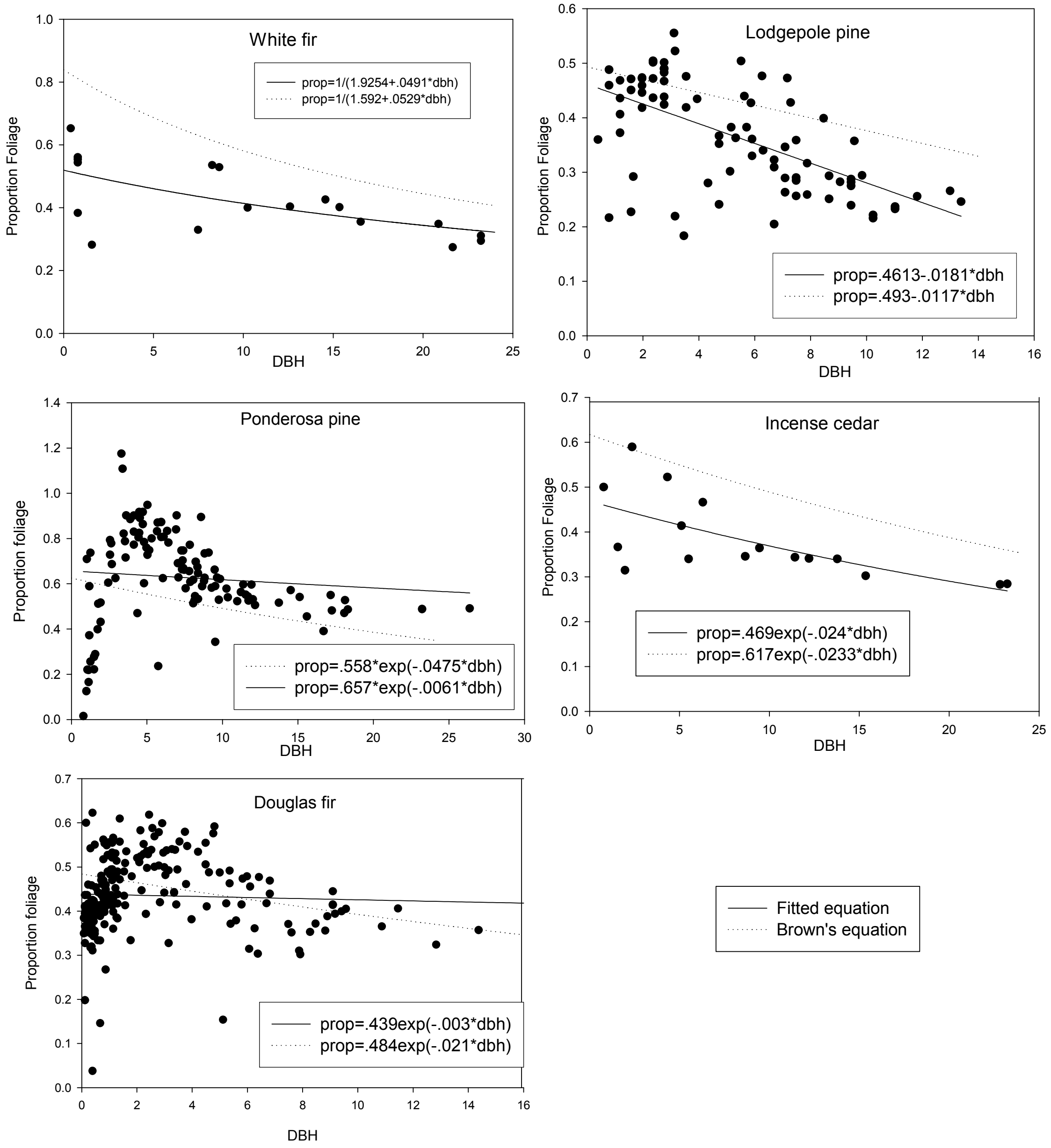

Figure 3: Scatterplots of the observed proportion of foliage in a given tree versus dbh (inches). Brown's equation for proportion of foliage and the fitted equation for proportion of foliage are both graphed on each scatterplot.

Figure 4.

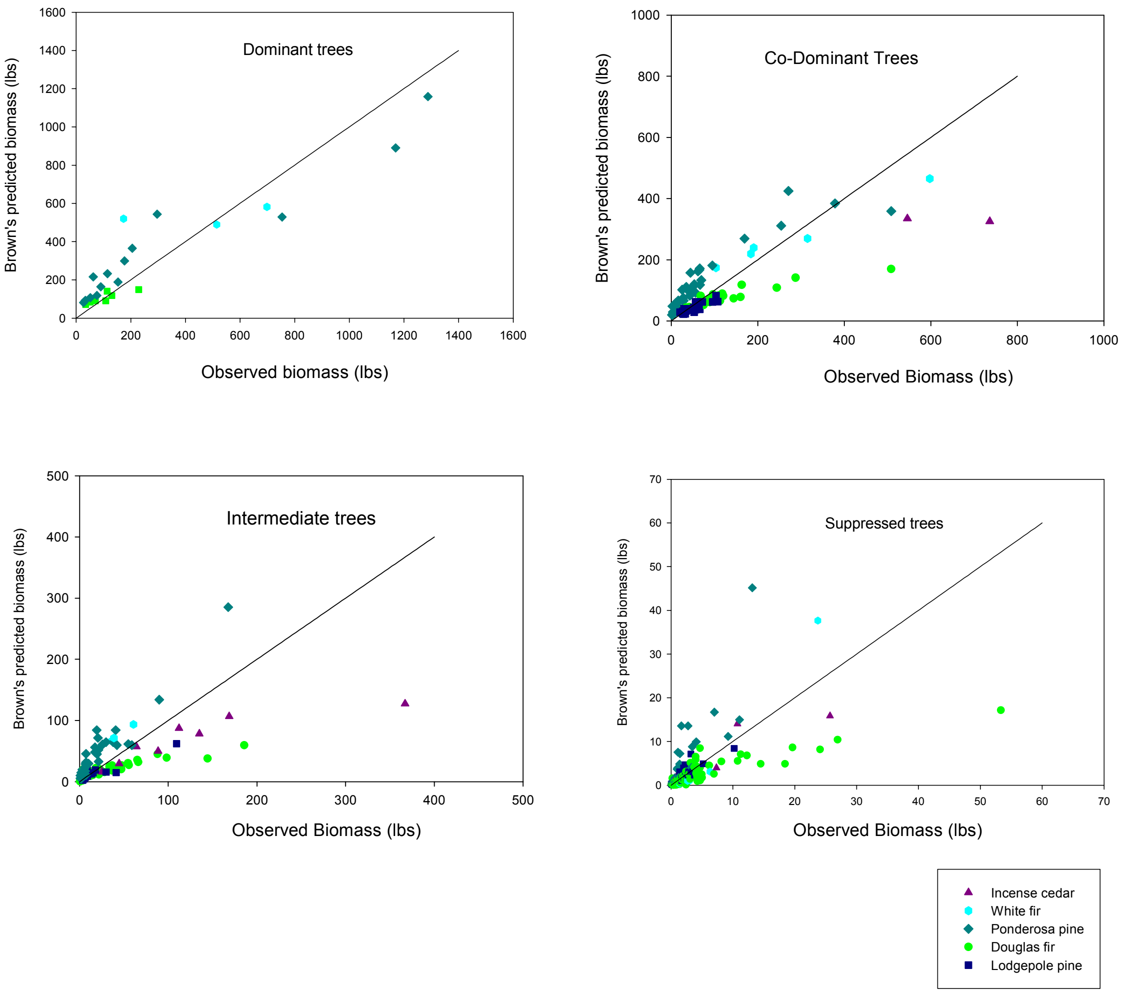

Figure 4: Scatterplots of predicted biomass using Brown's equations versus the observed biomass for dominant, co-dominant, intermediate, and suppressed trees.

Figure 5.

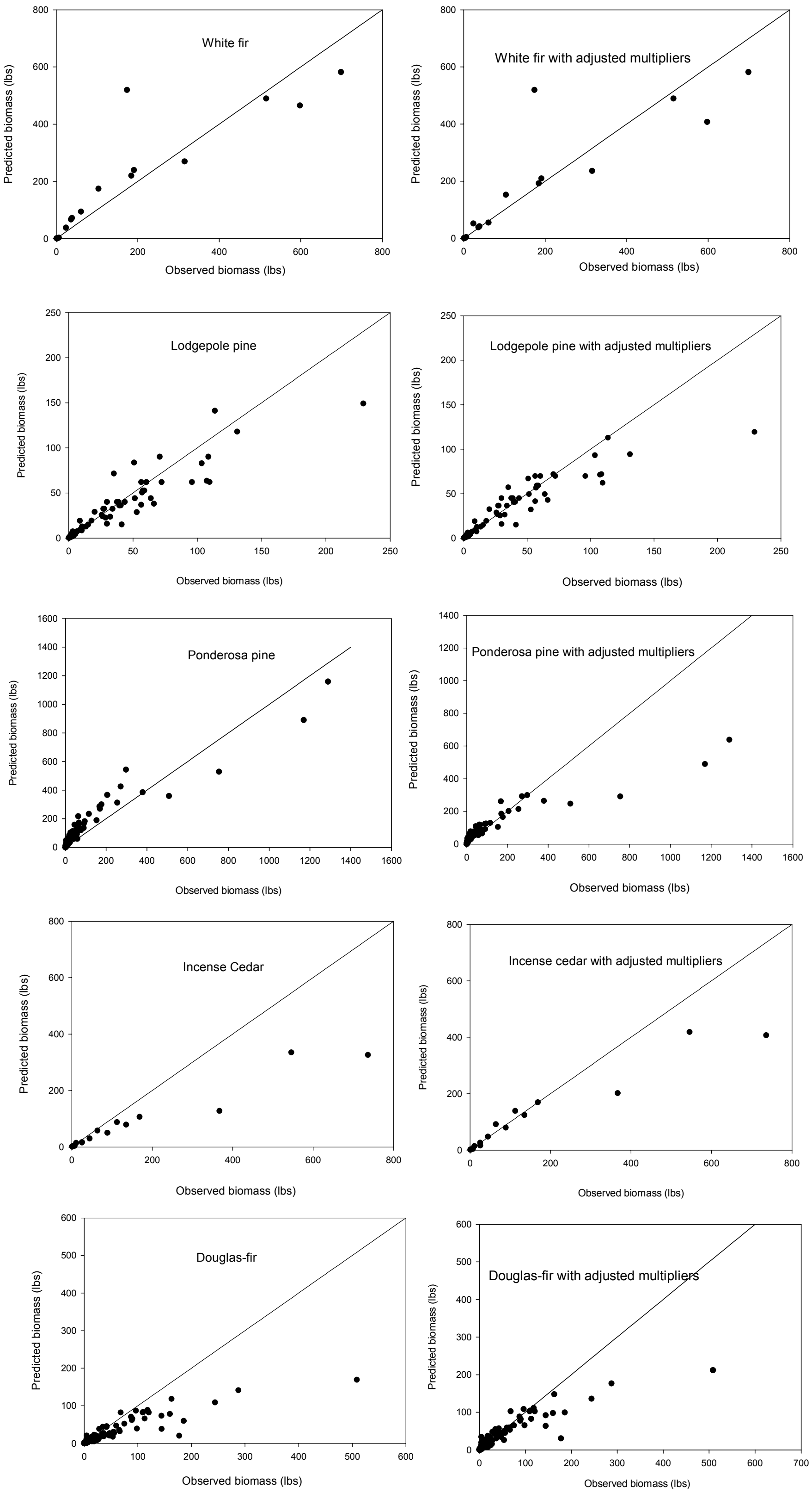

Figure 5: Scatterplots of predicted biomass versus observed biomass with original multipliers (left) and adjusted multipliers (right).