# BIOMASS EQUATIONS FOR PINUS RADIATA IN GIPPSLAND, VICTORIA

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## ABSTRACT

Published biomass equations, based on a large and widely dispersed sample, for the above-ground components of individual **Pinus radiata** D. Don trees were tested with a regional sample of up to 62 trees from Gippsland, Victoria. The masses of some components were considerably under-estimated, indicating that the widely based equations are inappropriate to the region. Biomass equations for unpruned trees growing in closed-canopy stands were therefore developed from our data for the Gippsland region. The mass of needles, of live branches, of total branches, of stem wood, of stem bark, and of total stem are given as functions of diameter at breast height, diameter at the base of the live crown, and total height. These equations are considered suitable for use in regional surveys.

## INTRODUCTION

Estimates of tree biomass are used in studies of productivity and nutrient distribution in forests. Since measurement of the biomass of all trees in a given area is usually impracticable, relationships between component masses and easily measured variables of individual trees ("dimensional analysis", Whittaker & Marks 1975) are commonly developed and used predictively. Biomass equations or tables for a wide range of tree species have been published (e.g., Young 1976).

For *Pinus radiata,* Dargavel (1970) published provisional tree weight tables based on 25 trees sampled in Gippsland, Victoria. Recently, Madgwick (1983a) presented biomass equations for *P. radiata* based on up to 557 trees sampled in New Zealand, Australia, and South Africa. In this paper we test Madgwick's general equations with a sample of up to 62 trees from four independent studies in Gippsland (south-eastern Australia). The Gippsland data are then combined and biomass equations are presented for the above-ground components of *P. radiata* in the region. Some possible approaches to improving the accuracy of generalised biomass equations are discussed.

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## METHODS

Data from four independent studies of above-ground biomass within components of *P. radiata* trees in Gippsland, Victoria, were available. All trees were unpruned and from closed-canopy stands managed primarily for pulpwood. The first study (Data Sets I and II, Table 1) was in forests of relatively high quality with an annual rainfall of 1000 mm. Trees for the second and third studies (Data Sets III and IV, Table 1) were growing on sands with an annual rainfall of 600 mm. Data Set IV is from a forest in which both potassium and phosphorus deficiencies were extreme; a factorial experiment using nitrogen, phosphorus, and potassium had been established at planting and the data set includes both fertilised and unfertilised trees. Data Set V (Table 1) includes trees from a number of stands and is based on 20 of the 25 trees sampled by Dargavel (1970, five trees less than 6 years old were excluded) plus five trees from a later sample (Dargavel, unpubl. data). An indication of the range of productivity of *P. radiata* in the region can be obtained from Turvey (1983).

TABLE 1—Details of the stands studied, and the range of dimensions of the sample trees

| | Data set | | | | |
|---|---|---|---|---|---|
| | I | II | III | IV | V |
| **Stand** | | | | | |
| Age (years) | 24 | 20 | 15 | 20 | 9–28 |
| Stocking (stems/ha) | 610 | 1330 | 1068 | 1600–2163 | — |
| Basal area ($m^2$/ha) | 45 | 49 | 32 | 29–46 | — |
| Mean dominant height (m) | 32 | 26 | 20 | 18–19 | — |
| **Sample trees** | | | | | |
| No. of trees | 5 | 6 | 10 | 16 | 25 |
| d* | 23–49 | 7–32 | 7–29 | 4–23 | 10–47 |
| $d_c$ | 16–35 | 6–21 | 7–23 | 2–19 | —† |
| h | 29–35 | 13–28 | 12–21 | 8–20 | 8–32 |

* d = stem diameter over bark at breast height (cm)
$d_c$ = stem diameter over bark at the base of the live crown (cm), nominally at 10 cm below the point of emergence from the stem of the lowest live branch.
h = total height of tree (m).
† Not measured.

The methods used for measuring oven-dry mass of tree components have been described for Data Sets III (Stewart *et al.* 1981) and V (Dargavel 1970). For the remaining data sets, the mass of the crown components was determined using similar methods to those described by Stewart *et al.* (1981). The mass of the bole components was determined from sectional volumes estimated from measurements of diameters over- and under-bark, and from wood and bark density measured on sample discs.

The measured masses of components of the Gippsland trees were compared with the masses estimated by the general equations of Madgwick (1983a). These equations are the "best" for *P. radiata* (Madgwick 1979), being simple linear regression after logarithmic transformation of both dependent and independent variables. The diameter over bark of the stem at the base of the green crown ($d_c$) is the independent variable for crown components. The combined variable $(d+1.9)^2h$, where d is the diameter over bark of the stem at breast height and h is the total tree height, is the independent variable for the stem. The constant in this combined variable is included to correct for curvilinearity of the relationship when "small" trees are considered.

Regression equations for each component of the Gippsland trees were then calculated separately for four groups – Data Sets I and II, III, IV, and V. Data Sets I and II were sampled from stands in close proximity, and they were combined to increase the degrees of freedom to a reasonable level for analysis. Regressions for crown components as functions of both $d_c$ and d, and for stem components as functions of both d and $d^2h$, were calculated. The effects of pooling all data were then tested using both the change in the co-efficient of determination ($r^2$) and the significance of the increase in the residual standard deviation of the regression ($s_{reg}$) (Warren 1974). Finally, pooled regressions were calculated for data sets which were found to be reasonably similar by the preceding analysis. It was not necessary to correct for curvilinearity in the relationships for the stem components.

## RESULTS AND DISCUSSION

Values of d, $d_c$, and h of the 62 trees in the Gippsland sample were within the ranges for which biomass equations were developed by Madgwick (1983a). These equations under-estimated the masses of all tree components, except for live branches from Data Sets III and IV and needles from Data Set IV (Table 2). The gross over-estimates of needle and live branch mass for Data Set IV were not surprising, because the trees were nutrient-deficient and sparsely foliated. Apart from these trees, the biases for crown components (Table 2) were within the ranges reported by Madgwick (1983a) for needles (–34% to 55%) and branches (–51% to 32%). The under-estimates of stem mass (which average –19%, Table 2) exceed the range of biases (–7% to 13%) reported by Madgwick (1983a). The independent variable $d^2h$ has a logical relationship to stem volume and, while observed variations in the basic density of *P. radiata* stem wood (e.g., Cown & McConchie 1982) could account for this difference, variation in form factor is probably also involved. The average basic density of stemwood increases with tree age and the temperature at which it is grown (Bamber & Burley 1983), and form factor increases with stand stocking (e.g., Larson 1963). The Gippsland trees are probably, on average, older, and grown under warmer conditions and in denser stands than those of Madgwick. Nutrient deficiency also tends to produce wood of greater basic density (Bamber & Burley 1983), and in this study the greatest bias for stems (Table 2) was found for Data Set IV.

For stem components (wood, bark, and total) of the Gippsland trees, $s_{reg}$ increased by an average of 7% and 24% in moving from separate to pooled regressions when $d^2h$ and d respectively were the independent variables. Although most of these increases were statistically significant ($p < 0.01$) they were associated with negligible loss of fit (average $r^2$ decreased from 0.99 to 0.98), and for practical purposes, there was no disadvantage in pooling the data for all 62 trees. For total branches there was no increase in $s_{reg}$ or loss of fit ($r^2 = 0.95$) when the data were pooled using d as the independent variable. However, when $d_c$ was the independent variable, $s_{reg}$ increased ($p < 0.01$) and there was loss of fit ($r^2$ decreased from 0.93 to 0.89). For needles and

**TABLE 2—Bias of estimated* mass (using equations from Madgwick (1983a) expressed as percentage of measured mass for components of trees sampled in Gippsland**

| Data set | Needles | Live branches | Total branches | Stem |
|---|---|---|---|---|
| I | –14 | –6 | –36 | –8 |
| II | –27 | –32 | –47 | –15 |
| III | –4 | 7 | –17 | –25 |
| IV | 106 | 25 | –39 | –26 |
| V | — | — | — | –21 |

* Corrected for bias due to logarithmic transformation (Baskerville 1972)

live branches, pooling the data caused relatively large (87% and 36% respectively) and statistically significant ($p < 0.01$) increases in $s_{reg}$; the loss of fit was less when $d_c$ was the independent variable (2% and 4% respectively) than when d was the independent variable (14% and 6% respectively). Scatterplots of the data for needles and live branches with d and $d_c$, and for total branches with $d_c$, showed that the nutrient-deficient trees from Data Set IV were invariably the major cause of the above increases in $s_{reg}$ and loss of fit when data were pooled, and these data were not used in calculating the final equations for crown components.

Pooled regression equations for estimating the oven-dry mass of components of *P. radiata* trees in Gippsland are given in Table 3. The equation for needles with $d_c$ as the independent variable is parallel to Madgwick's equation (1983a) but predicts 15% more mass (after correction for bias due to logarithmic transformation) for a given value of $d_c$. While this difference is within the observed seasonal variation in *P. radiata* (Madgwick 1983b), the trees on which the equation is based (Data Sets I, II, and III) were sampled in winter when needle mass is normally minimum. Across a range of $d_c$ (5 cm to 35 cm) the equations estimate 21% to 10% more live branches and 2% to 73% more total branches than the equations of Madgwick. The latter discrepancy is the more serious and may reflect the fact that some of the larger trees sampled by Madgwick were pruned. Assuming the average height-diameter relationship for the Gippsland trees, the equation for total stem predicts from 40% to 10% more mass than Madgwick's for a range of d from 10 cm to 50 cm. The data sets used in the present study were obtained from forests covering a range of ages, soils, and climates within the Gippsland region. The equations developed from the data (Table 3) show important differences to the general equations proposed by Madgwick (1983a) for *P. radiata.*

An independent set of data is now required to test the equations given in Table 3 for bias. It must be emphasised that the equations for the crown components are for trees without overt signs of nutrient deficiency, unpruned, and growing in closed-canopy stands. An indication of the bias can be obtained by applying the equations to the original data sets (Table 4). With the exception of stembark, $d^2h$ was a better estimator than d for stem components. Perhaps surprisingly for crown components, d was on average a marginally better estimator than $d_c$.

TABLE 3—Pooled regression equations for estimating the oven-dry mass of components of ***P. radiata*** trees in Gippsland (all regressions significant at $p < 0.001$)

| Component | No. of trees | Equation* | Error mean square | $r^2$† |
|---|---|---|---|---|
| Needles | 46 | $\ln(m) = 1.893 \ln(d) - 3.365$ | 0.1501 | 0.78 |
| | 21 | $\ln(m) = 2.192 \ln(d_c) - 3.779$ | 0.0370 | 0.97 |
| Live branches | 46 | $\ln(m) = 2.459 \ln(d) - 4.727$ | 0.1612 | 0.81 |
| | 21 | $\ln(m) = 2.785 \ln(d_c) - 5.090$ | 0.1414 | 0.96 |
| Total branches | 62 | $\ln(m) = 2.413 \ln(d) - 4.332$ | 0.1002 | 0.88 |
| | 21 | $\ln(m) = 2.717 \ln(d_c) - 4.530$ | 0.1107 | 0.94 |
| Stem wood | 62 | $\ln(m) = 2.342 \ln(d) - 2.399$ | 0.0376 | 0.98 |
| | 62 | $\ln(m) = 0.9243 \ln(d^2h) - 3.632$ | 0.0110 | 0.99 |
| Stem bark | 62 | $\ln(m) = 2.165 \ln(d) - 3.863$ | 0.0533 | 0.95 |
| | 62 | $\ln(m) = 0.8478 \ln(d^2h) - 4.946$ | 0.0529 | 0.88 |
| Total stem | 62 | $\ln(m) = 2.320 \ln(d) - 2.201$ | 0.0352 | 0.98 |
| | 62 | $\ln(m) = 0.9146 \ln(d^2h) - 3.415$ | 0.0120 | 0.98 |

* m = oven-dry mass (kg); d, $d_c$, and h as for Table 1

† Calculated from untransformed residuals

TABLE 4—Bias of estimated mass (using equations from Table 3)* expressed as percentage of measured mass for components of trees sampled in Gippsland (the mean and range of the biases for the five data sets are given)

| Component | Mean† | Range | Mean† | Range |
|---|---|---|---|---|
| | | Independent variable | | |
| | d | | $d_c$ | |
| Needles‡ | 11 | −6–22 | 9 | −16–10 |
| Live branches‡ | 12 | −10–29 | 16 | −23–21 |
| Total branches | 6 | −10–12 | 16 | −23–21 |
| | | Independent variable | | |
| | d | | $d^2h$ | |
| Stem wood | 6 | −12–8 | 3 | −4–4 |
| Stem bark | 6 | −11–9 | 14 | −13–24 |
| Total stem | 5 | −11–7 | 4 | −4–6 |

* Estimates corrected for bias due to logarithmic transformation

† Of the absolute values of the biases

‡ Excluding trees from Data Set IV. Biases for these nutrient-deficient trees ranged from 40% to 250%.

The development of widely applicable biomass equations for *P. radiata,* even when based on a large number of trees and using explanatory variables (e.g., $d_c$ and $d^2h$) generally accepted to be superior to d (as Madgwick 1983a has done), seems difficult in view of the magnitude and consistency of the biases they give for specific data sets (Table 1, and Madgwick 1983a). A case for developing regional biomass equations (as in this paper) for similarly grown trees is thereby established. However, considerable bias in estimating crown components can still be expected (Table 4) and further investigation is required to determine the causal factors.

For either generalised or regional equations, independent variables which are mechanistically or functionally related to dependent variables may give better estimates of biomass. Sapwood cross-sectional area can be a better estimator of foliage mass than total cross-sectional area (e.g., Grier & Waring 1974), but such a relationship would only be applicable to *P. radiata* trees older than 12 to 15 years, when heartwood begins to form (Bamber & Burley 1983). Further improvement by weighting cross-sectional area by wood permeability (Whitehead & Jarvis 1981) may be possible and might adjust for differences in wood density. However, Brix & Mitchell (1983) found that the ratio of foliage mass to sapwood cross-sectional area was influenced by thinning and nitrogen-fertiliser treatments, suggesting that additional variables may need to be included. For stem wood, mass can be calculated as the product of $d^2h$, form factor, and average basic density. Tree age may be a possible surrogate for density; for the Gippsland trees the residuals of the estimates for stem wood using the equation (ln $d^2h$) in Table 3 were negatively correlated ($p < 0.05$) with age. Inclusion of an upper stem diameter may account for differences in form, and Dargavel (1970) suggested that allowance for bark thickness would improve estimates of total tree mass.

Whatever new variables are considered to be important in future studies of biomass of *P. radiata* it would be desirable to standardise them amongst investigators. These variables, however, are likely to be more complex and more difficult to measure than those used at present, and the notion of accurately estimating mass, particularly of crown components, from easily measured variables using widely applicable equations may have to be abandoned. For research purposes, it will always be better to sample crown mass within the stand of interest. Nonetheless, the equations presented in this paper should be useful (particularly for stem components) for survey purposes in the Gippsland and similar regions since the stands on which they are based cover a range of growth conditions.

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