# ESTIMATING CROWN WEIGHTS OF *PINUS RADIATA* FROM BRANCH VARIABLES

H. A. I. MADGWICK and D. S. JACKSON
Forest Research Institute, New Zealand Forest Service, Rotorua

(Received for publication 15 February 1974)

ABSTRACT

Regression analysis of two sets of sample branches indicated that branch sample position within the crown affects the relationships between branch size and the weights of needles and wood material. Clonal variation was statistically significant in equations for predicting needle weight. Traditional methods of estimating crown weights from branch size underestimated actual weights in an independent set of sample trees. The degree of underestimation was small for wood plus bark, but as large as 19% for foliage weights. Correcting estimates for bias in the regression technique only partially compensated for the discrepancy in foliage estimates. The remaining bias was apparently due to the effect of branch position in crown on estimating equations. However, incorporating the relative height of the branch within crown in regressions led to over-compensation with weight estimates up to 21% above actual weights.

## INTRODUCTION

This study had two purposes. The first was to improve existing prediction equations for estimating crown development of radiata pine (*Pinus radiata* D. Don), particularly when destructive sampling is not possible. The second was to test prediction equations by comparing predicted versus actual weights in a set of sample trees.

Diameters of branches have been used to predict amount of foliage on them since Cummings (1941) suggested the method for silver maple. Subsequent investigators have extended it to estimate weights of crown components of individual trees (Attiwill, 1962, 1966), of understorey shrubs (Whittaker, 1965) and canopy components of tree stands (Rothacher, Blow and Potts, 1954). Recently, Forrest and Ovington (1971) have used the method in a study of clonal variation in radiata pine. Correlations between logarithm branch diameter and logarithms of foliage or wood and bark weights are characteristically high and prediction equations are consistently reported significant at probabilities less than 0.01. Residual mean squares for prediction equations are less frequently reported, but Attiwill (1962) found values of 0.0115 and 0.0081 on a logarithmic scale for *Eucalyptus* leaves and branch wood respectively.* Comparable estimates based on data in Table 2 of Forrest and Ovington (1971) give values of 0.0227 and 0.0114 for radiata pine. Since the variances are in logarithmic units they represent relatively large arithmetical sample standard errors of estimate for foliage and wood.

---

* All logarithms used are to base 10.

Finney (1941) pointed out that means determined following logarithmic transformation underestimate arithmetical means. The degree of bias increases with the variance of the transformed data. The data of Forrest and Ovington (1971) suggest that the bias due to logarithmic transformation would be small. We have found no tests of prediction equations against independent branch samples.

## MATERIALS AND METHODS

Two sets of sample branch material were available for developing the estimating equations. The first included eight branch collections made at approximately six week intervals from early May 1971 to March 1972. Each collection included one branch from each of four individuals of nine clones. Crowns were divided into four layers and sampled so that each layer of each clone was represented by one branch on each sampling date. The trees were in their fifth growing season and had live crowns almost to ground level. The clones had been planted in single tree plots at 1.2 × 1.2 m spacing near the Forest Research Institute, Rotorua.

The second sample of branches included one branch of each annual age class from three to seven trees of different genotypes in each of eight plantations on the northern boundary of Kaingaroa Forest. Stand age varied from 2 to 22 years and branch age from 1 to 13 years. Sampling was between late May and late August, 1971. For approximately half these trees the longest branch was selected in each annual age class. The other half of the sample included branches chosen at random within the age classes. Method of sampling (longest branch versus random selection) had no significant effect on regression analyses and will not be discussed further.

Sample branches were usually separated into woody material and needles by age class on the day of sampling and placed in forced draught ovens at 65°C until dry. For all branches, measurements included oven dry weights (0.1 g) by components, branch length in cm, basal diameter (2.5 cm from the stem on a vertical axis), diameter at one-fifth length, and age. Diameters were measured with Vernier calipers to 0.1 mm. For the first set (clonal material) height of insertion on tree, tree height, total number of branch clusters and clusters above the sample branch cluster were also recorded.

The data were analysed by multiple regression methods with one-year-old needles, total needle weight and branch wood plus bark as dependent variables. One-year-old needles were defined as those needles which expanded in the preceding growing season. The number of observations in regressions varies within data sets for two main reasons. First, the data were screened using regression analysis and noting points lying more than three standard deviations from initial regressions. The weights and sizes of such sample branches were re-examined for possible sources of error. If no cause for a discrepancy was found the branch was excluded from final analyses. Second, in the clonal data some branches sampled were too young and not yet bearing needles.

Between the first and second sampling of clonal material eight complete trees, representing eight of the nine clones in the study area, were felled and measured. Sampling measurements and methods were identical to those employed for sample branches except that all branches of a single cluster were subsequently combined for oven-drying and weighing. These provided the data for an independent test of the estimating equations, and were therefore not included in the initial analyses.

## RESULTS

Sample branches ranged in length from 2 to 241 cm for clonal material and from 4 to 835 cm for the Kaingaroa samples. Independent variables were highly correlated in each set. Correlations of length (L) and diameter (D) at branch base were 0.89 and 0.97, respectively. Consequently, log D and log ($D^2L$) were approximately equally correlated with logarithms of component weights (Table 1).

TABLE 1—Simple correlation coefficients between logarithms of branch size and log o.d. weights of radiata pine sample branches, for two different localities

| | 1-year-needles | | Total needles | | Wood + Bark | |
|---|---|---|---|---|---|---|
| | Long Mile | Kaingaroa | Long Mile | Kaingaroa | Long Mile | Kaingaroa |
| Basal diameter (D) | 0.84 | 0.85 | 0.90 | 0.92 | 0.96 | 0.99 |
| $D^2 \times$ length | 0.85 | 0.83 | 0.92 | 0.91 | 0.99 | 0.99 |

Branch size and the weight of wood plus bark both reflect the total history of the development of the branch whereas foliage weight, particularly one-year-old foliage, more strongly reflects recent development. As might be expectd, logarithm branch size was more closely correlated with logarithm wood plus bark weight than with logarithm foliage weight. Correlation coefficients were very similar for both sets of data (Table 1), but the error mean square decreased in the order one-year-old foliage, total foliage, branch wood plus bark (Table 2).

TABLE 2—Sample size, percentage variation accounted for, and error mean squares for multiple regression analysis of sample branches from Kaingaroa Forest

| Source of variation | Dependent Variables (logarithm to base 10) 1-year-needles | Total needles | Wood + Bark |
|---|---|---|---|
| Log diameter (D) | 71.9*** | 86.8*** | 98.8*** |
| Branch age | 14.6*** | 2.7*** | 0.3*** |
| Age $\times$ log D | 0.3* | 0.0 | 0.05** |
| Error mean square | 0.0968 | 0.0691 | 0.0100 |
| Log ($D^2 \times$ length) | 68.5*** | 85.0*** | 99.3*** |
| Branch age | 16.8*** | 3.8*** | 0.04*** |
| Age $\times$ size | 0.8*** | 0.1 | 0.02** |
| Error mean square | 0.1023 | 0.0727 | 0.0079 |
| Sample size | 229 | 230 | 238 |

* Significant at the 5% level
** Significant at the 1% level
*** Significant at the 0.1% level

For the Kaingaroa data separate regressions were calculated for each age class of branches. These showed a strong effect of branch age on the relationship between logarithm size and logarithm weight of one-year-old needles (Fig. 1). Including branch age as a second variable improved the fit of all regressions when data for all branches were combined (Table 3). This age effect might be interpreted as a reaction to increased shading in the lower canopy, with such shading more acute for small than for large branches. While interaction terms of branch size times age were statistically significant in reducing the error mean square for one-year needles and wood plus bark, the increase in precision was very small.

These results suggested possible improvements in the analysis of data from the clonal trees. Thus, different variables were included to account for position in canopy, namely relative height (height of branch insertion divided by tree heights) and relative

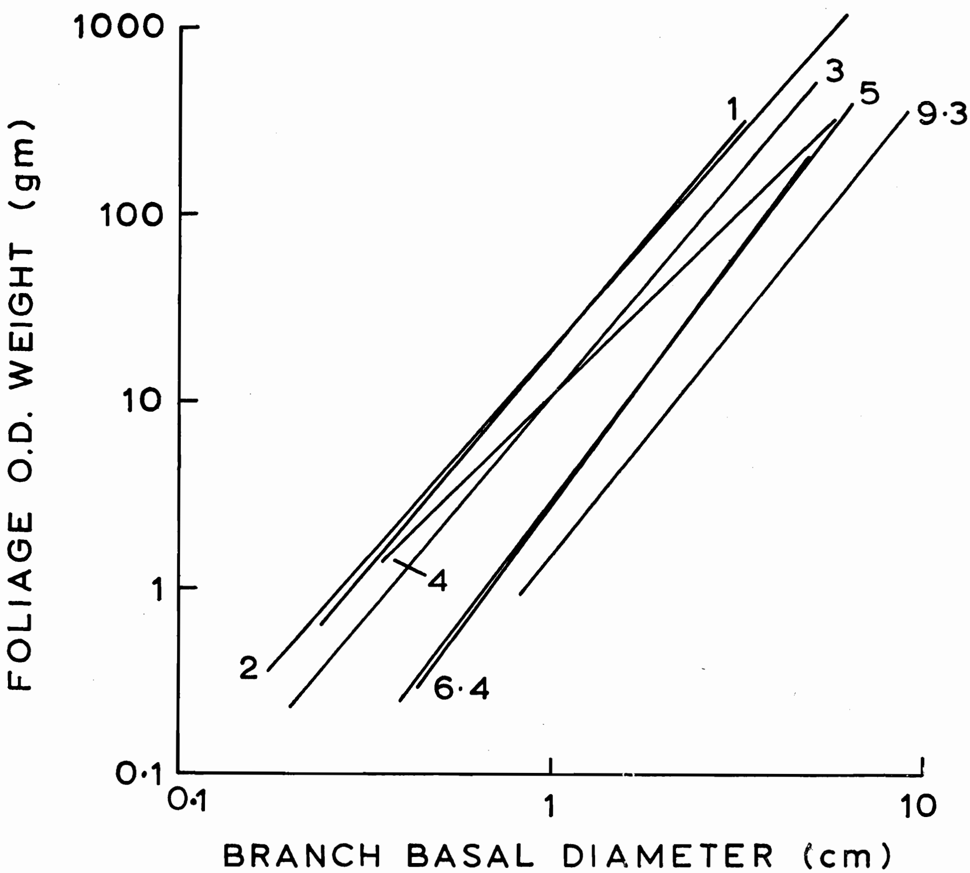


FIG. 1—Regressions relating logarithm one-year-old needle weight to logarithm branch diameters, for branch age classes of radiata pine on Kaingaroa Forest. Numbers by each line indicate average branch age in years. (Branches older than five years were limited in number and were divided into two groups including branches 6- and 7-year-old and over 7 years old, respectively.) Lines have been plotted over the range of sample diameters in each class.

TABLE 3—Multiple regression equations relating branch weights to size and age for sample branches from Kaingaroa Forest (Units: weights, g; diameter, mm × 10; length, cm; age, yrs)

| Independent Variable | Dependent Variables (logarithms to base 10) 1-year-needles Regression Coefficient | Standard Error | Total needles Regression Coefficient | Standard Error | Wood + Bark Regression Coefficient | Standard Error |
|---|---|---|---|---|---|---|
| Log diameter (D) | 2.184 | 0.104 | 2.213 | 0.088 | 2.997 | 0.033 |
| Branch age | –0.269 | 0.060 | –0.062 | 0.051 | 0.094 | 0.019 |
| Age × log D | 0.057 | 0.025 | 0.003 | 0.021 | –0.029 | 0.008 |
| Constant* | –2.883 | 0.233 | –3.010 | 0.198 | –4.891 | 0.074 |
| Log ($D^2$ × length) | 0.659 | 0.033 | 0.677 | 0.028 | 0.908 | 0.009 |
| Branch age | –0.352 | 0.059 | –0.134 | 0.050 | –0.033 | 0.016 |
| Age × log size | 0.029 | 0.008 | 0.010 | 0.007 | 0.006 | 0.002 |
| Constant* | –2.295 | 0.220 | –2.481 | 0.186 | –4.114 | 0.061 |

* Uncorrected for bias in logarithmic regressions.

cluster position (branch clusters from tree apex divided by total number of clusters on the tree). Of these, relative height proved the most useful. Branch size contributed most to each regression but significant improvements were obtained by including relative height (RH) and $(RH)^2$ (Table 4). Including clones as dummy variables decreased error variance significantly for foliage regressions ($P \cong 0.01$). The effect on wood plus bark regressions was not clear because clones always accounted for less than 2 percent of the variation in the dependent variable. Other variables tested included sampling date and the interaction of branch size and relative height. They did not contribute significantly to the regression.

TABLE 4—Sample size, percentage variation accounted for, and error mean squares for multiple regression analysis for sample branches from Long Mile

| Source of variation | Dependent Variables (logarithm to base 10) 1-year-needles | Total needles | Wood + Bark |
|---|---|---|---|
| Log diameter (D) | 68.2*** | 81.1*** | 93.7*** |
| Relative height (RH) and $(RH)^2$ | 9.3*** | 6.5*** | 2.64*** |
| Clone | 2.1** | 0.9** | 0.2* |
| Error mean square | 0.1223 | 0.0589 | 0.0230 |
| Log $D^2$ × length | 69.5*** | 84.7*** | 98.6*** |
| RH and $(RH)^2$ | 8.8*** | 5.3*** | 0.06*** |
| Clone | 2.2** | 0.9** | 0.04 |
| Error mean square | 0.1165 | 0.0464 | 0.0081 |
| Sample size | 233 | 266 | 279 |

* Significant at the 5% level
** Significant at the 1% level
*** Significant at the 0.1% level

The usefulness of branch sampling for estimating crown weights was tested using an independent sample of eight trees representing all but one of the nine clones. For each tree, component weights were calculated for each branch cluster. Prediction equations tested included ones involving either log D or log ($D^2L$) in combination with either clone or relative height variables or both, and were calculated using regressions based on only the first and second clonal branch sampling (this corresponded to the time of whole-tree sampling).

Estimates of the total weights of the three crown components of individual trees differed quite widely from actual values. Thus equations involving log D alone, corrected for the bias due to logarithmic transformation, gave estimated one-year-old needle weights within 79 and 119% of actual weights. For total needle weight and wood plus bark weights the ranges were 70 to 102% and 60 to 116% respectively. All eight equations yielded at least one prediction for at least one component that was outside the range of 75 to 125% of actual weight.

When the combined weight of all eight test trees was considered, two-thirds of the estimated component weights were within 10% of the actual weight when corrected for the logarithmic bias (Table 5).

TABLE 5—Predicted minus actual weights of crown components as a percentage of total component weights, based on eight sample trees with and without corrections for bias due to logarithmic transformation

| Predictor Variables | One-year-needles Without Corrections | One-year-needles With Corrections | Total needles Without Corrections | Total needles With Corrections | Wood + Bark Without Corrections | Wood + Bark With Corrections |
|---|---|---|---|---|---|---|
| D | -13 | -5 | -18 | -11 | -6 | -3 |
| D, RH, $(RH)^2$ | 13 | 17 | 1 | 5 | 9 | 10 |
| D, C | -13 | -5 | -13 | -5 | -9 | -6 |
| D, RH, $(RH)^2$, C | 18 | 21 | 13 | 17 | 6 | 7 |
| $D^2 \times L$ | -19 | -11 | -18 | -13 | -4 | -3 |
| $D^2L$, RH, $(RH)^2$ | 1 | 5 | -8 | -5 | -2 | -2 |
| $D^2L$, C | -18 | -9 | -10 | -3 | -2 | -2 |
| $D^2L$, RH, $(RH)^2$, C | 8 | 11 | 6 | 10 | -1 | -1 |

D = diameter; RH = relative height; L = length; C = clone.

Equations involving log D or log ($D^2L$), with or without clone effects, consistently underestimated foliage weights even when the bias due to transformation was accounted for. Incorporating relative height (RH) and $RH^2$ overcorrected to give positive bias when diameter was used as the size parameter. However, when $D^2L$ was used, without correction for clone effects, estimates of the total weights of the three components of the eight test trees were all within 5% of the actual weights.

The effects of attempting to account for position of the branch within the crown are illustrated in Fig. 2 using prediction equations for estimating the weights of one-year-old needles, with and without relative height-terms. Excluding relative height overestimated foliage weight on the small branches near the top and base while underestimating foliage weights on larger branches in the central part of the crown. Including relative height decreased the biases at the tops and base of the crown. However, biases in upper mid-crown become large and positive so leading to an over-estimate of total needle weight.

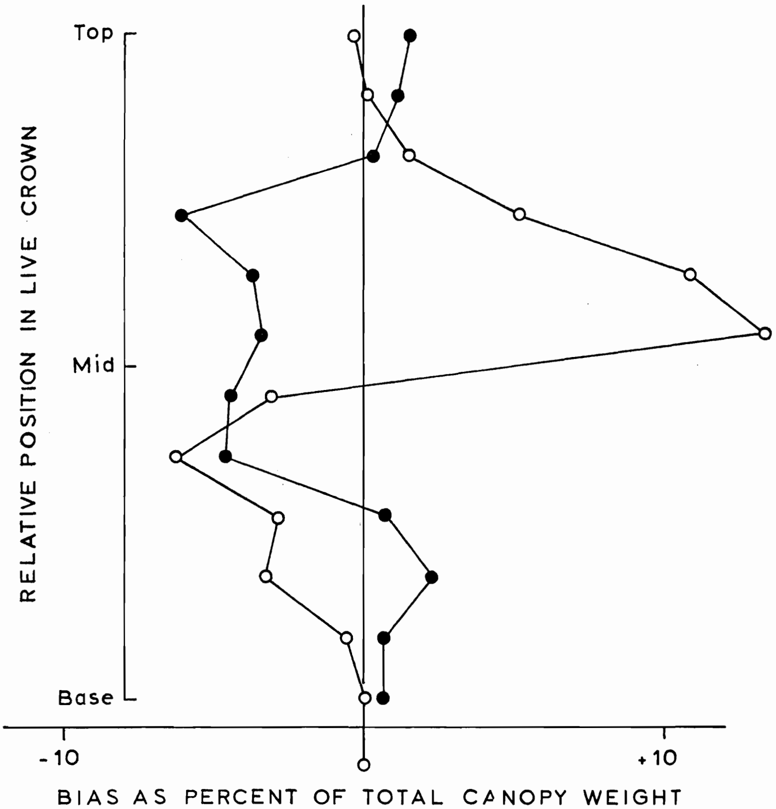


FIG. 2—Bias in estimated weights of one-year-old needles in crown, based on the regression of log weight on log (branch diameter$^2$ $\times$ length), with (o) and without (●) relative height (RH) and $(RH)^2$ included.

## DISCUSSION

The precision of prediction equations was greater for branch wood plus bark than for total needles. This agrees with the results previously published for radiata pine by Forrest and Ovington (1971). The precision of prediction equations was least for one-year-old needles. Less precision may be expected for foliage, because needle weights will be affected by shading within the crown, which is only approximately related to such variables as the relative height in the crown. Moreover, in the central North Island growing conditions are such that accurately differentiating needles by age classes becomes difficult—especially in young trees with no sharply defined dormant season. Independent estimates of the error variance of the logarithmically transformed weights were obtained using the near-neighbour techniques of Daniel and Wood (1971) for the clonal branch samples. Compared with the residual mean squares in Table 3 these estimates of the error variance of the logarithms of weights were similar for branch wood plus bark, 20% smaller for total needles and 40% smaller for one-year-old needles. These results suggest that the prediction equations for needle weight could be significantly improved by the identification and use of additional appropriate variables.

Two principal sources of bias affect the estimation of crown weights from branch dimensions. First, logarithmic transformation prior to regression analysis results in the estimation of geometric mean weights rather than arithmetic mean weights. This bias depends on the error variance in the regression and may be overcome by using the appropriate correction factor (Finney, 1941; Madgwick, 1970).

The second source of bias results from the fact that other factors, apart from size, affect the relationship between component weight and branch size. In the present study, using diameter (D) or $D^2 \times$ length as predictor variables overestimated weights at the top and base of the crown and underestimated weights in mid-crown. Overall, this led to an underestimate of total foliage weight. Using the relative height of branch insertion as an additional variable improved predictions for individual branches but overcompensated to give total foliage weight predictions greater than actual weights. The underlying biological variable affecting the relationship at the base of the crown is probably a shading effect and, if so, will depend on crown form and crowding within the stand canopy. In the upper crown differential rates of development of needles and branches probably cause the discrepancy between predicted and actual weights. For the trees studied, crown growth occurs almost continuously so that there are almost always young, developing branches in the topmost whorl. As such, the effect of position of sample branch in the crown may be expected to vary from species to species, locality to locality, as well as from one level of stocking to another. Consequently, any attempt to use branch size for estimating crown component weight should be tested against an independent set of crown data. Only by this method can one estimate the biases involved in the technique.

Measuring length as well as diameter of all branches on the test trees more than doubled the time necessary to measure a tree. $D^2L$ was only marginally better than D alone as a predictor of branch component weight. Time would be better used in sampling additional branches for weight or increasing the number of trees for which branch diameters were obtained rather than obtaining both diameter and length measurements.

In conclusion, branch sampling provides a not very precise method for estimating the total weights of canopy components under conditions where destructive sampling of whole trees is not possible. Existing methods can most probably be improved by closer attention to factors affecting foliage development within the tree crown. These will be pursued in a subsequent paper.

## ACKNOWLEDGMENT

The work was carried out when the senior author was a New Zealand Senior Research Fellow, on leave from the Department of Forestry and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

REFERENCES


ATTIWILL, P. M. 1962: Estimating branch dry weight and leaf area from measurements of branch girth in **Eucalyptus. For. Sci. 8:** 132-41.

——— 1966: A method for estimating crown weight in **Eucalyptus**, and some implications of relationships between crown weight and stem diameter. **Ecol. 47:** 795-804.

CUMMINGS, W. H. 1941: A method for sampling the foliage of a silver maple tree. **J. For. 39:** 382-4.

DANIEL, C. and WOOD, F. S. 1971: Fitting equations to data: Computer analysis of multifactor data for scientists and engineers. Wiley Interscience, New York. 342pp.

FINNEY, D. J. 1941: On the distribution of a variate whose logarithm is normally distributed. **J. Roy. Stat. Soc. Ser. B.7:** 155-161.

FORREST, W. G. and OVINGTON, J. D. 1971: Variation in dry weight and mineral nutrient content of **Pinus radiata** progeny. **Silvae. Genet. 20:** 174-9.

MADGWICK, H. A. I. 1970: Biomass and productivity of forest canopies. Pp. 47-54 **In** Ecological Studies; ed. Reichle, D.E. 1. Analysis and Synthesis. Springer-Verlag.

ROTHACHER, J. S., BLOW, F. E. and POTTS, S. M. 1954: Estimating the quantity of tree foliage in oak stands in the Tennessee Valley. **J. For. 52:** 169-73.

WHITTAKER, R. H. 1965: Branch dimensions and estimation of branch production. **Ecol. 46:** 365-70.