ABOVE GROUND TREE BIOMASS OF INTERIOR UNEVEN-AGED DOUGLAS-FIR STANDS

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Executive Summary

Data on the component biomass of 60 uneven-aged interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) trees, sampled near six permanent sample plots (PSPs) located on the Alex Fraser Research Forest, were collected as part of FRDA II project FC-GY-008. The objectives of the work reported in this paper were to use these data to develop equations to predict the biomass of several above ground tree components and to test whether stand density impacted on the form of the equations. In addition, the equations were used to characterize the biomass of the PSPs, based on tree measurements taken at the time of plot establishment.

The tree biomass components predicted were: (1) stump wood, (2) stump bark, (3) stem wood, (4) stem bark, (5) living branches, and (6) living needles. Total biomass (the sum of all six components) and crown biomass (the sum of components 5 and 6) were also predicted. Potential independent variables were: (1) outside bark diameter at breast height (dbh), (2) crown class of the sample tree, (3) percent crown closure at the location at which the sample tree was growing, (4) average crown width, (5) total height, (6) crown length, and (7) breast height age of the sample tree. In addition, the following combined variables were created: (1) dbh squared, (2) the product of dbh and total height, and (3) the product of dbh squared and total height. Five sets of prediction equations were developed by: (1) selecting variables from all available independent variables, (2) selecting variables from only those available for the trees measured in the permanent sample plots, (3) selecting variables from dbh, total height, and combinations of these variables, (4) by selecting variables from dbh, total height, and combinations of these variables and conditioning the equations for additivity, and (5) conditioning a set of simple linear regression equations to have zero intercepts.

The form of the biomass component equations differed among density class groupings. Of the various component equations, the equation for live needle biomass appeared to be the most robust, in that it was not significantly impacted by grouping according to plot condition or crown class. The equations for stump wood biomass and stump bark biomass also were not significantly impacted in at least one of the comparisons. The improvements in fit associated with grouping according to sample tree location or crown closure were not large in either an absolute or a relative sense.

The total above ground biomass determined for the various PSPs, together with the relative densities for these plots, provided an effective means of distinguishing differences in stand structures. Relative to the other biomass components, live needle biomass showed little difference among the plots despite the considerably different stand structures present. This is not surprising if it can be assumed that live needle biomass is closely related to leaf area index (LAI) and that LAI is reflective of the site productivity. Although these plots represent a range of stand conditions, the locations were chosen because the site conditions appeared similar among the plots and the stand conditions within a plot appeared relatively uniform, with limited evidence of recent disturbance.

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1.0 Introduction

Data on the component biomass of 60 uneven-aged interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) trees were collected as part of FRDA II project FC-GY-008. Ten trees were selected from the vicinity of each of six permanent sample plots established in 1988 on the Knife Creek Block of the Alex Fraser Research Forest (University of British Columbia) near Williams Lake, British Columbia. Details on the biomass data collection procedure are given in Hugh Hamilton Limited (1993) and descriptions of the permanent sample plots are given in Marshall (1988).

The objectives of this project were:

1. to develop equations to predict the biomass of several above ground components of interior Douglas-fir trees using the data provided;
2. to test to see whether stand density has an impact on the form of the biomass prediction equations; and
3. to characterize the biomass of each of the six permanent sample plots based on the equations developed and tree measurements taken at the time of establishment.

2.0 Data Preparation

The original data were stored in four ASCII files that contained the following data:

FTYPE1.DAT	- standing sample tree mensurational data
	- felled sample tree mensurational data
	- influence tree standing mensurational data
	- crown section stem analysis field data
	- bole section stem analysis data
FTYPE2.DAT	- plot tree mensurational data
	- influence tree mensurational data
FTYPE3.DAT	- tree disk lab measurement data
	- branch lab measurement data
FILETYP4.DAT	- disk section radius measurement data
	- disk section radius width increment measurement data

Before biomass prediction equations could be fit, it was necessary to inspect the original data, compute the ovendry biomass components of each sample tree, and prepare a dataset suitable for statistical analysis using SAS.

The original data appeared to be relatively free of errors. Only two data entry errors were detected:

(1) in FTYPE1.DAT, the value for SHTLC (sample tree height to live crown) was missing for tree number 20 (i.e., the record in columns 11-14 in line

428 of the data file was blank). The data for this tree were omitted when fitting any system of equations that used SHTLC or CRNLENG (crown length, which equals total tree height minus height to live crown) as potential dependent variables.

(2) in line 120 of FTYPE3.DAT, the value of WOODFRWT (green weight of wood - 190.5 g.) was less than the value of WOODODWT (ovendry weight of wood - 210.0 g.). Since it is impossible for the fresh weight of a disk to be less than its ovendry weight, it was assumed that these values were inadvertently interchanged and they were switched.

A SAS program was written to convert the original data formats, compute the ovendry biomass components of sample trees, and fit certain of the non-additive and additive prediction equation sets for the biomass components. In order to determine the ovendry biomass components of the sample trees, the average ratios of the ovendry/fresh weight of stem wood, stem bark, stump wood and stump bark for the bole, and the average ratios of the ovendry/fresh weight of live branches and needles for the crown, were first calculated for each sample tree based on the ovendry and fresh weight measurements of disks and median branches taken from the tree. These average ratios were then applied to the total fresh weights of the corresponding components of the sample tree to determine the total tree ovendry weights of each component. Since no disk data were available for section 99 (the stump) for all sample trees, in order to determine the ovendry weights of the stump wood and bark, the average ratios calculated for section 98 (0.3 - 0.65 m above the ground) or section 97 (0.65 - 1.30 m above the ground) were used. Since dead branches and needles are not usually considered to be a part of tree biomass by definition (Aldred and Alemdag 1988, p. 14), the total ovendry weights of branches and needles were determined based on the data for live branches and live needles only, although the data for dead branches and dead needles were also available.

The following ovendry biomass components were calculated and entered into a datafile: (1) stump wood (STUMWOOD); (2) stump bark (STUMBARK); (3) stem wood (STEMWOOD); (4) stem bark (STEMBARK); (5) living branches (LTWIGS); and (6) living needles (LNEEDLES). In addition, two combined variables were created: (1) the sum of LTWIGS and LNEEDLES (CROWN); and (2) the sum of all six biomass components (TOTAL). These variables comprise the dependent variables for the biomass component prediction equations. Other sample tree measurements were entered into the datafile to serve as potential independent variables for the biomass prediction equations. These were: (1) outside bark diameter at breast height (DBH); (2) crown class (CRNCLAS); (3) percent crown closure at the location at which the tree was growing (CRNCLOS); (4) average crown width (AVCRNWD); (5) total height (TOTHT); (6) crown length (CRNLENG); and (7) age at 1.3 m above the ground (AGE). In order to account for the non-linear patterns of the biomass components, the following transformed variables were also prepared: (1) DBH squared (DBHSQ); (2) product of DBH and total height (PDDH); and (3) the product of DBH squared and total height (PDDSQH).

The dataset developed for fitting the biomass component prediction equations is listed in Appendix I. Descriptive statistics and correlation coefficients for these data are listed in Appendix II and III, respectively.

3.0 Biomass Component Equations

Five sets of prediction equations for the ovendry biomass components were developed using multiple linear regression analysis. The methods employed, results, and application conditions for each set of equations are presented in the following subsections.

3.1 Equations Using Variables Selected from all Available Variables

Besides the basic tree attributes commonly measured in field applications (i.e., dbh and height), some measures of the tree crown (i.e., crown class, crown diameter, crown closure, and crown length) were available. These crown variables may help improve predictions for particular biomass components, particularly those related to the crown (i.e., living needle biomass and living branch biomass). Thus, it was decided to derive a set of equations using significant variables selected from the entire set of independent variables available. This set of equations should provide the best fit for individual biomass components of the five sets derived.

Since one tree was missing the crown length measurement, and it was thought that crown length would not likely be important given the presence of the other crown variables, the decision was made to omit CRNLENG from consideration as a potential independent variable and to use the data from all 60 trees.

The forward stepwise regression procedure of SAS was used to derive each of the component equations. The requirements were set as follows: (1) the analysis of variance of regression (overall F test) should be statistically significant at the 0.05 probability level; (2) all estimated regression coefficients should be significant at 0.05 probability level (t tests or partial F tests); (3) the multiple coefficient of determination (R^2) should be larger than 0.85; and (4) the standard error of estimate of regression (SEE) should be the smallest when compared to other equations with the same number of variables. The following biomass component equations were derived:

$$[1] STEMWOOD = 138.1113 + 0.5482 \times AGE - 42.3484 \times CRNCLAS - 0.4325 \times DBHSQ + 0.0275 \times PDDSQH$$
$$(R^2 = 0.984,\ \ SEE = 35.723)$$

$$[2] STEMBARK = \text{-}8.5739 + 0.2864 \times AGE - 0.8882 \times TOTHT + 0.0031 \times PPDSQH$$
$$(R^2 = 0.987,\ \ SEE = 7.761)$$

$$[3] LTWIGS = -46.9179 + 0.4380 \times AGE + 12.7831 \times AVCRNWD - 0.2395 \times DBHSQ + 0.0111 \times PDDSQH$$
$$(R^2 = 0.915, \ SEE = 24.171)$$

$$[4] LNEEDLES = -6.8161 + 2.7102 \times AVCRNWD + 0.0295 \times PPDH$$
$$(R^2 = 0.903, \ SEE = 4.974)$$

$$[5] STUMPWOOD = -5.3988 + 0.0760 \times AGE + 1.0501 \times DBH - 0.6282 \times TOTHT - 0.0352 \times DBHSQ + 0.0010 \times PDDSQH$$
$$(R^2 = 0.934, \ SEE = 2.089)$$

$$[6] STUMPBARK = -1.5327 + 0.0249 \times AGE + 0.0020 \times DBHSQ$$
$$(R^2 = 0.886, \ SEE = 0.8658)$$

$$[7] CROWN = -53.1318 + 0.4497 \times AGE + 15.6303 \times AVCRNWD - 0.2202 \times DBHSQ + 0.0109 \times PDDSQH$$
$$(R^2 = 0.925, \ SEE = 26.658)$$

$$[8] TOTAL = 152.6289 + 1.2650 \times AGE - 55.2445 \times CRNCLAS - 0.6448 \times DBHSQ + 0.0421 \times PDDSQH$$
$$(R^2 = 0.979, \ SEE = 65.264)$$

Since the equations for the different components involved different combinations of variables, they are not additive. That is the sum of the predicted values from Equations 1 to 6 will not equal the predicted values of Equation 8, for a given tree. Similarly, the sum of the predicted values from Equations 3 and 4 will not equal the predicted values of Equation 7. In order to predict the crown biomass and the total ovendry biomass above the ground, Equations 7 and 8, respectively, should be used rather than summing the predictions of the various components.

These equations generally have maximum R^2 and minimum SEE values when compared to other equations that were fit, because the variables were selected from all the available variables. It may be possible for other variable transformations or non-linear model forms to provide models with better fit; however, this is unlikely. Since these equations include variables that represent crown characteristics, they may be useful for studying the relationship between the growth of trees and their crown development.

3.2 Equations Based on Variables Available for the PSPs

The trees within the PSP boundaries were measured for dbh, total height, height to the base of the live crown, and crown width, but not for age and crown class. In order to develop a useable set of equations for predicting the component biomass on the PSPs, potential independent variables were limited to: (1) DBH; (2) DBHSQ; (3) TOTHT; (4) PDDH; (5) PDDSQH; (6) AVCRNWD; (7) CRNLENG. The forward stepwise regression option of SAS was used together with the predictive requirements outlined in section 3.1 to give the following equations:

$$[1] STEMWOOD = -30.0095 + 7.0994 \times DBH - 0.4632 \times DBHSQ + 0.0265 \times PDDSQH$$
$$(R^2 = 0.9773; \ SEE = 39.984)$$

$$[2] STEMBARK = 0.7291 + 0.0600 \times DBHSQ - 0.0497 \times PDDH + 0.0021 \times PDDSQH$$
$$(R^2 = 0.9770;\ SEE = 9.443)$$

$$[3] LTWIGS = -56.0638 + 6.9452 \times TOTHT + 11.8575 \times AVCRNWD - 0.4891 \times PDDH + 0.0110 \times PDDSQH$$
$$(R^2 = 0.9303;\ SEE = 21.493)$$

$$[4] LNEEDLES = -6.4910 + 2.6513 \times AVCRNWD + 0.0288 \times PDDH$$
$$(R^2 = 0.8930;\ SEE = 4.922)$$

$$[5] STUMWOOD = 0.0748 + 0.0106 \times DBHSQ$$
$$(R^2 = 0.8329;\ SEE = 2.579)$$

$$[6] STUMBARK = -0.0516 + 0.0034 \times DBHSQ$$
$$(R^2 = 0.9331;\ SEE = 1.018)$$

$$[7] CROWN = -57.9002 + 6.2061 \times TOTHT + 14.5738 \times AVCRNWD - 0.4334 \times PDDH + 0.0107 \times PDDSQH$$
$$(R^2 = 0.9308;\ SEE = 25.033)$$

$$[8] TOTAL = 29.9912 - 0.2266 \times DBHSQ + 0.0312 \times PDDSQH$$
$$(R^2 = 0.9692;\ SEE = 74.634)$$

As was the case for the previous set of component equations, this set is not additive. Equation 7 should be used to estimate crown biomass and Equation 8 should be used to estimate total biomass of a tree rather than summing predictions of the individual components.

Note that the equations in this set are not directly comparable to those in any of the other sets, because it was fit to data from only 59 of the 60 trees. This accounts for the apparently better fit for LTWIGS and LNEEDLES in the above equations compared to the equations in Section 3.1. Similarly, slightly different coefficient values and fit statistics are found in Section 3.3 for the equations that predict STEMWOOD, STEMBARK, STUMWOOD, STUMBARK, and TOTAL, even though the form of the equations is identical to those given above. The fact that CRNLENG did not contribute significantly to any of the equations in this set validates the decision to omit it from consideration as an independent variable in Section 3.1.

3.3 Equations Based on Dbh and Height

Many operational ground-based forest sampling designs only include measures of dbh and height on sampled trees. In order to provide component biomass equations based on these measurements, a set of equations that only used dbh (DBH) and height (TOTHT) and modifications of these variables (DBHSQ, PDDSQH, PDDH) was derived.

Forward stepwise regression was used again to select the best models from the reduced set of variables. The forward stepwise regression option of SAS was used together with the predictive requirements outlined in section 3.1 to give the following equations:

$$[1]\, STEMWOOD = -29.7680 + 7.0610 \times DBH - 0.4615 \times DBHSQ + 0.0265 \times PDDSQH$$
$$(R^2 = 0.980,\ SEE = 39.626)$$

$$[2]\, STEMBARK = 0.8941 + 0.0642 \times DBHSQ - 0.0545 \times PDDH + 0.0021 \times PDDSQH$$
$$(R^2 = 0.980,\ SEE = 9.411)$$

$$[3]\, LTWIGS = 8.2260 - 0.1230 \times DBHSQ + 0.0084 \times PDDSQH$$
$$(R^2 = 0.895,\ SEE = 26.312)$$

$$[4]\, LNEEDLES = 0.0344 + 0.0386 \times PDDH$$
$$(R^2 = 0.891,\ SEE = 5.219)$$

$$[5]\, STUMPWOOD = 0.1344 + 0.0104 \times DBHSQ$$
$$(R^2 = 0.891,\ SEE = 2.581)$$

$$[6]\, STUMPBARK = -0.0089 + 0.00326 \times DBHSQ$$
$$(R^2 = 0.891,\ SEE = 1.032)$$

$$[7]\, CROWN = 10.0156 - 0.0916 \times DBHSQ + 0.0080 \times PDDSQH$$
$$(R^2 = 0.907,\ SEE = 29.091)$$

$$[8]\, TOTAL = 32.129 - 0.2342 \times DBHSQ + 0.0312 \times PDDSQH$$
$$(R^2 = 0.972,\ SEE = 74.969)$$

Like the previous sets of equations, this set is not additive. Therefore, to estimate the crown biomass and the total ovendry biomass above ground for a tree, equations [7] and [8], respectively, should be used rather than summing the predictions of the individual components.

3.4 Additive Biomass Component Equations

In some situations, users of tree component biomass prediction equations may prefer to have a set of additive equations. It is possible to fit component and total equations in such a way that the sum of the predicted values for the components would give the predicted value from the total equations. The cost of doing this is a possible loss in predictive power of the individual component equations. The conditions for obtaining a additive set of component equations are (Kozak 1970): (1) exactly the same model is fitted for all of the component and total equations; (2) if transformation is required for the dependent variable, a linear transformation should be used instead of non-linear transformation; and (3) all equations must be fitted using the same set of observations.

To obtain a additive set of component equations, Kozak's (1970) methods were used. Four independent variables (PDDSQH, DBHSQ, DBH and PDDH) were chosen based on the component equations in Section 3.3. The resulting additive component equations were:

$$[1]STEMWOOD = -87.6484 + 0.0350 \times PDDSQH - 0.6594 \times DBHSQ + 18.6937 \times DBH - 0.4425 \times PDDH$$
$$(R^2 = 0.981,\ SEE = 38.919)$$

$$[2]STEMBARK = -4.1937 + 0.0028 \times PDDSQH + 0.0455 \times DBHSQ + 0.9694 \times DBH - 0.0877 \times PDDH$$
$$(R^2 = 0.980,\ SEE = 9.469)$$

$$[3]LTWIGS = -61.4782 + 0.0188 \times PDDSQH - 0.3564 \times DBHSQ + 14.2277 \times DBH - 0.5563 \times PDDH$$
$$(R^2 = 0.914,\ SEE = 24.159)$$

$$[4]LNEEDLES = -6.3050 + 0.00056 \times PDDSQH - 0.0048 \times DBHSQ + 1.2559 \times DBH - 0.0221 \times PDDH$$
$$(R^2 = 0.903,\ SEE = 5.0609)$$

$$[5]STUMPWOOD = -2.9811 + 0.00061 \times PDDSQH - 0.0085 \times DBHSQ + 0.5993 \times DBH - 0.0150 \times PDDH$$
$$(R^2 = 0.899,\ SEE = 2.549)$$

$$[6]STUMPBARK = -0.4455 - 0.000006 \times PDDSQH + 0.0038 \times DBHSQ + 0.0634 \times DBH - 0.0027 \times PDDH$$
$$(R^2 = 0.853,\ SEE = 1.057)$$

3.5 Simple Component Equations Without An Intercept

Empirical multiple linear regression models may perform poorly outside of the range of data from which they were developed. The range of dbh for the data set used in deriving the biomass component equations listed above was from 5.4 to 53.7 cm, and total tree height ranged from 5.7 to 31.1 m (see Appendix I). Similar equations to those derived above have been widely employed for predicting tree ovendry biomass in various parts of Canada (e.g., Singh 1982, 1984, Standish *et al.* 1985). When using these equations in compiling the national biomass inventory, Wang (1994) found that equations with an intercept often performed poorly for smaller trees. Negative intercepts could cause predicted biomass to be negative; positive intercepts could cause predicted biomass to be unrealistically large.

Possible solutions to this problem are to develop different prediction equations for small and large trees (e.g., Lavigne 1982, Alemdag 1983; 1984) or to use some simple non-linear model forms (e.g., Ker 1984). Fitting separate equations for large and small trees was not feasible for this project because there were no smaller trees (i.e., less than 5.4

cm dbh and 5.7 m in height) in the data. The simple non-linear model forms suggested by Ker (1984) were fit to the data, but the fit statistics did not met the requirements given previously.

To solve the problem of unrealistic biomass estimates for small trees, four simple linear biomass models suggested by Aldred and Alemdag (1988) were fit. The best of these models (based on the highest R^2 and lowest SEE) was then selected for each component equation. The intercepts of these simple prediction models were not significantly different from 0 at the 0.05 probability level. Therefore, the intercept terms were dropped from each model and the models refit conditioned to go through zero. The resulting equations were:

$$[1] STEMWOOD = 0.014186 \times PDDSQH \quad (R^2 = 0.980,\ SEE = 45.868)$$

$$[2]\ STEMBARK = 0.003396 \times PDDSQH \quad (R^2 = 0.982,\ SEE = 10.329)$$

$$[3] LTWIGS = 0.003788 \times PDDSQH \quad (R^2 = 0.899,\ SEE = 28.925)$$

$$[4] LNEEDLES = 0.038669 \times PDDH \quad (R^2 = 0.942,\ SEE = 5.175)$$

$$[5] STUMPWOOD = 0.010506 \times DBHSQ \quad (R^2 = 0.932,\ SEE = 2.561)$$

$$[6] STUMPBARK = 0.003262 \times DBHSQ \quad (R^2 = 0.891,\ SEE = 1.032)$$

$$[7] CROWN = 0.004677 \times PDDSQH \quad (R^2 = 0.926,\ SEE = 29.994)$$

$$[8] TOTAL = 0.022802 \times PDDSQH \quad (R^2 = 0.978,\ SEE = 77.426)$$

It should be noted that the R^2 value of a regression model without intercept is redefined by SAS (and many other statistical packages). Therefore, the R^2 values associated with these component equations should not be compared to those of similar equations with an intercept (i.e., those in the other equation sets). However, the SEE's are directly comparable.

In general, this set of component equations has a lower predictive power than the other sets. Hence, we suggest that they only be used for small trees. For other situations, these equations will not be as accurate as those presented previously. If biomass estimates are required for both small and large trees, these equations could be used in conjunction with one of the other equation sets. The tree size (dbh) at which one should switch from one equation set to another will vary with the equation set used for the larger trees. Ideally, the switch should be made at a point when predictions from both equations are quite similar; this point will vary from tree to tree. A single compromise dbh can be selected through trial and error which should suffice for most practical purposes.

3.6 Testing for Violation of Linear Regression Assumptions

In order to confirm the assumptions of regression, graphical methods and statistics provided by the REG and UNIVARIATE procedures of SAS were used to examine the residuals associated with each suggested equation. A normal probability plot was created to examine the normality of the residuals. To examine the independence and homogeneity of the error variances, 2D plots were used, and residuals were plotted against DBH and height. Collinearity among the independent variables was tested using the variance inflation factor (VIF) and condition indices (CDIs). A VIF value of larger than 10.0 will indicate a problem of collinearity (Kleinbaum *et al.* 1988). CDIs are the square roots of the ratio of the largest eigenvalue to each individual eigenvalue of the matrix of X'X, where X is the regression data matrix. A collinearity problem exists when a principal component associated with a high CDI contributes strongly to the variance of two or more variables (Kleinbaum *et al.* 1988).

The results of the testing indicated that collinearity was not a problem. A few of the equations showed a slight pattern of non-homogeneous error variances. No other departures from the regression assumptions were detected. Therefore, predictions made using the component equations should be accurate for this particular population of interior Douglas-fir.

4.0 Testing the Impact of Different Locations and Density Classes

The six PSP's established in 1988 were intended to represent a range of stand conditions (Table 1). Plots 1 and 2 were located in moderately dense conditions (RD = 10.14 and 9.96, respectively), with a greater percentage of trees and basal area in trees greater than 20 cm dbh than the other plots. Plots 3 and 4 were slightly less dense (RD = 8.45 and 8.72, respectively) than Plots 1 and 2, with a greater percentage of stems and basal area comprised of trees between 10 and 20 cm dbh than the other plots. Plots 5 and 6 were the densest of the plots (RD = 12.99 and 10.34, respectively), with a greater percentage of stems and basal area in trees less than 10 cm than the other plots.

Ten of the trees that were destructively sampled to obtain component biomass data were located in the vicinity of each of the plots. An attempt was made to find a location for these trees that was similar in appearance to the prevailing conditions in each of the plots. In order to determine whether the conditions under which the sample trees were growing affected the form of the equations used to predict the biomass of the various components, three comparisons were done. For the first comparison, the biomass data were split into three groups: (1) trees selected in the vicinity of Plots 1 and 2; (2) trees selected in the vicinity of Plots 3 and 4; and (3) trees selected in the vicinity of Plots 5 and 6. For the

Table 1. Summary of initial PSP conditions (1988)

PSP	Stems/Ha	BA/Ha (m^2)	Dq[a] (cm)	RD[b]	Percentage Composition Stems /Ha < 10	Stems/Ha 10 - 20	Stems/Ha > 20	BA/Ha < 10	BA/Ha 10 - 20	BA/Ha > 20
1	1610	43.75	18.6	10.14	73.3	11.8	14.9	4.6	6.3	89.1
2	1170	47.46	22.73	9.96	60.4	14.5	25.1	1.5	5.0	93.5
3	2520	29.53	12.2	8.45	63.9	31.0	5.1	9.1	40.6	50.3
4	1530	36.40	17.4	8.72	30.7	54.9	14.4	4.3	38.4	57.3
5	5640	40.06	9.51	12.99	88.3	5.7	6.0	16.6	14.4	69.0
6	4300	32.34	9.79	10.34	83.3	10.7	6.0	15.7	17.4	66.9

a Quadratic mean diameter.
b Curtis's (1982) relative density.

second comparison, the biomass data were split into six groups, comprised of the trees selected in the vicinity of each of the plots. For the third comparison, the biomass data were split into three groups on the basis of the degree of crown closure (CRNCLOS) associated with each sample tree. The following group boundaries were chosen to make the number of trees in each group roughly similar: (1) CRNCLOS ≤ 30% (low density); (2) CRNCLOS > 30% but ≤ 50% (medium density); and (3) CRNCLOS > 50% (high density).

To conduct these analyses, the biomass equations developed in Section 3.3 (i.e., the equations using only dbh, height, and certain combinations of these variables) were used. Indicator (dummy) variables were used to separate the equations according to the various groups.

Regression models were fit that included all the original variables, the indicator variables, and interaction terms between the original variables and the indicator variables. These models are known as the "full models". As an example, consider a situation with three groups. Two indicator variables (X_1 and X_2) are required to differentiate the three groups. The model used for predicting the biomass of live branches in the third set of component equations is:

$$LTWIGS = b_0 + b_1 \times DBHSQ + b_2 \times PDDSQH + e_i$$

where b_0, b_1, and b_2 are regression coefficients and e_i is the error (residual) associated with the estimate for the i^{th} tree. This model form is known as the "reduced model" and the values for the coefficients are given in the previous section. The full model form for the three group situation is:

$$LTWIGS = b_0 + b_1 \times DBHSQ + b_2 \times PDDSQH + b_3 \times X_1 + b_4 \times X_2 + b_5 \times DBHSQ \times X_1 + b_6 \times PDDSQH \times X_1 + b_7 \times DBHSQ \times X_2 + b_8 \times PDDSQH \times X_2 + e_i$$

The full and the reduced model are used to test the null hypothesis that the regression models for each of the groups are identical. This is equivalent to testing the null hypothesis that the true regression coefficients for b_4 through b_8 (β_4 through β_8) are all equal to 0. The appropriate test statistic for this is:

$$F = \{[SSR(full) - SSR(reduced)] / DF1\} / [SSE(full) / DF2]$$

where F follows the F distribution with degrees of freedom DF1 (the number of regression coefficients to be tested in the null hypothesis, i.e., 5 in this example) and DF2 (the degrees of freedom associated with the residual error term in the full model, i.e., n-9 in this example, where n is the number of sample trees); and SSR(full) and SSR(reduced) are sums of squares due to the regression equation in the full and reduced models, respectively. If the probability associated with the value of F under the null hypothesis is sufficiently small (i.e., < 0.05), the null hypothesis is rejected. The conclusion would be that there is a statistically significance difference among the coefficient values from the different groups. This may mean that there are differences in the intercepts, the slopes, or both.

4.1 Data Split into Three Groups According to Plot Conditions

Two indicator variables were used to differentiate the three groups: $X_1 = 1$, if the sample tree was located in the vicinity of Plot 1 or Plot 2, and $X_1 = 0$, otherwise; and $X_2 = 1$, if the sample tree was located in the vicinity of Plot 3 or Plot 4, and $X_2 = 0$, otherwise. If the sample tree came from the vicinity of Plot 5 or Plot 6, $X_1 = X_2 = 0$.

The results of the statistical tests (Table 2) indicate that the biomass component equations, with the exception of the equations for live needle biomass, varied among the groups. This implies that there would be some statistical advantages to fitting separate biomass component equations to the data associated with each of the plot condition groups.

4.2 Data Split into Six Groups According to Plot Number

Five indicator variables were used to differentiate the six plots: $X_1 = 1$, if the trees were located near Plot 1 and $X_1 = 0$, otherwise; $X_2 = 1$, if the trees were located near Plot 2 and $X_2 = 0$, otherwise; $X_3 = 1$, if the trees were located near Plot 3 and $X_3 = 0$, otherwise; $X_4 = 1$, if the trees were located near Plot 4 and $X_4 = 0$, otherwise; and $X_5 = 1$, if the trees were located near Plot 5 and $X_5 = 0$, otherwise. If the sampled trees came from the vicinity of plot 6, all of the indicator variables would equal 0.

Table 2. Results of testing the impact of plot condition on the biomass component equations.

Biomass Component	F Value	Test Conclusion
STEMWOOD	4.205	**
STEMBARK	4.958	**
LTWIGS	9.003	**
LNEEDLES	2.003	NS
STUMPWOOD	3.647	*
STUMPBARK	12.060	**
TOTAL	7.440	**
CROWN	7.823	**

The statistical tests (Table 3) indicated that all the component equations, with the exception of the equation for the bark biomass of the stump, varied among the groups. This implies that there would be some statistical advantages to fitting separate biomass component equations to the data associated with each of the plots.

Table 3. Results of testing the impact of plot linkage on the biomass component equations.

Biomass Component	F Value	Test Conclusion
STEMWOOD	507.94	**
STEMBARK	7.70	**
LTWIGS	7.43	**
LNEEDLES	2.39	*
STUMPWOOD	2.67	*
STUMPBARK	5.80	NS
TOTAL	4.25	**
CROWN	6.30	**

NOTE: * and ** denote significant differences at $\alpha = 0.05$ and 0.01, respectively, and NS means no significant difference at $\alpha = 0.05$.

4.3 Data Split into Three Groups on the Basis of Crown Closure

Two indicator variables were used to differentiate the three groups: $X_1 = 1$, if the crown closure class was low and $X_1 = 0$, otherwise; and $X_2 = 1$, if the crown closure class is medium and $X_2 = 0$, otherwise. If the crown closure class is high, $X_1 = X_2 = 0$.

The statistical tests (Table 4) indicated that the biomass component equations, with the exception of the equations for the bark biomass of the stump and the live needle biomass, varied among the groups. This implies that there would be some statistical advantages to fitting separate biomass component equations to the data associated with each of the crown classes.

Table 4. Results of testing the impact of crown closure on the biomass component equations.

Biomass Component	F Value	Test Conclusion
STEMWOOD	8.24	**
STEMBARK	4.62	**
LTWIGS	58.37	**
LNEEDLES	0.89	NS
STUMPWOOD	3.26	*
STUMPBARK	0.90	NS
TOTAL	8.54	**
CROWN	10.33	*

NOTE: * and ** denote significant differences at $\alpha = 0.05$ and 0.01, respectively, and NS means no significant difference at $\alpha = 0.05$.

4.4 Discussion

Despite good fits among the biomass component equations (indicated by high R^2 values), many of the component equations could be improved statistically by recognizing the location of the PSP near which each tree was sampled. The PSPs were located to represent a range of stand structural conditions. However, stand structure within a PSP was somewhat variable, with stocking conditions running the entire gamut from very open to quite closed, on the scale of the individual trees. It is likely that this was also the case for the trees that were destructively sampled outside each of the plots. This possibility is supported by the range of crown closure values present for these trees. Thus, differences among the biomass component equations associated with individual plots, or plots grouped according to general structure, are difficult to interpret.

The differences among the equations associated with differences in crown closure were expected. Crown closure should impact on the size and shape of the crown primarily, but it can also impact on the shape of the bole. In part, these impacts may be explained by the dependent variables present in the prediction equation. However, if the relationship among these variables changes with crown closure, then knowing crown closure can improve the prediction. This appeared to be the case for most of the biomass components. It should be kept in mind that the crown closure conditions at the time of sampling may not be similar to conditions which existed at earlier points in each tree's development.

Of the various component equations, the equation for live needle biomass appeared to be the most robust with respect to changes in tree location or crown closure, in that it was not significantly impacted by grouping according to plot condition or crown class. The equations for stump wood biomass and stump bark biomass also were not significantly impacted in at least one of the comparisons. It should be kept in mind that statistical significance does not necessarily translate to practical significance. The improvements in fit associated with grouping according to sample tree location or crown closure were not large in either an absolute or a relative sense. The standard error of estimate associated with each of the equations generally decreased by only a little, amounting only to a few percent at best.

5.0 Biomass in Each of the PSPs

5.1 Methods

The biomass component equations given in Section 3.2 were used for the larger trees and those given in section 3.5 were used for the smaller trees on each of the plots. Based on some initial exploration, the decision was made to switch from the equations for smaller trees to those for larger trees at a dbh of 7.0 cm, if the intercept in the equations for the larger trees was negative (i.e., the equations for STEMWOOD, LTWIGS, LNEEDLES, STUMBARK, and CROWN). In a few cases, the estimated value of some of the crown biomass components (i.e., LTWIGS, LNEEDLES, and CROWN) were negative using the larger tree equations at dbh values above 7 cm. If this occurred, the negative value was replaced with the value from the small tree equation. When the intercept in the equations for the larger trees was positive (i.e., the equations for STEMBARK, STUMWOOD, and TOTAL), the switch from the smaller tree equations to those for larger trees was made at a dbh of 10 cm.

5.2 Results

The estimated biomass per ha of the various components for all the trees in each of the plots is given in Table 5. The estimated biomass of the various components for the smaller trees is suspect because no small trees were included in the original biomass data. A relatively large number of the smaller trees were poorly formed and badly suppressed. The form of the small tree equations relative to the large tree equations, which had relatively large negative intercepts, suggests that the biomass for many of these small trees is likely being overestimated using the small tree equation. While this may be of concern on a tree by tree basis, it has relatively little impact on the per ha plot values since most of the biomass is contributed by trees with a dbh of 10 cm or larger (Table 6). It can be readily seen from comparing Tables 5 and 6 that the great majority of biomass is contained in the larger trees, despite there being a large number of smaller trees in many of the plots.

Table 5. Biomass (kg/ha) of various components for each of the PSPs.

Plot #	Stems /Ha	STEMWOOD	STEMBARK	LTWIGS	LNEEDLES	STUMWOOD	STUMBARK	CROWN	TOTAL
1	1610	214941	48380	74604	12545	5935	1861	86296	346340
2	1170	230310	51216	66233	13695	6443	2026	79808	366969
3	2520	106901	23955	31895	11098	4051	1216	42026	167024
4	1530	126026	29691	33794	13043	4990	1509	45728	198335
5	5600[a]	132874	31466	27329	12891	5314	1621	37000	209437
6	4260[b]	106918	23927	27997	12208	4204	1274	38760	166267

[a] Only the Douglas-fir trees are included. There were two relatively large lodgepole pine trees (the equivalent of 40 stems per ha) that were excluded from the biomass calculations.

[b] Only the Douglas-fir trees are included. There were two relatively large trees (a lodgepole pine and a trembling aspen - the equivalent of 40 stems per ha) that were excluded from the biomass calculations.

Table 6. Biomass (kg/ha) of various components for each of the PSPs in trees greater than 9.9 cm dbh. Bracketed values are % of the component biomass for all trees.

Plot #	Stems /Ha	STEMWOOD	STEMBARK	LTWIGS	LNEEDLES	STUMWOOD	STUMBARK	CROWN	TOTAL
1	430	211905	47810	71832	11200	5667	1785	82646	342512
	(26.7)	(98.6)	(98.8)	(96.3)	(89.3)	(95.5)	(95.9)	(95.8)	(98.9)
2	440	229500	51051	65260	13187	6347	1998	78531	365860
	(37.6)	(99.6)	(99.7)	(98.5)	(96.3)	(98.5)	(98.6)	(98.4)	(99.7)
3	910	102579	23161	30059	9699	3688	1114	39343	161691
	(36.1)	(96.0)	(96.7)	(94.2)	(87.4)	(91.0)	(91.6)	(93.6)	(96.8)
4	1060	122698	29127	32618	12337	4777	1452	44111	194547
	(69.3)	(97.4)	(98.1)	(96.5)	(94.6)	(95.7)	(96.2)	(96.5)	(98.1)
5	620[a]	124418	29480	25181	9550	4398	1364	33788	198089
	(11.1)	(93.6)	(93.7)	(92.1)	(74.1)	(82.8)	(84.1)	(91.3)	(94.6)
6	680[b]	100449	22647	24461	9398	3537	1082	33823	157669
	(16.0)	(93.9)	(94.7)	(87.4)	(77.0)	(84.1)	(84.9)	(87.3)	(94.8)

[a] Only the Douglas-fir trees are included. There were two relatively large lodgepole pine trees (the equivalent of 40 stems per ha) that were excluded from the biomass calculations.

[b] Only the Douglas-fir trees are included. There were two relatively large trees (a lodgepole pine and a trembling aspen - the equivalent of 40 stems per ha) that were excluded from the biomass calculations.

5.3 Discussion

Combining the estimated biomass of the various plots (Tables 5 and 6) with the relative density (Table 1), gives a more complete picture of the plot conditions than using either of these indicators alone. For example, looking only at relative density, it would appear that plots 1 and 2 are similar to plots 3 and 4. However, it is apparent from the total biomass figures that plots 1 and 2 carry considerable more biomass. Similarly, plots 3 and 4 are similar to plots 5 and 6 in terms of total biomass, but noticeably different in terms of relative density.

Relative to the other biomass components, live needle biomass showed little difference among the plots despite the considerably different structures present. This is not surprising if it can be assumed that live needle biomass is closely related to leaf area index (LAI) and that LAI is reflective of the site productivity. Although these plots represent a range of stand conditions, the locations were chosen because the site conditions appeared similar among the plots and the stand conditions within a plot appeared relatively uniform, with limited evidence of recent disturbance. Under these conditions, it is possible that the LAI has had an opportunity to reflect the site productivity. It will be interesting to see whether this similarity in live needle biomass is reflected by similar stemwood biomass growth rates among the plots.

The biomass component equations used for "large trees" for living branches, live needle biomass, and the total crown biomass were more sensitive to differences in stand conditions than the other component equations. All these equations had negative intercepts. Although 7.0 cm was used as the limit for switching from the "small tree" equations to the "large tree" equations, some trees with dbh greater than 7.0 cm still had negative estimates of certain of these biomass components. If this occurred, the component estimate was replaced with a value calculated using the appropriate "small tree" equation. The frequency of negative estimates noticeably increased in the denser plots (plots 5 and 6) compared to the more open plots (plots 1 to 4). This was likely due to the use of crown width as one of the independent variables in the "large tree" equations for these components. Crown width is highly sensitive to crowding at the individual tree level; trees that were crowded had narrower crowns for a given dbh compared to the average. This tended to result in negative estimates for at least some of these biomass components in some of the trees up to about 14 cm in diameter. In future work, this difficulty could be avoided in a number of ways, including omitting crown width as an independent variable and/or using nonlinear prediction functions that are constrained to yield realistic biomass estimates for small trees.

6.0 References

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APPENDIX I

SAMPLE TREE DATA FOR BIOMASS MODELLING

TREE	AGE (yrs.)	DBH (cm)	TOTHT (m)	AVCRNWD (m)	CRNLENG (m)	SCRNCLAS	SCRNCLOS (%)
1	42	6.7	5.8	2.325	4.5	3	10
2	49	7.2	10.4	3.750	7.3	3	30
3	72	10.5	9.5	3.375	6.0	3	40
4	42	7.5	5.9	2.000	2.6	4	30
5	97	22.4	17.4	4.350	8.7	2	40
6	113	45.0	25.8	5.550	11.7	2	30
7	153	53.7	31.1	7.950	17.0	1	50
8	83	24.0	18.2	2.775	8.0	2	30
9	102	35.1	25.3	4.650	13.6	1	60
10	52	8.1	7.8	2.750	4.0	3	25
11	104	23.5	18.1	4.600	9.7	2	60
12	28	10.3	8.1	3.075	6.8	3	60
13	19	8.3	6.9	2.725	5.6	3	20
14	99	23.9	20.5	4.250	13.4	2	30
15	56	12.5	11.0	3.675	7.1	3	40
16	59	15.1	13.4	3.350	9.5	3	35
17	95	30.4	19.8	5.175	12.2	2	40
18	95	37.1	25.2	4.725	13.1	2	40
19	74	23.0	21.5	3.775	13.0	2	20
20	192	49.9	25.6	7.025	.	1	30
21	64	10.5	11.2	2.925	4.6	3	45
22	80	18.2	15.1	4.275	6.8	2	25
23	74	8.5	9.5	2.325	2.8	3	50
24	135	43.2	25.6	7.325	12.8	1	70
25	52	5.8	5.7	2.475	3.5	4	30
26	109	27.8	19.5	5.350	9.4	2	40
27	90	13.8	12.7	4.250	7.0	3	30
28	82	13.3	13.9	3.250	5.0	3	40
29	171	34.7	22.2	4.050	12.6	1	35
30	101	20.9	16.8	3.825	7.0	2	55
31	177	47.0	23.4	7.100	13.3	1	80
32	67	13.2	10.4	3.300	6.3	3	30
33	90	18.0	14.3	3.625	7.6	2	35
34	92	17.1	13.8	3.825	10.4	3	70
35	91	25.1	19.3	4.500	10.5	1	80
36	67	7.8	7.4	2.775	5.5	4	60
37	61	12.8	12.2	3.550	6.6	3	50
38	60	8.8	8.7	2.075	5.4	3	30
39	92	23.6	20.4	4.025	13.3	2	50
40	42	7.4	6.7	3.000	4.5	4	30
41	91	16.7	16.5	3.150	5.9	2	45
42	97	21.3	17.4	4.300	5.7	2	45
43	108	12.7	11.3	2.850	5.0	3	50
44	66	8.6	8.5	2.475	3.0	3	60
45	57	5.4	5.8	2.025	1.6	4	60

TREE	AGE (yrs.)	DBH (cm)	TOTHT (m)	AVCRNWD (m)	CRNLENG (m)	SCRNCLAS	SCRNCLOS (%)
46	82	17.8	15.8	4.425	7.3	2	35
47	59	7.2	8.1	1.650	2.3	3	60
48	168	42.9	23.2	6.225	12.0	1	70
49	104	29.4	20.1	3.850	9.6	2	40
50	273	48.0	24.4	5.975	11.7	1	30
51	98	11.8	16.8	2.125	7.0	3	70
52	110	33.3	22.3	5.325	9.8	2	70
53	102	26.3	16.9	4.350	7.2	2	65
54	95	15.0	15.0	2.925	5.0	3	70
55	66	8.9	8.5	2.475	2.7	3	35
56	56	11.0	9.6	2.775	5.6	3	40
57	52	6.7	7.4	2.450	3.3	4	35
58	92	12.5	13.3	2.900	4.4	3	65
59	65	6.0	8.3	1.550	0.7	4	65
60	108	23.3	18.4	5.050	8.7	2	45

TREE	DBHSQ	PDDH	PDDSQH	STEMWOOD (kg.)	STEMBARK (kg.)	LTWIGS (kg.)
1	44.89	38.86	260.36	3.35	0.823	2.086
2	51.84	74.88	539.14	24.85	5.577	9.234
3	110.25	99.75	1047.38	17.77	4.236	6.709
4	56.25	44.25	331.88	5.22	1.105	1.693
5	501.76	389.76	8730.62	139.06	28.239	35.552
6	2025.00	1161.00	52245.00	505.47	138.149	82.042
7	2883.69	1670.07	89682.76	1467.44	291.034	480.820
8	576.00	436.80	10483.20	164.72	37.658	25.529
9	1232.01	888.03	31169.85	459.73	85.795	66.708
10	65.61	63.18	511.76	7.74	1.498	3.051
11	552.25	425.35	9995.73	129.67	33.740	26.042
12	106.09	83.43	859.33	9.15	2.177	4.576
13	68.89	57.27	475.34	4.19	1.029	3.350
14	571.21	489.95	11709.80	207.03	34.905	37.208
15	156.25	137.50	1718.75	7.74	1.595	9.421
16	228.01	202.34	3055.33	50.25	10.867	14.511
17	924.16	601.92	18298.37	174.499	39.404	48.578
18	1376.41	934.92	34685.53	462.064	125.328	88.351
19	529.00	494.50	11373.50	175.698	30.777	28.674
20	2490.01	1277.44	63744.26	862.560	231.588	173.896
21	110.25	117.60	1234.80	20.311	3.523	2.692
22	331.24	274.82	5001.72	90.373	15.529	18.593
23	72.25	80.75	686.38	11.794	2.965	1.758
24	1866.24	1105.92	47775.74	660.371	145.625	156.219
25	33.64	33.06	191.75	2.378	0.669	1.043
26	772.84	542.10	15070.38	218.849	47.125	50.479
27	190.44	175.26	2418.59	30.940	9.274	5.546
28	176.89	184.87	2458.77	41.682	8.215	6.079

TREE	DBHSQ	PDDH	PDDSQH	STEMWOOD (kg.)	STEMBARK (kg.)	LTWIGS (kg.)
29	1204.09	770.34	26730.80	339.236	101.906	83.298
30	436.81	351.12	7338.41	122.595	32.182	10.720
31	2209.00	1099.80	51690.60	685.549	172.998	228.659
32	174.24	137.28	1812.10	40.747	9.584	10.110
33	324.00	257.40	4633.20	78.028	19.199	21.029
34	292.41	235.98	4035.26	66.578	18.835	18.961
35	630.01	484.43	12159.19	202.596	40.299	51.743
36	60.84	57.72	450.22	6.768	1.415	2.986
37	163.84	156.16	1998.85	33.650	6.546	8.425
38	77.44	76.56	673.73	7.174	2.029	1.806
39	556.96	481.44	11361.98	212.724	40.657	44.560
40	54.76	49.58	366.89	3.419	0.680	4.100
41	278.89	275.55	4601.69	97.655	14.461	10.722
42	453.69	370.62	7894.21	135.807	35.944	19.597
43	161.29	143.51	1822.58	24.960	5.007	3.868
44	73.96	73.10	628.66	9.550	2.129	1.421
45	29.16	31.32	169.13	2.734	0.744	0.473
46	316.84	281.24	5006.07	104.810	23.934	29.953
47	51.84	58.32	419.90	6.422	1.358	0.333
48	1840.41	995.28	42697.51	597.154	173.851	201.658
49	864.36	590.94	17373.64	306.322	66.193	54.126
50	2304.00	1171.20	56217.60	793.911	229.819	231.743
51	139.24	198.24	2339.23	37.759	7.236	2.407
52	1108.89	742.59	24728.25	351.578	83.356	69.414
53	691.69	444.47	11689.56	197.871	47.780	50.274
54	225.00	225.00	3375.00	58.487	10.249	4.200
55	79.21	75.65	673.29	10.119	1.972	1.779
56	121.00	105.60	1161.60	16.147	4.012	4.797
57	44.89	49.58	332.19	5.459	0.923	1.147
58	156.25	166.25	2078.13	32.796	6.100	4.787
59	36.00	49.80	298.80	5.601	0.963	0.232
60	542.89	428.72	9989.18	163.431	44.061	21.159

TREE	LNEEDLES (kg.)	STUMWOOD (kg.)	STUMBARK (kg.)	TOTAL (kg.)	CROWN (kg.)
1	1.7852	0.9375	0.2375	9.22	3.871
2	8.7284	2.3833	0.6121	51.38	17.962
3	6.7939	1.1301	0.3535	36.99	13.503
4	1.9434	0.3174	0.1017	10.38	3.637
5	16.8825	0.5246	0.1433	220.40	52.435
6	21.6300	12.2392	4.1687	763.70	103.672
7	64.4348	36.7121	9.5861	2350.03	545.255
8	10.8886	5.6104	1.6378	246.05	36.418
9	27.0128	12.4924	3.5207	655.26	93.721
10	2.1964	0.5699	0.1193	15.17	5.247
11	11.2322	4.6002	1.5181	206.80	37.274

TREE	LNEEDLES (kg.)	STUMWOOD (kg.)	STUMBARK (kg.)	TOTAL (kg.)	CROWN (kg.)
12	5.2768	0.9360	0.2500	22.36	9.853
13	3.2580	0.3287	0.0911	12.25	6.608
14	20.4325	6.2674	1.3345	307.18	57.640
15	7.2894	0.1662	0.0426	26.25	16.710
16	8.9901	3.2115	0.5985	88.42	23.501
17	28.4345	9.1644	2.8258	302.91	77.012
18	37.4837	11.1472	3.9130	728.29	125.834
19	18.6077	3.8226	1.0262	258.60	47.281
20	56.7437	23.5728	6.3483	1354.71	230.640
21	3.1208	1.0377	0.1986	30.88	5.813
22	11.8453	4.7220	0.7731	141.84	30.439
23	2.8603	1.2209	0.3385	20.94	4.618
24	48.1451	18.8159	5.0150	1034.19	204.364
25	1.2384	0.3348	0.0837	5.75	2.282
26	25.5952	8.9622	2.3050	353.32	76.074
27	6.8900	1.6588	0.7294	55.04	12.436
28	5.6706	1.8927	0.4807	64.02	11.749
29	30.3446	18.5584	7.1680	580.51	113.642
30	13.4320	4.8690	1.6934	185.49	24.152
31	40.2697	15.8932	4.9178	1148.29	268.929
32	7.8123	2.2657	0.5925	71.11	17.922
33	18.1231	3.8587	1.2494	141.49	39.152
34	7.5998	2.9693	1.0326	115.98	26.561
35	20.7422	5.9349	1.6614	322.98	72.485
36	1.4799	0.4339	0.0911	13.17	4.466
37	6.3277	1.8309	0.4115	57.19	14.753
38	1.8062	0.6394	0.2160	13.67	3.612
39	21.0597	5.8123	1.4829	326.30	65.620
40	2.6069	0.3819	0.0723	11.26	6.707
41	7.1715	4.9203	0.8696	135.80	17.894
42	8.9027	4.7134	1.7278	206.69	28.500
43	2.6954	1.3103	0.2802	38.12	6.563
44	2.4316	0.6280	0.1492	16.31	3.853
45	0.5497	0.2195	0.0673	4.79	1.022
46	14.1522	3.4760	1.1321	177.46	44.105
47	0.5867	0.6061	0.1439	9.45	0.920
48	53.6926	17.9319	6.5204	1050.81	255.351
49	27.5633	14.9548	4.4186	473.58	81.689
50	47.9644	30.9920	12.2573	1346.69	279.707
51	1.9610	1.1658	0.3050	50.83	4.368
52	21.6741	14.8451	4.5022	545.37	91.088
53	28.0412	8.6967	2.9603	335.62	78.316
54	6.2890	2.2941	0.5134	82.03	10.489
55	1.6898	0.6369	0.1126	16.31	3.469
56	3.9231	1.1614	0.3871	30.43	8.720
57	0.9122	0.5556	0.0994	9.10	2.059
58	5.2759	2.1601	0.4744	51.59	10.063
59	0.2195	0.4080	0.0720	7.50	0.451
60	6.8947	10.1674	4.0266	249.74	28.054

APPENDIX II

DESCRIPTIVE STATISTICS FOR THE BIOMASS DATA

Variable	N	Mean	Std. Dev.	Sum	Minimum	Maximum
AGE	60	89.533333	42.517580	5372.000000	19.000000	273.000000
SDBH	60	19.941667	12.984388	1196.500000	5.400000	53.700000
STOTHT	60	15.061667	6.496025	903.700000	5.700000	31.100000
AVCRNWD	60	3.808750	1.438439	228.525000	1.550000	7.950000
CRNLENG	59	7.579661	3.693740	447.200000	0.700000	17.000000
SCRNCLAS	60	2.483333	0.892372	149.000000	1.000000	4.000000
SCRNCLOS	60	45.166667	16.466882	2710.000000	10.000000	80.000000
DBHSQ	60	563.454500	703.408570	33807	29.160000	2883.690000
PDDH	60	378.672833	382.815990	22720	31.320000	1670.070000
PDDSQH	60	12375	19003	742503	169.128000	89683
STEMWOOD	60	178.541912	271.461038	10713	2.377570	1467.441517
STEMBARK	60	42.414540	65.101040	2544.872429	0.668692	291.033645
LTWIGS	60	43.182098	79.738442	2590.925887	0.231707	480.819885
LNEEDLES	60	14.660083	15.665093	879.604985	0.219512	64.434848
STUMWOOD	60	6.001167	7.758083	360.070015	0.166160	36.712114
STUMBARK	60	1.832680	2.519796	109.960810	0.042586	12.257272
TOTAL	60	286.632481	437.213606	17198	4.786569	2350.028074
CROWN	60	57.842181	93.832259	3470.530872	0.451220	545.254734

APPENDIX III

PEARSON CORRELATION COEFFICIENTS FOR THE BIOMASS DATA

	AGE	DBH	TOTHT	AVCRNWD	CRNLENG	SCRNCLAS	SCRNCLOS	DBHSQ	PDDH
AGE	1.00000	0.84434	0.77621	0.74580	0.62625	-0.75829	0.21581	0.83546	0.81588
DBH	0.84434	1.00000	0.94426	0.91586	0.86573	-0.87812	0.17377	0.97084	0.98689
TOTHT	0.77621	0.94426	1.00000	0.85510	0.89523	-0.89495	0.20589	0.86542	0.92924
AVCRNWD	0.74580	0.91586	0.85510	1.00000	0.83326	-0.81871	0.16532	0.89167	0.90037
CRNLENG	0.62625	0.86573	0.89523	0.83326	1.00000	-0.81622	0.10547	0.79366	0.85100
CRNCLAS	-0.75829	-0.87812	-0.89495	-0.81871	-0.81622	1.00000	-0.16129	-0.79038	-0.83582
CRNCLOS	0.21581	0.17377	0.20589	0.16532	0.10547	-0.16129	1.00000	0.15049	0.16065
BHSQ	0.83546	0.97084	0.86542	0.89167	0.79366	-0.79038	0.15049	1.00000	0.98608
PDDH	0.81588	0.98689	0.92924	0.90037	0.85100	-0.83582	0.16065	0.98608	1.00000
PDDSQH	0.79034	0.93843	0.83297	0.86590	0.76332	-0.73982	0.13211	0.99008	0.97478
STEMWOOD	0.77608	0.91544	0.82648	0.85748	0.75889	-0.74228	0.14621	0.96641	0.95843
STEMBARK	0.84012	0.93299	0.81736	0.85691	0.74426	-0.74779	0.12950	0.98453	0.96104
LTWIGS	0.72776	0.82880	0.71876	0.80783	0.67756	-0.66022	0.16844	0.90287	0.87817
LNEEDLES	0.80393	0.94289	0.86342	0.89695	0.83439	-0.83094	0.14671	0.94224	0.94387
STUMWOOD	0.85076	0.91835	0.82899	0.83965	0.74549	-0.77484	0.11553	0.94404	0.93782
STUMBARK	0.88938	0.89359	0.79098	0.79181	0.70072	-0.75601	0.09741	0.91237	0.89808
TOTAL	0.78871	0.91369	0.81615	0.85893	0.75203	-0.74051	0.14865	0.96707	0.95397
CROWN	0.75266	0.86173	0.75495	0.83624	0.71382	-0.69978	0.16763	0.92457	0.90384

	PDDSQH	STEMWOOD	STEMBARK	LTWIGS	LNEEDLES	STUMWOOD	STUMBARK	TOTAL	CROWN
AGE	0.79034	0.77608	0.84012	0.72776	0.80393	0.85076	0.88938	0.78871	0.75266
DBH	0.93843	0.91544	0.93299	0.82880	0.94289	0.91835	0.89359	0.91369	0.86173
TOTHT	0.83297	0.82648	0.81736	0.71876	0.86342	0.82899	0.79098	0.81615	0.75495
AVCRNWD	0.86590	0.85748	0.85691	0.80783	0.89695	0.83965	0.79181	0.85893	0.83624
CRNLENG	0.76332	0.75889	0.74426	0.67756	0.83439	0.74549	0.70072	0.75203	0.71382
CRNCLAS	-0.73982	-0.74228	-0.74779	-0.66022	-0.83094	-0.77484	-0.75601	-0.74051	-0.69978
CRNCLOS	0.13211	0.14621	0.12950	0.16844	0.14671	0.11553	0.09741	0.14865	0.16763
BHSQ	0.99008	0.96641	0.98453	0.90287	0.94224	0.94400	0.91237	0.96707	0.92457
PDDH	0.97478	0.95843	0.96104	0.87817	0.94387	0.93782	0.89808	0.95397	0.90384
PDDSQH	1.00000	0.98571	0.98736	0.93357	0.92359	0.94235	0.89550	0.98427	0.94753
STEMWOOD	0.98571	1.00000	0.98119	0.96594	0.92837	0.95444	0.89355	0.99850	0.97585
STEMBARK	0.98736	0.98119	1.00000	0.93752	0.93646	0.95964	0.93151	0.98504	0.95304
LTWIGS	0.93357	0.96594	0.93752	1.00000	0.88098	0.91078	0.85259	0.97436	0.99688
LNEEDLES	0.92359	0.92837	0.93646	0.88098	1.00000	0.92280	0.88214	0.93381	0.91560
STUMWOOD	0.94235	0.95444	0.95964	0.91078	0.92280	1.00000	0.97550	0.95803	0.92803
STUMBARK	0.89550	0.89355	0.93151	0.85259	0.88214	0.97550	1.00000	0.90367	0.87180
TOTAL	0.98427	0.99850	0.98504	0.97436	0.93381	0.95803	0.90367	1.00000	0.98391
CROWN	0.94753	0.97585	0.95304	0.99688	0.91560	0.92803	0.87180	0.98391	1.00000