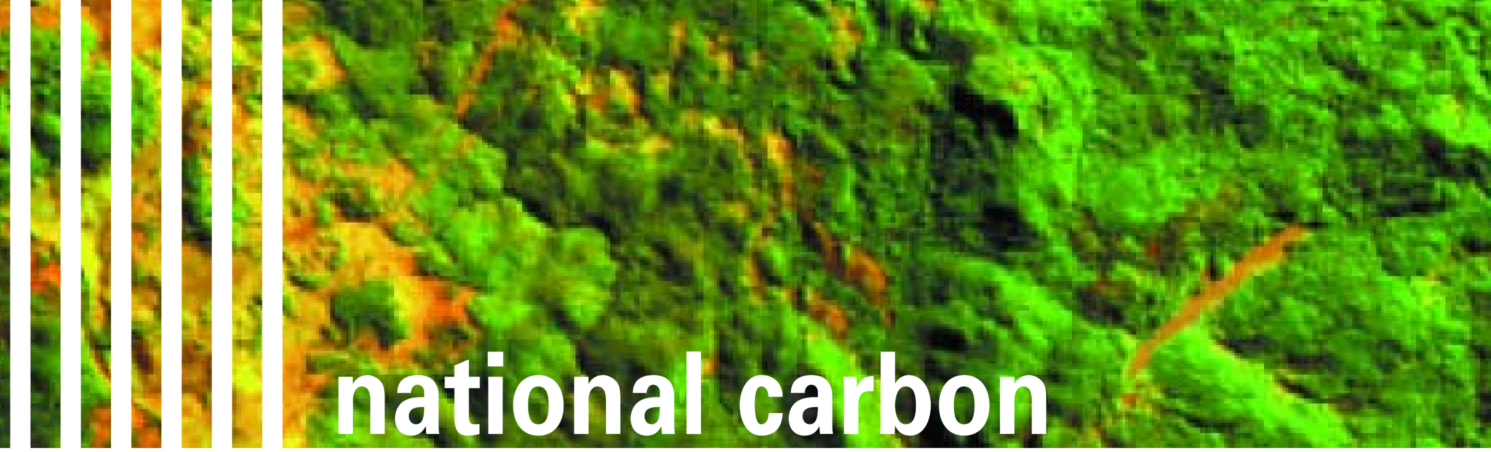

national carbon accounting system

technical report no. 5b

Review of Allometric Relationships for Estimating Woody Biomass for New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia

Heather Keith
Damian Barrett
Rod Keenan

AUSTRALIAN
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National Carbon Accounting System
Technical Report No. 5B

August 2000

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SUMMARY

1. Allometric equations provide a means of estimating tree biomass from the relationship between component biomass and tree dimensions. Equations, associated statistical information and characteristics of the trees, sites and methods were collated from the published literature and CSIRO unpublished data and summarised in an Access database. Error terms were converted (where possible) to a standard form of the Error Mean Square to facilitate comparisons in the estimation of biomass.

2. Availability of equations is limited in terms of the vegetation types and range of tree sizes from which they were derived. Vegetation types that are under-represented include rainforest, woodlands (including callitris, acacia and eucalypt) and shrublands. Data from WA, NT and Qld may be applicable, but would require testing in southern and eastern vegetation types. Large trees are particularly under-represented. Equations that include trees of DBH 100 cm or more include Applegate (1982), Ash and Helman (1990) and Keith (unpubl.), and there are 12 additional equations that include trees of DBH more than 50 cm, from a total of 112 site-specific equations.

3. Sources of inventory data of measured tree dimensions collected by State agencies are summarised. Potentially, these data will form the input for application of allometric equations to estimate biomass density at the plot level. However, these data are restricted to production forest types, sometimes only merchantable stems and species, and stems above a certain DBH, often 10 cm. DBH is the most commonly measured and standard variable. Height and bole volume have various definitions according to State or vegetation type and, usually, are not measured on every tree in an inventory. Hence, allometric equations based on DBH only are recommended for large-scale estimation of biomass. Height may be useful as a modifying variable in response to environmental conditions.

4. In vegetation types where inventory plot data of tree dimension measurements are not available, such as non-commercial forest types, reserves, young regrowth and woodlands, collection of some plot data will be required together with development of general relationships between vegetation structure and biomass. There is potential to modify estimates of biomass from production forests to apply to other forest types using calibrations with respect to growth form of trees and stocking and size distribution of stands.

5. Volume equations have been derived for many productive forest types, and refer to merchantable bole volume, which has various definitions. Conversion to total biomass requires multiplication by wood density and an expansion factor, which accounts for the bole as a proportion of the total including non-merchantable stem, bark, branches, twigs, leaves and roots. A high degree of uncertainty is associated with these conversion factors and there is little data to quantify the errors. Additionally, merchantable bole volume only accounts for merchantable trees and species. The expansion factor is only as accurate as the equations used to calculate total biomass of trees used in the calibration. It is recommended that the original data of DBH and height be applied directly to allometric equations to estimate biomass.

6. Limited information exists as a basis for estimating root biomass. There are insufficient data and allometric equations that relate root mass to DBH to allow extrapolation to other vegetation types and regions. Estimates of belowground biomass will have to be based on below-to-aboveground biomass ratios that are constrained by upper and lower limits, and vary in response to factors that control partitioning of biomass. A constant ratio is not appropriate and will result in large variances. The ratio of below-to-aboveground biomass changes in response to environmental conditions that affect the relative limitations to growth of assimilation by the canopy, or of water and nutrient uptake by roots. The general response is of decreased C allocation belowground with increased nutrient and/or water availability. The ratio can be modified in response to these factors to produce general trends based on an understanding of the processes, as well as specific conditions such as deep water tables or impermeable soil layers. The most appropriate scales at which general trends should be applied to modify the ratio, and the relevant predictive variables, will vary among vegetation types. Derivation of responses to environmental factors depends on identifying the most appropriate functional groups of vegetation at different scales; this requires careful consideration. Estimation of belowground biomass will be based on limited data combined with application of physiological principals that govern partitioning of biomass.

7. The generality of allometric equations can be evaluated either by comparing species within a region or broad vegetation type, or by comparing the same species growing at different sites. The different mathematical forms of the equations, use of different independent variables, and lack of statistical information and raw data provided in published literature, prevented direct comparison or combining of original equations. A rigorous comparison among all allometric equations, including those with two independent variables, would be possible if the source data was available from which the equations were derived. (Collection of unpublished data may be a consideration for the AGO.) However, comparisons among some of the equations were made using standard forms of the equations derived from test datasets. Differences in biomass estimates were compared between site-specific equations and general equations derived for each vegetation type. Equations were reasonably similar for some species across a range of sites, or for several species within a site. But large differences occurred among other species and sites. Extrapolation beyond the size range of trees used to derive the equation is a likely major cause of error in estimation of biomass. Many of the differences between species or sites can be interpreted in relation to age, dominance class and growth form of trees, or site conditions. This comparison of specific and general equations indicates the potential to use existing allometric equations combined in a general form in conjunction with modifying coefficients in response to tree, stand and site conditions.

8. The allometric relationship varies in response to climatic conditions, nutrient availability, genotype, age and growth form of trees. Nutrient availability is a major factor influencing the proportion of foliage and root mass. Increased nutrient availability resulted in increased canopy components, reduced root mass and no change in stem allometry in most cases, but there are some cases where no significant

change occurred. The main effect of increased nutrients was to increase the rate of growth and hence the stage of ontogeny in young trees. Allometric relationships often differ with age in young trees, but become similar after canopy closure and when trees develop a more mature form. Genetic factors influence the growth form of trees at all taxonomic levels, including family, species and subgenera. The effects of these factors will determine the variances associated with spatial extrapolation of these equations.

9. Landuse change and management practices are likely to change many of these factors that influence allometric relationships and their relative importance. Such changes will impact upon the application of allometric equations and the propagation of errors.

10. Application of general allometric equations to broad vegetation types will be associated with large variances in some cases where there are major differences in conditions. Potential variances that may be propagated were predicted by comparing the biomass estimated by the general equation compared with site-specific equation using test datasets. Prediction of biomass for individual tree sizes was up to ±60% and prediction of biomass density was up to 2.5-fold different. Differences of up to 10-fold occurred in comparisons of plantations of different ages. However, careful application of equations with respect to matching tree size, age and growth form, and general environmental conditions, will minimise these errors. Matching stage of ontogeny is particularly important in young plantations.

11. General equations for vegetation types have been used in other countries to estimate biomass at regional and national scales. There is potential to use similar methods in Australia. General equations may be appropriate for total biomass but are less so for predicting biomass of individual components. Use of the current information on allometric relationships to extrapolate to spatial predictions of biomass will require careful interpretation and application of equations, and some additional information about the environmental factors and tree form characteristics that influence allometric relationships, in order to modify coefficients in the equations. Understanding of the processes controlling production and partitioning of biomass will underpin the application of allometric equations for spatial prediction of biomass.

12. The main sources of error in applying allometric equations for estimation of tree biomass per plot are:

    i. the error arising from use of the regression (i.e. allometric) equation to estimate individual tree mass,

    ii. the inaccurate estimation of total variance from the summation of biomass components when there is a lack of statistical information to determine the covariance,

    iii. the bias associated with applying the allometric equation to trees beyond the calibration range (i.e. inappropriate application of allometric equations developed elsewhere). This is likely to be a large source of error, particularly for estimation of biomass of large trees.

13. The main sources of error in upscaling estimates of biomass from plots to regions are:

    i. the representativeness of plot sampling to cover the natural heterogeneity within forest strata,

    ii. the number of plots sampled within strata,
    iii. the magnitude of the error in estimation of strata area within a regions.

14. There is potential for combining allometric equations to produce equations of more general applicability. However, this process must be done with due consideration for the sources of data, forms of equations, size range of trees and area of extrapolation.

15. Improvement of the spatial prediction of biomass in the future will be achieved through strategic data collection from poorly represented vegetation types large trees, belowground biomass and targeted to define responses of existing equations to varying environmental and genetic factors.

INTRODUCTION

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) stipulates mechanisms (eg. Article 3.3, 3.7, Clean Development Mechanisms, and Joint Implementation) whereby storage of carbon in terrestrial sinks may be allowable for inclusion in national greenhouse gas inventories. This includes post-1990 C storage in forests as an allowable C-sink to offset fossil fuel based greenhouse gas emissions.

Predicting the effect of landuse and climate change on the role of forests in the carbon cycle requires an understanding of how climate, resource availability, stand development and forest management practices influence biomass production, accumulation and allocation.

Allometric equations provide an attractive means of quantifying C stocks in biomass because they allow the use of existing and easily-measured variables, such as tree diameter, height or bole volume. Allometric equations provide a means of estimating biomass of individual trees of all sizes with in the population from measurements of tree dimensions. Equations are applied to plot inventory data to provide ground-based estimates of biomass density of plots. Adequate sampling of plots within the vegetation type enables scaling up of plot data to regional biomass estimates. Any form of spatial estimate of biomass at project, regional or continental scales, for example using remote sensing or models of plant production, require validation and calibration from such ground-based estimates of biomass. The wide-ranging adoption of this methodology, however, must contend with natural heterogeneity of the vegetation, interpolation errors, data insufficiency and bias.

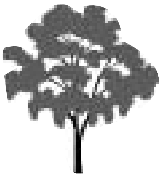
Allometric equations have been derived for various purposes, mainly for developing nutrient budgets for ecological purposes and also for calculating timber volume of forest plots for the purpose of predicting harvest yields. There is now demand to use this existing information for the purpose of national C inventories by estimating mean biomass density for defined vegetation strata within regions across the Intensive Land Use Zone of the continent. Calculation of these C stocks in biomass must be both transparent and verifiable for inclusion in national greenhouse gas inventories, and hence robust evaluation of the variance, or some other measure of uncertainty, is necessary.

In this report, allometric equations published in the literature have been collated and summarised with respect to characteristics of trees and sites. Equations differ in terms of their mathematical forms, independent variables and error terms. These differences and the absence of raw data limit the comparisons that can be achieved between studies. The generality of these equations was evaluated in terms of the estimated biomass of trees of a range of sizes and biomass per hectare using predicted means and variances. Use of these equations for the estimation of biomass density at project, regional and continental scales is evaluated in terms of current understanding, data deficiencies, error propagation and possible further research requirements. The outcomes from this review and analysis are required for the establishment of credible and verifiable biomass stocks in the National Carbon Accounting System.

SCALES OF BIOMASS ESTIMATION

Estimation of biomass for the purposes of C accounting at project to continental scales requires a process involving several scales of prediction and the propagation of errors between scales. Estimation of biomass and the associated error is considered at four levels (refer Table 4):

1. A single tree where biomass is estimated from an allometric equation applied to measurements of tree dimensions.



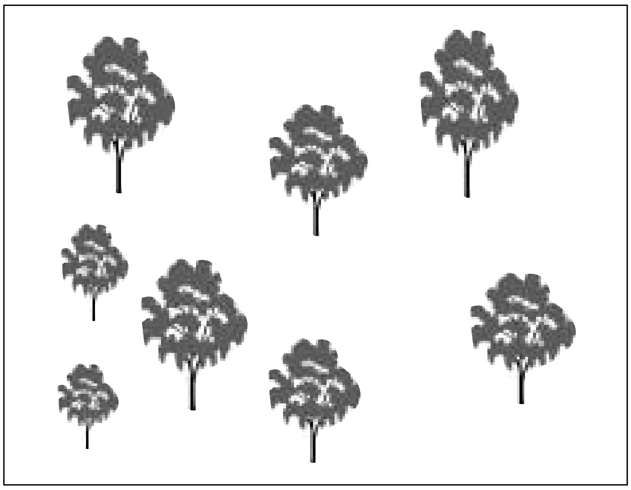
M_T (t tree^{-1}) = f (DBH) + ε_T

where, M_T = mass of tree, ε_T = error associated with the regression equation

There are several sources of error associated with application of the allometric equation to estimate tree biomass:

- Selection of the calibration trees on which biomass was measured to derive the allometric equation can introduce bias. Most studies reported in the literature were conducted for a specific purpose at a particular site, rather than for general use of predicting biomass across a region. Hence, the trees selected may not be representative of the whole population of trees within the forest stand;
- Measurement of biomass of individual trees usually requires a strategy of sampling for each biomass component and prediction based on this sampling because it is not feasible to weigh an entire tree. Various strategies have been used and this creates difficulties in comparing errors associated with predicted values of biomass among different strategies. These errors relate mainly to precision rather than bias; and
- Allometric equations are derived to relate various tree dimensions to tree biomass. The error associated with regression analysis is due to precision. Some form of aggregated error term, usually the coefficient of determination of the regression (r^2) is provided in most studies.

2. In a single plot, where every tree in a defined area is measured in terms of dimensions (DBH, height, etc.), an allometric equation is applied to estimate biomass of each tree, and the sum of all trees provides a value of biomass density of the plot.



M_P (t ha^{-1}) = $\sum_{1}^{n} M_T / A_P$

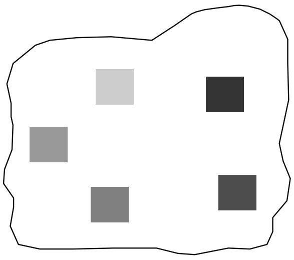
$\varepsilon_P = \sum_{1}^{n} \varepsilon_T / A_P$

where, M_P = plot biomass density, A_P = plot area (ha), ε_T = error in biomass density at the plot level, n = number of trees per plot

- Allometric equations can be applied to any trees with measurements of their dimensions to predict biomass. However, application of an equation to trees beyond the calibration range from which the allometric equation was developed can introduce bias. This range may be defined in terms of tree size, species, growth form, age, and environmental conditions for growth. The generality of allometric equations over a range of these parameters is unknown. The errors involved will depend on the degree to which these parameters control the partitioning of biomass among components and the geometrical relationships of the tree; and

- the frequency distribution of tree sizes in a plot will affect the estimate of plot biomass density. Where the distribution is skewed, the median value is a better estimate of the central tendency of the population of trees on a single plot.

3. Strata are areas assumed to contain trees from a single population (in terms of statistical prediction). Within-strata vegetation characteristics will be similar in terms of structure, species composition, size class, growth form, age, canopy characteristics and may be associated with natural topographical features such as aspect and slope angle. Strata also refer to whatever local scale classification maybe used to group relatively homogeneous woody vegetation and includes terms such as vegetation association, coup, compartment and logging unit.



The estimation of strata mean biomass density (and its uncertainty) is derived from the estimates of plot biomass density (an associated uncertainty), $M_P + \varepsilon_P$. This assumes that plots sample the strata representatively.

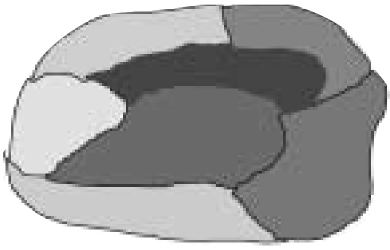
An average biomass density for each stratum is calculated: M_S (t ha^{-1}) $= \sum_1^m M_P / m$

$$\varepsilon_S = \sum_1^m \varepsilon_P / m$$

where, M_S = mean stratum biomass density, ε_S = error associated with the stratum level, m = number of plots in the stratum

Location of plots within strata is a sampling problem as plots cover only a small proportion of the total area of the stratum. Selection of the location of these plots can introduce bias, unless they representatively sample the distribution of vegetation types, location in the landscape and various stands of trees in the stratum. A mean value of biomass density is calculated from all the plots in the stratum. If there are a sufficient number of plots sampled within a stratum, then the mean biomass density for the stratum of repeated samplings will approximate a normal distribution, according to the Central Limit Theorem.

4. Regions are denoted by geographical boundaries. The entire region is divided into stratified homogeneous units (strata) that are spatially contiguous. Total biomass of each stratum is calculated as the product of mean biomass density and stratum area. Defining and mapping strata boundaries can be a source of error in some landscapes. Total biomass of the region is then the sum of the biomass for all strata. Errors arise also from measurement of the boundaries between strata as these are inexact (e.g. from air photo or satellite data interpretation).



Heterogeneity of vegetation across the landscape is a large source of error in estimation of biomass density at all scales. There are two main sources of this error: first, the range over which an allometric equation can be applied, and second, the representativeness of sample plots within a stratum.

DERIVATION OF ALLOMETRIC RELATIONSHIPS

Living organisms exhibit size-correlated variations in form and this is referred to as allometry (derived from Greek: allos – other, metron – measure) (Huxley 1932 cited in Niklas 1994). The relationship between size and form is based on the premise that size influences the behaviour of structural, mechanical and chemical systems. The dimensions and shape of an organism must be designed for structural stability to sustain its own weight and physiological properties where increment in biomass is dependent on capacity of components to take up resources for growth (Attiwill 1966, Niklas 1994). In the development of tree trunks, for example, the increasing ratio of girth to height represents the scaling of primary growth in stem elongation in relation to secondary growth that increases stem girth. This development maintains compensatory changes in the flexural stiffness of tree trunks as the compressive stresses produced by accumulation of biomass in the crown increase annually. The static equilibrium depends on the allometric relationship between the changes in flexural stiffness or strength of the trunk and changes in the weight of the crown. Allometry varies with species and plant ontogeny in relation to mechanical stability (Niklas 1992).

There are three commonly-used variations to the meaning of allometry (Niklas 1994):

1) growth of a component of an organism in relation to some other component or the total organism;

2) study of the consequences of size on form and processes of organisms; and

3) the condition of geometric similitude which results when geometry and shape are conserved among organisms differing in size.

Derivation of allometric relationships is based on the third meaning. These relationships provide a means of quantitatively describing the behaviour of the system so that it can be used in scaling analysis.

Allometric equations are used to relate biomass of components to easily measured auxiliary variables that are easily measured, such as tree dimensions. This procedure was originally referred to as dimension analysis (Whittaker and Woodwell 1968). Calibration data are obtained for biomass and tree dimensions from individual trees that cover a range of sizes and are representative of the population. The relationship is derived by regression analysis, which provides an expected value of the dependent variable (component biomass) for a given value of the independent value (measured tree dimensions), an associated error and a test of confidence in the prediction. The least squares linear regression is defined as the straight line that results in the sum of the deviations of the observed values from the expected values being at a minimum. Variability of the dependent variable is "explained" by variability in the independent variables. Measurement of the independent variables is assumed, usually, to be without error. The geometric relationships between dimensions and biomass describe the mechanistic dependency that underpins the statistical correlation.

Common practice for equations reported in the scientific literature is to develop a set of these equations for various tree components (i.e. leaves, branch, stem etc) and less common to publish a single allometric equation of whole tree biomass as a function of dimensions. Allometric relationships have been derived mostly for site specific purposes based on individual trees within a small area.

The usual form of the regression function is :

$$M_i = f_i(X) + \varepsilon_i$$

where M is the mass of the i^{th} component (leaves, branches, stems), f_i is the allometric equation, ε_i is the error term and X the vector of independent variates, such as diameter and height.

Generally data transformations, often logarithmic transformations to base e, are used to ensure independence of mean and variance and that residuals conform to a normal distribution. These criteria are necessary to satisfy assumptions of the linear regression analysis that underpin the allometric methodology. The general form of f_i with *ln*-transformation of data is:

$$f_i\,(X) = \exp\left[\beta_0 + \sum_{j=1}^{n} \beta_j\, ln(x_j)\right]$$

where β_0 and β_j are estimates of the regression coefficients and x_j is the jth independent variate (such as diameter or height).

Since the dependent variable is transformed prior to estimation, there is an inherent negative bias in the regression parameters. The bias is not an arithmetic constant but a constant proportion of the estimated value. The mean of logY is the median Y of the distribution on untransformed values of Y, or the geometric mean rather than the arithmetic mean. Several correction factors have been derived from the variance of the regression to convert geometric to arithmetic units (Baskerville 1972, Beauchamp and Olson 1973, Flewelling and Pienaar 1981). A ratio method was described by Snowdon (1991), which showed that the proportional bias in logarithmic regressions could be estimated from the ratio of the arithmetic mean of the sample and the mean of the back-transformed values predicted from the regression.

PARTITIONING OF BIOMASS COMPONENTS

Partitioning of biomass among components is governed by genetic, physiological and ecological processes that occur, in part, in response to environmental factors. Improved understanding of these processes is necessary to develop a strategy for spatial prediction of biomass based on site-specific allometric equations. Predicting biomass partitioning to above- and below-ground components, in particular, will need to be based on an understanding of these processes as there is little empirical information.

Allocation of carbon from photosynthesis is the process of distribution of C within plants to the various components. It is a flux with units or quantity per unit time. Of the C transferred to each plant tissue, some is lost in respiration, incorporated into plant structures, converted to defence chemicals and stored. Partitioning of biomass within a plant represents accumulation of the end product of plant productivity and allocation in terms of biomass increment (Gower *et al.* 1994) and is a stock with units of quantity. In terms of plant function, partitioning of biomass is controlled by the required balance between assimilation of C by foliage, acquisition of nutrients by fine roots, mechanical support and the mortality rate of tissues (Dewar *et al.* 1994). Biomass partitioning between tissues is poorly related to allocation of photosynthate between tissues (e.g leaves and fine roots have a high allocation of photosynthate but a relatively low partitioning of biomass in trees because the turnover rate of these tissues if high).

Large differences have been reported in biomass partitioning for various forests (Cannell 1985). In young plantations of mixed native species, the proportion of biomass components differed considerably, for example 34 to 47% stemwood and 19 to 40% foliage (Birk *et al.* 1995). Among species in native eucalypt forest, the range in proportion of stemwood was 50 to 91%, for branches was 9 to 22% and for leaves was 1 to 2.3% (Stewart *et al.* 1979).

Factors affecting the partitioning of biomass include tree age, climate, nutrient availability and genetic control, however, the relative importance of these factors varies (Beets and Pollock 1987). Both general and specific results relating to each of these factors are summarised below.

TREE AGE AND STAND DEVELOPMENT

- Total aboveground biomass accumulates throughout stand development, however, partitioning among components changes. Partitioning of biomass shifts from foliage to wood production during stand development. Foliage mass increases with age up to a maximum after canopy closure and then becomes a steady or declining amount.

Hence, the foliage-to-total mass ratio decreases rapidly with age and the wood-to-total mass ratio increases with age. Both stem and branch wood increase with age. The shape and time courses of these general response curves vary among species.

- Aboveground production (biomass accumulation) can increase with stand age while maintaining a constant leaf area index because of a shift in partitioning from roots to stemwood, rather than an increase in total production. Hence, large errors can be incurred by relating aboveground production directly to intercepted radiation (Beets and Pollock 1987).
- Specific examples reported in the literature concerning changes in partitioning give some conflicting results; these are likely due to differences in the relative importance of factors under different situations. For example, partitioning to stems was constant or declined after canopy closure in some conifer stands (Satoo and Madgwick 1982, and Cannell 1985), but increased in *P. radiata* (Madgwick and Oliver 1985).

CLIMATE

- Production generally increases in response to rainfall and temperature unless other factors are limiting, and there is a greater relative increase in foliage mass. The ratio of below-to above-ground biomass varies in pine forests of various species across climatic biomes; 0.16 in tropical, 0.26 in temperate, 0.40 in boreal, and the ratio of foliage-to-root mass is 0.48 in tropical, 0.30 in temperate and 0.21 in boreal (Gower *et al.* 1994).

NUTRIENT AVAILABILITY

- The effects of soil nutrient availability are often tested by fertilizer experiments or comparing sites with different soil fertility status. Increased nutrient availability usually increases production but the relative increase in components differs and this alters the partitioning. The highest relative increase usually occurs in canopy biomass, for example increases of 3 to 70% have been reported in closed canopy stands (Gower *et al.* 1994).
- Availability of different nutrient elements have differing effects on biomass production and partitioning, depending on the relative limitation of the nutrient and its role in the allocation process. For example, application fertilizer to mature *Eucalyptus pauciflora* forests resulted in increased canopy biomass with N application, but increased stemwood and decreased partitioning belowground with P application (Keith *et al.* 1997). The total annual C flux was similar in unfertilized and P-fertilized stands, but the ratio of below-to above-ground C allocation was significantly reduced in the P-fertilized stand.
- Nutrient availability is a major influence on partitioning to fine roots because nutrient uptake is primarily limited by access of roots to sources of nutrients in the soil, hence greater fine root mass is the main mechanism for increasing nutrient uptake (Clarkson 1985). The main effect of nutrient availability is in shifting partitioning between foliage and fine roots.
- Increased nutrient availability in a fertilzer experiment in a young *E. nitens* plantation resulted in a significant decrease in belowground production per unit aboveground production of biomass. The ratio of below-to-aboveground biomass was 0.44 in unfertilized and 0.28 in fertilized treatments. Fine root biomass remained similar in some treatments while aboveground mass increased (Misra *et al.* 1998).

GENETIC CONTROL

Biomass partitioning is partly genetically controlled and characteristic of species, families and provenances. Differences in partitioning can be due to photosynthetic efficiency, growing season, production efficiency related to plant architecture and strength of various C sinks (Gower *et al.* 1994). However, there are few data available with which to assess the relative importance of genetic versus environmental controls.

SOURCES OF ALLOMETRIC EQUATIONS

Allometric equations for woody vegetation in NSW, Victoria, ACT, Tasmania and South Australia have been collated from sources in the published literature and CSIRO unpublished data. Use of material in the scientific literature has the advantage that the quality has been assessed by the peer review system, associated background information about sites and methods is available (mostly), and references can be cited and so provide an easily traced audit of information. CSIRO data is in the process of being published and the reference will be provided as soon as it is available.

Publication of original data from which the allometric equations were derived or the details of correlation coefficients between biomass components are virtually non-existent. Equations are developed in different forms, using different independent variables and error terms. This creates difficulties in comparing differences between equations, predicted biomass and associated variances for upscaling tree-based allometric relationships to regions.

The information is summarised in two tables (linked in an Access database):

1. Characteristics of the sites and species (Table 1).

Includes: reference, species, site and location, corresponding IBRA (Interim Biogeographic Regionalisation of Australia; Thackway and Cresswell 1995) region, climate, soil type and vegetation of the site, specific treatments applied to the site, methods of tree selection and estimation of biomass, independent variables measured, range of age and DBH of trees, number of trees sampled, total basal area (m^2/ha) and biomass density (t/ha) of the stand. These characteristics are important for the application and interpretation of this information, including determining the range of conditions over which the equations should be applied, and potential bias inherent in the derivation of the equation. Location of the sites, geographically and within vegetation types or environmental regions, shows the distribution of data on a continental basis.

2. Equations and statistical information (Table 2).

Equations are given for each biomass component, with notes describing the units, independent variables, and separated sections of components (e.g. wood and bark). Statistical information is required about the error term associated with each equation in order to apply equations for estimation of biomass and to make comparisons between biomass predicted from different equations. Information provided by the source material describing the error term, conversions to Error Mean Square (where possible), goodness of fit of the equation and number of samples are collated in the most consistent manner possible.

Table 1: Summary of the characteristics of species, sites and methods from which allometric equations were derived.

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
1	Adams and Attiwill (1988) a	*E. obliqua*	NE Tasmania (2 sites)	41 09'S 147 13'E	717	cool temperate maritime, temperatures mean max 22.5 to min 4.7 C, rainfall 800-1000 mm	sedimentary, acid partly to strongly bleached, structured to massive, gradational to duplex soil	up to 100	native forest, wet to dry sclerophyll
2	Adams and Attiwill (1988) b	*E. amygdalina*	NE Tasmania (1 site)	41 03'S 147 02'E	717	cool temperate maritime, temperatures mean max 21.3 to min 5.3 C, rainfall 750 mm	sedimentary, acid, strongly bleached, massive, uniform loam	up to 100	native forest, dry sclerophyll
3	Applegate (1982) a	*E. pilularis*	Fraser Island-QLD	25 20'S 153 10'E	391	maritime subtropical, 1500 mm rainfall, mean temp. max. 28.6 C, min. 14C	siliceous sands	14	wet sclerophyll - sapling stage
4	Applegate (1982) b	*E. pilularis*	Fraser Island-QLD	25 20'S 153 10'E	391	maritime subtropical	siliceous sands	45	wet sclerophyll - pole stage
5	Applegate (1982) c	*E. pilularis*	Fraser Island-QLD	25 20'S 153 10'E	391	maritime subtropical	siliceous sands	up to 500	wet sclerophyll - old growth
6	Applegate (1982) d	*E. intermedia*	Fraser Island-QLD	25 20'S 153 10'E	391	maritime subtropical	siliceous sands	14	wet sclerophyll
7	Ash and Helman (1990) b	*E. maculata*, *E. pilularis*, *E. botryoides*, *Acacia mabellae*	Kioloa, NSW south coast	35 33' 150 22'E	444	mesothermal, 1200 mm rainfall, mean max temp from 16C to 23C, and mean min. 9C to 17C.	yellow podzolic soils on sandstone		sclerophyll forest
8	Ashton (1976)	*E. sieberi / E. regnans*	Beenak, Victoria	37 52'54"S 45 41'32"E	512	1400 mm rainfall	krasnozem/red podzolic on granite (low P)	27	dry / wet sclerophyll
9	Attiwill (1966)	*E. obliqua*	Mt Dis-appointment, Victoria	37 25'41"S 145 08'07"E	512	1000mm rainfall, 11C mean annual temperature	krasnozems on granodiorite	50 (35 - 75)	open forest, wet sclerophyll
10	Feller (1980) a	*E. regnans*	Maroondah, Victoria	37 38'S, 145 35'E	512	warm temperate rainy, 1660 mm rainfall, mean annual temperature 10.7C	krasnozem, Gn4.31,deep profile on quartz -biotite-dacite parent material	approx. 38	wet sclerophyll
11	Feller (1980) c	*E. obliqua*	Maroondah, Victoria	37 38'S, 145 35'E	512	warm temperate rainy, 1200 mm rainfall, mean annual temperature 15.5C	krasnozem-podzolic, Gn4.54, deep profile on quartz-dacite parent material	approx. 38	dry sclerophyll

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
	trees selected to cover size range in stand + 10 trees from Baker (1984)	branch regressions from Attiwill (1962), measured branch diamters and stem volume and density	DBH	29.6 - 89.7	8 + 10	49	330 - 363
	trees selected to cover size range in stand	branch regressions from Attiwill (1962), measured branch diamters and stem volume and density	DBH	21.4 - 51.2	5	35	158
regeneration following harvesting trees selected	across size range in stand	total fresh weight and ratio fresh:dry weight	DBH	13.1 - 25.3	7	16.7	76.37 (above-ground)
regeneration following harvesting	trees selected across size range in stand	total fresh weight and ratio fresh:dry weight	DBH	17.8 - 53.4	9	35.4	265.57 (above-ground)
regeneration + old growth	single large tree added to above sites	total fresh weight and ratio fresh:dry weight	DBH	13.1 - 128.9	17	68.1	1701.65 (above-ground)
regeneration following harvesting	trees selected across size range in stand	total fresh weight and ratio fresh:dry weight	DBH	13.4 - 25.5	4	16.7	76.37 (above-ground)
light selective logging	systematic location of points	measured dimensions, calulcated volume, conversion	DBH	40 - 100 ?	13 to 66 for different components		588
regeneration after wildfire	range of tree sizes and classes	weighed all leaves, branches and stem discs fresh,	girth at 1.3m	approx. 8 - 45 approx. 16 - 54	6 5		883 793
sites with various site indices	stratified by size class, and random, and 4 rep plots	branch regression equations	DBH	13 - 64	75	64.81	370.7
natural regeneration after wildfire	trees covered range of diameters of species in stand	canopy components weighed fresh, subsample measured fresh:dry ratio, dimensions of stem and large branches under and over bark measured, volume calculated and converted to weight using published wood densities and measured bark densities	DBH^2.H, DBH	approx. 17-67	6	52.1	622.8
natural regeneration after wildfire	trees covered range of diameters of species in stand	canopy components weighed fresh, subsample measured fresh:dry ratio, dimensions of stem and large branches under and over bark measured, volume calculated and converted to weight using published wood densities and measured bark densities	DBH^2.H, DBH	approx. 9-37	6	65.8	372.8

Table 1 ***continued***

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
12	Feller (1980) d	*E. dives*	Maroondah, Victoria	37 38'S, 145 35'E	512	warm temperate rainy, 1200 mm rainfall, mean annual temperature 15.5C	krasnozem -podzolic, Gn4.54, deep profile on quartz-dacite parent material	approx. 38	dry sclerophyll
13	Keith et al. (1997)	*E. pauciflora*	Brindabella Range, ACT	35 23'S, 148 48' E	448	montane cool temperate, 1200 mm rainfall	red earth	up to 40 years	native forest, mostly wildfire re-generation
14	Keith et al. (unpubl.) a	*E. obliqua*	southern forests, Tas.	43 09'S 146 49'E	727	cool, wet temperate	higher fertility on dolerite parent material	up tp 300 years	oldgrowth and regrowth native forest
15	Keith et al. (unpubl.) b	*E. obliqua*	southern forests, Tas.	43 09'S 146 49'E	727	cool, wet temperate	lower fertility on sandstone parent amterial		uneven-aged native forest
16	Keith et al. (unpubl.) c	*E. obliqua*	Tallaganda, NSW	35 31'S, 149 31'E	448	800-900 mm rainfall, average temperatures 23-29C summer, 7-13 C winter	higher fertility on igneous intrusive parent material		uneven-aged native forest
17	Keith et al. (unpubl.) d	*E. obliqua*	Tallaganda, NSW	35 37'S, 149 41'E	443	800-900 mm rainfall, average temperatures 23-29C summer, 7-13 C winter	lower fertility on sedimentary parent material		uneven-aged native forest
18	Mackowski (1987)	*E. pilularis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	subtropical		up to 150	mixed eucalypt forest with previous selective logging
19	Raison et al. (unpubl.)	*E. delegatensis*	Brindabella Range, ACT	35 23'S, 148 48' E	448	montane cool emperate, 1200 mm rainfall	red earth	25 - 86 years	native forest, mostly wildfire regeneration
20	Stewart et al. (1979) a	*E. muellerana*	Genoa, eastern Victoria	37 25'S, 149 33'E	521	927 mm rainfall, mean monthly temperature range from 13C to 26C	yellow podzolic, duplex granitoid on biotite adamellite	up to 100 years	uneven-aged mixed sclerophyll
21	Stewart et al. (1979) b	*E. agglomerata*	Genoa, eastern Victoria	37 25'S, 149 33'E	521	927 mm rainfall, mean monthly temperature range from 13C to 26C	yellow podzolic, duplex granitoid on biotite adamellite	up to 100 years	uneven-aged mixed sclerophyll

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
natural regeneration after wildfire	trees covered range of diameters of species in stand	canopy components weighed fresh, subsample measured fresh:dry ratio, dimensions of stem and large branches under and over bark measured, volume calculated and converted to weight using published wood densities and measured bark densities	DBH^2.H, DBH	approx. 10-22	5		
	subjectively selected by availability, and to cover size range	regression of canopy components on branch diameter, and all components on DBH	DBH	8.5 - 59.2 cm DBH	12	33.2	221.4
	subjectively selected by availability, and to cover size range of healthy trees	randomised branch sampling and importance sampling	DBH	26.2 - 284.0 cm DBH	10	92	775
	subjectively selected by availability, and to cover size range of healthy trees	randomised branch sampling and importance sampling	DBH	21.1 - 55.3 cm DBH	5	19	72
	subjectively selected by availability, and to cover size range of healthy trees	randomised branch sampling and importance sampling	DBH	25.4 - 78.0 cm DBH	10	71	497
	subjectively selected by availability, and to cover size range of healthy trees	randomised branch sampling and importance sampling	DBH	29.9 - 70.8 cm DBH	5	52	493
	stratified random sampling within size classes	stem and branch volume and number of leaves measured, multiplied by wood density and leaf weight	DBH	1.3 to 184.2	90		
	subjectively selected by availability, and to cover size range	regression of canopy components on branch diameter, and all components on DBH	DBH	11.9 - 83.2	11 - 17		
	subjectively selected trees in small, medium and large size classes, healthy trees	regression of canopy component mass to branch diameter, fresh mass of total stem, subsamples of all components to determine fresh:dry mass ratio, regressions of total component mass to tree DBH	DBH	26 - 87 cm DBH, 18.6 - 32.4 m height	11	30.1	325.4
	subjectively selected trees in small, medium and large size classes, healthy trees	regression of canopy component mass to branch diameter, fresh mass of total stem, subsamples of all components to determine fresh:dry mass ratio, regressions of total component mass to tree DBH	DBH	25 - 94 cm DBH and 18.2 - 31.4 m height	10	30.1	325.4

Table 1 ***continued***

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
22	Stewart et al. (1979) c	*E. sieberi*	Genoa, eastern Victoria	37 25'S, 149 33'E	521	927 mm rainfall, mean monthly temperature range from 13C to 26C	yellow podzolic, duplex granitoid on biotite adamellite	up to 100 years	uneven-aged mixed sclerophyll
23	West et al. (1991) a	*E. regnans*	Buckland, Tasmania	42 30'S 147 49'E	727	cool temperate		12	regrowth
24	West et al. (1991) b	*E. regnans*	Toolangi, Victoria	37 30'S 145 29'E	512	cool temperate		8	regrowth
25	West et al. (1991) c	*E. regnans*	Geeveston, Tasmania	43 5'S 146 48'E	727	cool temperate		20	regrowth
26	West et al. (1991) d	*E. regnans*	Geeveston, Tasmania	43 5'S 146 48'E	727	cool temperate		20	regrowth
27	Anderson and Ingram (1994) a	general	general - tropical			tropical, wet > 4000 mm rainfall			
28	Anderson and Ingram (1994) b	general	general - tropical			tropical, moist 1500-4000 mm rainfall			
29	Anderson and Ingram (1994) c	general	general - tropical			tropical, dry <1500 mm rainfall			
30	Ash and Helman (1990) a	rainforest: *Commersonis fraseri, Acmena smithii, Backhousia myrtifolia, Doryphora sassafras, Cryptocarya microneura-smithii, B*	Kioloa, NSW south coast	35 33' 150 22'E	444	mesothermal, 1200 mm rainfall, mean max temp from 16C to 23C.	yellow podzolic soils on sandstone		notophyll-rainforest
31	Feller (1980) b	*Acacia obliquinervia/ A. dealbata*	Maroondah, Victoria	37 38'S, 145 35'E	512	warm temperate rainy, 1200 mm rainfall, mean annual temp-erature 15.5C	krasnozem, Gn4.31,deep profile on quartz-biotite-dacite parent material	approx. 38	wet sclerophyll
32	Turner et al. (1989)	subtropical rainforest	Wiangaree, northern NSW	28 30'S 153 E	420	sub-tropical, 3000 mm rainfall, mean monthly temps max 27C to min. 7C	krasnozems on basalt		subtropical rainforest, range of species
33	Harrington (1979) a	*E. populnea*	Coolabah, NSW	30 55'S, 146 30'E	429			mature trees (trunk diam. > 25 cm)	woodland
34	Harrington (1979) b	*Geijera parviflora* (> 4m high)	Coolabah, NSW	30 55'S, 146 30'E	429				woodland

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
	subjectively selected trees in small, medium and large size classes, healthy trees	regression of canopy component mass to branch diameter, fresh mass of total stem, subsamples of all components to determine fresh: dry mass ratio, regressions of total component mass to tree DBH	DBH	28 - 89 cm DBH, 20.3 - 36.1 m height	10	30.1	325.4
	stratified randon to cover all tree sizes		DBH, H		10		
	stratified randon to cover all tree sizes		DBH, H		10		
unthinned	stratified randon to cover all tree sizes		DBH, H		11		
thinned	stratified randon to cover all tree sizes		DBH, H		11		
light selective logging	systematic location of points	measured dimensions, calulcated volume, conversion	DBH		4 to 67 for different components		347
natural regeneration after wildfire	trees covered range of diameters of species in stand	canopy components weighed fresh, subsample measured fresh:dry ratio, dimensions of stem and large branches measured, volume calculated and converted to weight using published densities combining wood and bark	D^2.H	approx. 6-21	5		
undisturbed	trees selected across a range of diameter classes		DBH		51 - 58	52	356
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H		20		54.7
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H range)	3.85 - 7.02 (m height	9		

Table 1 *continued*

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
35	Harrington (1979) c	*Eremophila mitchellii* (> 4m high)	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
36	Harrington (1979) d	*Geijera parviflora* (< 4m high)	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
37	Harrington (1979) e	*Cassia nemophila*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
38	Harrington (1979) f	*Dodonea viscosa*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
39	Harrington (1979) g	*Eremophila mitchellii* (< 4m high)	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
40	Harrington (1979) h	*E. sturtii*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
41	Harrington (1979) I	*E. bowmanii*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
42	Harrington (1979) j	*Myoporum deserti*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
43	Harrington (1979) k	*Acacia aneura*	Coolabah, NSW	30 55'S, 146 30'E	429				woodland
44	Holland (1969)	*E. incrassata*	Wyperfeld, western Victoria	35 45'S 142 10'E	478	semi-arid, rainfall 350 mm	sand dune	25- re-generated shoots	mallee woodland, fire regrowth
45	Holland (1969)	*E. dumosa*	Yara, Mt Hope, central NSW	32 45'S 145 58'E	429	semi-arid, rainfall 380 mm	red sandy loam, acidic, subsoil pan	up to 60- re-generated shoots	mallee woodland, fire regrowth
46	Holland (1969)	*E. oleosa*	Yara, Mt Hope, central NSW	32 45'S 145 58'E	429	semi-arid, rainfall 380 mm	red sandy loam, acidic, subsoil pan	up to 60- re-generated shoots	mallee woodland, fire regrowth
47	Bennett et al. (1997)	*E. globulus*	Gippsland, Victoria,3 sites	38 14'S 146 30'E	538	620 to 1000 mm duplex sandy	uniform sand, loam, gradational clay	6	plantation P fertilizer addi
48	Birk and Turner (1992) a	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1500 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	shallow brown to deep red earths on greywacke	9.75	plantation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.6 - 5.2 (m height range)	18		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.6 - 4.5 (m height range)	9		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.6 - 2 (m height range)	19		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.2 - 2 (m height range)	10		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.6 - 5 (m height range)	18		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.3 - 3 (m height range)	22		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.2 - 1.8 (m height range)	18		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.2 - 2 (m height range)	17		
regeneration after clearing	random stratified by size class	branch mass regressed on primary branch diameter, canopy and trunk mass regressed on stem diameter	D(at 30 cm), H	0.2 - 3.5 (m height range)	19		
	random	measured total fresh weight of components, ratio of fresh:dry weight	basal circumference (BC)	8.8 - 22.7 (basal circumference)	19		8.864
	random, along transect	measured total fresh weight of components, ratio of fresh:dry weight	age from ring counts	12 to 62 years	49		7.207 E. dumosa in total of 19.835
	random, along transect	measured total fresh weight of components, ratio of fresh:dry weight	age from ring counts	5 to 59 years	24		12.628 E. oleosa in total of 19.835
3 rates of N and	stratified by size	total frest weight, subsample for twig:leaf ratio and frsh:dry ratio	DBH, H	7.5 - 22.8	24 3sitesx 4 treatment x2trees		43 to 109
control, fertilized with 2180 kgN/ha, 1904 kgP/ha, 1489 kgK/ha over 6 years, plus weedicide	trees selected to cover the diameter distribution	stem dimensions, volume and density of discs converted to biomass PLUS	DBH	7 - 35	24	17.5 in C 34.7 in F	123 in C 274 in F

Table 1 ***continued***

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
49	Birk and Turner (1992) b	*Acacia melanoxylon* and *A. idorata*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1500 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	shallow brown to deep red earths on greywacke	9.75	plantation
50	Birk et al. (1995) a	Acacia falcata	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
51	Birk et al. (1995) b	*A. filicifolia / A.decurrens*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
52	Birk et al. (1995) c	*A. longifolia*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
53	Birk et al. (1995) d	*A. saligna*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
54	Birk et al. (1995) e	*Allocasuarina torulosa*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	3 - 5	natural regeneration
55	Birk et al. (1995) f	*Casuarina glauca / C.cunning-hamiana*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
56	Birk et al. (1995) g	*E. cladocalyx*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
57	Birk et al. (1995) h	*E. dawsonii*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation minesite rehabilitation
58	Birk et al. (1995) i	*E. maculata*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
59	Birk et al. (1995) j	*E. moluccana*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
60	Birk et al. (1995) k	*E. punctata*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
61	Birk et al. (1995) l	*E. tereticornis*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
62	Birk et al. (1995) m	*E. maculata*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation
63	Birk et al. (1995) n	*Melaleuca armillaris*	Hunter Valley, NSW	32 34'S 151 10'E	444	warm temperate	parent materials -sandstone, siltstone, mudstone, shale	2 - 9	plantation, minesite rehabilitation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
control, fertilized with 2180 kgN/ha, 1904 kgP/ha, 1489 kgK/ha over 6 years	trees selected to cover the diameter distribution	canopy mass derived from branch diameter regressions, biomass estimates not corected for bias in back-transforamtion	DBH		4		30
direct- seeded, tube stock, over-burden, topsoil, chitter	re- presentative trees across the range of tree sizes	whole tree fresh weight and fresh: dry mass ratio conversion for small trees (<5cm diam.), bole volume, wood density and branch regressions for large trees	DBH, H	0.55 - 3.2	4	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.8 - 14.6	4	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	2.2 - 8.7	4	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	3.3 - 28.5	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	0.3 - 2.6	6		8.1 to 15.4
	representative trees across the range of tree sizes	whole tree fresh weight and fresh: dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	4.35 - 16.0	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	3.1 - 16.7	6	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	3.16 - 21.5	8	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	0.9 - 17.8	17	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.1 - 16.9	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.1 - 16.9	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.1 - 16.9	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.1 - 16.9	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)
	representative trees across the range of tree sizes	whole tree fresh weight and fresh:dry mass ratio conversion for small trees, bole volume, wood density	DBH, H	5.1 - 16.9	5	0.6-4.13 (3yrs) up to 16.25 (9yrs)	2.0-3.8 (3yrs) up to 54.5 (9 yrs)

Table 1 *continued*

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
64	Bradstock (1981) a	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments	2	plantation
65	Bradstock (1981) b	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments	5	plantation
66	Bradstock (1981) c	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments	6	plantation
67	Bradstock (1981) d	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	granodiorite	10	plantation
68	Bradstock (1981) e	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	granodiorite	12	plantation
69	Bradstock (1981) f	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	granodiorite	15	plantation
70	Bradstock (1981) g	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments	16	plantation
71	Bradstock (1981) h	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments	27	plantation
72	Bradstock (1981) I	*E. grandis*	Coffs Harbour, NSW	30 08'S 153 07'E	420	sub-tropical, 1759 mm rainfall, mean annual temp. max. 23.1C and min. 13.6C	sediments and granodiorite	all sites 2 - 27	plantation
73	Cromer et al (1975) a	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	2	plantation
74	Cromer et al (1975) b	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	4	plantation
75	Cromer et al (1975) c	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	4	plantation
76	Cromer et al (1975) d	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	4	plantation
77	Cromer et al (1975) e	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	4	plantation
78	Cromer and Williams (1982) a	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	6	plantation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
fertilized	mean tree in each size class	stem dimensions, volume and density of discs converted to biomass PLUS	DBH	3.3 - 10.7	5	4.89	18.3
fertilized	mean tree in each size class	canopy mass derived from branch diameter regressions, PLUS	DBH	3.3 - 18.8	4	12.3	53.2
fertilized	mean tree in each size class	biomass estimates not corected for bias in back-transforamtion	DBH	2.8 - 16	4	7.5	27.5
fertilized	mean tree in each size class	stem dimensions, volume and density of discs converted to biomass PLUS	DBH	3.7 - 25.3	4	13.1	84.2
fertilized	mean tree in each size class	canopy mass derived from branch diameter regressions, PLUS	DBH	4.7 - 27.8	4	22.5	196.7
fertilized	mean tree in each size class	biomass estimates not corected for bias in back-transforamtion	DBH	4.1 - 29.4	4	31.5	164.7
fertilized	mean tree in each size class	stem dimensions, volume and density of discs converted to biomass PLUS	DBH	4.2 - 33.4	6	23.3	187.4
fertilized	mean tree in each size class	canopy mass derived from branch diameter regressions	DBH	4.1 - 41.0	5	30.4	394.0
fertilized	mean tree in each size class	stem dimensions, volume and density of discs converted to biomass, canopy mass derived from branch diameter regressions, biomass estimates not corected for bias in back-tr	DBH	approx. 4 - 40	36		
control + fertilizer treatments	mean trees	total fresh weight and ratio fresh:dry weight	BA	mean 0.5 (C) o 3.57 (F)	16	0.04 (C) to 2.39 (F)	1 (C) to 8.6 (F)
control	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 3.3	12	2.06	6.3
34 kgN/ha + 15 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 5.65	12	5.21	15.5
101 kgN/ha + 45 kg P/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 6.45	12	6.47	21.4
202 kgN/ha + 90 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 7.10	12	8.32	30.3
control	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 4.5	12		11

Table 1 *continued*

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
79	Cromer and Williams (1982) b	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	6	plantation
80	Cromer and Williams (1982) c	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	6	plantation
81	Cromer and Williams (1982) d	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	6	plantation
82	Cromer and Williams (1982) e	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	9.5	plantation
83	Cromer and Williams (1982) f	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	9.5	plantation
84	Cromer and Williams (1982) g	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	9.5	plantation
85	Cromer and Williams (1982) h	*E. globulus*	Silver Creek, Gippsland, Victoria	38 20'S 146 15'E	538	1000 mm rainfall	krasnozem, red to brown earth on basalt	9.5	plantation
86	Cromer et al. (1993) a	*E. grandis*	Gympie, Qld.	26 S 152 45'E	375	sub-tropical, 1100 mm rainfall	yellow earth / gleyed podzolic	0.3 to 0.7	plantation
87	Cromer et al. (1993) b	*E. grandis*	Gympie, Qld.	26 S 152 45'E	375	sub-tropical, 1100 mm rainfall	yellow earth / gleyed podzolic	1.2 to 2.2	plantation
88	Cromer et al. (1993) c	*E. grandis*	Gympie, Qld.	26 S 152 45'E	375	sub-tropical, 1100 mm rainfall	yellow earth / gleyed podzolic	1.2 to 2.2	plantation
89	Madgwick et al. (1991) a	*E. fastigata*	NZ					4	plantation
90	Madgwick et al. (1991) b	*E. nitens*	NZ					4 - 7	plantation
91	Madgwick et al. (1991) c	*E. regnans*	NZ North Island	38 20'S, 175 45'E			pumice soil	4 - 17	plantation
92	Madgwick et al. (1991) d	*E. saligna*	NZ					8	plantation
93	O'Brien (1998)	*E. grandis*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	10 months	plantation
94	O'Brien (1998)	*E. grandis*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	16 months	plantation
95	O'Brien (1998)	*E. grandis*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	22 months	plantation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
34 kgN/ha + 15 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 7.3	12		20
101 kgN/ha + 45 kg P/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 8	12		31
202 kgN/ha + 90 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 8.2	12		41
control	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 6.8	12		30.5
34 kgN/ha + 15 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 9.7	12		58.2
101 kgN/ha + 45 kg P/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 10.5	12		74.3
202 kgN/ha + 90 kgP/ha	stratified by diameter class and random	total fresh weight and ratio fresh:dry weight	BA	mean 10.5	12		81.9
control and fertilized with 1536 kgN/ha + 461 kgP/ha + basal dressing			sectional area at 30 cm, height	0.7 to 5.6	20		
control			BA, height	3 to 13	20		11 after 3 years
fertilized with 1536 kgN/ha + 461 kgP/ha + basal dressing			BA, height	3 to 13	20		55 after 3 years
	trees selected across range of diameters in plot	total fresh weight of components and subsample for fresh:dry ratio	DCB, DBH^2.H	1.5 - 10.3	7		
	trees selected across range of diameters in plot	total fresh weight of components and subsample for fresh: dry ratio	DCB, DBH^2.H	2.4 - 22.8	52		
	trees selected randomly in strata by diameters in plot	total fresh weight of components and subsample for fresh: dry ratio of canopy components and discs	DCB, DBH^2.H	5 - 37.3	51	39.1 at age 8	171.6 at age 8
	trees selected across range of diameters in plot	total fresh weight of components and subsample for fresh: dry ratio	DCB, DBH^2.H	12.3 - 23.9	9		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	D at 30 cm height		27		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	D at 30 cm height	mean 5.09 cm D	5		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	DBH		24		

Table 1 ***continued***

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
96	O'Brien (1998)	*E. grandis*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	28 months	plantation
97	O'Brien (1998)	*E. grandis*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	34 months	plantation
98	West et al. (1991) e	*E. delegatensis*	Esperence, Tasmania	43 18'S 146 55'E	727	cool temperate 60 m elevation		4 and 5	plantation
99	West et al. (1991) f	*E. nitens*	Esperence, Tasmania	43 18'S 146 55'E	727	cool temperate 60 m elevation		4 and 5	plantation
100	West et al. (1991) g	*E. nitens*	Esperence, Tasmania	43 17'S 146 52'E	727	cool temperate 240 m elevation		4	plantation
101	West et al. (1991) h	*E. nitens*	Esperence, Tasmania	43 15'S 146 49'E	727	cool temperate 4450 m elevation		4	plantation
102	West et al. (1991) l	*E. grandis*	Samford, Queensland	27 22'S 152 53'E	375	subtropical, rainfall 1100 mm	parent material phyllite, lithosols, red and yellow podzolics, gleyed podzolics	1.5 - 5	plantation
103	West et al. (1991) j	*E. grandis*	Toolara, Queensland	26 20'S 152 48'E	375	subtropical		1.5 - 2.5	plantation
104	West et al. (1991) k	all sites-fresh							
105	West et al. (1991) l	all sites-dry							
106	Baker et al. (1984)	*P. radiata*	Gippsland, Victoria	38 20'S 146 15'E	538	600-1000mm rainfall	variable	9 - 28	plantation
107	Birk (1992)	*P. radiata*	Sunny Corner SF, Blue Mts., NSW	33 22'S 149 52'E	448	1017 mm rainfall, mean max. temp. 25C and min. 0C	stoney siltstone soils	21	plantation
108	Cannell (1984)	*P. radiata*							plantation
109	Cromer et al. (1985)	*P. radiata*	Traralgon, Victoria	38 16'S, 146 40'E	529	700 mm rainfall		10	plantation
110	Dargavel (1970)	*P. radiata*	APM, Gippsland, Victoria		538			5-18	plantation
111	Feller (1984)	*P. radiata*	Maroondah, Victoria	37 38'S 145 35'E	512	warm temperate rainy, 1200 mm rainfall, mean annual temp. 15.5C	krasnozem-podzolic, Gn4.54, deep profile on quartz-dacite parent material	37	plantation
112	Forrest (1969)	*P. radiata*	25 km NE of Tumut, NSW	35 12'S 148 26'E	448	1450 mm rainfall, mean min temp 4.2C, max 19.0C	red earths on granite parent material	5	plantation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	DBH		5		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	DBH	mean 9.57 cm DBH	12	12.2	44
	stratified randon to cover all tree sizes		DBH, H		14		
	stratified randon to cover all tree sizes		DBH, H		13		
	stratified randon to cover all tree sizes		DBH, H		7		
	stratified randon to cover all tree sizes		DBH, H		7		
	random at various sampling times		DBH, H		83		
	random at various sampling times		DBH, H		54		
			DBH, H		220		
			DBH, H		220		
fertilized and unfertilized trees	see Stewart et al 1981, Dargavel (1970)	see Stewart et al 1981, Dargavel (1970)	Dc, D2H	4 - 49	62	29 - 49	270.0
previous landuse: native forest, pasture, cultivated		branch regressions for canopy components, and estimated from diameters of all branches on the tree, stem mass derived from volume and density	DBH	means of 23.1 to 25.1	9 11 9	50.3 63.1 60.1	259.2 320.1 362.7
			stand BA, H		13 stands		
control, fertilized with N, P, K	stratified random sampling by diameter class	total fresh weight, stratified subsample for fresh:dry ratio measurement and discs	BA	11.2 - 15.4 (means)	20	17.7(C) 32.0(F)	63 for C, 117 for F
	random	total fresh weight, sample ratio of fresh:dry weight	BA, height	1.32 - 10.9 "	25		
	trees covered range of diameters of species in stand	canopy components weighed fresh, subsample measured fresh:dry ratio, dimensions of stem and large branches under and over bark measured, volume calculated and converted to weight using published wood densities and measured bark densities	DBH, H	mean 29	5	51.2	
	stratified random sampling by diameter class	whole trees sampled, divided into components, dried and weighed	DBH, H	1.4 - 5.8	9	2	5.58

Table 1 *continued*

ID	Author	Species	Site	Location	IBRA	Climate	Soil type	Tree age	Vege type
113	Forrest (1969)	*P. radiata*	Tumut, NSW	35 12'S 148 26'E	448	1450 mm rainfall, mean min temp 4.2C, max 19.0C	red earths on granite parent material	7	plantation
114	Forrest (1969)	*P.radiata*	Tumut, NSW	35 12'S 148 26'E	448	1450 mm rainfall, mean min temp 4.2C, max 19.0C	red earths on granite parent material	9	plantation
115	Forrest (1969)	*P. radiata*	Tumut, NSW	35 12'S 148 26'E	448	1450 mm rainfall, mean min temp 4.2C, max 19.0C	red earths on granite parent material	12	plantation
116	Jackson and Chittenden (1981)	*P. radiata*	NZ	38 07'S single site		1511 mm rainfall, mean annual temperature 12.1C	pumiceous sandy loam	3 - 8	
117	Jackson and Chittenden (1981)	*P. radiata*	combined sites NZ, Aust., South Africa					3 - 39 years	
118	Madgwick (1983)	*P. radiata*	NZ						plantation
119	Madgwick (1994) a	*P. radiata*	NZ						plantation
120	Madgwick (1994) b	*P. radiata*	NZ					1 to 42	plantation
121	O'Brien (1998)	*P. radiata*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	10 months	plantation
122	O'Brien (1998)	*P. radiata*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	16 months	plantation
123	O'Brien (1998)	*P. radiata*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	22 months	plantation
124	O'Brien (1998)	*P. radiata*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	28 months	plantation
125	O'Brien (1998)	*P. radiata*	Wagga Wagga, NSW	35 10'S 147 28'E	443	570 mm rainfall, mean min temp. 3C max 31C.	red podzolics to red earths or red chromosols to red kandosols	34 months	plantation
126	Snowdon (1985)	*P. radiata*	Belanglo SF, NSW	34 36'S 150 24'E	444	rainfall 880 mm, mean max. temp. 24.5C and min. 1.6C	podzolic sandy loam on sandstone	3-4 years	plantation
127	Snowdon and Benson (1992)	*P. radiata*	BFG, Canberra, ACT	35 21'S 148 56"E	504	791 mm rainfall, temp. mean max. 28C, min. 1C	duplex yellow podzolics on adamellite parent material	10 to 14	plantation
128	Watson and O'Loughlin (1990)	*P. radiata*	NZ	39S 178 E		1320 - 2100 mm rainfall	fragmented pumice and sedimentary parent material	8, 16 and 25 years	plantation
129	Williams (1976)	*P. radiata*	Merriang, NE Victoria	36 37'S 146 39'E	510			12	plantation

Treatments	Tree selection	Biomass Measurement	Variables	DBH range	Tree no	Stand BA (m^2/ha)	Est biomass (t/ha)
	stratified random sampling by diameter class	whole trees sampled, divided into components, dried and weighed	DBH, H	6.4 - 14.5	9	16	50.73
	stratified random sampling by diameter class	whole trees sampled, divided into components, dried and weighed	DBH, H	9.7 - 18.4	9	25	73.41
	stratified random sampling by diameter class	whole trees sampled, divided into components, dried and weighed	DBH, H	10.3 - 19.8	9	32	118.76
		root excavation from trenches and washing and sieving	DBH	mean 2.1 - 14.3	97		
		roots > 5 cm diameter, oven-dry	DBH	3.4 to 56.3	247		
			DC (diam at base of live crown)	1.4 - 62.1	298 - 557		
			DBH, H		801		
			stand BA, H, Age, stocking		139 stands		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	D at 30 cm height		25		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	D at 30 cm height	mean 3.25 cm D	5		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	D at 30 cm height		24		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	DBH		5		
irrigated with effluent at various rates	random within stratified size classes	total fresh weight, subsample for dry weight of > 20% of branches, and discs of stem	DBH	mean 8.57 cm DBH	12	9.63	24
fertilizer, family			D2/H, D/H		435		
ferilized and irrigated	random, stratified by size class and treatment	total freah material weighed, and ratio of fresh:dry weight from samples	DBH, height	14.1 - 25.3 (means)	67 (across years and treatments)	11.9-13.1 (10yrs) 24-38.2 (14yrs)	28 (10yrs) 135 (14yrs with I+F)
		all root size classes, hydraulic excavation, air-dry	DBH	stump diameter 17 - 65 cm	13		8.8, 67, 151 t/ha root mass
	random	total dry weight of crown, stem volume and density	DBH	17.1 mean	12	27.5	115.5

Table 2: Summary of allometric equations for each biomass component and associated statistical information.

The error terms provided in Table 2 include: standard deviation of the regression (a), standard error of the regression (b), variance of the regression (c), standard error of the estimate (d), and error mean square (e), standard error of the slope (f), and standard error of the intercept (g).

1 Adams ana Attiwill (1988)a

Equation-stem	se-s	EMS-s	n-s	r2-s
InM(kg) = -3.609 + 2.629 InDBH(cm) (heartwood)	0.252 d	0.0635	18	0.951
InM(kg) = -2.434 + 1.957 InDBH(cm) (sapwood)	0.448 d	0.2007	18	0.775
InM(kg) = -2.086 + 1.788 InDBH(cm) (bark)	0.245 d	0.0600	18	0.905

Equation-leaves	se-1	EMS-1	n-1	r2-l
InM(kg) = -4.611 + 1.99 InDBH(cm)	0.415 d	0.1722	18	0.806

Equation - branches	se-b	EMS-b	n-b	r2-b
InM(kg) = -8.855 + 3.253 InDBH(cm) (roughbark)	0.667 d	0.4449	18	0.811
InM(kg) = -7.069 + 2.53 InDNH(cm) (smoothbark)	0.548 d	0.3003	18	0.793
InM(kg) = -4.613 + 1.898 InDBH(cm) (small)	0.421 d	0.1772	18	0.785

2 Adams ana Attiwill (1988)b

Equation-stem	se-s	EMS-s	n-s	r2-s
InM(kg) = -1.158 + 1.875 InDBH(cm) (heartwood)	0.223 d	0.0497	5	0.921
InM(kg) = -0.225 + 1.102 InDBH(cm) (sapwood)	0.091 d	0.0083	5	0.96
InM(kg) = -1.416 + 1.468 InDBH(cm) (bark)	0.065 d	0.0042	5	0.988

Equation - leaves	se-l	EMS-l	n-l	r2-l
InM(kg) = -5.932 + 2.457 InDBH(cm)	0.442 d	0.1954	18	0.836

Equation - branches	se-b	EMS-b	n-b	r2-b
InM(kg) = -10.048 + 3.87 InDBH(cm) (roughbark)	0.544 d	0.2959	18	0.893
InM(kg) = -8.908 + 3.214 InDNH(cm)(smooth)	0.502 d	0.252	18	0.871
InM(kg) = -6.016 + 2.369 InDBH(cm) (small)	0.436 d	0.1901	18	0.829

3 Applegate (1982) a

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -0.8406 + 2.2228 log DBH(cm)	0.0813 d	0.0463	7	0.923

Equation - crown	se-c	EMS-c	n-c	r2-c
logM(kg) = -2.835 + 3.2953 logDBH(cm)	0.2152 d	0.3242	7	0.789

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(kg) = -2.8318 + 2.9433 logDBH(cm)	0.1383 d	0.1339	7	0.878

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(kg) = -3.258 + 3.4673 logDBH(cm)	0.2743 d	0.5267	7	0.718

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
logM(kg) = -1.013 + 2.4351 logDBH(cm)	0.0959 d	0.0644	7	0.911

Equation - roots	se-r	EMS-r	n-r	r2-r
logM(kg) = -2.6206 + 3.1487 logDBH(cm)	0.0156 d	0.0007	3	0.999

Equation - total	se-t	EMS-t	n-t	r2-t
logM(kg) = -1.1589 + 2.6064 logDBH(cm)	0.0439 d	0.0058	3	0.991

4 Applegate (1982) b

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.2253 + 2.5911 logDBH(cm)	0.0503 d	0.0228	9	0.986

Equation - crown	se-c	EMS-c	n-c	r2-c
logM(kg) = -3.5814 + 3.5202 logDBH(cm)	0.214 d	0.4122	9	0.882

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(kg) = -3.8701 + 3.1618 logDBH(cm)	0.1952 d	0.3429	9	0.878

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(kg) = -3.7375 + 3.5724 log DBH(cm)	0.2336 d	0.4911	9	0.865

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
logM(kg) = -1.3086 + 2.6803 logDBH(cm)	0.0534 d	0.0257	9	0.986

Equation - roots	se-r	EMS-r	n-r	r2-r
logM(kg) = -2.1516 + 2.6864 logDBH(cm)	0.073 d	0.0213	4	0.989

Equation - total	se-t	EMS-t	n-t	r2-t
logM(kg) = -1.0356 + 2.5270 logDBH(cm)	0.0402 d	0.0065	4	0.996

5 Applegate (1982) c

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
logM(kg) = -1.3326 + 2.6934 logDBH(cm)	0.0693 d	0.0816	17	0.99

Equation - roots	se-r	EMS-r	n-r	r2-r
logM(kg) = -1.9128 + 2.5462 logDBH(cm)	0.0758 d	0.046	8	0.993

Equation - total	se-t	EMS-t	n-t	r2-t
logM(kg) = -1.2241 + 2.6588 logDBH(cm)	0.0380 d	0.0116	8	0.998

6 Applegate (1982) d

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.1234 + 2.3190 logDBH(cm)	0.032 d	0.0041	4	0.991

Equation - crown	se-c	EMS-c	n-c	r2-c
logM(kg) = -3.39366 + 3.9500 logDBH(cm)	0.1093 d	0.0478	4	0.966

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(kg) = -3.6181 + 3.3261 logDBH(cm)	0.0966 d	0.0373	4	0.962

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(kg) = -4.5443 + 4.2691 logDBH(cm)	0.2417 d	0.2337	4	0.871

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
logM(kg) = -1.4044 + 2.6018 logDBH(cm)	0.0086 d	0.0003	4	0.999

7 Ash and Helman (1990) b

Equation - roots	se-r	EMS-r	n-r	r2-r
logVolume(L) = -0.91 + 2.01 logDBHUB(cm) (root)	0.206		41	0.977
logVolume(L) = -2.46 + 2.59 logDBHUB(cm) (root stock)	0.165		40	0.991
logM(kg) = -0.92 + 2.56 logDBH(cm)				

8 Ashton (1976)

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
logM(kg) = -2.43 + 2.58 logGirth(cm)			11	

9 Attiwill (1966)

Equation-stem	se-s	EMS-s	n-s	r2-s
sum of individual stem sections by height and component				

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM (g)= 1.0452 + 2.6496 logDBH(")	0.0225 c	0.0225	75	

Equation - branches	se-b	EMS-b	n-b	r2-b
logM (g)= 0.6730 + 3.4052 logDBH(")	0.0306 c	0.0306	75	

Table 2 ***continued***

10 Feller (1980) a

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
M(kg) = -45.6 + 248.9 DBH^2(m).H(m)	103.4 d	64149	6	0.997
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
M(kg) = -16.9 + 6.4 lnDBH(cm)	1.7 d	14.5	5	0.78
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
M(kg) = -42.2 + 25.7 DBH^2(m).H(m)	63.3 d	24041	6	0.94

11 Feller (1980) c

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
M(kg) = -631.2 + 287.4 lnDBH(cm) (wood), M(kg) = -195.6 + 89.1 ln DBH(cm) (bark)	45.8 d 13.6 d	12586 1112	6 6	0.93 0.93
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
M(kg) = 0.9 + 1.7 DBH^2(m).H(m)	0.5 d	1	4	0.95
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
M(kg) = -1.7 + 13.4 DBH^2(m).H(m)	7.4 d	329	6	0.84

12 Feller (1980) d

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
M(kg) = 6.0 + 404.3 DBH^2(m).H(m)	18.3 d	1674	5	0.97
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
M(kg) = -16.5 + 6.8 lnDBH(cm)	1.3 d	8.5	5	0.75
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
M(kg) = -55.6 + 23.1 lnDBH(cm) (live), M(kg) = -13.6 + 6.6 lnDBH(cm) (dead)	2.6 d 1.4 d	33.8 9.8	5 5	0.87 0.86

13 Keith et al. (1997)

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -3.4614 + 2.6112 lnDBH(cm) (wood), lnM(kg) = -3.8697 + 2.1291 ln DBH(cm) (bark)	0.0640 e 0.0250 e	0.0640 0.0250	12 12	0.97 0.98
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(g) = 3.932 + 1.6123 ln DBH(cm)	0.0564 e	0.0564	10	0.95
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
lnM(g) = 4.0821 + 2.0952 lnDBH(cm)	0.1902 e	0.1902	18	0.90
Equation - twigs	**se-g**	**EMS-g**	**n-g**	**r2-g**
lnM(g) = 3.3032 + 1.6666 lnDBH(cm)	0.0560 e	0.0560	10	0.95

14 Keith et al. (unpubl.) a

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -1.816 + 2.269 lnDBH (cm)	0.1015 e	0.1015	10	0.967
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = 0.089 + 0.794 lnDBH (cm)	0.2647 e	0.2647	10	0.576
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
lnM(kg) = -3.873 + 2.406 lnDBH (cm)	0.2146 e	0.2146	10	0.939

Equation - twigs	se-g	EMS-g	n-g	r2-g
lnM(kg) = 0.096 + 0.744 lnDBH (cm)	0.3368 e	0.3368	10	0.484

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = -1.598 + 2.283 lnDBH(cm)	0.0253 e	0.0253	10	0.992

15 Keith et al. (unpubl.) b

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -4.155 + 2.705 lnDBH (cm)	0.0037 e	0.0037	5	0.997

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -1.93 + 1.329 lnDBH (cm)	0.0184 e	0.0184	5	0.947

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -4.934 + 2.77 lnDBH (cm)	0.2370 e	0.237	5	0.858

Equation - twigs	se-g	EMS-g	n-g	r2-g
lnM(kg) = -3.097 + 1.616 lnDBH (cm)	0.1579 e	0.1579	5	0.755

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = -3.351 + 2.642 lnDBH(cm)	0.0265 e	0.0265	5	0.98

16 Keith et al. (unpubl.) c

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.468 + 2.338 lnDBH (cm)	0.0354 e	0.0354	10	0.969

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -1.909 + 1.281 lnDBH (cm)	0.2014 e	0.2014	10	0.625

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -5.096 + 2.823 lnDBH (cm)	0.2529 e	0.2529	10	0.866

Equation - twigs	se-g	EMS-g	n-g	r2-g
lnM(kg) = -2.903 + 1.532 lnDBH (cm)	0.2072 e	0.2072	10	0.698

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = -2.050 + 2.353 lnDBH(cm)	0.0159 e	0.0159	10	0.986

17 Keith et al. (unpubl.) d

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -0.965 + 1.974 lnDBH (cm)	0.0477 e	0.0477	5	0.938

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -5.256 + 2.131 lnDBH (cm)	0.0401 e	0.0401	5	0.954

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -8.800 + 3.873 lnDBH (cm)	0.2629 e	0.2629	5	0.914

Equation - twigs	se-g	EMS-g	n-g	r2-g
lnM(kg) = -7.388 + 2.683 lnDBH (cm)	0.0600 e	0.06	5	0.957

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = -2.742 + 2.584 lnDBH(cm)	0.0146 e	0.0146	5	0.988

18 Mackowski (1987)

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg)=[0.00012446.(DBH(cm)^2.4596)].710 (<60cmDBH)			53	0.992
M(kg)=[0.00069615.(DBH(cm)^2.0345)].710 (60-100cm)			13	0.90
M(kg)=[(0.284517.DBH)-21.3757].710 (>100cmDBH)			24	0.83

Table 2 *continued*

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(g)=[81.4946xDBH^1.5725]x0.3392(<80cm)			60	0.98
M(g)=[176.475xDBH^1.3953]x0.3392(80-110cm)			9	0.76
M(g)=[81168.7xlnDBH-250917]x0.3392(>110cm)			21	0.12

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = [0.0001258 x DBH^2.5441] x 710 (<90 cm DBH)			60	0.996
M(kg) = [0.000527127xDBH^2.19699]x710 (45-135cm)			9	0.828
M(kg) = [0.3938 x DBH - 26.9781] x 710 (>90 cm DBH)			21	0.903
(stems and branches to a diameter of 10% of DBH)				

19 Raison et al. (unpubl.)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -3.102 + 2.595 lnDBH(cm) (wood),	0.0969 e	0.0969	11	0.971
lnM(kg) = -3.146 + 2.029 lnDBH(cm) (bark),	0.0620 e	0.0620	11	0.970

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 3.625 + 1.575 lnDBH(cm)	0.4075 e	0.4075	16	0.919

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 1.505 + 2.552 lnDBH(cm)	0.3797 e	0.3797	15	0.970

Equation - twigs	se-g	EMS-g	n-g	r2-g
lnM(g) = 2.833 + 1.719 lnDBH(cm)	0.2718 e	0.2718	15	0.956

20 Stewart et al. (1979) a

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.2827 + 2.5199 logDBH (cm) (wood),	0.08609 a	0.0074	11	0.975
logM(kg) = -1.1425 + 1.9912 logDBH (cm) (bark)	0.1032 a	0.0107	11	0.944

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = -21.7251 + 1.1342 DBH (cm)	9.4998 a	90.25	11	0.89

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -268.9465 + 11.0133 DBH (cm) (wood),	86.401 a	7465	11	0.902
M(kg) = -44.6393 + 1.8681 DBH (cm) (bark)	14.669 a	215	11	0.902

Equation - twigs	se-g	EMS-g	n-g	r2-g
M(kg) = -23.0795 + 1.2088 DBH (cm)	10.1354 a	102.7	11	0.89

21 Stewart et al. (1979) b

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -0.9497 + 2.3156 logDBH (cm) (wood),	0.07605 a	0.0058	10	0.980
logM(kg) = -1.3879 + 2.2365 logDBH (cm) (bark)	0.07575 a	0.0057	10	0.978

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = -33.4589 + 1.6786 DBH (cm)	8.1575 a	66.54	9	0.945

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -251.466 + 11.2664 DBH (cm) (wood),	51.731 a	2676	9	0.958
M(kg) = -67.1107 + 3.0277 DBH (cm) (bark)	13.007 a	169	9	0.957

Equation - twigs	se-g	EMS-g	n-g	r2-g
M(kg) = -39.0393 + 1.9268 DBH(cm)	9.3075 a	86.6	9	0.947

22 Stewart et al. (1979) c

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.0373 + 2.3867 logDBH (cm) (wood)	0.07103 a	0.0050	10	0.976
logM(kg) = -2.1434 + 2.7344 logDBH (cm) (bark)	0.08243 a	0.0068	10	0.976

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = 4.7424 + 0.01026 DBH^2 (cm)	7.6438 a	58.43	10	0.931

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -246.9228 + 0.2254 DBH^2(cm) (wood),	135.02 a	18231	10	0.954,
M(kg) = -69.5361 + 0.059 DBH^2 (cm) (bark)	36.538 a	1335	10	0.951

Equation - twigs	se-g	EMS-g	n-g	r2-g
M(kg) = 3.4289 + 0.0133 DBH^2 (cm)	9.5012 a	90.3	10	0.936

23 West et al. (1991) a

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 9.5732 + 0.0125 lnH(m) + 2.376 lnDBH(cm)			10	

24 West et al. (1991) b

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 13.4328 - 1.118 lnH(m) + 2.7213 lnDBH(cm)			10	

25 West et al. (1991) c

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 6.8787 + 0.7415 lnH(m) + 2.0318 lnDBH(cm)			11	

26 West et al. (1991) d

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 12.1779 - 0.5356 lnH(m) + 2.9963 lnDBH(cm)			11	

27 Anderson and Ingram (1994) a

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = 13.2579 - 4.8945 DBH + 0.6713 DBH^2 (cm)			69,	0.90
OR lnM(kg) = -3.3012 + 0.9439 ln (DBH^2.H) (cm)			69	0.90

28 Anderson and Ingram (1994) b

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = 38.4908 - 11.7883 DBH(cm) + 1.1926 DBH^2			168	0.78
OR lnM(kg) = -3.1141 + 0.9719 ln (DBH^2.H) (cm)			168	0.97
OR lnM(kg) = -2.4090 + 0.9522 ln (DBH^2.H.Density) (cm. t/m3)			94	0.99

29 Anderson and Ingram (1994) c

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = 34.4703 - 8.0671 DBH + 0.6589 DBH^2 (cm)			32	0.67

30 Ash and Helman (1990) a

Equation - roots	se-r	EMS-r	n-r	r2-r
logVolume(L) = -0.76 + 1.75 logDBHUB(cm) (root)	0.216		13	0.921
logVolume(L) = -2.19 + 2.38 logDBHUB(cm) (root stock)	0.148		13	0.978

Equation - total	se-t	EMS-t	n-t	r2-t
logM(kg) = -0.72 + 2.39 logDBH(cm)				

Table 2 *continued*

31 Feller (1980) b

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = 1.9 + 424.9 DBH^2(m).H(m)	61.3 d	18788	5	0.98
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
M(kg) = 0.6 + 8.0 DBH^2(m).H(m)	1.0 d	5	5	0.94
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
M(kg) = -24.8 + 209.9 D^2(m).H(m)	31.0 d	4805	5	0.91

32 Turner et al. (1989)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g) = 4.5688 + 2.3726 lnDBH(cm)			51	0.985
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(g) = 3.28085 + 1.81147 lnDBH(cm)			51	0.745
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
lnM(g) = 2.94695 + 2.3534 lnDBH(cm)			51	0.835

33 Harrington (1979) a

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -1.011 + 1.275 lnD(cm at 30cm high)		0.0396	20	0.79
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
lnM(kg) = -0.518 + 1.850 lnD(cm at 30cm high))		0.0396	20	0.88
Equation - twigs	**se-g**	**EMS-g**	**n-g**	**r2-g**
lnM(kg) = -2.081 + 1.171 lnD (cm at 30cm high)		0.0396	20	0.72

34 Harrington (1979) b

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.028 + 2.119 ln D(cm at 30 cm)	0.12 d	0.1296	9	0.86
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -2.156 + 1.614 lnD (cm at 30cm high)	0.09 d	0.0729	9	0.66

35 Harrington (1979) c

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -3.89 + 2.623 lnD(cm at 0 cm)	0.09 d	0.1458	18	0.96
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -4.453 + 2.257 lnD (cm at 0cm high)	0.13 d	0.3042	18	0.86

36 Harrington (1979) d

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -1.784 + 3.442 lnH (m)	0.14 d	0.1764	9	0.96
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -2.206 + 3.079 lnH (m)	0.15 d	0.2025	9	0.94

37 Harrington (1979) e

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -1.31 + 3.297 lnH (m)	0.11 d	0.2299	19	0.88
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -1.867 + 2.286 lnH (m)	0.09 d	0.1539	19	0.86

38 Harrington (1979) f

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -3.275 + 3.38 ln H (m)	0.15 d	0.9000	40	0.88
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -3.940 + 2.492 lnH (m)	0.16 d	1.0240	40	0.79

39 Harrington (1979) g

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -1.79 + 3.002 ln H (m)	0.13 d	0.3042	18	0.92
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -2.612 + 2.532 lnH (m)	0.16 d	0.4608	18	0.83

40 Harrington (1979) h

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -1.189 + 3.246 ln H (m)	0.03 d	0.0198	22	0.94
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -2.050 + 2.868 lnH (m)	0.02 d	0.0088	22	0.96

41 Harrington (1979) I

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -0.259 + 3.522 ln H (m)	0.03 d	0.0162	18	0.94
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -3.236 + 2.586 lnH (m)	0.03 d	0.0162	18	0.90

42 Harrington (1979) j

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -0.998 + 3.030 ln H (m)	0.06 d	0.0612	17	0.92
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -1.535 + 2.449 lnH (m)	0.07 d	0.0833		0.85

43 Harrington (1979) k

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
lnM(kg) = -1.736 + 2.404 ln H (m)	0.03 d	0.0171	19	0.94
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -2.589 + 2.116 lnH (m)	0.03 d	0.0171	19	0.94

44 Holland (1969)

Equation - Aboveground	**se-a**	**EMS-a**	**n-a**	**r2-a**
M(kg) = 3.0692 -0.5872 BC(cm) + 0.05053 BC(cm)^2	0.66 d	8.2764	19	0.86

Table 2 *continued*

45 Holland (1969)

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
InM(kg) = 0.3993 + 2.5755 InAge(years)			49	0.76

46 Holland (1969)

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
InM(kg) = 0.7294 + 2.4825 InAge (years)			24	0.90

47 Bennett et al. (1997)

Equation-stem	se-s	EMS-s	n-s	r2-s
InM(kg) = -2.12 + 1.99*InDBH(cm) (stemwood<4m)	0.071 d	0.121	24	0.985
InM(kg) = -21.71 + 1.55*InDBH(cm) + 2.81InH(cm) (>4m)	0.143 d	0.491	24	0.979
InM(kg) = -3.28 + 1.84*InDBH(cm) (stembark<4m)	0.191 d	0.876	24	0.883
InM(kg) = -19.99 + 1.66*InDBH(cm) + 2.28InH(cm) (>4m)	0.231d	1.281	24	0.937

Equation - leaves	se-l	EMS-l	n-l	r2-l
InM(kg) = -4.77 + 2.48*InDBH(cm)	0.292 d	2.0463	24	0.854

Equation - branches	se-b	EMS-b	n-b	r2-b
InM(kg) = -3.21 + 1.81In*DBH(cm) (<2cm diam.)	0.259 d	1.610	24	0.797
InM(kg) = -9.23 + 3.78In*DBH(cm) (>2 cm diam.)	0.609 d	8.901	24	0.711

Equation - twigs	se-g	EMS-g	n-g	r2-g
InM(kg) = -4.96 + 2.11*InDBH(cm)	0.241 d	1.394	24	0.862

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
InM(kg) = -1.92 + 2.30*InDBH(cm)	0.095 d	0.217	24	0.980

48 Birk and Turner (1992) a

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = 3.3626.DBH^0.002546 (cm) (heartwood)			24	0.942
M(kg) = 1.9664.DBH^0.2839 (cm) (sapwood)			24	0.896
M(kg) = 2.08967.DBH^0.07721 (cm) (bark)			24	0.936

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = 2.961 . DBH ^ 0.000899 (cm)			24	0.846

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = 3.507 . DBH ^ 0.000425 (cm)			24	0.872

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = 2.322 . DBH ^ 0.221 (cm)			24	0.966

49 Birk and Turner (1992) b

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
M(kg) = 2.148 . DBH ^ 0.492 (cm)			4	0.987

50 Birk et al. (1995) a

Equation-stem	se-s	EMS-s	n-s	r2-s
InM(kg) = -2.947278 + 2.643428 InDBH(cm)	0.022 d	0.0019	4	0.996

Equation - leaves	se-l	EMS-l	n-l	r2-l
InM(kg) = -3.339179 + 2.218883 InDBH(cm)	0.017 d	0.0012	4	0.996

51 Birk et al. (1995) b

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kh) = -3.409846 + 2.335007 lnDBH(cm) (wood)	0.017 d	0.0012	4	0.989
lnM(kg) = -2.806678 + 1.699023 lnDBH(cm) (bark)	0.037 d	0.0055		0.957

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.138380 + 1.626102 lnDBH (cm)	0.074 d	0.0219	4	0.909

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -3.770551 + 2.448320 lnDBH(cm)(live)	0.018 d	0.0013	4	0.989
lnM(kg)=-13.233146 + 4.448079lnDBH(cm)(dead)	0.174 d	0.1211		0.982

52 Birk et al. (1995) c

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -3.516575 + 2.405807 lnDBH(cm)	0.085 d	0.0289	4	0.985

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.940253 + 2.015874 lnDBH(cm)	0.034 d	0.0046	4	0.985

53 Birk et al. (1995) d

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -4.200247 + 2.642436 lnDBH(cm)	0.070 d	0.0245	5	0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.184487 + 1.681727 lnDBH(cm)	0.161 d	0.1296	5	0.943

54 Birk et al. (1995) e

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.031912 + 1.994510 lnDBH(cm) (wood)	0.383 d	0.8801	6	0.954
lnM(kg) = -2.718281 + 1.816082 lnDBH(cm) (bark)	0.317 d	0.6029		0.954

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.880194 + 0.977292 lnDBH(cm)	0.115 d	0.0793	6	0.863

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -3.034681 + 1.295514 lnDBH(cm)	0.090 d	0.0486	6	0.956

55 Birk et al. (1995) f

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.019548 + 0.776106lnDBH^2(cm).H(m)(wood)	0.029 d	0.0042	5	0.986
lnM(kg) = -3.561428 + 0.791599 lnDBH^2(cm).H(m)(bark)	0.096 d	0.0461		0.956

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -1.045571 + 1.433353 lnDBH(cm)	0.013 d	0.0008	5	0.986

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -1.016450+ 1.620337lnDBH(cm)(live)	0.009 d	0.0004	5	0.993
lnM(kg) = -3.685964+ 0.851365lnDBH(cm)(dead)	0.076 d	0.0289		0.853

56 Birk et al. (1995) g

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = -2.767419 + 0.810759 lnDBH^2(cm).H(m) (sapwood)	0.023 d	0.0032	6	0.988
lnM(kg) = -8.483099 + 1.455459 lnDBH(cm)(heartwood)	0.085 d	0.0434		0.964
lnM(kg) = -4.30973 + 0.918145 lnDBH^2(cm).H(m)(bark)"	0.073 d	0.032		0.972

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.248924 + 1.62669 lnDBH (cm)	0.141 d	0.1193	6	0.903

Table 2 ***continued***

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -2.52773 + 1.964188 lnDBH(cm)	0.155 d	0.1442	6	0.925

57 Birk et al. (1995) h

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = -2.310987 + 0.729691 lnDBH^2(cm).H(m) (sapwood)	0.102 d	0.0832	8	0.944
lnM(kg) = -14.221254 + 6.011975 lnDBH(cm)(heartwood)	0.246 d	0.4841		0.959
lnM(kg) = -5.350151 + 0.965483 lnDBH^2(cm).H(m)(bark)"	1.270 d	12.9032		0.702

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.324370 + 2.099982 lnDBH(cm)	0.115 d	0.1058	8	0.948

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -2.908904 + 2.309914 lnDBH(cm)	0.083 d	0.0551	8	0.969

58 Birk et al. (1995) l

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -1.990131 + 1.988949 lnDBH(cm) (sapwood)	0.080 d	0.1088	17	0.972
lnM(kg) = -3.451441 + 2.223520 lnDBH(cm) (bark)	0.209 d	0.7426		0.949

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.338728 + 1.523220 lnDBH(cm)	0.076 d	0.0982	17	0.96

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -2.462106 + 1.867544 lnDBH(cm)	0.134 d	0.3053	17	0.953

59 Birk et al. (1995) j

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.438625 + 2.189404 lnDBH(cm) (sapwood)	0.037 d	0.0068	5	0.974
lnM(kg) = -6.710382 + 3.348059 lnDBH(cm) (heartwood)	0.582 d	1.6936		0.848
lnM(kg) = -2.486982 + 2.041429 lnDBH(cm) (bark)	0.028 d	0.0039		0.977

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.338728 + 1.942893 lnDBH(cm)	0.179 d	0.1602	5	0.913

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -2.678597 + 2.028358 lnDBH(cm)	0.153 d	0.117	5	0.930

60 Birk et al. (1995) k

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = -2.19186 + 0.773807 lnDBH^2(cm).H(m) (sapwood)	0.016 d	0.0013	5	0.981
lnM(kg) = -19.159326 + 7.668149 lnDBH(cm)(heartwood)	0.175 d	0.1531		0.959
lnM(kg) = -3.603543 + 0.88751 lnDBH^2(cm).H(m)(bark)"	0.007 d	0.0002		0.994

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.877663 + 2.241257 lnDBH(cm)	0.023 d	0.0026	5	0.975

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -3.610644 + 2.484497 lnDBH(cm)	0.025 d	0.0031	5	0.979

61 Birk et al. (1995) l

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = -2.641812 + 0.816066 lnDBH^2(cm).H(m) (sapwood)	0.126 d	0.1111	7	0.962
lnM(kg) = -3.638201 + 0.878658 lnDBH^2(cm).H(m)(bark)	0.316 d	0.699		0.921

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -2.926638 + 1.76178 lnDBH(cm)	0.094 d	0.0619	7	0.96

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -3.222188 + 2.3158 lnDBH(cm)	0.217 d	0.3296	7	0.947

62 Birk et al. (1995) m

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = -2.165181 + 1.884547 lnDBH(cm)(sapwood) lnM(kg) = -3.394298 + 1.966874 lnDBH(cm) (bark)"	0.016 d 0.035 d	0.0015 0.0074	6	0.991 0.983

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -1.927395 + 1.387949 lnDBH(cm)	0.019 d	0.0022	6	0.981

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -2.59406 + 1.700454 lnDBH(cm)	0.051d	0.0156	6	0.967

63 Birk et al. (1995) n

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.074726 + 2.736423 lnDBH (cm)	0.002 d	0.00001	3	0.999

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -3.211084 + 2.356353 lnDBH (cm)	0.079 d	0.0187	3	0.983

64 Bradstock (1981) a

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.47 + 2.47 logDBH(cm) (sapwood) logM(kg) = -2.12 + 2.66 logDBH (cm) (bark)	0.045 a 0.118 a	0.002 0.0139	5 5	0.996 0.977

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 1.60 + 2.17 logDBH(cm)	0.11 a	0.0121	5	0.972

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 1.93 + 2.02 logDBH(cm)	0.032 a	0.001	5	0.997

65 Bradstock (1981) b

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.86 + 2.98 logDBH(cm) (sapwood) logM(kg) = -0.69 + 1.36 logDBH (cm) (bark)	0.127 a 0.063 a	0.0161 0.0040	4 4	0.993 0.993

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 0.97 + 2.42 logDBH(cm)	0.045 a	0.002	4	0.999

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 0.95 + 2.77 logDBH(cm)	0.045 a	0.002	4	0.999

66 Bradstock (1981) c

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.53 + 2.76 logDBH(cm) (sapwood) logM(kg) = -2.22 + 2.80 logDBH (cm) (bark)	0.100 a 0.045 a	0.01 0.002	4 4	0.989 0.998

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 1.76 + 1.66 logDBH(cm)	0.195 a	0.038	4	0.888

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 2.54 + 1.35 logDBH(cm)	0.184 a	0.0339	4	0.858

Table 2 *continued*

67 Bradstock (1981) d

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.79 + 2.75 logDBH (cm) (heartwood)	0.017 a	0.0003	4	0.999
logM(kg) = -1.81 + 2.91 logDBH(cm) (sapwood)	0.084 a	0.0071	4	0.996
logM(kg) = -2.57 + 3.10 logDBH (cm) (bark)	0.114 a	0.013	4	0.994

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 1.39 + 1.99 logDBH(cm)	0.084 a	0.0071	4	0.993

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 0.97 + 2.59 logDBH(cm)	0.095 a	0.009	4	0.994

68 Bradstock (1981) e

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -4.58 + 5.00 logDBH (cm) (heartwood)	0.378 a	0.1429	4	0.978
logM(kg) = -1.62 + 2.81 logDBH(cm) (sapwood)	0.071 a	0.005	4	0.997
logM(kg) = -2.56 + 3.21 logDBH (cm) (bark)	0.084 a	0.0071	4	0.997

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = -0.04 + 2.97 logDBH(cm)	0.221 a	0.0488	4	0.979

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 1.93 + 1.84 logDBH(cm)	0.224 a	0.0502	4	0.946

69 Bradstock (1981) f

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -2.14 + 3.20 logDBH (cm) (heartwood)	0.123 a	0.0151	4	0.995
logM(kg) = -0.99 + 2.16 logDBH(cm) (sapwood)	0.071 a	0.0050	4	0.996
logM(kg) = -2.26 + 2.81 logDBH (cm) (bark)	0.055 a	0.003	4	0.999

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 0.23 + 2.67 logDBH(cm)	0.100 a	0.01	4	0.995

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 0.90 + 2.53 logDBH(cm)	0.055 a	0.003	4	0.998

70 Bradstock (1981) g

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.98 + 2.95 logDBH (cm) (heartwood)	0.078 a	0.0061	6	0.996
logM(kg) = -1.29 + 2.47 logDBH(cm) (sapwood)	0.100 a	0.01	6	0.990
logM(kg) = -1.73 + 2.48 logDBH (cm) (bark)	0.118 a	0.0139	6	0.988

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = -0.95 + 3.59 logDBH(cm)	0.152 a	0.0231	6	0.973

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = -0.53 + 3.64 logDBH(cm)	0.063 a	0.004	6	0.996

71 Bradstock (1981) h

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.59 + 3.00 logDBH (cm) (heartwood)	0.078 a	0.0061	5	0.997
logM(kg) = -1.45 + 2.62 logDBH(cm) (sapwood)	0.123 a	0.0151	5	0.990
logM(kg) = -1.97 + 2.65 logDBH (cm) (bark)	0.084 a	0.0071	5	0.995

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(g) = 1.20 + 1.99 logDBH(cm)	0.110 a	0.0121	5	0.968

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(g) = 0.105 + 2.58 logDBH(cm)	0.105 a	0.011	5	0.981

72 Bradstock (1981) I

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(kg) = -1.77 + 3.12 logDBH (cm) (all sites)	0.017 a	0.0003	36	0.965

73 Cromer et al. (1975) a

Equation-stem	se-s	EMS-s	n-s	r2-s
M(g) = 45.08 + 118.15 BA(cm^2) (wood)	86 d	7396	16	0.98
M(g) = 20.82 + 27.13 BA (cm^2) (bark)	25 d	625	16	0.96

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(g) = 154.69 + 94.0 BA(cm^2)	155	24025	16	0.89

Equation - branches	se-b	EMS-b	n-b	r2-b
M(g) = 38.06 + 61.52 BA(cm^2)	149	22201	16	0.79

74 Cromer et al. (1975) b

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = 0.0952 + 0.1452 BA(cm^2) (wood)	0.617	0.3807	12	0.923
M(kg) = 0.01784 + 0.02862 BA(cm^2) (bark)	0.059	0.0035	12	0.981

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = 0.1861 + 0.03018 BA(cm^2)	0.446	0.1989	12	0.496

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -0.01556 + 0.03589 BA(cm^2)	0.07	0.0049	12	0.983

75 Cromer et al. (1975) c

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = -0.5954 + 0.17432 BA(cm^2) (wood)	1.203	1.4472	12	0.922
M(kg) = -0.03471 + 0.03522 BA(cm^2) (bark)	0.164	0.0269	12	0.963

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = -0.2106 + 0.05293 BA(cm^2)	0.376	0.1414	12	0.918

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -0.08415 + 0.03877 BA(cm^2)	0.36	0.1296	12	0.867

76 Cromer et al. (1975) d

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = -0.3953 + 0.18697 BA(cm^2) (wood)	0.762	0.5806	12	0.984
M(kg) = 0.0346 + 0.03702 BA(cm^2) (bark)	0.290	0.0841	12	0.943

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = 0.1536 + 0.04387 BA(cm^2)	0.689	0.4747	12	0.804

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = 0.0456 + 0.03261 BA(cm^2)	0.342	0.117	12	0.902

77 Cromer et al. (1975) e

Equation-stem	se-s	EMS-s	n-s	r2-s
"M(kg) = -0.5902 + 0.19255 BA(cm^2) (wood)	0.544	0.2959	12	0.995
M(kg) = 0.0656 + 0.03432 BA(cm^2) (bark)"	0.153	0.0234	12	0.987

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = 0.0656 + 0.07128 BA(cm^2)	0.75	0.5625	12	0.929

Table 2 ***continued***

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -0.4397 + 0.05266 BA(cm^2)	0.471	0.2218	12	0.948

78 Cromer and Williams (1982) a

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 4.418 + 0.843 lnBA (bark) lnM = 4.772 + 1.088 lnBA (wood)"			12 12	0.97 0.97

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 3.608 + 1.081 lnBA			12	0.90

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 3.142 + 1.094 lnBA			12	0.91

79 Cromer and Williams (1982) b

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 4.077 + 0.973 lnBA (bark) lnM = 3.973 + 1.316 ln BA (wood)"			12 12	0.97 0.97

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 1.512 + 1.587 lnBA			12	0.90

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 2.063 + 1.344 lnBA			12	0.91

80 Cromer and Williams (1982) c

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.642 + 1.044 lnBA (bark) lnM = 3.528 + 1.401 lnBA (wood)"			12 12	0.97 0.97

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 1.271 + 1.607 lnBA			12	0.90

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 0.746 + 1.624 lnBA			12	0.91

81 Cromer and Williams (1982) d

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.315 + 1.156 lnBA (bark) lnM = 4.079 + 1.283 lnBA (wood)"			12 12	0.97 0.97

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 1.881 + 1.441 lnBA			12	0.90

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 1.725 + 1.418 lnBA			12	0.91

82 Cromer and Williams (1982) e

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.357 + 1.127 lnBA (bark) lnM = 4.433 + 1.244 lnBA (wood)"			12 12	0.99 0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 2.582 + 1.288 lnBA			12	0.91

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 2.322 + 1.265 lnBA			12	0.97

83 Cromer and Williams (1982) f

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.407 + 1.127 lnBA (bark)			12	0.99
lnM = 4.523 + 1.244 lnBA (wood)"			12	0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 2.066 + 1.288 lnBA			12	0.91

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 1.995 + 1.265 lnBA			12	0.97

84 Cromer and Williams (1982) g

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.383 + 1.127 lnBA (bark)			12	0.99
lnM = 4.598 + 1.244 lnBA (wood)"			12	0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 2.195 + 1.288 lnBA			12	0.91

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 1.963 + 1.265 lnBA			12	0.97

85 Cromer and Williams (1982) h

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 3.197 + 1.127 lnBA (bark)			12	0.99
lnM = 4.410 + 1.244 lnBA (wood)"			12	0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 2.333 + 1.288 lnBA			12	0.91

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 2.292 + 1.265 lnBA			12	0.97

86 Cromer et al. (1993) a

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 1.89 + 0.702 lnSA0.3 + 0.946 lnH (bark)			20	0.985
lnM = 3.05 + 0.557 lnSA0.3 + 1.53 lnH (wood)"			20	0.992

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 4.18 + 0.873 lnSA0.3 + 0.517 lnH			20	0.986

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 3.35 + 0.885 lnSA0.3 + 1.108 lnH			20	0.988

87 Cromer et al. (1993) b

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM = 2.82 + 0.806 lnBA + 0.619 lnH (bark)			20	0.980
lnM = 3.59 + 0.925 lnBA + 0.75 lnH (wood)"			20	0.993

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM = 4.19 + 0.666 lnSACB + 0.883 lnCl			20	0.953

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM = 3.33 + 0.717 lnSACB + 1.428 lnCl			20	0.923

Table 2 ***continued***

88 Cromer et al. (1993) c

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
"InM = 2.77 + 0.806 InBA + 0.619 InH (bark)			20	0.980
InM = 3.65 + 0.925 InBA + 0.75 InH (wood)"			20	0.993

Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
InM = 4.19 + 0.666 InSACB + 0.883 InCl			20	0.953

Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
InM = 3.33 + 0.717 InSACB + 1.428 InCl			20	0.923

89 Madgwick et al. (1991) a

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
InM(kg) = -3.82 + 0.96ln(DBH^2.H) (cm^2.m)	0.09 d	0.0567	7	

Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
InM(kg) = -3.18 + 2.10 ln(DCB) (cm)	0.38 d	1.0108	7	

Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
InM(kg) = -3.00 + 2.14 ln(DCB) (cm)	0.42		7	

90 Madgwick et al. (1991) b

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
InM(kg) = -3.94 + 0.96ln(DBH^2.H) (cm^2.m)	0.09 d	0.4212	52	

Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
InM(kg) = -3.66 + 2.10 ln(DCB) (cm)	0.38 d	7.5088	52	

Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
InM(kg) = -2.74 + 2.14 ln(DCB) (cm)	0.42		52	

91 Madgwick et al. (1991) c

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
InM(kg) = -3.88 + 0.96ln(DBH^2.H) (cm^2.m)	0.09 d	0.4131	51	

Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
InM(kg) = -3.57 + 2.10 ln(DCB) (cm)	0.38 d	7.3644	51	

Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
InM(kg) = -2.61 + 2.14 ln(DCB) (cm)	0.42		51	

92 Madgwick et al. (1991) d

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
InM(kg) = -3.78 + 0.96ln(DBH^2.H) (cm^2.m)	0.09 d	0.0729	9	

Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
InM(kg) = -3.28 + 2.10 ln(DCB) (cm)	0.38 d	1.2996	9	

Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
InM(kg) = -2.19 + 2.14 ln(DCB) (cm)	0.42		9	

93 O'Brien (1998)

Equation-stem	**se-s**	**EMS-s**	**n-s**	**r2-s**
InM(g) = 3.197 + 2.028*InD(cm) + 0.202*(InD)^2(cm)(wood)				0.992
InM(g) = 2.136 + 1.942*InD(cm) (bark)				0.987

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 4.039 + 1.844*lnD(cm) + 0.123*(lnD)^2(cm)				0.966

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 3.271 + 2.17*lnD(cm)				0.951

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 4.741 + 1.962*lnD(cm) + 0.132*(lnD)^2(cm)				0.976

94 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g) = 2.877 + 2.041*lnD(cm) + 0.226*(lnD)^2(cm)(wood) lnM(g) = 2.05 + 1.864*lnD(cm) + 0.122*(lnD)^2(cm) (bark)				0.992 0.993

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 3.641 + 1.855*lnD(cm) + 0.144*(lnD)^2(cm)				0.978

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 3.048 + 2.195*lnD(cm) + 0.093*(lnD)^2(cm)				0.975

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 4.458 + 1.976*lnD(cm) + 0.156*(lnD)^2(cm)				0.987

95 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s	
"lnM(g) = 4.63 + 1.952*lnDBH(cm) (wood) lnM(g) = 4.00 + 1.02*lnDBH(cm) + 0.224*(lnDBH)^2(cm) (bark)"					0.970 0.981

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 5.06 + 1.65*lnDBH(cm)				0.923

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 4.94 + 1.77*lnDBH(cm)				0.93

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 6.1 + 1.771*lnDBH(cm)				0.957

96 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(g) = 4.987 + 1.37*lnDBH(cm) + 0.225*(lnDBH)^2(cm) (wood) lnM(g) = 4.072 + 0.94*lnDBH(cm) + 0.261*(lnDBH)^2(cm) (bark)"				0.981 0.985

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 5.19 + 0.651*(lnDBH)^2(cm)				0.909

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 4.91 + 1.37*lnDBH(cm) + 0.225*(lnDBH)^2(cm)				0.981

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 6.24 + 1.12*lnDBH(cm) + 0.268*(lnDBH)^2(cm)				0.967

97 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g) = 6.39 + 0.57*(lnDBH)^2(cm) (wood) lnM(g) = 3.07 + 2.042*lnDBH(cm) (bark)				0.972 0.976

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 1.52 + 2.93*lnDBH(cm)				0.969

Table 2 ***continued***

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 2.28 + 2.82*lnDBH(cm)				0.901
Equation - Aboveground	**se-a**	**EMS-a**	**n-a**	**r2-a**
lnM(g) = 4.68 + 2.404*lnDBH(cm)				0.988

98 West et al. (1991) e

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 13.8256 - 1.4972 lnH(m) + 2.9499 lnDBH(cm)			14	

99 West et al. (1991) f

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 9.7150 - 0.1276 lnH(m) + 2.3916 lnDBH(cm)			13	

100 West et al. (1991) g

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 10.0194 - 0.2285 lnH(m) + 2.410 lnDBH(cm)			7	

101 West et al. (1991) h

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 13.787 - 1.3502 lnH(m) + 3.0837 lnDBH(cm)			7	

102 West et al. (1991) I

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 11.450 - 0.4757 lnH(m) + 2.7409 lnDBH(cm)			83	

103 West et al. (1991) j

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 31.0791 - 5.0252 lnH(m) + 6.7626 lnDBH(cm)			54	

104 West et al. (1991) k

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg fresh) = 11.0292 - 0.3099 lnH(m) + 2.7106 lnDBH(cm)			220	

105 West et al. (1991) l

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg dry) = 10.1267 - 0.2177 lnH(m) + 2.7535 lnDBH(cm)			220	

106 Baker et al.(1984)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = -2.201 + 2.320 lnDBH(cm) lnM(kg) = -3.415 + 0.9146 ln(DBH^2.H) (cm^2.m)"	0.0352 e 0.0120 e	0.0352 0.0120	62 62	0.98 0.98
Equation - leaves	**se-l**	**EMS-l**	**n-l**	**r2-l**
lnM(kg) = -3.365 + 1.893 lnDBH(cm)	0.1501 e	0.1501	46	0.780
Equation - branches	**se-b**	**EMS-b**	**n-b**	**r2-b**
lnM(kg)= -4.727 + 2.459 lnDBH(cm)	0.1612 e	0.1612	46	

107 Birk (1992)

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = 0.07596 . DBH^2.3694 (cm) (sapwood)	0.133 e	0.133	29	0.979
M(kg) = 0.005931 . DBH^2.3149 (cm) (heartwood)	0.485 e	0.485	29	0.768
M(kg) = 0.02045 . DBH^2.3911 (cm) (bark)	0.122 e	0.122	29	0.982

Equation - leaves	se-l	EMS-l	n-l	r2-l
"M(kg) = 0.02654.DBH^3.630 (cm)(lower crown)	0.516 e	0.516	29	0.889
M(kg) = 1.5172.DBH^2.4644 (cm)(upper crown)"	0.338 e	0.338	29	0.886

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = 6.5456. DBH^2.345 (cm) (dead)	0.621 e	0.621	29	0.698
M(kg) = 0.0306. DBH^3.8913 (cm) (lower live)	0.463 e	0.463	29	0.912
M(kg) = 1.5542. DBH^3.1899 (cm) (upper live)	0.479 e	0.479	29	0.866

108 Cannell (1984)

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(t/ha) = 11.0 + 0.17 x BA.H (m^2/ha . m)	0.005 f		13	

109 Cromer et al. (1985)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(g) = 3.279 + 1.056lnBA(cm^2) (bark)			20	0.924
lnM(g) = 4.768 + 1.123 lnBA(cm^2) (wood)"			20	0.979

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 2.399 + 1.244 lnBA(cm^2)			20	0.916

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 1.653 + 1.433 lnBA(cm^2)			20	0.903

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 5.142 + 1.127 lnBA(cm^2)			20	0.978

110 Dargavel (1970)

Equation-stem	se-s	EMS-s	n-s	r2-s
logM(lb) = 0.6521 + 0.4168 logH(ft) + 0.7494 log(BA.H) (sq.ft.x ft.)			25	0.998

Equation - leaves	se-l	EMS-l	n-l	r2-l
logM(lb) = 1.7848 + 0.8499 logBA(sq.ft.)			25	0.876

Equation - branches	se-b	EMS-b	n-b	r2-b
logM(lb) = 5.5555 + 1.9542 logBA(sq.ft.) - 1.7649 logH(ft.)			25	0.961

Equation - roots	se-r	EMS-r	n-r	r2-r
logM(lb) = 2.1866 + 1.4014 logBA(sq.ft.)			25	0.978

Equation - total	se-t	EMS-t	n-t	r2-t
logM(lb) = 2.2046 + 0.5297 logBA(sq.ft.) + 0.4642 log(BA.H) (sq.ft.x ft.)			25	0.998

111 Feller (1984)

Equation-stem	se-s	EMS-s	n-s	r2-s
M(kg) = 5 + 171.3 DBH^2(m).H(m) (wood)	91.4 d	41769	5	0.96
M(kg) = 0.8 + 27.4 DBH^2(m).H(m) (bark)	14.6 d	1066	5	0.96

Equation - leaves	se-l	EMS-l	n-l	r2-l
M(kg) = -1.2 + 3.2 DBH^2(m).H(m)	0.6 d	1.44	4	0.99

Equation - branches	se-b	EMS-b	n-b	r2-b
M(kg) = -2.4 + 9.3 DBH^2(m).H(m)	2.6 d	27	4	0.98

Table 2 *continued*

112 Forrest (1969)

Equation-stem	se-s	EMS-s	n-s	r2-s	
"lnM(kg) = 8.459 + 0.645*ln(BA.H)(m^3) (wood)	0.043 f		9		
lnM(kg) = 6.415 + 0.574*ln(BA.H)(m^3) (bark) OR	0.058 f		9		
lnM(kg) = -1.923 + 1.589*lnDBH(cm) (wood)	0.0083 e	0.0107			
lnM(kg) = -3.541 + 1.384*lnDBH(cm) (bark)"	0.0348 e	0.0275		0.977	0.925

Equation - leaves	se-l	EMS-l	n-l	r2-l
"lnM(kg) = 8.632 + 0.798*ln(BA.H)(m^3) (branch)	0.072 f		9	
lnM(kg) = 5.367 + 0.238*ln(BA.H)(m^3) (bole) OR	0.089 f		9	
lnM(kg) = -2.014 + 1.652*lnDBH(cm)"	0.0288 e	0.0288		0.944

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = 8.498 + 1.015*ln(BA.H)(m^3) OR	0.111 f		9	
lnM(kg) = -3.881 + 2.506*lnDBH (cm)	0.0935 e	0.0404	0.922	

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = 9.561 + 1.706*ln(BA.H)(m^3) OR	0.054 f		9	
lnM(kg) = -1.132 + 1.727*lnDBH(cm)	0.196 e	0.196	0.964	

113 Forrest (1969)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = 8.492 +0.937*ln(BA.H)(m^3) (wood)	0.042 f		9	
lnM(kg) = 6.569 + 0.84*ln(BA.H)(m^3) (bark) OR	0.05 f		9	
lnM(kg) =-3.026 + 2.311*lnDBH(cm) (wood)	0.0045 e	0.0083		0.975
lnM(kg) = -4.519 + 2.092*lnDBH(cm) (bark)	0.0472 e	0.0348		0.882

Equation - leaves	se-l	EMS-l	n-l	r2-l
"lnM(kg) = 7.715 + 1.049*ln(BA.H)(m^3) (branch)	0.095 f		9	
lnM(kg) = 5.572 + 0.156*ln(BA.H)(m^3) (bole) OR	0.156 f		9	
lnM(kg) = -3.920 + 2.428*lnDBH(cm)"	0.0264 e	0.0264		0.939

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = 7.476 +1.437*ln(BA.H)(m^3) OR	0.19 f		9	
lnM(kg) = -6.804 + 3.669*lnDBH(cm)	0.0410 e	0.0410		0.952

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = 9.203 + 1.065*ln(BA.H)(m^3) OR	0.068 f		9	
lnM(kg) = -3.033 + 2.663*lnDBH(cm)	0.0043 e	0.0043		0.99

114 Forrest (1969)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = 8.714 +0.845*ln(BA.H)(m^3) (wood)	0.07 f		9	
lnM(kg) = 6.848 + 0.702*ln(BA.H)(m^3) (bark) OR	0.129 f		9	
lnM(kg) = -1.921 + 2.008*lnDBH(cm) (wood)	0.0190 e	0.0190		0.904
lnM(kg) = -3.153 + 1.667*lnDBH(cm) (bark)"	0.0381 e	0.0381		0.760

Equation - leaves	se-l	EMS-l	n-l	r2-l
"lnM(kg) = 7.601 + 0.533*ln(BA.H)(m^3) (branch)	0.129 f		9	
lnM(kg) = 5.872 - 0.222*ln(BA.H)(m^3) (bole) OR	0.323 f		9	
lnM(kg) = -1.315 + 1.155*lnDBH(cm)"	0.038 e	0.038		0.594

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = 7.207 +0.808*ln(BA.H)(m^3) OR	0.12 f		9	
lnM(kg) = -3.313 + 1.939*lnDBH(cm)	0.0336 e	0.0336		0.831

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = 9.265 + 0.781*ln(BA.H)(m^3) OR	0.07 f		9	
lnM(kg) = -1.090 + 1.858*lnDBH(cm)	0.0175 e	0.0175		0.898

115 Forrest (1969)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(kg) = 8.471 + 0.969*ln(BA.H)(m^3) (wood)	0.035 f		9	
lnM(kg) = 7.065 + 0.653*ln(BA.H)(m^3) (bark) OR	0.141 f		9	
lnM(kg) = -2.373 + 2.265*lnDBH(cm) (wood)	0.0107 e	0.0045		0.985
lnM(kg) = -2.491 + 1.524*lnDBH(cm) (bark)"	0.0275 e	0.0472		0.736

Equation - leaves	se-l	EMS-l	n-l	r2-l
"lnM(kg) = 4.783 + 1.543*ln(BA.H)(m^3) (branch)	0.087 f		9	
lnM(kg) = 4.736 + 0.263*ln(BA.H)(m^3) (bole) OR	0.385 f		9	
lnM(kg) = -7.476 + 3.298*lnDBH(cm)"	0.0175 e	0.0175		0.973

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = 5.824 +1.419*ln(BA.H)(m^3) OR	0.124 f		9	
lnM(kg) = -6.845 + 3.315*lnDBH(cm)	0.0404 e	0.0935		0.941

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(kg) = 8.701 + 1.029*ln(BA.H)(m^3) OR	0.038 f		9	
lnM(kg) = -2.138 + 2.318*lnDBH(cm)	0.007 e	0.007		0.978

116 Jackson and Chittenden (1981)

Equation - roots	se-r	EMS-r	n-r	r2-r
M(kg) = 5.87 * DBH(cm)^2.938 * 0.001				0.883

117 Jackson and Chittenden (1981)

Equation - roots	se-r	EMS-r	n-r	r2-r
logM(kg) = -5.009 + 2.7296 logDBH(cm)	0.3609 d	32.172	247	0.97

118 Madgwick(1983)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = 1.028*ln(DBH(cm) + 1.9)^2 * H(m)) -4.892	0.033 e	0.033	557	

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -3.952 + 2.193*lnDC(cm)	0.103 e	0.103	328	

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -5.336 + 2.835 lnDC(cm)	0.096 e	0.096	298	

119 Madgwick (1994) a

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(kg) = 0.849 ln(DBH^2 . H)(cm^2 . m) - 3.097 OR	0.102 e	0.102	801	
lnM(kg) = -3.138 + 1.479 ln DBH(cm) + ln H(m)				

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(kg) = -4.123 + 2.53 lnDCB(cm)	0.132 e	0.132	583	

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(kg) = -4.189 + 2.448 lnDCB(cm)	0.245 e	0.245	332	

120 Madgwick (1994) b

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(t/ha) = -3.56 + 1.10 lnH(m) + 0.62 ln(BA+1)(m^2/ha)	0.150 d	0.0225	139	0.99
+ 0.36 lnAge(yrs) + 0.28 lnN(stocking/ha) OR				0.98
lnM(t/ha) = -1.213 + 0.91 ln(H.(BA+1)) (m.m^2/ha)				

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(t/ha) = -1.337 + 0.742 ln(BA+1)(m^2/ha) + 1.487 lnAge - 0.404(lnAge)^2	0.333 d	0.111	164	0.84

Table 2 ***continued***

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(t/ha) = -1.15 + 0.43 H - 0.0009 N + 1.20 Mf	2.4	5.76		0.87

121 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(g) = 2.822 + 2.086*lnD(cm) (wood)				0.95
lnM(g) = 2.215 + 1.64*lnD(cm) (bark)"				0.948

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnMkg) = 3.673 + 1.6*lnD(cm)				0.906

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 2.03 + 1.84*lnD(cm)				0.805
lnM(g) = 0.52 + 1.57*lnD(cm) + 0.52*(lnD)^2(cm) (tip)				0.844

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 4.345 + 1.728*lnD(cm)				0.926

122 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g) = 2.681 + 2.072*lnD(cm) + 0.159*(lnD)^2(cm)(wood)				0.988
lnM(g) = 1.904 + 1.64*lnD(cm) + 0.092*(lnD)^2(cm) (bark)				0.983

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 3.706 + 1.573*lnD(cm) + 0.209*(lnD)^2(cm)				0.983

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 2.092 + 1.784*lnD(cm) + 0.396*(lnDBH)^2(cm)				0.97
lnM(g) = 0.626 + 1.56*lnDBH(cm) + 0.32*(lnD)^2(cm) (tip)				0.947

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 4.247 + 1.704*lnDBH(cm) + 0.244*(lnDBH)^2(cm)				0.987

123 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
"lnM(g) = 2.36 + 2.55*lnD(cm) (wood)				0.962
lnM(g) = 1.82 + 1.93*lnD(cm) (bark)"				0.928

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 3.11 + 2.191*lnD(cm)				0.96

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 3.35 + 0.955*(lnD)^2(cm)				0.939
lnM(g) = 1.15 + 0.787*(lnD)^2(cm) (tip)				0.865

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 3.67 + 2.436*lnD(cm)				0.973

124 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g)=5.21+ 0.85*lnDBH(cm) + 0.29*(lnDBH)^2(cm)(wood)				0.952
lnM(g)=3.843+ 0.51*lnDBH(cm) + 0.32*(lnDBH)^2(cm)(bark)				0.958

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 6.11 + 1.05*lnDBH(cm)				0.89

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 4.78 + 0.784*(lnDBH)^2(cm)				0.885
lnM(g) = 1.54 + 1.08*lnDBH(cm) (tip)				0.764

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 6.60 + 0.72*lnDBH(cm) + 0.3*(lnDBH)^2(cm)				0.928

125 O'Brien (1998)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g)=5.33+ 0.85*lnDBH(cm) + 0.29*(lnDBH)^2(cm)(wood)				0.952
lnM(g)=4.013+ 0.51*lnDBH(cm) + 0.32*(lnDBH)^2(cm)(bark)				0.958

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = 6.14 + 1.05*lnDBH(cm)				0.89

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = 4.5 + 0.784*(lnDBH)^2(cm)				0.885
lnM(g) = 2.5 + 1.08*lnDBH(cm) (tip)				0.764

Equation - Aboveground	se-a	EMS-a	n-a	r2-a
lnM(g) = 6.63 + 0.72*lnDBH(cm) + 0.3*(lnDBH)^2(cm)				0.928

126 Snowdon (1985)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM = 0.003 + 1.451 lnD + 0.659 lnH			435	

Equation - crown	se-c	EMS-c	n-c	r2-c
lnM = -1.543 + 2.688 lnD + 0.141 lnH	0.111 e.	0.111	435	

127 Snowdon and Benson (1992)

Equation-stem	se-s	EMS-s	n-s	r2-s
lnM(g) = 3.01 + 1.79 lnDBH(cm) + 1.01 lnH(m) (wood)	0.006 e	0.006	67	0.99
lnM(g) = 1.88 + 1.70 lnDBH(cm) + 0.81 lnH(m) (bark)	0.023 e	0.023	67	0.94

Equation - leaves	se-l	EMS-l	n-l	r2-l
lnM(g) = (1.56 to 1.94) + 2.55 lnDBH(cm)	0.041 e	0.041	67	0.90

Equation - branches	se-b	EMS-b	n-b	r2-b
lnM(g) = (0.21 to 0.86) + 3.10 lnDBH(cm)	0.057 e	0.067	67	0.91

128 Watson and O'Loughlin (1990)

Equation - roots	se-r	EMS-r	n-r	r2-r	
lnM = -2.68 + 2.24 lnDBH	0.14 f 0.46 g			13	0.99

129 Williams (1970)

Equation-stem	se-s	EMS-s	n-s	r2-s	
"logM(kg) = -0.595 + 1.995 logDBH(cm) (merchantable)	0.021 d	0.029 d	0.0053	12	0.97
logM(kg) = 2.516 - 1.255 logDBH(cm) (non-merchantable)"	0.198 f	0.216 f	0.0101	12	0.92

Equation - crown	se-c	EMS-c	n-c	r2-c	
logM(kg) = -0.67 + 2.164 logDBH(cm)	0.015 d 0.101 f			12	0.99

Equation - leaves	se-l	EMS-l	n-l	r2-l	
logM(kg) = -2.362 + 2.554 logDBH(cm)	0.075 d 0.561 f		0.0675	12	0.89

Equation - branches	se-b	EMS-b	n-b	r2-b	
logM(kg) = -2.285 + 2.827 logDBH(cm)	0.04 d 0.223 f		0.0192	12	0.97

In these tables, equations for each type of tree are allocated a single record. Hence, one record contains all site information and equations for each of the biomass components for a type of tree. A type of tree is defined as having unique equations, this may be due to differences in species, age or treatment within a site from one study.

Distribution of the records is summarised in Table 3 by general vegetation types and IBRA regions. This provides some indication of representation in various regions, however, the number of records is not indicative of coverage within a region. Many of the records are related, for example several species, ages or treatments at the one site. A few records have been included in Tables 2 and 3 for sites outside Australia because they provide generalised equations for a vegetation type that is useful for comparison, for example tropical forests by Anderson and Ingram (1994), pine and eucalypt plantations by Madgwick (1994) and Cannell (1984). These records are not included in the summaries in Table 4. The location of sites across the continent and in relation to IBRA regions is shown in Figure 1.

Table 3: Distribution of records of allometric equations (site-specific) by vegetation type and IBRA region.

vegetation type	number of records	IBRA region		number of records
native sclerophyll forest	26	South Eastern Queensland	375	5
rainforest	3	South Eastern Queensland	391	4
native plantation	53	NSW North Coast	420	13
radiata pine plantation	22	Cobar Peneplain	429	12
woodland - trees	6	NSW South Western Slopes	443	11
woodland - shrubs	8	Sydney Basin	444	17
		South Eastern Highlands	448	8
		Murray Darling Depression	478	1
		South Eastern Highlands	504	1
		Victorian Midlands	510	1
		South Eastern Highlands	512	8
		South East Corner	521	3
		South East Coastal Plain	529	1
		South Eastern Highlands	538	16
		Ben Lomand	717	2
		Dentrecasteaux	727	9

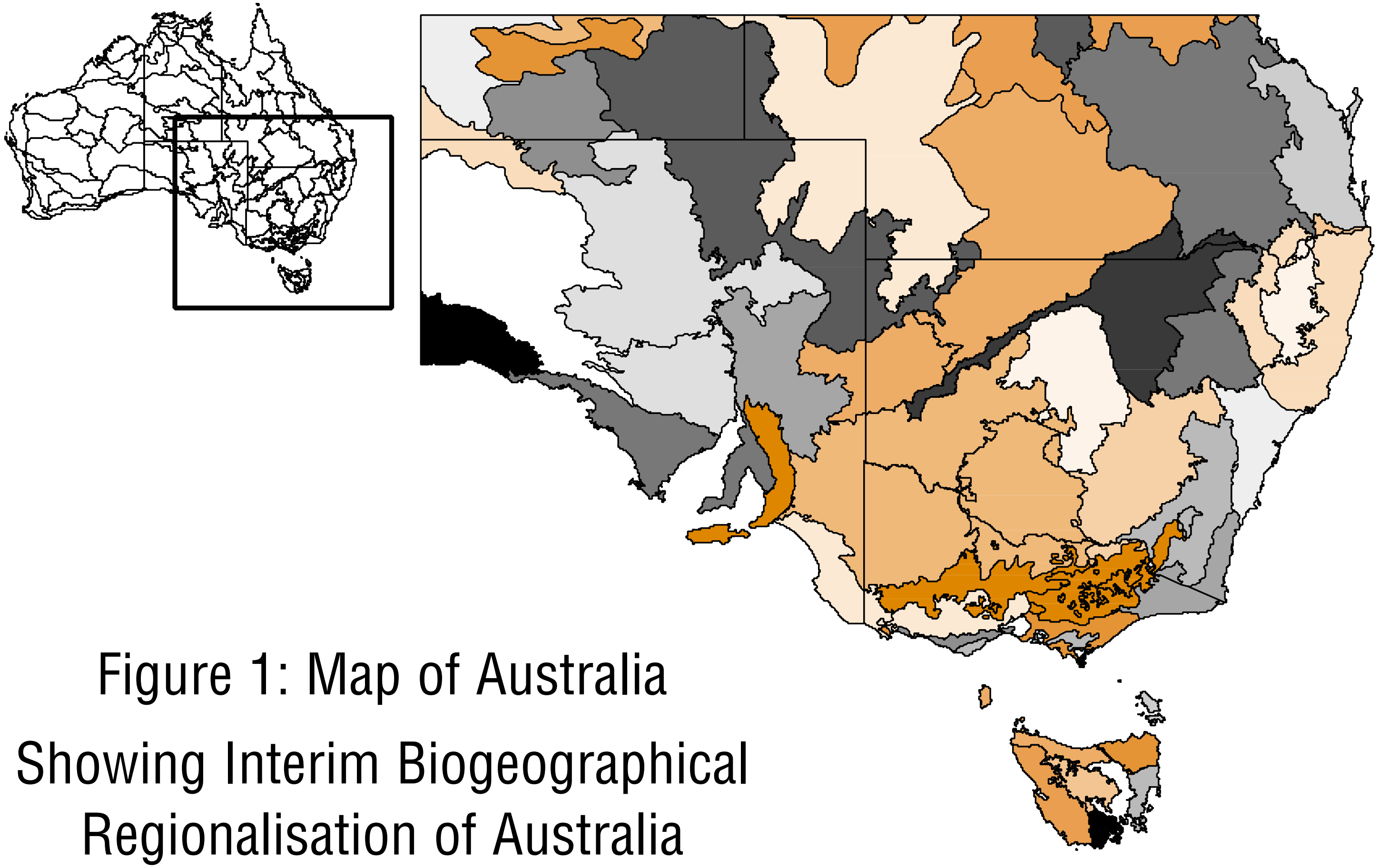


Figure 1: Map of Australia

Showing Interim Biogeographical Regionalisation of Australia (IBRA regions) and locations of sites from which allometric data were collected.

D. Barrett, CSIRO, Plant Industry

SOURCES OF UNPUBLISHED DATA FROM STATE AGENCIES

Most of the unpublished information in State agencies that might be of use for biomass estimation is in plot inventory data of DBH and height, and derived stem volume equations. Stem volume is a function of tree height, basal area, shape, and bark thickness. Volume is often estimated for specific purposes. Interpretation of the volume estimate will depend on the units of measurement, standards of use, and other specifications. For example:

- *Biological volume* is the volume of stem with branches trimmed at the junction with the stem, but usually excluding irregularities not part of the natural growth habit (e.g. malformation due to insects, fungi, fire, and mechanical damage);
- *Utilisable or merchantable volume* excludes some volume within irregularities of the bole shape caused by normal growth in addition to those irregularities not part of natural growth. For example, the volume contained in the swelling around a branch node may be excluded because this volume could not be utilised (by a nominated user);
- *Gross volume* estimates include defective and decayed wood; and
- *Net volume* estimates exclude defective and decayed wood.

There are a number of practical approaches for determining stand volume (Brack 1999), such as:

- ocular estimation;
- sample tree where an average tree is selected and the volume measured, then this value is inflated to estimate stand volume;
- measuring the stand for DBH and height, estimating the volume of each tree using a tree volume table or equation, and adding up individual tree volume estimates to derive stand volume; and
- deriving and using a stand volume equation.

VARIABLES MEASURED IN STANDARD FOREST INVENTORIES

Standard forest inventories can take a variety of forms depending on the scale of the area being assessed and the purpose of the inventory. Inventories can be undertaken using a full census, where the entire population of interest is measured, or map inventories, or various forms of ground based sampling. Inventories can be divided generally into two broad categories: strategic and operational. Australia does not have a comprehensive national approach to forest inventory.

Inventory systems have been based generally on the approach of stratified random samples and fixed area plots that were developed in the 1940’s. Brack (1997) points out that there has been little advance toward using more effective sampling methodologies, and that there is a need for the application of more innovative inventory techniques to measure and monitor forest characteristics more efficiently under varying forms of management. These techniques include multi-stage and multi-phase sampling (eg. the system applied to sample jarrah forest in WA described by Spencer 1992), variable probability sampling, and sequential (optimal stop) sampling.

Strategic inventories are undertaken to estimate timber resources across large forest estates (around 50,000 – 1,000,000 ha) and are used for long-term planning. Most strategic level inventories involve a combination of forest mapping to identify the area of forest to which the inventory data will apply, and to delineate forest types within the forest area. Forest types are used for stratification of the forest for sampling and for management planning purposes. Strategic inventories generally involve the measurement of sample plots at relatively low intensities (1 plot per 200 – 2,000 ha or more) across the estate. Plots are established in identified forest type strata, with the number per strata varying depending on the contribution of the strata to total area and the variability within the strata. Data from strategic inventories are stored and processed in purpose-designed computer systems. Strategic inventories that involve establishment of permanent plots that are re-measured over time to estimate change in forest condition due to growth, harvesting or other disturbances are often called continuous forest inventory (CFI) systems. In strategic inventories, all trees above a certain minimum diameter (often 10 cm) are measured at 1.3 m. Measurements generally include:

- DBH;
- height of bole, usually to some merchantable limit (the definition of bole height varies among States); and
- average top or dominant height of the stand, although measuring to the top of the canopy is often difficult in native eucalypt forest.

In some cases other information may be recorded such as bark thickness and level of defect on individual trees, and understorey vegetation or logs on the ground.

Operational level inventories are undertaken shortly before harvesting, generally, to assess the volume of timber available for sale. They are carried out on smaller areas (20 to 200 ha) subject to a single harvesting operation. They can involve a complete measurement of all merchantable trees (particularly in selection systems, such as those used in native tropical forest). The alternative approach is to sample the area to be harvested using parallel transects at a relatively intense sampling (usually around 5 percent of the area). Generally, measurements are restricted to merchantable trees. For sawlog operations these are often greater than 30-40 cm (in diameter).

Measurement plots are also established within forests for research and growth modelling purposes. Plots established for growth modelling are often specifically located to cover the full range of site or stand conditions experienced in the plantation or native forest, or to capture the effects of different management treatments.

Common stand parameters derived from inventories include:

- number of trees;
- average stand diameter;
- stand diameter class frequencies;
- stand structure and species composition;
- stand basal area;
- stand height;
- crown closure;
- stand density; and
- stand volume (total stem or merchantable volume).

TYPES OF INVENTORIES IN EACH STATE

NSW

Historically, a variety of approaches have been used for strategic and operational inventory of native forests and plantations in NSW. Generally these have been based on stratified random sampling and fixed-area plots. Bi and Hamilton (1998) published equations to predict total stem volume underbark for 25 native species in NSW and Victoria. There are few other published equations for native tree species in NSW (Bi 1994a and b). New inventories of native forest and hardwood plantations have been undertaken for the Comprehensive Regional Assessments undertaken for the development of Regional Forest Agreements between State and Federal governments. The techniques adopted for these inventories are described briefly, using the strategic inventory for north-eastern NSW as an example (Anon 1999).

The objectives of the inventory, were to:

1. provide estimates at stratum level (aggregated forest types by structure class) of total timber volume and volume by timber quality class with associated confidence limits, and estimates of volume by log product class;
2. provide data for prediction of long term wood flows using stand structure information;
3. assign total and available timber volume by quality class, calculated at stratum level, to stand unit (sub-compartment) where stand units comprise strata within a compartment; and
4. provide a spatial link for forest attribute and inventory data.

The accuracy target was to estimate unit volume of all useable wood (that is, all products and species) and unit volume of high value wood, in any given stratum, with a 95% confidence limit within ±30% of the true value. The inventory was not designed to provide accurate estimates for compartments or within compartments. Estimates of total volumes at the compartment level can be made using per hectare values for each stratum (based on the arithmetic mean volume of all plots in that stratum). These are not accurate estimates of volume for particular compartments, because within-compartment variation was not assessed. Accurate estimates for individual compartments would require some form of assessment for all compartments.

As part of the inventory process, a percentage of all plots established by each measuring crew (in both native forest and plantation) was checked by an audit team. The audit aimed to provide a quantitative measure of the accuracy of data collected by field crews in native forests, to ensure that data was of a satisfactory standard, and to ensure compliance with "standard of measurement" conditions of the contract between State Forest and the contractor in the inventory.

Native Forests

Forest types used in the inventory were those defined by the Forestry Commission of NSW (1989). These were mapped in the CRA Aerial Photo Interpretation Project (CRAFTI). The net mapped area for the inventory (the sample) was determined by the Geographic Information System (GIS) Branch of State Forests. The gross area was reduced to net area available for harvest by excluding the following:

- physically and economically inaccessible forests areas;
- steep land (contiguous blocks of land, with an area greater than 1 hectare, and with a slope greater than 30 degrees);
- non-commercial forest types;
- eucalypt plantations;
- unavailable Preferred Management Priority (PMP) zones;
- areas excluded because of conservation protocols; and
- drainage buffers (filterstrips).

Other areas removed from the analysis were identified as part of the Priority Management Planning process. These included:

- PMP 1.2 Undeveloped Native Forest;
- PMP 1.3 Preserved Natural Forest;
- PMP 1.1.5 Catchment Protection (where timber harvesting was excluded);
- PMP 1.1.6 Visual Resource Protection (where timber harvesting was excluded); and
- PMP 1.1.7 Flora and Fauna Protection (where timber harvesting was excluded).

Strata used in the inventory were a combination of yield association and structure class. A yield association is an amalgam of forest types. Sample plots were allocated to strata within the net mapped area of native eucalypt forest. In the early stages of the inventory, plots were allocated to strata in proportion to net area, that is, each plot represented the same number of hectares. Proportional allocation was adopted to facilitate restratification. In later stages, plots were added to under-represented strata, which altered the proportional representation of some strata. Allocation of plots was achieved using ARC/INFO software that was used to generate a random-start grid from which sample points were selected. The grid size was adjusted so that the number of points selected was about 20% more than required by the net area. The extra plots, termed reserve plots, were used to replace main plots, or as additional plots in some strata. Plots were fixed area 0.1 ha circular plots (horizontal radius of 17.84 m). The same size plot was used for all strata to facilitate restratification. All field work was done by State Forests' staff.

Variables recorded on each plot included:

- plot number;
- State Forest identifier;
- compartment number;
- measure date;
- coordinates (zone, easting, northing);
- site height;
- plot area;
- distance to filter strip (if <=50 m);
- stratum identifier;
- name of measurer(s);
- aspect; and
- slope.

Variables measured on individual trees included:

- tree number;
- species code;
- DBH;
- Dominance;
- crown quality;
- tree height (selected trees);
- hollow status;
- logging impediment; and
- MARVL tree description (quality codes and height).

Sample points were predetermined in the office; transect bearings and distances were calculated from identifiable take-off points to each sample point. A hip chain and compass were used to locate the points. A plot was established at each sample point using either a tape and clinometer (in conjunction with a conversion table to correct for variation in slope) or a Forestor "Vertex" hypsometer (which automatically corrects for variation in slope). To facilitate possible relocation, the centre point of each plot was marked with a painted peg. Individual tree numbers were sprayed on each sample tree to permit relocation for audit purposes. All trees with DBH equal to or greater than 10 cm were measured.

The MARVL (Method for Assessment of Recoverable Volume by Log Types, Deadman and Golding, 1978) method was used to provide detailed information on the potential yield and log size distribution likely to result from felling a stand of trees. A MARVL tree description was recorded for each tree. This describes the morphology of each tree and the quality of the timber it contains. Height was measured only on trees with no evidence of past or present damage to their crowns (that is, those trees which had a "typical" height/DBH ratio). Trees for height measurement were selected from across the DBH range of each plot.

Hardwood Plantations

Forty-nine strata were defined for hardwood plantations based on species group, stand condition and age class variables. Plantation inventory plots were generally 0.03 ha, although 0.10 ha plots were used in some cases. The basic approach was similar to the method used in the native forest, except that a contractor was used for all field work. Plot locations within strata were selected using an ARCVIEW systematic sampling tool.

The following parameters were recorded for each plot:

- plot number;
- measure date;
- plot area;
- stratum identifier; and
- name of measurer(s)

The following variables were measured for each ‘crop’ tree:

- tree number;
- species code;
- DBH;
- crown quality;
- tree height;
- MARVL tree description (quality codes and height); and
- availability for harvest.

Non-crop trees (that is, those trees not deliberately planted or seeded) were counted by 5 cm diameter classes. No additional tree parameters were measured for these trees.

All data were processed using the MARVL software package. MARVL differs from other inventory systems in that it separates the field assessment of size and quality of stems from the actual cross-cutting. When the stand is cruised, no attempt is made to divide the stem into logs or estimate merchantable limits at any point on the tree. The program produces one or more reports, using different views as input, cutting strategies and projection dates.

Victoria

In 1994, the Victorian Department of Natural Resources and Environment embarked on a new inventory program for native forests. The Statewide Forest Resource Inventory (SFRI) is intended to provide the first comprehensive, standardised statement of the State's native forest resources. The SFRI aims to provide forest managers with a reliable, timely and complete set of forest resource information for making informed and consistent sustainable yield forecasts, decisions on forest land-use planning and resource allocation, and a range of other investigations such as old-growth forest mapping. The Inventory is described extensively on the internet (http://www.nre.vic.gov.au/forests/sfri/index.htm). A brief description is included here.

The SFRI is an improvement on previous resource inventories in that it will provide a systematic coverage of most native eucalypt forests using a consistent forest stand classification system. Tree measurements are independent of particular forest products, allowing accurate volume estimation even if sawlog and other timber product specifications change. Structural, habitat and biodiversity information is also being collected. These data allow for a broad range of analyses, including habitat modelling.

The SFRI is based on a consistent mapping program using air photo interpretation that incorporates classes of species, crown cover, crown form, and height. State Forests are generally mapped for all characteristics, to derive growth stage as well as a basis for stratifying the forest for volume sampling. National Parks and other reserves are mapped for growth stage (crown cover and form) only. Evidence of disturbance (harvesting or fire) is also noted, and a code for Psyllid damage is included where this insect occurs. Mallee woodlands are not being mapped at this stage. Stand maps are transferred to a GIS for storage and analysis.

Detailed field measurements are made in productive stand classes in State Forests. Sample plots are established to collect tree numbers and species. A new system, TREEMAP, has been developed for stem profiling and is used to record tree dimensions, stem features and information about hollows. Inventory plots are selected according to a sampling design and are located in the field using chain and compass traverse and global positioning system (GPS). The GPS readings are differentially corrected and are accurate to less than 5m horizontally.

The field sampling employs a two stage design. In the first stage detailed measurements of trees are made on each plot. A variable radius plot is established using an optical wedge. This increases the probability that trees of larger basal area will be measured. All 'in' trees are measured for:

- DBH;
- Species;
- crown form;
- size and number of hollows; and
- height of top point of merchantable bole.

In the second stage, a sample of three of the 'in' trees is selected for profiling on each plot using Point Modified List Sampling. The probability of a tree being selected is proportional to the top point of that tree, and hence is a biased sample. These trees, known as TREEMAP trees, undergo detailed stem profiling to measure and map:

- position, class and size of all visible defects;
- diameter over bark at 0.5m above ground level (AGL);
- diameter over bark at 1/3 top point AGL; and
- diameter over bark at top point AGL (top point is assumed to be height of crown break or estimated merchantability limit in terms on small-end log diameter).

These measurements are used to calculate individual tree volumes. Volume per hectare is determined by weighting the individual tree volume estimates to account for the measured trees' probability of selection or contribution to stand volume.

On selected plots, each of the TREEMAP trees is felled for further measurements of: bark thickness, diameter at top point height and one third height to top point, diameter of pipe defect at two points up the stem, height of 'smash' (wood damaged during the tree fall) at the base and top of the stem, and size and location of hollows. In mixed species forests, additional trees may be felled for stem cross sections, or wood samples are collected without felling. These sections and samples later undergo tree ring analysis to develop growth estimates and yield curves.

Many of the field measurements are made using a laser measuring instrument which transmits data directly to a pen computer via a radio modem. The pen computer runs software specifically designed for the TREEMAP inventory. The combination of direct data entry, diagrammatic display of plot and tree information, and validation of the data while on the plot means that data collection is efficient and of high quality. This is a good model for inventory systems.

Log volume equations have been developed for a range of Victorian native species (Elliott 1989). Equations vary with species and height class and give under-bark volume on the basis of DBH over bark with an adjustment for stump height. These are still used to estimate gross bole volume, although small-end diameter merchantability limits mean that the equations do not give a complete estimate of bole volume. More recently the program VOLCALC has been developed for use in the Statewide Forest Resources Inventory of native forests. This uses data from each tree on a field plot to estimate current standing volume of that tree. VOLCALC is based on a statistical model. Volume models have been developed for each defined species group by relating volume per hectare estimates for all plots with a mathematical relationship to stand crown form, crown cover and height. Environmental variables, such as slope, aspect, elevation or climatic parameters, have been added to increase the precision of the models (Hamilton and Brack 1998).

The model incorporates the effect of location, type and size of external defects and internal defect parameters to determine the distribution of defective wood in a tree, compares this distribution with log grading rules, and optimises the yield of timber products from the tree. Using this system, a variety of log grading standards can be applied. Optimisation of timber product yield is based on cutting the highest grades wherever possible.

For the main Victorian plantation species, *Pinus radiata*, volume equations have been developed for eight different management areas around the state (Anon 1988). These were developed from regional volume functions to predict total tree volume, regional taper functions to predict height for a given small-end diameter, and regional tree height functions to predict individual tree height given tree DBH and stand height. The equations give individual tree volume under bark for a given diameter class, stand top height and small end log diameter. No allowance is made for defect or degrade.

Tasmania

Forestry Tasmania and the forest companies with large native forest and plantation estates have had a long history of forest mensuration in both native forests and plantation (Tasmanian Public Land Use Commission 1996). This includes:

- regular re-measurement of permanently established growth plots throughout a range of forest types and structures;
- measurement of standing volume using a series of temporary and permanent inventory plots in a CFI system; and
- Controlled experiments and case studies are also conducted to determine the performance of prescriptions against their objectives (for example, stocking levels and habitat retention).

The CFI system uses stratified random plot sampling. Area of forest is determined using mapping based on interpretation of aerial photographs to describe a number of attributes for each patch of forest greater than two hectares. These are incorporated into a computerised area database (GIS). Strata are based on a combination of height (e.g. 0-15m, 15-22m, 22-34m, 34-41m, 41-55m, and 55m or more) and density (the proportion of the area covered by tree crowns in each age class). Density classes vary according to whether the forest is mature, regrowth or regeneration.

A series of temporary and permanent plots has been established across the State over a long period. The plots are located within separate regions (stratified) at an intensity of one plot every 250 hectares. In regrowth forests plots are 50 x 20 m (0.1 ha) and in mixed age forests plots are 100 x 20 m (0.2 ha). Permanent plots are measured every 10 years.

Measurement standards are developed jointly by Forestry Tasmania and industry. Standard measurements on each tree include:

- DBH;
- height of bole, usually to some merchantable limit; and
- average height of the stand (in regrowth).

Volume calculations are made using the height and diameter measurements. Volumes can vary significantly, ranging from 1000 cubic metres per hectare in some areas of wet forest to as little as 50 cubic metres per hectare in the dry forests of the east coast.

Volume equations have been derived for native forest and plantation species. For native forest species a generic volume equation as a function of DBH and height has been developed for all commercial species in Tasmania. It defines merchantable volume using varying parameters for each species. This is a variable taper function based on the equation described by Goodwin (1992). It is a three segment function integrating a hyperbola, parabola and a cone. Eight dominant commercial species have individual parameterisations. The function will accept any height and diameter but only certain ranges have been used for calibration, for example, the range used for *E. obliqua* was 8-350 cm in diameter and 3 to 85 m in height.

For *P. radiata* the equation is a compatible taper function which predicts entire stem volume as a function of diameter and tree height (Candy 1989). An equation of similar form has been developed for *E. nitens* in plantations. However, this equation is confidential because it was done under contract using data from private companies. It can be used for trees ranging from 5 to 17 years old, with DBH from 12 cm to 50 cm, and total height from 9 to 33 m. There are no equations available for *E. globulus*, the other main plantation species.

South Australia

There has been little historical management of native forests for timber production in South Australia and consequently there have been no volume equations or other mensurational tools developed for native tree species. Vegetation surveys are carried out on 30 m x 30 m plots that use cover and abundance scores and height of five overstorey trees.

There is a large *P. radiata* plantation estate (140,000 ha) and significant effort has gone into developing stem volume estimation techniques for this species. These are described in Lewis *et al.* (1977). Estimation is based on a volume line that is used as the standard means of estimating volumes of permanent sample plots that have been used to derive yield tables and to develop stand tariff relationships that are used to estimate standing volumes of inventory plots.

The system aims to provide data on volume available for thinning and clearfelling to 7 cm top diameter, volume by log size and quality assortments, and the location and accessibility of these volumes. Different assessment methods (cruise, strip assessment or plot sampling) are used depending on the nature of information required and the stand condition. Historically there has been no specified sampling framework, with sampling intensity dependent on available resources. For inventories undertaken prior to thinning or final harvest a logging unit of 30 ha might contain 5 or 6 sample plots. Plots vary in size depending on the spacing but are generally about 0.1 ha. Measurements are designed to obtain information on tree diameter class distributions to support optimal marketing of the resource. The diameter of every tree in the plot is measured. An estimate of stand predominant height (mean height of the 75 tallest trees per hectare) is obtained by either:

1. using site quality as a guide; or
2. by measuring height of the 40 largest diameter trees per ha (4 trees per plot) and using a relationship between the mean of this value and predominant height.

Functions and models that are more sophisticated have also been developed to break up the total stand volume into piece sizes for marketing purposes. These use tree taper, sweep, branch size index, and pruned height to make estimates of yields of logs of specified size and quality according to their position up the stem. These can present greater sampling and prediction difficulties than estimation of entire stand volume (Lewis and Ferguson 1993).

ACT

The ACT has a relatively small (<20,000 ha) estate of *P. radiata*. These plantations are measured prior to commercial thinning or clearfelling using the MARVL-based inventory procedures described above for NSW. These are processed using the MARVL program, but log volume functions are included that are specific for different forest areas within the ACT estate. Growth functions have also been developed that are specific to these areas.

ASSESSMENT OF THE USE OF VOLUME EQUATIONS AND THEIR POTENTIAL LINK TO WHOLE-TREE BIOMASS

Volume equations can take many forms (Brack 1999):

- individual tree volume equations / table, including one-way equation / tables (where volume is predicted using diameter only) and two-way tables (using a combination of diameter and total tree or merchantable height);
- a mixture of tree and stand parameters as independent variables. For example, tree bole volume (V) may be predicted using the individual tree basal area (BA) and a measure of stand height (H). A ratio of merchantable volume (volume up to a merchantable diameter limit) to total volume can be correlated with tree and stand parameters;
- volume line or tariff based on tree basal area. These determine stand volume without measuring individual tree basal area;
- stand volume equations that correlate stand volume to some expression of stand height, stand basal area, and stand form factor; and
- aerial volume equations / tables where parameters measured from aerial photographs can be used as independent variables in stand volume equations. These are relatively common in northern America, but have not been used extensively in Australia.

A number of studies have converted individual trees or stand level estimates of volume to biomass. This can be done by converting wood volume estimates to biomass using estimates of wood density and applying an expansion factor to convert merchantable wood biomass to total biomass, or by using a direct ratio developed from estimates of stand volume and biomass where both are available from a particular site. The expansion factor usually refers to the conversion of a measured merchantable bole volume. Basic density refers to the oven-dry mass of wood divided by the fresh volume. There are published values for average wood density for a range of common species (eg Kingston and Risdon 1961, Bootle 1981). The range of values that have been used as expansion factors are shown in Table 5.

Table 4: Expansion factors or the ratio of stem-to-total volume.

reference	ratio
Eucalypts:	
Greenhouse Challenge Vegetation Sinks Workbook (1998)	0.7
Grierson *et al.* (1992) (based on 16 records from the literature)	0.51 – 0.85
Subtropical rainforest: Turner *et al.* (1989)	0.83
Pines:	
Greenhouse Challenge Vegetation Sinks Workbook (1998) (derived from Madgwick(1994)	0.68
Birk (1993) (various site conditions)	0.78 – 0.85
Snowdon and Benson (1992) (fertilizer and irrigation treatments)	0.55 – 0.69
All trees: National Greenhouse Gas Inventory	0.53

There are a number of problems in using this approach, particularly when the aim is to apply 'standardised' or default values to a species or group of species across a range of ages and sites. These are:

1. Wood density is determined by cell wall thickness and the proportion of earlywood and latewood (Wilkes 1989). Density changes over time in relation to tree age and stand stocking, with higher density in older trees and lower stocking (Madgwick 1994). Density is lower in sapwood than heartwood, therefore total tree density varies as these proportions change with tree size. Hence, density varies with species, age, position up the stem, and from the pith to the outer wood in larger trees. There can be large variation in density both within and between trees. Maximum variation across species is from 0.04 to 1.4 g cm^{-3} and within species is approximately 2-fold (Pardé 1980). The range in wood densities among eucalypt species is 0.68 to 1.13 g cm^{-3} and among all tree species measured in Australia is 0.37 to 1.25 g cm^{-3} (records mainly consist of commercial species) (Bootle 1981). Variation in wood density of *P. radiata* across 22 sites in NSW was from 0.366 to 0.445 kg m-3 (Wilkes 1989). Variation between trees at a site can frequently exceed 20%, and the difference between sites can be 20%. Differences between sites are related to growth factors such as rainfall and nutrient availability, tree age and stand stocking (Hillis *et al.* 1978). In an age series of *P. radiata*, Forrest (1969) found an increase in density with tree age. Systematic variation within trees includes an increase in the centrifugal direction, e.g. of 44%, and a basipetal increase near the base. Variation with height in the tree is not systematic (Hillis 1978). Variation in wood density within a tree for three native eucalypts (*E. rossii*, *E. mannifera, E. macrorhyncha*) was found to be relatively small, with a coefficient of variation of 2 to 10%, and no systematic variation in relation to tree diameter (Crockford and Richardson 1998). Generally, within-tree variation is related to age and between-tree variation is related to genetic and environmental factors. There is little information to quantify these variances in density if this calculation was to be used to estimate biomass density and upscaled to regional and continental scales. Incorporation of the error term arising from wood density into regional estimates of biomass would require further research.

2. Applying wood density figures derived from timber or biomass studies could result in overestimates where they have not accounted for factors such as hollows, internal defect, fungal or insect damage. These problems are likely to be particularly severe in stands with large, old trees.

3. Reported values of density often refer to wood of different moisture content, commonly fresh or 12% moisture content used for timber compared with oven-dried to constant weight used to estimate biomass.

4. The stem component is variously defined as total stem or merchantable bole and the measurement varies among State agencies and forest types. Stem volume equations often only estimate volume to a nominal small-end diameter, which in many cases is quite large (20 cm or more). Thus, the residual material in the upper bole can vary considerably depending on tree height, form and growth stage. The proportion of total biomass in the measured merchantable bolewood varies. Merchantable wood does not include small and over-mature trees, non-commercial species, trees with defect and dead standing trees. Proportion of merchantable wood depends on the definition of merchantable bole, the merchantability standards applied by the forest resource agencies and industry, and characteristics of the trees. In some native forests, more than 50% of the wood volume of commercial species is non-merchantable due to defect resulting from fire, fungal and insect attack. In addition, many native forests are mixed-species with some non-commercial species that are not included in inventories of merchantable wood (Curtin 1970). In some North American forests, total biomass is underestimated by 55% when based on merchantable wood. The range of expansion factors derived from different definitions of merchantable bolewood and forest characteristics was 0.4 to 0.77 (Johnson and Sharpe 1983).

5. Expansion factors from stem mass to total biomass can vary considerably with tree size and age, tree form, site conditions, stand density and degree of disturbance. The ratio is higher for small trees and old-growth trees, poor growing conditions and nutritional status, and a high degree of disturbance that reduces tree density, which all result in greater branching thereby increasing the expansion factor. The relationship between merchantable bole height and total height varies with tree age; the increase in bole height with DBH plateaux before that of total height as crown height continues to increase. In *E. grandis,* for example, the ratio of stem mass-to-total aboveground mass was 0.45 at 2 years and 0.93 at 27 years (Bradstock 1981). Therefore, an expansion factor to convert bole volume to total volume is not constant with tree age (Mackowski 1987). Stem volume often refers to wood only or under bark. The ratio of wood-to-bark varies with the bark type of the species and this must be incorporated in the derived expansion factor. If these factors have been derived across a range of sites and ages then they may be applied with confidence. However, this is rarely the case. There is inadequate information to quantify responses to environmental variables and tree characteristics and their interactions.

To develop accurate biomass estimates at the stand and site level it is preferable to develop local timber density estimates, defect estimates and expansion factors, as described for the Victorian SFRI below.

Estimation of total biomass in tropical rainforest by Brown *et al.* (1989) showed that estimates based on volume and expansion factors were 28 to 47% lower that estimates based on small destructive samples and allometric equations.

The derived expansion factor is only as accurate as the equations used to calculate total biomass of trees from dimension analysis. If a total biomass equation exists, it can be applied directly to tree dimension data to calculate biomass, rather than adding error terms by calculating merchantable volume. In the guide to monitoring carbon storage in forests, MacDicken (1997) recommends that direct conversion from tree dimensions to biomass be used rather than from stem volume tables and wood density.

COMPARISON OF ALLOMETRIC EQUATIONS

RATIONALE

The concept of using generalised allometric equations for spatial prediction of biomass refers to either one species across its geographical range, or for a suite of species growing in similar environmental conditions. Composite datasets pooled over species or sites are used to derive the general equation. Evaluating the validity of this concept requires determining the feasibility of using equations for sites or species other than those for which they were developed. The evaluation assumes that the specific equations are more accurate than the general models because they account for species and site differences that are known to exist. The important question is whether the increase in error or bias imparted by using the general equation is acceptable. Assessing the use of generalised equations to predict biomass involves determining the effect of environmental conditions, species, age and growth form of the trees on the biomass estimated. Additionally, the sources and propagation of errors must be considered, both at the scale at which the equation was derived and for prediction at larger scales.

Differences between equations can be tested if they are in the same form, use the same independent variables and units, and the error mean square is provided. Tests of differences are done on the variances, the slope and intercept to determine statistical homogeneity. However, this direct comparison of allometric equations was not possible due to the type of information available. Some of the difficulties included:

- Equations were provided in various mathematical forms, including linear, polynomial, linear-logarithmic, logarithmic and natural logarithmic;
- Independent variables used in the equations include diameter at 30 cm and 130 cm height, height, diameter^2, diameter^2 x height, girth, basal area, diameter at the base of the crown, and crown length. Some of these variables are not available in inventory datasets;
- Various biomass components were described by the equations, including stem, crown, leaves, branches, twigs, aboveground, roots and total. Some components were separated further, for example bark and wood, sapwood and heartwood. The equations for these components cannot be simply added when in logarithmic form;
- No biomass component was common to all studies; and
- Error terms were not provided for all equations.

A strategy was developed to provide a comparison of the predicted biomass derived from the various allometric equations by calculating the relative differences between a generalised allometric equation for each vegetation type in Table 3 and the specific allometric equations used to generate the general equation. Estimates of biomass were calculated by applying the allometric equations to test datasets of independent variables. Two types of datasets were used; individual trees and a population of trees with a random distribution of sizes; to provide estimates of biomass at the tree and plot scale. Groups of equations, based on the vegetation types specified in Table 3, were compared in terms of their estimated biomass. A general equation was derived for each vegetation type by combining values generated from each original equation.

The main criteria for grouping species for the use of generalised biomass relationships are tree form and wood density. The main difference in tree form is branching pattern, which may be excurrent where the stem extends to the top of the crown, or deliquescent where the tree lacks a main axis. Crown ratio is a useful parameter to describe branching pattern. The form influences both partitioning of biomass among components and the allometric relationship. MacDicken (1997) considers that allometric equations can be highly variable among species, but recommends that if generalised allometric equations are going to be used, species should be grouped carefully by morphology.

Application of equations for the estimation of biomass requires prediction of total biomass for given tree sizes and a quantified variance. The form of error terms provided in the source material varied so that it was difficult to make a direct comparison of predicted values. The error terms provided in Table 2 include: standard deviation of the regression (a), standard error of the regression (b), variance of the regression (c), standard error of the estimate (d), and error mean square (e), standard error of the slope (f), and standard error of the intercept (g).

A value of uncertainty associated with an allometric equation should be calculated as a variance or standard deviation, as the equation is derived from individual trees across a range of sizes. The term ‘standard error’ refers to the standard deviation of sample means, which is derived from repeated samples taken from the one population and each with a calculated mean (Shiver and Borders 1996).

The standard error of the estimate should be calculated for each predicted biomass value (Y_i). The standard error of the regression represents the standard error of the estimated mean biomass. The standard error of an estimated value of biomass will vary depending on its distance from the mean, and hence the standard error of the regression is multiplied by a correction factor. The correction factor involves the distance from the mean, the sum of squares and the number of samples. Hence, it can only be applied if the original data are available to define the range and distribution of tree sizes used in the regression and the mean tree size. Where this is not possible, the standard error of the estimate term can be used as an approximation of the standard error of the regression (Shiver and Borders 1996).

The standard error of a predicted Y_i for a given value X_i is :

$$S_{\hat{Y}_i} = \sqrt{S^2_{Y.X}\left[1+\frac{1}{n}+\frac{(X_i-\bar{X})^2}{\sum X^2}\right]} \text{(Sokal and Rohlf 1994)}$$

Error terms were converted, where possible, to a standard form of the Error (or Residual) Mean Square (EMS), which is equivalent to the unexplained variance of the regression analysis, using the following formulae (Sokal and Rohlf 1994):

$S^2_{Y.X}$	variance of the regression of Y on X equivalent to EMS
$S^2_{Y.X}$	$= (S_{Y.X})^2$
$S_{Y.X}$	standard deviation of the regression of Y on X
S_{Y_i}	standard error of the mean of Y
n	number of samples

METHOD

- Total aboveground biomass was estimated for each record in Table 2 by applying the allometric equations for each biomass component and then summing the components. Only equations based on single independent variables could be calculated using the test dataset, unless the relationship between two variables was provided.

- Estimation of biomass from logarithmic equations required back-transformation and correction for bias. This was calculated using a standard formula (Baskerville 1972) for all equations. This calculation required the unexplained variance of the regression, which was obtained by converting the various error terms provided.

mean $\hat{Y} = e^{(\mu + s^2 / 2)}$

variance $\hat{s}^2 = e^{(2s^2 + 2\mu)} - e^{(s^2 + 2\mu)}$

where, μ is the mean estimated value, and s^2 is the unexplained variance of the regression.

- Biomass (kg) of individual trees was calculated for a range of tree sizes applicable to the vegetation type; from 10 to 100 cm DBH with 10 cm increments for forests, 10 to 50 cm for woodland trees, 0.5 to 4 m height for woodland shrubs, 0 to 20 cm for eucalypt plantations, and 0 to 30 cm for pine plantations.

- An allometric relationship is shown for each record from Table 2 and grouped according to the vegetation types in Table 3 (Figure 2). The ranges of tree sizes from which the equations were derived are shown as horizontal bars on the graphs.

- A general equation for each vegetation type was derived by combining the predicted biomass values from each record shown in Figure 2 (Figure 3). The predicted values were restricted to the DBH range of the original data. Woodlands were not included because the independent variables were not compatible; the independent variate for trees was diameter at 30 cm height above the ground and for shrubs was height. The general equations for each vegetation type are given in Table 5. Variability of the general equation was assessed relative to the original equations by several statistical parameters. The R^2 of the general equation indicates the amount of variation in predictions by the original regression equation accounted for by the general equation. The error mean square gives the variance of the deviations of predicted values around the mean Y value from which confidence intervals can be developed. The mean % difference between predictions by the general equation and the original equations for the range of values selected gives the average deviation of the general equation from the original equation.

- Differences in biomass values predicted from original site-specific equations compared with those predicted from the general equation are shown in Table 6. Figures in bold represent predicted values restricted to the DBH range of the original data for each record, and figures in normal type represent the effect of extrapolating beyond this range.

- Biomass density (t ha^{-1}) was calculated for a population of trees using test datasets with normal, positive and negative skew distributions and different mean tree sizes (Table 7). The test dataset was derived from randomly selected numbers within a specified diameter range (appropriate to the vegetation type), a constant stand basal area, and variable mean tree diameter and number of trees according to the frequency distribution of tree sizes. Derivation of the test dataset and calculations were done using Genstat 5.3 (Payne *et al.* 1988). This analysis provided information about the errors involved in applying allometric equations on an areal basis to predict biomass density.

Table 5: General allometric equations for each vegetation type, derived from predicted values.

vegetation type	allometric equation	no. of records	no. of points	EMS	R^2
	Y = aboveground biomass (kg), X = DBH (cm)				
native sclerophyll forest	$\ln Y = -2.3267 + 2.4855 \ln X$	25	135	0.09393	0.963
rainforest	$\ln Y = -1.8957 + 2.3698 \ln X$	5	50	0.08658	0.969
native plantation	$\ln Y = -2.0536 + 2.3110 \ln X$	4	24	0.6229	0.922
pine plantation	$\ln Y = -2.1376 + 2.2476 \ln X$	8	47	0.3112	0.855
woodland trees	$\ln Y = -1.4595 + 2.0618 \ln X$ (D 30 cm)	4	18	0.1408	0.939
woodland shrubs	$\ln Y = -1.0668 + 2.8807 \ln X$ (H in m)	8	45	0.4080	0.898

RESULTS

Among the native sclerophyll species, there are differences in allometric equations at a site (Figure 2a). These differences can mostly be interpreted in relation to the age or dominance class of the trees, or site conditions. For *E. pilularis*, mature forests of more than 45 years old appear to have similar relationships, whereas younger trees have a lower biomass for a given DBH. Of the two species of younger trees in the stand, *E. pilularis* was dominant compared with *E. intermedia*. *E. delegatensis* and *E. pauciflora* are both montane species, but *E. delegatensis* grows at lower elevations and sites with higher moisture and soil fertility. For a given DBH, *E. delegatensis* has a greater height and biomass than *E. pauciflora*. In coastal mixed-species forests, *E. sieberi* is the dominant species and has greater biomass for a given DBH than *E. agglomerata* and *E. muellerana*. Among these co-existing species, Stewart *et al.* (1979) found differences in partitioning among biomass components, mainly in the canopy and the proportion of bark and wood in the stem. This difference is similar in the forests with mixed *E. obliqua* and *E. amygdalina* (Adams and Attiwill 1988). Ashton (1976) found no significant difference in the allometric relationships for *E. regnans* and *E. sieberi* sampled from the same catchment but on different aspects and slopes in wet and dry sclerophyll forest type. Allometric relationships between branch diameter and leaf mass showed that three stringybark species, *E. agglomerata*, *E. muellerana* and *E. obliqua* (Attiwill 1962), had similar relationships but the ash species, *E. sieberi*, had different crown characteristics. Variation in tree allometry among some co-existing species means that there is not necessarily a constant relationship at a site between tree dimensions and biomass, such as total stand basal area and biomass. Similarity in allometry among species will depend on characteristics of partitioning of biomass and dominance in the stand. The highest biomass predicted in trees up to 100 cm DBH was for mixed coastal forest of *E. maculata* / *E. pilularis* / *E. botryoides* (Ash and Helman 1990)

Species common to several sites were compared to assess the effect of differences in environmental conditions (Figure 2b). Among the mature stands of *E. pilularis*, the highest biomass occurred at the temperate site (Ash and Helman 1990), compared with Queensland subtropical site (Applegate 1982) and the lowest value at the NSW subtropical site (Mackowski 1987). The equations for *E. obliqua* were similar at four sites (Keith *et al.* 1999, Feller 1980, Adams and Attiwill 1988), but with higher biomass at the wettest site. The reason for the high biomass at the dry, low fertility site is uncertain but appears to be related to the low stocking at the site resulting in a high proportion of canopy mass and the possibly old trees in an undisturbed stand. The equations for *E. sieberi* / *E. regnans* were similar at three sites (Stewart *et al.* 1979, Ashton 1976 and Feller 1980). However, the equation used by Feller (1980) was an unusual form using DBH^2 and height, which appeared to give erroneous values at high DBH (above 40 cm).

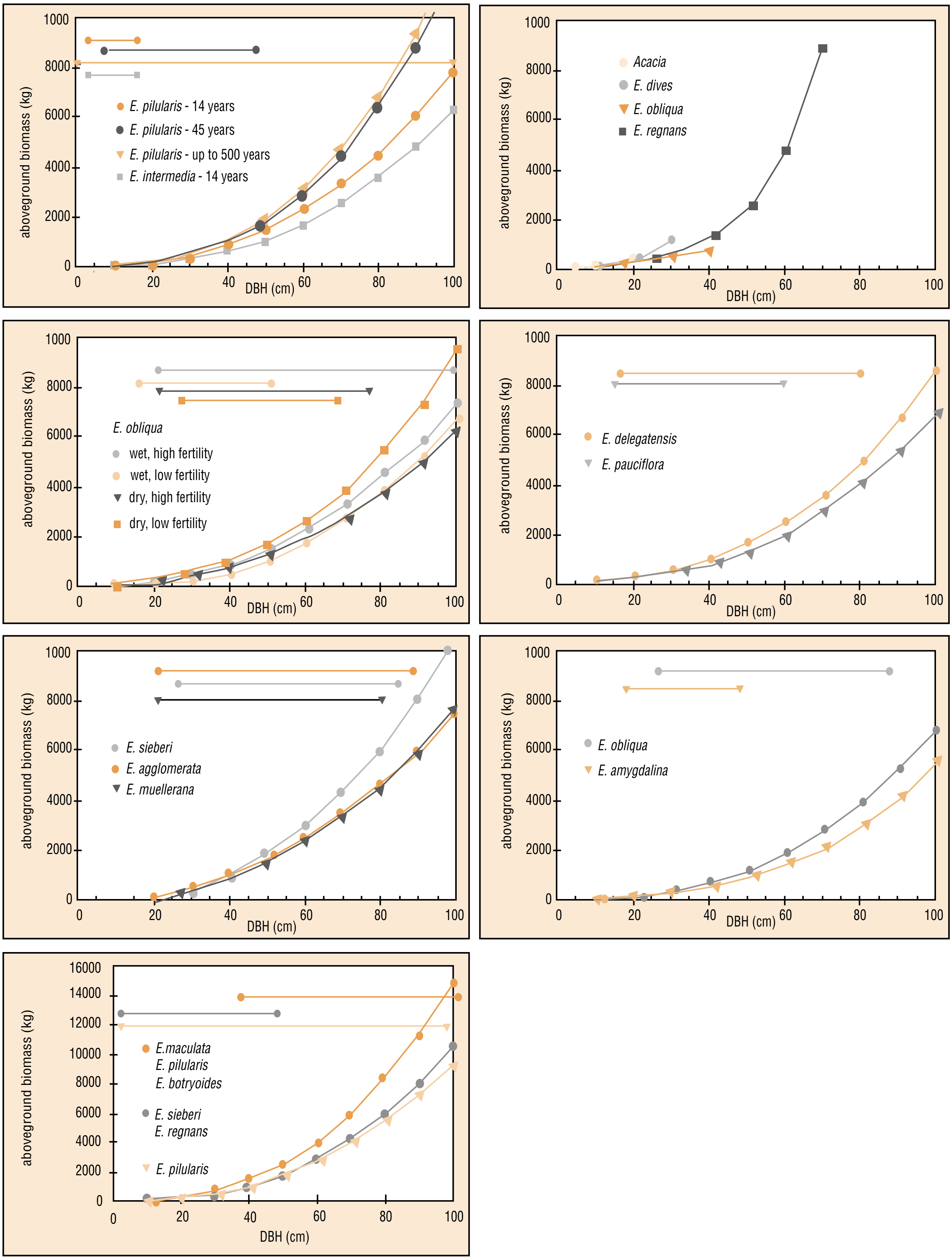


Figure 2a: Native sclerophyll forest at each Site - Site-and species-specific allometric equations derived for each record, showing the relationship between DBH and aboveground biomass. Horizontal bars on the graphs represent the range of tree sizes from which the original equation was derived.

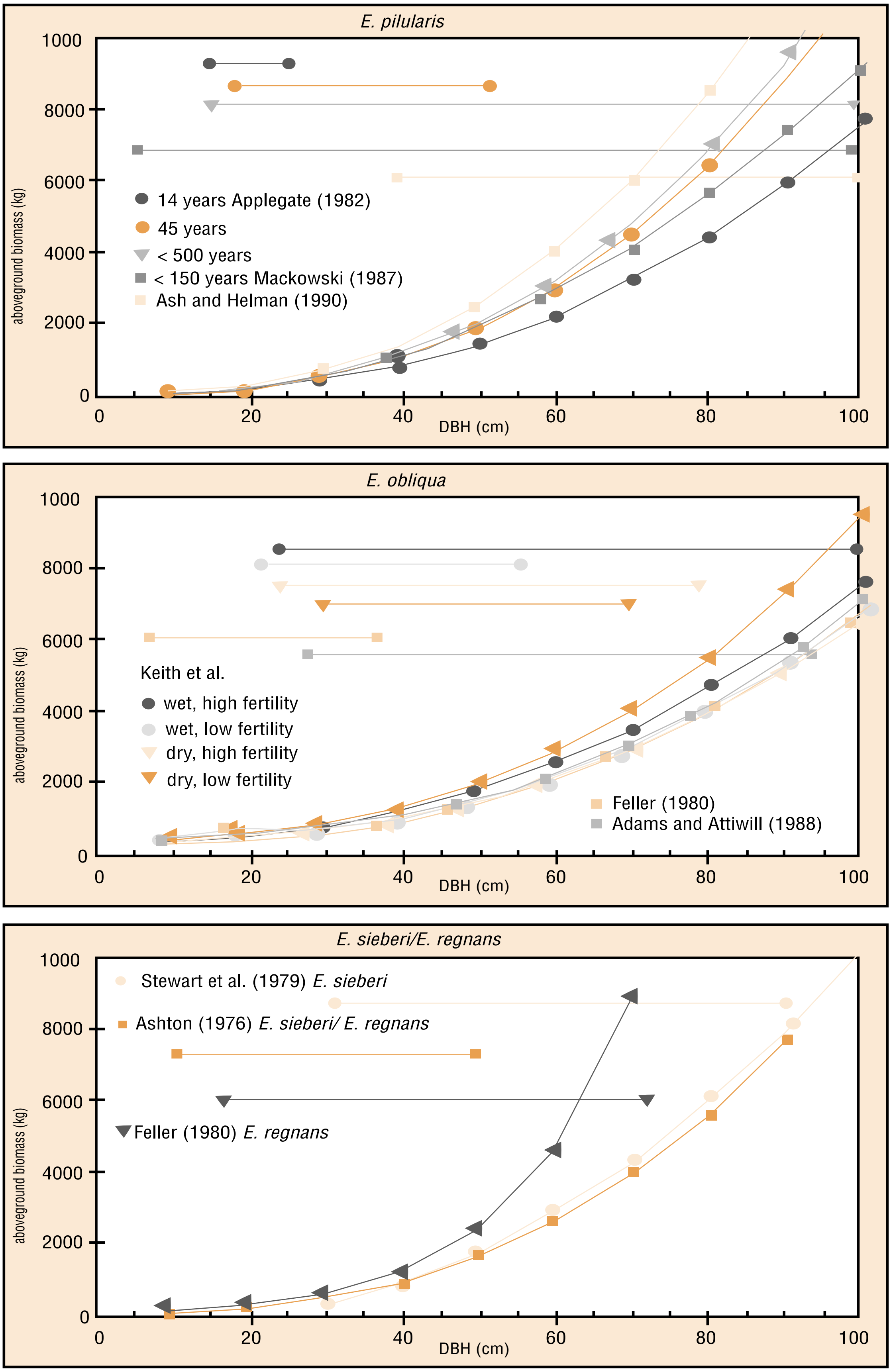


Figure 2b: Native sclerophyll forest for each species

Predictions of biomass for individual tree sizes using the general equation for native sclerophyll forest gave differences from the specific equations from –56% to +57% (Table 6a). Many of the species, however, were within 30%. (Equations of unusual forms that appeared to give erroneous values at high DBH have been excluded from these summaries.) The range in biomass density that was calculated from the normal distribution of the test dataset was from 124 to 312 t ha^{-1} (Table 7a). The frequency distribution of tree sizes affects the total biomass; a negative skew decreased biomass by 4 to 18% and a positive skew increased biomass by 1 to 16% (these values will depend on the degree of skew of the distribution). These results indicate the errors that can be propagated by the use of a general equation and the likely differences due to stand structure.

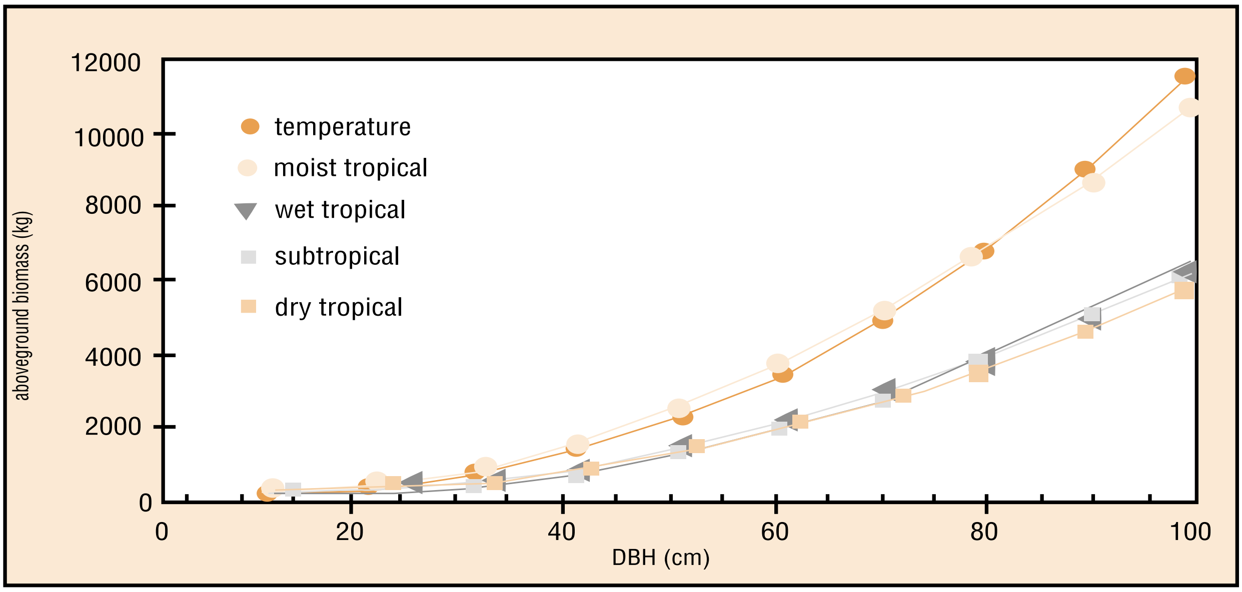


Figure 2c: Rainforest

The general equations for rainforest in Figure 2c combine generalised equations for world tropical forests (wet, moist and dry tropical) and site specific equations from Australia (temperate and subtropical). These equations appear to form two groups, with the highest biomass produced for a given DBH by moist tropical and temperate rainforests, and lower biomass produced by wet and dry tropical and subtropical forests. Predictions of biomass for individual tree sizes using the general equation for rainforest gave differences from the specific equations from –59% to +44% (Table 6b). The range in biomass density calculated from the normal distribution of the test data set was from 150 to 283 t ha^{-1}, and a negative skew distribution decreased the predicted biomass by 6.3 to 10.4%, and a positive skew increased biomass by 1.3 to 8.1% (Table 7b).

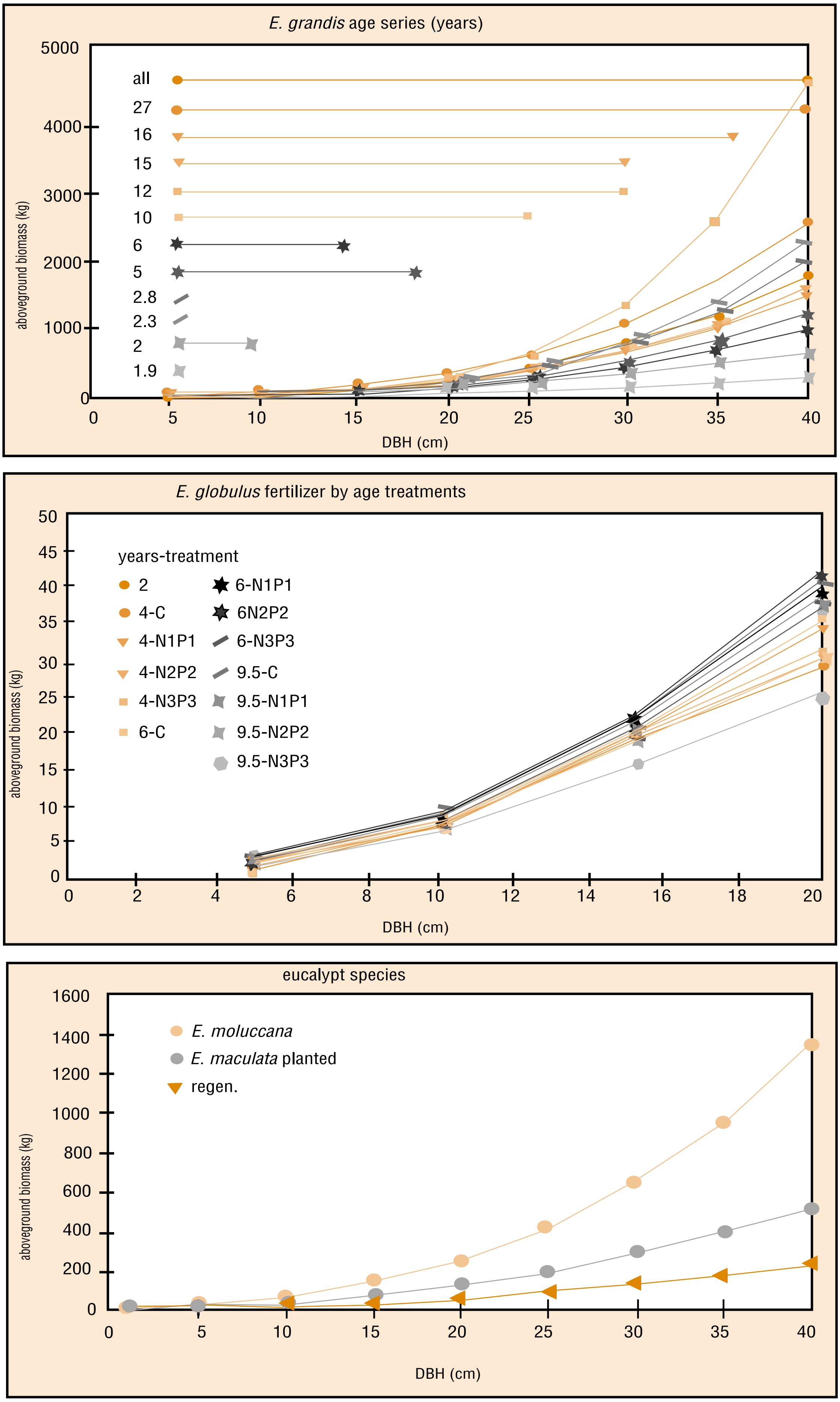


Figure 2d: Native species plantations

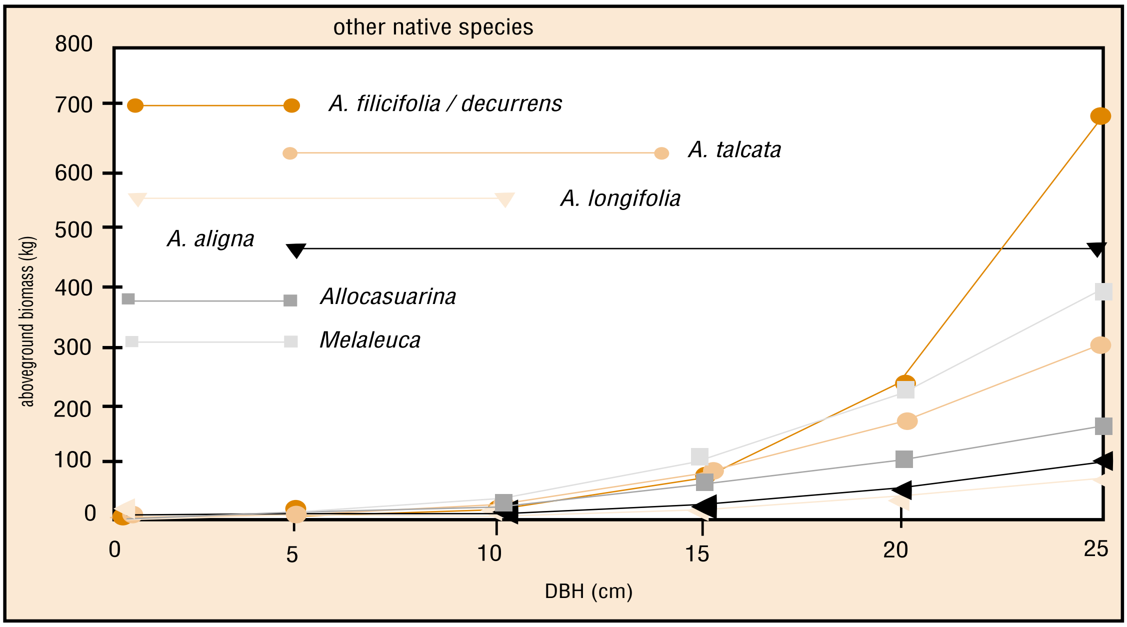


Figure 2d: Native species plantations (cont.)

There is a great range in the allometric equations for plantations of native species. Differences are related to tree age such as the age series of *E. grandis* (Bradstock 1981 and O'Brien 1998), nutrient availability such as the fertilizer treatments of *E. globulus* (Cromer *et al.* 1975, Cromer and Williams 1982), and species (Birk *et al.* 1995) (Figures 2 d and e). The general trend is for higher biomass for a given DBH in older trees and with higher nutrient availability. This trend is not entirely consistent, which probably indicates the problems with experimental design in field trials. Tree age has a greater effect than nutrient availability, and this is seen by the large deviations from the general equation for the age series of *E. grandis* compared with fertilizer treatments in a narrower age range of *E. globulus* (Table 6c). The allometric relationship between DBH and stem biomass was similar for the stands of *E. grandis* (ages 2 to 27) (Bradstock 1981), which suggests that the main difference occurred in the canopy during stand development. Large differences occurred among species in the allometric relationships and deviations from the general equation. This may indicate differences in tree form and dominance during early growth and suitability for site conditions. The stages of rapid early development and canopy closure are a time of great change in tree form, and differences occur among species in developmental stage. Hence, it is difficult to generalise an allometric relationship. The range in biomass density calculated from the normal distribution of the test dataset across all species was from 25 to 249 t ka^{-1} (Table 7c). There were also large differences in estimated biomass from the skewed distributions, particularly for the stands with high biomass such as the older *E. grandis* and *E. globulus*, and *E. moluccana.*

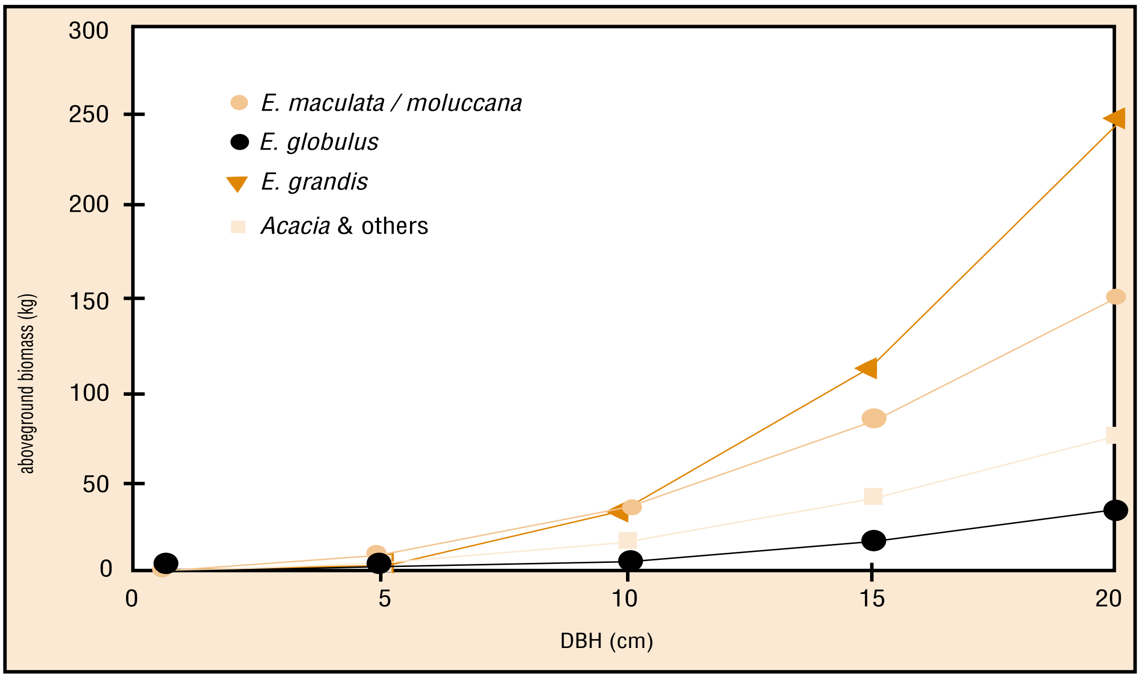


Figure 2e: Native species plantations grouped by species

Plantations of *P. radiata*, like the plantation species above, vary greatly in allometric relationships with stand age (Figure 2f). Inconsistencies in this trend may reflect differences in site conditions as the age series covers a wide range of sites. Differences in the site and age specific equations are reflected in the large deviations from the general equation (Table 6d). The range in biomass density that was calculated from the normal distribution of the test dataset was from 17 to 88 t ha^{-1} (Table 7d). The effect of the skewed distribution was greatest on the young stands and this may indicate that these equations are not reliable when extrapolated to larger tree sizes.

The allometric equations for woodland trees have both different slopes and forms, and the two eucalypts differ (Figure 2g). Deviations from the general equation are large, from –80 to +78% (Table 6e) and there is a 2-fold range in the predicted biomass density (Table 7e). Some of the woodland shrub species have similar allometric relationships (Figure 2h), which may reflect groups of shrubs with similar growth forms. Derivation of a general equation for all shrubs results in large deviations (Table 6f) and a large range in predicted biomass from the test dataset from 1.3 to 10.2 t ha^{-1} (Table 7f). The skewed distributions have a large effect on the predicted biomass, from –34% to +33%.

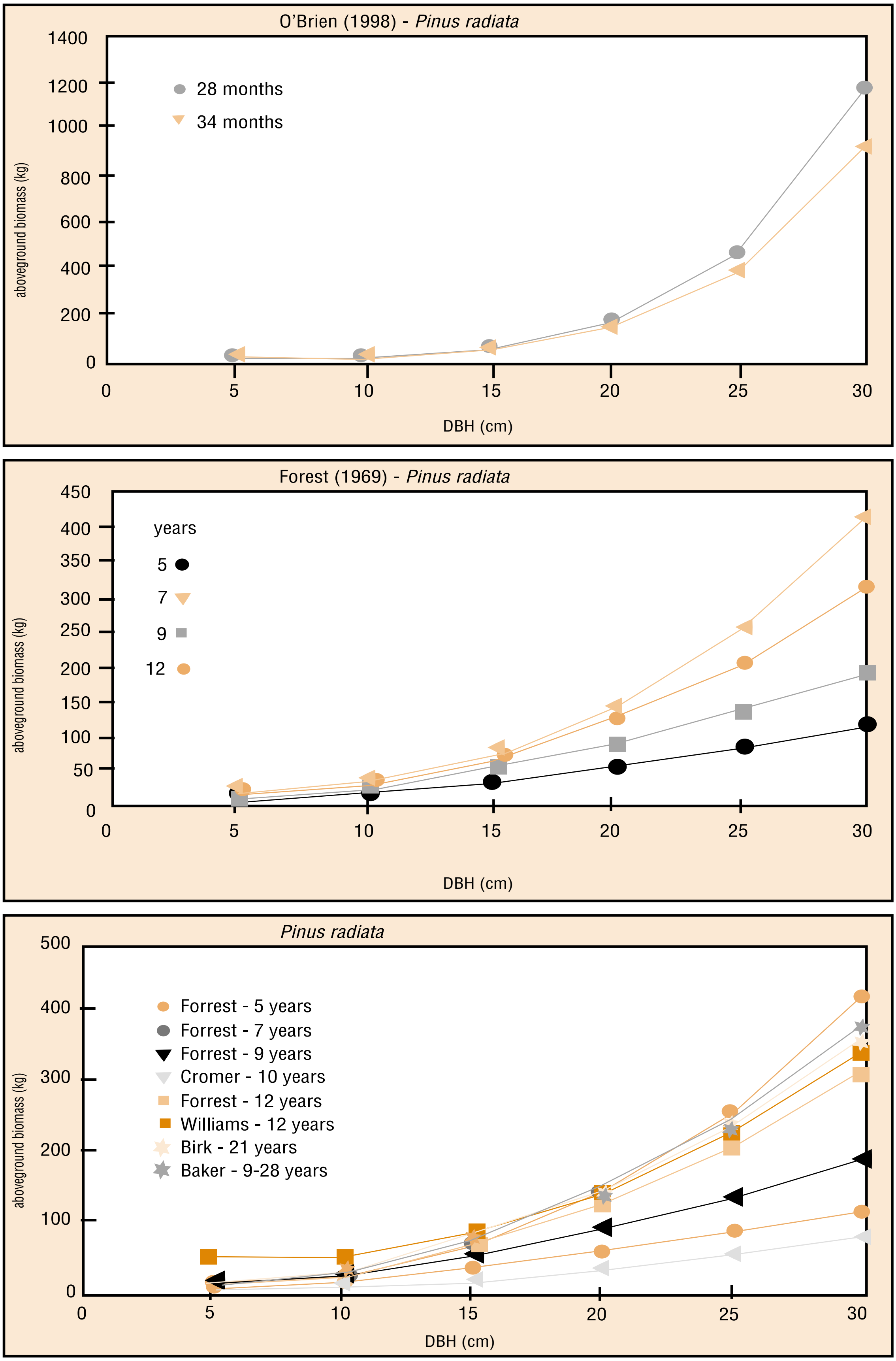


Figure 2f: ***Pinus radiata*** **plantations**

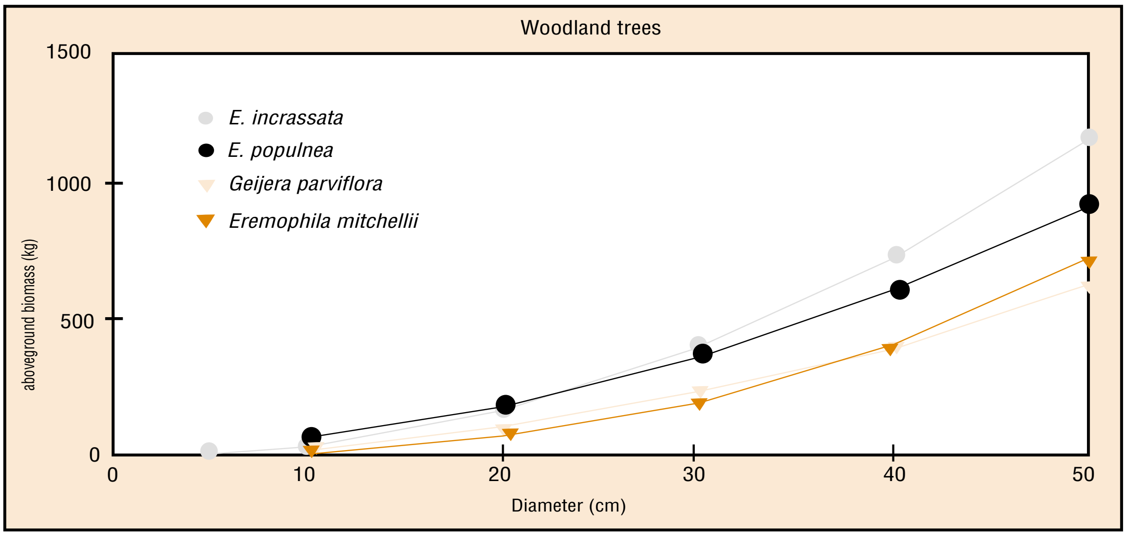


Figure 2g: Woodland trees

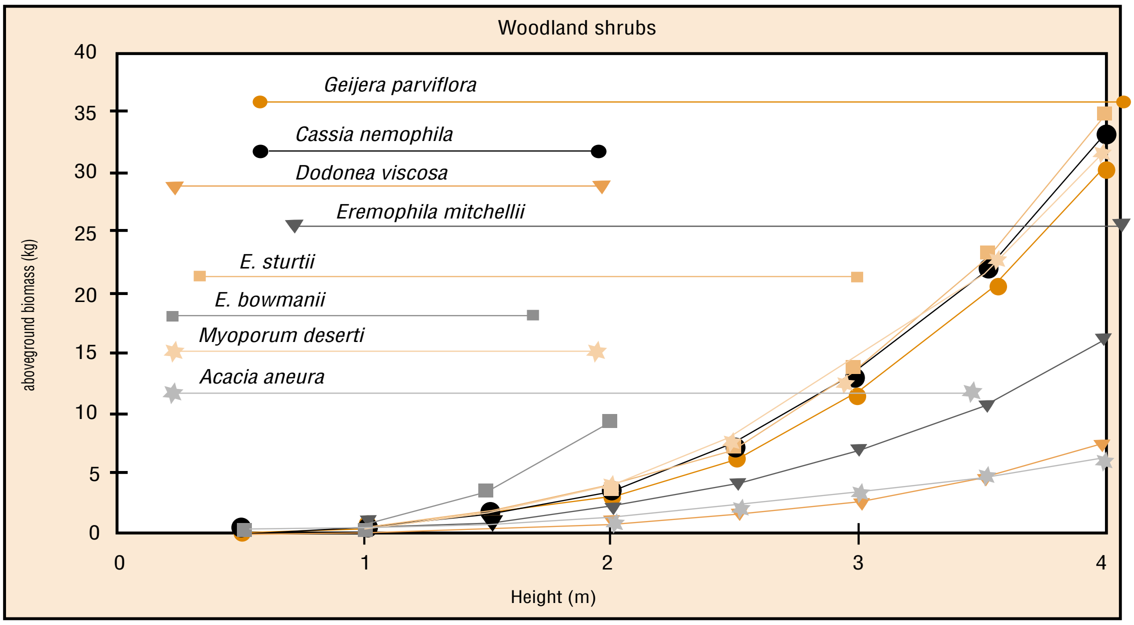


Figure 2h: Woodland shrubs

In the cases where large differences occur in allometric relationships between species, sites, ages, or other factors, then predictions of biomass from a general equation would be biased. Where the differences occur in the slope coefficient of the equation, the proportional bias would vary in a complex manner with differences in tree size.

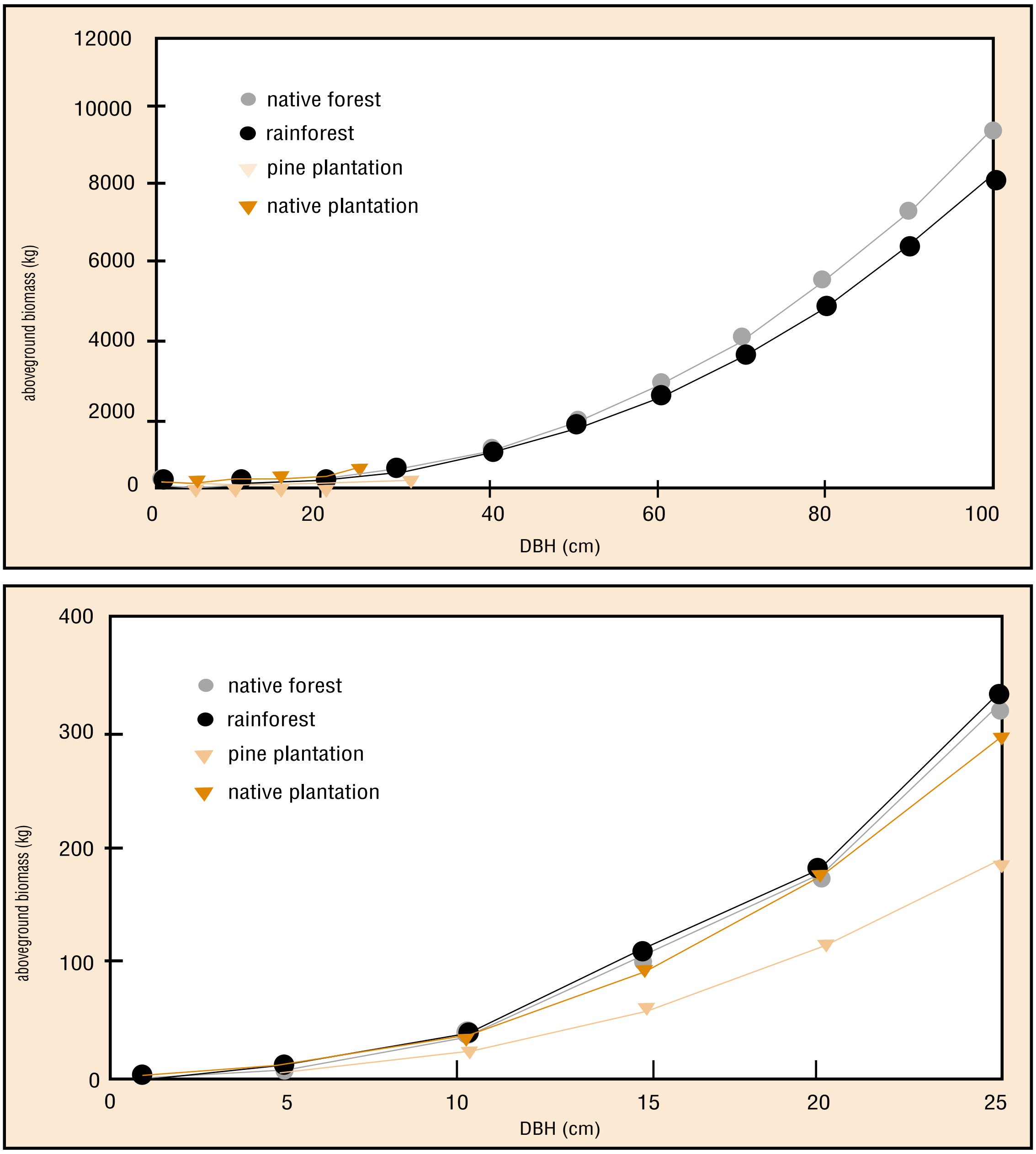


Figure 3: General equations derived for the main vegetation types; native sclerophyll forest, rainforest, native species plantations, pine plantations. (Woodland trees and shrubs could not be included because the equations did not use DBH as the independent variable.)

The general allometric equations for the four vegetation types where the independent variable is DBH are shown in Figure 3. The relationship is reasonably similar for the native species, when compared over the size range from which the original data were derived. The pine plantations have a lower biomass for a given DBH than the native species.

Table 6: Percent difference in biomass values predicted from original site - and species - specific equations compared with those predicted from the general equation for each vegetation type. Figures in bold type represent predicted values restricted to the DBH range of the original data for each record (where this information is provided), and figures in normal type represent the effect of extrapolating beyond this range.

a) Native sclerophyll forest

DBH (cm)	***Eucalyptus obliqua***	***E. amygdalina***	***E.pilularis*** **14 years**	***E.pilularis*** **45 years**	***E.pilularis*** **up to 500 yrs**	***E. intermedia*** **14 years**	***E. maculata*** ***E. pilularis*** ***E. botryoides***	***E. sieberi*** ***E. regnans***	***E. regnans***	***E. obliqua***	***E. dives***
record number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**10**	**11**	**12**
10	1.64	-39.09	9.03	22.52	19.43	49.64	-17.23	13.43	-165.93	-33.35	-144.32
20	17.31	16.85	12.16	11.32	6.94	45.41	-30.11	7.57	-42.20	-76.40	-79.82
30	22.72	34.40	13.93	4.03	-1.24	42.77	-37.05	3.96	-17.49	-1.12	-144.68
40	25.21	41.98	15.17	-1.50	-7.48	40.82	-41.78	1.31	-19.16	30.64	-361.53
50	26.47	45.33	16.12	-6.01	-12.59	39.27	-45.36	-0.79	-36.78	36.55	-940.32
60	27.10	46.41	16.89	-9.84	-16.94	37.97	-48.24	-2.54	-70.85	13.40	-2511.19
70	27.35	46.10	17.53	-13.19	-20.75	36.84	-50.65	-4.05	-127.00	-70.07	-6942.36
80	27.38	44.84	18.09	-16.17	-24.14	35.86	-52.71	-5.37	-216.17	-312.01	-19902.41
90	27.26	42.88	18.57	-18.87	-27.22	34.97	-54.52	-6.55	-357.00	-1001.10	-58989.28
100	27.03	40.40	19.00	-21.33	-30.04	34.17	-56.13	-7.61	-580.56	-2991.83	-179936.88

DBH (cm)	***E. pauciflora***	***E. obliqua*** **wet, fertile**	***E. obliqua*** **wet, infertile**	***E. obliqua*** **dry, fertile**	***E. obliqua*** **dry, infertile**	***E. pilularis***	***E. delegatensis***	***E. muellerana***	***E. agglomerata***	***E. sieberi***
record number	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
10	11.65	-25.62	50.23	6.53	20.40	0.09	10.50	680.31	680.35	902.38
20	20.85	-9.17	44.52	14.73	14.78	-4.05	13.57	57.55	33.37	123.60
30	24.07	-0.56	40.89	19.19	11.30	-6.56	13.77	8.45	-9.65	25.51
40	25.62	5.13	38.17	22.22	8.75	-8.37	13.37	4.59	-8.21	0.81
50	26.45	9.32	35.97	24.48	6.73	-9.79	12.81	7.30	-1.53	-7.05
60	26.93	12.61	34.11	26.29	5.04	-12.26	12.20	10.75	4.97	-9.59
70	27.19	15.29	32.51	27.78	3.58	-7.38	11.58	13.83	10.49	-10.12
80	27.33	17.55	31.08	29.04	2.31	-3.32	10.99	16.41	15.06	-9.84
90	27.39	19.50	29.80	30.14	1.17	0.13	10.41	18.53	18.87	-9.22
100	27.38	21.20	28.63	31.11	0.14	3.12	9.86	20.28	22.07	-8.47

Table 6 *continued*

b) Rainforest

DBH (cm)		wet tropical	moist tropical	dry tropical	temperate	subtropical
	record number	27	28	29	30	32
10		10.67	-13.27	44.06	-32.89	18.28
20		-1.08	-53.78	24.86	-34.76	19.87
30		1.04	-59.43	18.94	-35.87	20.55
40		5.18	-56.88	18.53	-36.66	20.95
50		9.33	-52.33	19.88	-37.28	21.21
60		13.09	-47.46	21.78	-37.79	21.41
70		16.43	-42.78	23.81	-38.22	21.56
80		19.39	-38.43	25.80	-38.59	21.68
90		22.02	-34.44	27.70	-38.92	21.78
100		24.38	-30.78	29.47	-39.22	21.86

c) Native species plantations

E. grandis

DBH (cm)	age (years)	1.9	2	2.3	2.8	5	6	10	12	15	16	27
	record number	94	63	95	96	64	65	66	67	68	69	70
5		-47.48	-15.39	-18.96	9.74	6.73	-39.39	8.68	8.71	-11.63	-0.74	-35.69
10		26.26	20.33	17.34	30.08	27.59	10.89	12.20	15.06	5.80	9.89	-33.97
15		50.29	35.07	22.43	30.46	31.86	24.72	12.76	5.74	10.61	13.79	-34.70
20		62.19	43.54	19.51	26.13	33.04	30.99	12.63	-12.04	12.01	15.48	-35.91
25		69.28	49.18	12.24	19.23	33.22	34.54	12.28	-37.18	12.04	16.13	-37.21
30		73.98	53.28	1.50	10.27	33.02	36.82	11.84	-69.48	11.42	16.20	-38.51
35		77.32	56.42	-12.60	-0.65	32.65	38.42	11.36	-109.01	10.45	15.91	-39.76
40		79.81	58.93	-30.32	-13.59	32.20	39.61	10.88	-155.90	9.30	15.40	-40.96

E. globulus

DBH (cm)	age/ treatment	2-all	4-C	4-N1P1	4-N2P2	4-N3P3	6-C	^-N1P1	6-N2P2	6-N3P3	9.5-C	9.5-N1P1	9.5-N2P2	9.5-N3P3
	record number	72	73	74	75	76	77	78	79	80	81	82	83	84
5		-51.10	-25.97	32.32	-21.27	-19.68	-19.81	20.94	42.66	28.17	8.65	8.39	3.19	14.74
10		-11.49	9.98	5.32	-5.35	-18.55	-2.51	8.69	25.24	13.62	-2.18	-1.99	-8.03	4.50
15		3.16	22.34	9.70	5.64	-8.42	5.69	-2.27	9.89	3.14	-9.33	-8.81	-15.40	-2.23
20		11.79	29.43	15.11	13.11	-0.54	10.83	-12.19	-4.16	-5.37	-14.79	-14.01	-21.02	-7.38

Table 6 *continued*

E. maculata / moluccana

DBH (cm)		*E. moluccana* planted	*E. maculata* planted	*E. maculata* regen.
	record number	**58**	**57**	**61**
1		1.82	-9.33	-3.35
5		-9.13	9.59	38.40
10		-22.24	13.70	48.79
15		-36.24	15.28	53.62
20		-51.17	16.08	56.60

Other species

DBH (cm)		*A. falcata*	*A. filicifolia*	*A. longifolia*	*A. saligna*	*Allocasuarina*	*Melaleuca*
	record number	**49**	**50**	**51**	**52**	**53**	**62**
0.5		50.1	99.0	67.3	49.6	-99.8	167.4
1		36.2	97.2	64.1	57.0	-70.6	190.8
5		-21.6	123.1	52.3	57.6	-113.7	146.0
10		-65.3	115.3	44.7	49.9	-131.1	134.1
15		-99.2	115.1	39.4	42.5	-170.7	123.1
20		-127.9	115.6	35.2	35.8	-223.3	115.8
25		-153.4	116.3	31.7	29.5	-293.9	110.8

d) Pine plantations

DBH (cm)	reference	O'Brien	O'Brien	Forrest	Forrest	Forrest	Cromer	Forrest	Williams	Birk	Baker
	years	**2.3**	**2.9**	**4**	**7**	**9**	**10**	**12**	**12**	**21**	**9 to 28**
	record number	**122**	**123**	**111**	**112**	**113**	**108**	**114**	**127**	**106**	**105**
5		-0.20	-1.48	3.85	-31.42	31.65	74.95	-2.27	-897.16	2.25	-16.93
10		19.69	23.13	-0.97	-0.30	8.88	74.16	28.69	-100.95	-11.78	-19.87
15		-3.12	7.88	-3.90	14.36	-7.81	73.48	42.25	-38.21	-22.89	-22.16
20		-56.68	-32.36	-6.02	23.45	-21.48	72.87	50.28	-24.10	-32.83	-24.03
25		-150.45	-103.71	-7.71	29.82	-33.26	72.31	55.73	-19.33	-42.18	-25.60
30		-301.51	-218.73	-9.10	34.64	-43.74	71.80	59.73	-17.48	-51.19	-26.97

e) Woodland trees

D at 30cm (cm)		*Eucalyptus populnea*	*Geijera parviflora*	*Eremophila mitchellii*	*Eucalyptus incrassata*
	record number	**33**	**34**	**35**	**44**
10		-80.56	18.57	59.36	78.03
20		-46.88	20.55	42.85	71.25
30		-31.32	21.07	29.94	40.14
40		-21.68	21.21	18.90	20.82
50		-14.86	21.19	9.07	8.34

Table 6 *continued*

f) Woodland shrubs

H (m)	***Geijera parviflora***	***Cassia nemophila***	***Dodonea viscosa***	***Eremophila mitchellii***	***Eucalyptus sturtii***	***Eucalyptus bowmanii***	***Myoporum deserti***	***Acacia aneura***
record number	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**
0.5	45.36	-13.50	80.00	29.76	12.51	-29.74	-53.01	10.89
1	27.64	-11.29	78.27	32.04	-3.53	-93.79	-43.30	39.93
1.5	14.11	-16.01	76.23	32.60	-15.00	-147.49	-40.37	52.12
2	2.71	-21.92	74.27	32.70	-24.26	-195.26	-39.35	59.17
2.5	-7.35	-27.99	72.41	32.61	-32.15	-239.02	-39.11	63.88
3	-16.46	-33.91	70.66	32.44	-39.09	-279.81	-39.25	67.30
3.5	-24.85	-39.62	69.01	32.23	-45.34	-318.26	-39.59	69.93
4	-32.68	-45.09	67.44	31.99	-51.05	-354.83	-40.04	72.03

Table 7: Total Biomass (t/ha^{-1}) calculated for each record from a population of trees using datasets with normal, positive and negative skew distributions and different mean tree sizes.

a) Native sclerophyll forest

(calculated from a test data set of a randomly selected trees with a DBH range from 1 to 100 cm and constant total BA of 22 m2 ha-1)

				E. obliqua	***E. amygdalina***	***E.pilularis 14 years***	***E.pilularis 45 years***	***E.pilularis up to 500 yrs***	***E. intermedia 14 years***	***E. maculata E. pilularis E. botryoides***	***E. sieberi E. regnans***	***E. regnans***
distribution	**mean DBH (cm)**	**number of trees**	**record number**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**10**
normal	50.9	100		156.6	124.0	175.5	232.5	247.8	131.1	312.8	216.9	547.1
negative skew	29.7	246		141.2	118.9	155.6	196.0	208.4	112.2	267.4	186.5	494.6
positive skew	71.4	51		168.2	125.5	191.7	269.0	287.6	149.0	356.0	245.3	929.5

	E. obliqua	***E. dives*** **wet, fertile**	***E. pauciflora*** **wet, infertile**	***E. obliqua*** **dry, fertile**	***E. obliqua*** **dry, infertile**	***E. obliqua***	***E. obliqua***	***E. pilularis***	***E. delegatensis***	***E. muellerana***	***E. agglomerata***	***E. sieberi***
record number	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
	180.3	577.0	155.6	184.7	139.3	155.7	200.7	228.9	186.5	185.9	198.7	225.6
	214.6	479.4	138.9	169.9	118.3	140.7	172.4	197.6	163.3	158.1	173.6	183.9
	149.9	630.8	168.9	194.5	159.8	166.7	227.2	243.4	206.7	198.5	202.9	256.8

b) Rainforest

(calculated from a test data set of randomly selected trees with DBH range of 1 to 100 cm and a total BA of 22 m2 ha-1)

distribution	mean DBH (cm)	number of trees		wet tropical	moist tropical	dry tropical	temperate	subtropical
			record number	27	28	29	30	32
normal	50.9	100.0		167.5	283.3	149.9	266.0	152.0
negative skew	29.7	246.0		157.0	259.7	135.3	238.3	137.4
positive skew	71.4	51.0		169.6	290.5	155.4	287.5	162.7

c) Native species plantations

(calculated from a test data set of randomly selected trees with DBH range of 1 to 40 cm and a constant total BA of 18 m2 ha-1)

E. grandis

distribution	mean DBH (cm)	number of trees	age (years)	1.9	2	2.3	2.8	5	6	10	12	15	16	27
			record number	94	63	95	96	64	65	66	67	68	69	70
normal	19.6	1000		97.9	151.8	275.3	244.5	194.2	196.8	248.3	415.3	254.9	275.3	386.8
negative skew	12.9	2184		102.9	137.4	213.0	185.5	158.2	172.4	195.1	286.1	205.0	213.0	301.5
positive skew	26.2	584		94.3	162.1	329.3	296.6	223.7	215.2	293.6	542.6	296.3	329.3	460.2

E. globulus

distribution	mean DBH (cm)	number of trees	age/ treatment	2-all	4-C	4-N1P1	4-N2P2	4-N3P3	6-C	^-N1P1	6-N2P2	6-N3P3	9.5-C	9.5-N1P1	9.5-N2P2	9.5-N3P3
			record number	72	73	74	75	76	77	78	79	80	81	82	83	84
normal	19.6	1000		31.4	25.1	30.3	30.9	35.8	32.1	42.7	31.4	31.4	42.8	42.6	45.1	40.0
negative skew	12.9	2184		31.7	25.5	29.1	30.7	35.2	30.8	35.7	31.7	32.1	36.9	36.8	38.9	34.5
positive skew	26.2	584		31.2	24.9	30.6	30.9	35.9	32.8	48.4	31.2	30.8	47.3	46.9	49.7	44.2

E. maculata / moluccana

distribution	mean DBH (cm)	number of trees		*E. moluccana* planted	*E. maculata* planted	*E. maculata* regen.
			record number	58	57	61
normal	19.6	1000		248.9	133.5	68.0
negative skew	12.9	2184		181.1	135.6	73.9
positive skew	26.2	584		289.2	131.6	64.0

Other species

distribution	mean DBH (cm)	number of trees		A. falcata	A. filicifolia	A. longifolia	A. saligna	Allocasuarina	Melaleuca
			record number	49	50	51	52	53	62
normal	19.6	1000		180.4	184.6	51.7	47.1	103.4	233.8
negative skew	12.9	2184		161.3	156.8	47.0	44.2	109.3	194.1
positive skew	26.2	584		194.3	206.2	54.9	49.0	99.2	265.7

EFFECTS OF ENVIRONMENTAL CONDITIONS, SPECIES, AGE AND GROWTH FORM OF TREES ON ALLOMETRIC RELATIONSHIPS

A range of responses in allometric relationships to these factors has been reported. Most information comes from plantations with experimental treatments designed to test specific factors, but some come from native sites where individual factors vary. Comparison of these studies may allow some general conclusions about key factors and trends.

In a native eucalypt forest, no significant difference occurred in the allometric relationships between pole and mature-aged stands for any of the components, and there was a difference for foliage only between the sapling and pole stands (Applegate 1982). The difference in foliage mass was probably due to branch suppression and fewer leaves in older stands. Two species at the sapling site, *E. intermedia* (bloodwood) and *E. pilularis* (blackbutt), had significantly different equations for total aboveground mass. Measured biomass of other species at the site showed that some individual trees were outside the 95% confidence limits of the *E. pilularis* equation.

The growth response of *P. radiata* to multiple applications of N fertilizer was an increase in total biomass but a 2-fold increase in foliage biomass due to greater retention of foliage. There was no difference in the stem form factor between fertilized and unfertilized trees (Neilsen *et al.* 1992). Similarly, Snowdon (1985) found that the effect of fertilizer treatments on the allometric equations for *P. radiata* was that of no significant difference for stem biomass, but a difference in regression intercepts for the crown, and different intercepts and slopes for root mass. Other studies, too, have found that site and treatment affected the relationship between DBH and crown biomass but not stem mass (Birk 1992, Cromer *et al.* 1985 and Snowdon and Benson 1992). The main effect of irrigation was to reduce the proportion of foliage and increase that to stems, and the effect of fertilization was to increase the proportion to branches and foliage and reduce that to stems. This suggests that the canopy is more sensitive to nutrient availability than the stem. However, Baker and Attiwill (1985) found that two *P. radiata* stands had similar allometric relationships for canopy components despite growing at sites with different soil fertility status. No significant effect of nutrient availability on partitioning of biomass and allometric relationships have been found at other sites, for example, in young *E. grandis* and *P. radiata* plantations (O'Brien 1998), in *E. grandis* plantations, and comparing plantations and native forest (Birk and Turner 1992). Nutrient availability in terms of both fertilizer addition treatments and sites with different soil types influenced tree form and proportions of components in young *E. globulus* plantations, but did not significantly affect allometric equations (Bennett *et al.* 1997). However, the lack of detection of differences may have been due to low sample numbers.

The main effect of increased nutrients is to increase the rate of growth and hence the stage of ontogeny for given tree ages. This stage is reflected in the rate of canopy development, time to canopy closure and growth rate of the bole. Partitioning of biomass components changes with respect to ontogeny. Hence, comparison between treatments is equivalent to comparison at different ages. Distribution of biomass among components varies greatly with tree age, particularly at the time of canopy closure. This was observed in plantations of both *P. radiata* and *E. globulus* (Cromer and Williams 1982, Cromer *et al.* 1985). Effects of fertilizer treatment decreased with tree age. When all trees had a mature structure and inter-tree competition assumed importance, the growth curves from different treatments tended to become parallel. A common equation could be used for all treatments in *E. globulus* after 9.5 years.

After canopy closure in pine plantations, Forrest (1969) and Stewart *et al.* (1981) suggest that the weight of foliage is relatively uniform, at approximately 10 t ha^{-1} , over a range of site

Table 7 *continued*

d) Pine plantations

(calculated from a test data set of randomly selected trees with DBH range of 1 to 30 cm and a constant total BA of 18 m^2 ha-1)

distribution	**mean DBH (cm)**	**number of trees**	**reference years**	**O'Brien 2.3**	**O'Brien 2.9**	**Forrest 4**	**Forrest 7**	**Forrest 9**	**Cromer 10**	**Forrest 12**	**Williams 12**	**Birk 21**	**Baker 9 to 28**
			record number	**122**	**123**	**111**	**112**	**113**	**108**	**114**	**127**	**106**	**105**
normal	14.6	1000		71.8	63.0	35.0	71.0	52.4	17.1	66.0	88.2	80.8	77.8
negative skew	9.6	2201		55.1	50.4	38.4	57.8	54.8	15.4	59.5	129.3	69.2	70.6
positive skew	19.5	582		103.9	88.2	32.7	81.7	50.5	18.3	70.6	81.4	89.8	83.0

e)Woodland trees

(calculated from a test data set of randomly selected trees with diameter (at 30 cm) range of 1 to 50 cm and a total BA of 5.5 $m^2 ha^{-1}$)

distribution	**mean DBH (cm)**	**number of trees**	**reference years**	***Eucalyptus populnea***	***Geijera parviflora***	***Eremophila mitchellii***	***Geijera parviflora***	***Cassia nemophila***
			record number	**33**	**34**	**35**	**36**	**37**
normal	25.2	100.0		28.9	17.1	15.0	3.32	4.15
negative skew	14.6	249		29.4	16.7	12.9	2.30	3.11
positive skew	35.4	51		26.8	17.0	17.0	4.31	5.10

f) Woodland shrubs

(calculated from a test data set of randomly selected shrubs with height range 0.1 to 4 m)

distribution	**mean height (m)**	**number of shrubs**		***Dodonea viscosa***	***Eremophila mitchellii***	***Eucalyptus sturtii***	***Eucalyptus bowmanii***	***Myoporum deserti***	***Acacia aneura***	***Eucalyptus incrassata***
			record number	**38**	**39**	**40**	**41**	**42**	**43**	**44**
normal	1.91	1000		0.88	2.20	4.16	10.16	4.56	1.27	30.5
negative skew	1.28	2114		0.64	1.70	3.00	6.79	3.56	1.15	28.7
positive skew	2.53	594		1.11	2.63	5.24	13.60	5.43	1.36	31.0

conditions (except poor site quality sites) and stand age. For example, in *P. radiata* stands planted on a range of site qualities, foliage mass was similar but there were large differences in aboveground mass and the proportion of stem and branch mass (Birk 1992). Trees at a high fertility site had a high proportion of branches and low proportion of stem, and hence a relatively low merchantable volume although total aboveground mass was the highest. Total weight of branchwood increased with age and was highly dependent on stand density. However, Siemon *et al.* (1980) found that stand density, manipulated by thinning in plantations, did not affect allometric relationships between DBH and foliage mass of individual trees, but did affect the total amount of foliage with a range from 4.9 to 11.3 t ha^{-1} in pine plantations.

Differences in growth form of trees at a site are sometimes related to successional stage. Claussen and Maycock (1995) found that there was no significant difference in stem geometry, defined by the relationship between height and diameter, in rainforest trees of the same successional stage, but the stages were different. Stem geometry is influenced by a tree's life-span, wood density and environmental conditions in the crown region. In tall trees, early successsional species exhibit a low stability safety margin while late successional species have moderate stability safety margins due to their greater diameter per unit height. In forests with complex structure, such as rainforests, allometric equations will be required for each growth form.

Genetic effects on allometric relationships occur between species and families. The effect of genetic control was demonstrated in 3 to 4-year-old *P. radiata* where the greatest differences in allometric relationships were due to family, rather than fertilizer treatment or site preparation (Snowdon 1985, and Snowdon and Waring 1985). Crown and root mass were affected more than stem mass by family and fertilizer treatment, for example a 17% and 8% difference in foliage and root mass, respectively, due to fertilizer treatment, and a 59% and 41% difference in foliage and root mass, respectively, due to families. The main characteristics of the tree that were affected included shape of stems, wood density, crown shape and proportion of root mass. The branch-to-stem ratio ranged from 0.215 to 0.505, and the root-to-shoot ratio ranged from 0.154 to 0.199.

USE OF DIFFERENT INDEPENDENT VARIABLES AND FORMS OF THE EQUATION

Many variables have been used in allometric equations, as described in the section on sources of data. Variables are selected to provide the best estimation of the biomass data at the site. However, if the equations are to be used to estimate biomass over a broad area based on dimension variables measured in inventories, then the equation must use standard variables that are widely available.

DBH is the most widely available variable and was recommended by Pardé (1980) in a review of forest biomass. However, the relationship between diameter and height often varies over the range of a species depending on site conditions, and so general equations would be better to include both DBH and height (Wharton and Griffith 1993). Individual tree measurements of height are not usually available in standard inventories. A possible solution is to develop DBH – height relationships for the range of conditions of the species' occurrence.

The optimum independent variables for estimating biomass of shrubs can differ according to plant structure (Harrington 1979). Diameter measurements are usually near ground level to avoid branching of the stem. Height is often a good variable especially when there are multiple stems, but it is not suitable for taller shrubs with a weeping habit. Canopy width can be a good variable for spreading shrubs.

Madgwick (1994) compared different forms of the allometric equation; ln(stem volume), $\ln((DBH + c)^2 . H)$, ln(DBH), ln(H); and found that all accounted for a high proportion of the variance. Pardé (1980) recommended a log/log (or natural log) form of the equation. A logarithmic transformation of the data is often required to satisfy the condition of homoscedasticity for the regression analysis.

Ter-Mikaelian and Korzukhin (1997) investigated biomass equations for 65 North American species and concluded that the logarithmic form of the allometric equation with an independent variable of DBH was preferred because it provided a good balance of accurate prediction and low data requirements. Inclusion of other variables did not usually lead to substantial increases in R^2 or decrease in the standard error of the estimate.

The best regression fit for biomass equations may vary with tree age; reflecting the change in allometric relationships from the indeterminate growth stage to growth under the influence of competition from surrounding trees. This was illustrated in *E. globulus* plantations where a linear model provided the best fit at ages 2 and 4 years and a logarithmic model at ages 6 and 9.5 years (Cromer and Williams 1982).

One of the main characteristics of the allometric equation that should be considered is the form of the curve beyond the size range of the data. Polynomial and exponential functions, for example, can produce unusual results when extrapolated. Functions with more conservative forms and slopes are preferable.

USE OF GENERAL ALLOMETRIC EQUATIONS

The use of general equations to predict biomass has been investigated in other countries. Jacobs and Monteith (1981) compared weight tables for a range of species and regions in the USA and concluded that allometric relationships may be stable for some species over wide geographical regions, but not for other species. Pastor *et al.* (1984) cite several studies from the USA that showed that equations were similar for one species developed at different sites, and that equations for total aboveground mass were similar although partitioning of biomass among components varied (Tritton and Hornbeck 1981, Bickelhaupt *et al.* 1973, Schmitt and Grigal 1981). Pastor *et al.* (1984) found that general equations accounted for > 95% of the variation in prediction by the original equations. The estimates of relative error were < 5% of the mean Y value predicted by the general equations, whereas the relative error between the original equations and data sets were 10 – 30%. The mean difference between values predicted by the general and original equations for total aboveground mass was generally 10 – 15%, but was 39% for one species. Pastor *et al.* (1984) consider that these studies provide some justification and precedence for using allometric equations developed at one site for other areas. The general equation was best for total aboveground biomass rather than a summation of biomass components. A similar method for deriving and testing general equations was used by Brand and Smith (1985) for several tall shrub species in North America. They found that 89 – 98% of the variation in the combined data was explained by the general equation. Buech and Rugg (1989) also assessed biomass relations for tall shrubs in North America and concluded that species and site specific equations were significantly more accurate, but general equations could provide satisfactory estimates of total biomass. The R^2 was reduced by less than 0.01 in most cases but up to 0.2 for leaves and twigs for the general equation and the root mean square error was reduced by less than 15%. Cannell (1984) assessed the biomass relationships of 640 stands and divided these into 32 species groups, each of which had significantly different regression coefficients. Differences between the species groups were due to wood density (particularly separating conifers and broadleaved species), and proportion of branches.

Biomass of tropical rainforests has been estimated in several studies and the feasibility of using generalised allometric equations assessed. Crow (1977) found no significant difference in equations to predict total aboveground biomass between forest types of similar stem form and wood density in Thailand and Puerto Rica. Error terms associated with estimates of branch and leaf mass were much greater than that for stem or total aboveground mass. Crow (1977) suggested that a general allometric equation for total aboveground biomass might have wide application, but that such general equations for individual components are not as appropriate. Brown *et al.* (1989) concluded that general allometric equations could be developed for life zones or vegetation types within tropical forests, but that there were significant differences between these types.

Madgwick *et al.* (1991) collated data on biomass density of eucalypts at the stand level from 136 stands including 22 species and ranging in age from 1 to 100 years old. They found a similar relationship for stem mass with basal area and maximum height across all stands. There were some significant differences due to species, but these were not related to wood density. Biomass data for four fast-growing plantation eucalypts (*E. regnans, E. delegatensis, E. nitens* and *E. grandis*) were combined and the variance assessed for the combined equation compared with the individual equations (West *et al.* 1991). The 95% confidence interval for the DBH variable was ±16% for estimates of biomass for individual trees and ±5% for mean trees, and for the height variable was ±23% for individual trees and ±7% for mean trees. Allometric equations for E. obliqua were compared among subgroups of the data based on tree age, crown class and site quality within a region, and no significant differences were detected (Attiwill 1966).

Allometric equations derived from data from eucalypt plantations in New Zealand were tested against independent data for the same species at other sites (Madgwick *et al.* 1991). Predicted values were within 8% of measurements in Brazil, 4.5 to 75% of measurements at an independent site in New Zealand, and 20 to 40% of measurements in South Africa. Differences between sites were considered to be mainly due to nutrient availability. Four species were tested in the plantations, *E. fastigata, E. nitens, E. regnans, E. saligna,* and there were some significant differences between species in the regression constants for individual components, although the absolute differences were not large.

Allometric equations for crown components of eucalypts based on diameter of primary branches showed similar relationships for different tree ages and site environmental conditions (Curtin 1969). Curtin (1969) concluded that the relative dimensions of primary branches are quite stable under a range of conditions, even though the absolute dimensions respond to the conditions.

Madgwick (1994) considered that general equations for canopy components of *P. radiata* were of limited value because the relationship between tree size and canopy component mass was highly variable in relation to environmental conditions, genetic factors, dominance class of the tree, stand density and age, and seasonal variations in growth. Even general equations for stems can be biased from –50% to +100% when applied to specific sites.

Estimated biomass of *P. radiata* at sites in Gippsland differed between regions and from the general equation for the species (Madgwick 1983), by 10-40%, which reflected differences in environmental and silvicultural conditions (Baker *et al.* 1984). However, combining data from the six sites in Gippsland resulted in only a small increase in the error term and coefficient of determination. The greatest difference across the sites was in foliage mass. Baker *et al.* (1984) recommend that general biomass equations could be developed for regions, but that a continental wide equation for *P. radiata* was not feasible.

Estimating biomass of shrub species using general allometric equations was assessed by Brown (1976) for 25 species in the USA. The coefficient of variation was 60 to 340% across 12 stands. Separate equations for groups of shrubs (low, medium and high height) differed significantly from the general equation. In Australian chenopod shrublands, Andrew *et al.* (1979) found that biomass density was most accurately estimated by counting the number of standard units of biomass (the "Adelaide technique") rather than by dimension analysis. If dimension analysis was used the best independent variable was canopy volume (length x width x height).

ESTIMATION OF BIOMASS WITHOUT INVENTORY DATA

The methods described to apply allometric equations in the spatial prediction of biomass will not be possible in vegetation types where inventory plot data of tree dimension measurements are not available, such as non-commercial forest types, young regrowth, reserves and woodlands. In these regions, collection of some plot data will be required together with development of general relationships between vegetation structure and biomass. Vegetation structure needs to be characterised in terms of growth form of trees and stocking and size distribution in the stands. This may be achieved by interpretation of aerial photographs or remote sensing images. Additional work will be required to calibrate existing estimates of biomass from vegetation types where allometric equations and inventory data exist to vegetation types of different structure. Information from plantations, in terms of allometric relationships and size class distributions, could be applied to young regrowth forests to estimate biomass of stands of known age and mean size.

ESTIMATING BELOWGROUND BIOMASS

A few allometric equations have been derived that relate root mass, volume or total mass to DBH (records 3-5, 7, 30, 110, 116-117, 128 from 5 references in Table 2). Comparison of equations from different sites show some similarities. Jackson and Chittenden (1981) combined data for *P. radiata* from their own sites in New Zealand with that published by Ovington *et al.* (1967) and Dargavel (1970) in Australia and Heth and Donald (1978) from South Africa covering an age range from 8 to 39 years (record 117 in Table 3). This data could be fitted to a single regression line. When Watson and O'Loughlin (1990) compared their data with the above combined equation they found that their data was within the 95% confidence limits of the Heth and Donald (1978) data but was consistently higher than the combined equation. They suggested that their greater root mass was likely due to their more efficient hydraulic extraction technique. However, there are insufficient data and equations to extrapolate generally to other vegetation types and regions.

Estimates of belowground biomass will probably have to be based on below-to-aboveground biomass ratios that are constrained by upper and lower limits, and vary in response to factors that control partitioning of biomass. The range of values of the ratio has been estimated for various vegetation types; 0.11 to 0.67 for world forests by MacDicken (1997), 0.04 to 0.69 for boreal to tropical forests by (Vogt *et al.* 1996) who collated 200 datasets, 0.18 to 0.43 for broadleafed forest by Bazilevich and Rodin (1968), and 0.03 to 0.49 for tropical and subtropical forests with a range in root mass of 11 to 130 t ha^{-1} by Brown (1997) and Vogt *et al.* (1997). In a global analysis of root distribution, Jackson *et al.* (1996) found that root mass varied from 0.2 to 5 kg m^{-2} across biomes, with the highest biomass in tropical evergreen forests, then other forest types and sclerophyllous shrublands. Root:shoot ratios varied from 4 – 7 in deserts and grasslands to 0.1 – 0.5 in forests. The proportion of root mass at depths in the soil profile varied across biomes and plant functional groups, so that a standard depth of sampling could not be used.

The default value for the below-to above-ground ratio used in the Greenhouse Challenge Vegetation Sinks Workbook (1998) is 0.2. The default value used in the National Greenhouse Gas Inventory Workbook 2 (1997) is 0.25 for all forest classes, which is based on reports in Cooper (1983) and Ulrich *et al.* (1981). Records of below-to-aboveground biomass ratios that have been published in the literature are summarised in Table 8.

Table 8: Review of estimated ratios of below-to-aboveground biomass from the literature.

reference	vegetation type / species		ratio
Applegate (1982)	native eucalypt forest	- sapling	0.47
		- pole	0.33
		- old growth	0.10
Ash and Helman (1990)	wet sclerophyll forest	- sapling	0.22
		- large trees	0.14
Crockford and Richardson (1998)	*E. rossii* native forest	(DBH 15, 18, 25 cm)	0.30, 0.32, 0.37
Feller (1980)	native forest	- *E. regnans*	0.102
		- *E. obliqua*	0.122
Keith *et al.* (unpubl.)	*E. globulus* plantation	- 2 year old unfertilized	1.94
		- 2 year old P fertilized	0.64
	E. sieberi regrowth	- 5.5 year old unfertilized	1.50
		- 5.5 year old P fertilized	0.41
Misra et al (1998)	*E. nitens* plantation	- 3 year old	0.28 – 0.44
Specht et al (1957)	heathland	- 25 years old	0.68
Groves and Specht (1965)	heathland	- dry	0.59
		- wet	0.36
Beets and Pollock (1987)	*P. radiata* plantation	- 6 years old	0.50
		- 12 years old	0.20
Madgwick (1994)	*P. radiata* plantations	(1 to 42 years old)	0.12 – 0.67
Ryan *et al.* (1996)	*P. radiata* plantation	(irrigation and fertilizer)	0.24 – 0.29
Briggs (1977)	*Avicennia marina*	(temperate mangrove)	1.02 – 1.41
Brown (1997)	tropical forest	- range	0.04 – 2.3
		- averages for 4 forest types	0.12, 0.22, 0.47, 1.5
Pardé (1980) citing Overend (1978)	spruce forest- mature	0.11 – 0.25	
citing Mitscherlich (1975)	oak forest	- 1 year old	2.85
		- 50 years old	0.27

The large range in this ratio and the differences with forest type indicate the difference that estimates of belowground biomass can make to the total biomass. A constant ratio for all vegetation types, ages and environmental conditions is an oversimplification.

The ratio of below-to-aboveground biomass changes in response to environmental conditions that affect the relative limitations to growth by assimilation by the canopy, or by water and nutrient uptake by roots. The general response is of decreased C allocation belowground with increased nutrient and / or water availability (Keyes and Grier 1981, Kurz 1989, Vogt *et al.* 1990, Gower *et al.* 1992,1994). The change in C allocation belowground influences both rates of root turnover and the standing crop of root biomass (Nadelhoffer *et al.* 1985, Pregitzer *et al.* 1993).

Specht (1981) investigated general trends in the ratio in relation to climatic zones by summarising data collated by Bazilevich and Rodin (1968). A negative curvilinear relationship was defined between total biomass and the ratio of below-to-total biomass, with approximately 20% of biomass belowground in humid regions and up to 85% belowground in arid regions. The general trend was for an increase in the proportion of biomass belowground as growing conditions decreased. The shape of this response curve differed with vegetation type, with the ratio of below-to-aboveground mass generally lower in coniferous forests than broadleafed forests, but with a steeper response curve as total biomass increased.

Vogt *et al.* (1996) reviewed patterns of above- and belowground biomass from 200 published datasets from boreal to tropical zones in relation to climate, forest type, species and soil order. There were no significant or consistent patterns for above- and belowground biomass accumulation across the climatic forest types or by soil order. All forest types had broad ranges of partitioning belowground with no clear trends at this scale. This result suggested that this level of grouping did not reflect the variables that control the amount of total or fine root biomass maintained in an ecosystem. Climatic variables and nutrient pools are the important controlling factors in determining the amount of fine root biomass maintained at a site. Species groups within the broad forest types varied in their sensitivity to water and nutrient availability. Variables that were correlated with fine root biomass at a site included mean annual temperature, temperature:precipitation ratio, soil nitrogen mineralization rates, nitrate production rates, litterfall nitrogen and calcium concentration, and forest floor nitrogen mean residence time. The ability of these variables to explain fine root biomass and dynamics varied with climatic region and forest type. Predictive variables changed depending on the scale of the analysis, for example climatic zones, evergreen versus deciduous forest, species groups. The most useful predictive variables were not transferable among groupings; this indicated that adaptive strategies varied significantly by functional or species groups. Derivation of responses to environmental variables depends on identifying the most appropriate functional groups at different scales.

Examples of trends in the below- to- aboveground biomass ratio have been observed in response to specific environmental factors. Changes in biomass along a water availability gradient were investigated by Schulze *et al.* (1996) in Patagonia. The below-to-aboveground ratio changed from 0.44 in mesic forest, to 1.26 in scrub, and 2.20 in desert scrub with a change in total biomass from 48.9 to 0.47 kg m^{-2}.

The ratio may change with age or growth stage of the plant. Kurz *et al.* (1996) described a curvilinear relationship, with a decrease in the ratio with accumulation of aboveground biomass. Younger trees usually have a higher ratio, but there is not always a consistent trend with age.

Partitioning of below- and aboveground biomass is not exclusively linked to factors that control overall productivity and balancing resource acquisition. Root biomass and distribution are also related to soil physical and chemical properties that enhance or restrict root proliferation. For example, root distribution was investigated in *P. radiata* plantations of similar age and climatic conditions but different soil types (Davis *et al.* 1983). Fine root length density varied 4.5-fold and was related to organic matter content, soil depth, and extractable P concentration. A complex interaction between bulk density, aeration and soil strength affected root growth and distribution.

Many examples have been reported of extensive root systems in response to environmental conditions and genotypic differences that illustrate the great variations that exist in below- to- aboveground biomass ratios. The maximum extent of roots reported is 8 m vertically for *P. radiata* with several reports of 2 – 4 m, and 60 m for eucalypts in karst landscapes and 40 m in regolith with up to a 30 m radius (Stone and Kalisz 1991). The extent of roots depends on soil properties, aeration, regolith, water table, climate and species. Deep roots are particularly important for water uptake in arid or seasonally dry environments, but may also be important for uptake of some nutrients from the subsoil.

The effect of species on root distribution was illustrated by comparing species grown under the same experimental conditions, where *E. camaldulensis* had up to a 10-fold greater root mass than eucalypt species originating from mesic environments (Forence 1996). Differences have also been observed among subgenera of Eucalyptus, for example Monocalyptus species (*E. regnans* and *E. delegatensis*) had shallow roots and Symphyomyrtus species (*E. globulus* and *E. nitens*) had deeper roots with tap and sinker roots (Turnbull *et al.* 1993). Variations in root characteristics of pines were observed in relation to genotype x site interactions (Theodorou *et al.* 1991).

General patterns of root:shoot ratios do not account for lignotubers and trees that regenerate from rootstocks in water and / or nutrient limited environments. Many eucalypts form lignotubers or root stocks that represent large underground pools of biomass. The extent and size of lignotubers increase with the harshness of environmental condition, and are developed best in mallees and infertile coastal areas. Size of the lignotuber often is not related to size of the aboveground tree because the lignotuber may persist through many cycles of resprouting. Lignotubers are often a plate-like form and have been measured up to 6 m in diameter (Lacey 1983).

Estimates of root mass from many studies are likely to be underestimates because they do not include excavation of the root bole, roots directly beneath the trunk and depth of sampling is less than the extent of the root system. Fine root mass has a rapid turnover rate and the standing crop amount depends on current soil conditions, particularly moisture. Hence, time of sampling can have a large effect on the fine root mass measured.

The factors influencing belowground biomass differ between the structural and functional components. Structural components of the plant, coarse roots and stem, are correlated well in most cases (Kurz *et al.* 1996). Fine root biomass is often calculated as a small proportion of total biomass, but soil properties are an important factor controlling fine root growth and turnover. Additionally, fine root mass as a proportion of total mass decreases with tree age.

The method of linking below- and aboveground biomass for prediction of total biomass was used in the Canadian C budget model for the forest sector (Kurz *et al.* 1996). Total root mass was estimated using regression models that incorporated aboveground biomass as an independent variable. The relationship was derived from data collated from temperate and boreal ecosystems in North America, USSR, northern and central Europe and New Zealand that provided 345 points for above- and belowground biomass. The relationship was linear for softwoods ($R^2 = 0.72$) and logarithmic for hardwoods ($R^2 = 0.77$). The range in predicted root biomass was 19% and 17 – 36% of total biomass for softwoods and hardwoods, respectively. If aboveground biomass of hardwoods was low (< 2.7 t ha^{-1}), then predicted root mass would be greater than aboveground mass. Improved understanding of the reason for differences in this relationship between species groups will aid their general use for biomass prediction. Fine root biomass was estimated as a proportion of total root biomass, based on 16 data points. However, the correlation was poor ($R^2 = 0.28$) and the relationship was negative logarithmic. Hence, belowground biomass was linked to aboveground biomass, and the latter could be estimated from data on stand characteristics derived from national forest inventory. These estimates were used to predict average values and were not to be used to predict specific ecosystem values, where species, site and stand characteristics have a major influence.

ESTIMATING BIOMASS OF STANDING DEAD TREES

The term biomass usually refers to the amount of living organic matter in vegetation. However, dead organic material also represents a C store, although it decreases over time as decomposition occurs.

Biomass of dead standing trees can be estimated from allometric equations for stemwood. However, the result will be an overestimate if the top of the stem is broken off or there are hollows, fire scars and decayed wood in the stem.

The amount of dead wood in a stand is extremely variable and depends on stand age and density, disturbance, management practices and climate. Feller (1980) estimated that 23 to 34% of standing stems were dead in 38-year-old *E. regnans and E. obliqua* forests and this represented 3 to 5% of live aboveground biomass. Brown (1997) estimated that dead wood in tropical forests, both standing and fallen, could represent 50% or more of the living aboveground mass in some forests.

UNCERTAINTY IN ESTIMATION OF BIOMASS

Estimating the uncertainties of regional biomass density derived from upscaling of tree mass predictions from allometric equations on forest plots has difficulties. A large component of these difficulties is due to the fact that allometric equations were developed for a different purpose than for quantifying total above- and belowground biomass at a regional scale. Consequently, important statistical information required to accurately quantify these uncertainties, such as sample variability and independence of measurements, are unknown. For example, the absence of information about correlations between tree components (i.e. between branch, root and leaf tissues) makes accurate quantification of the variance term impossible for the calculation of total biomass from the sum of the components. However, with some assumptions about the sources of the majority of variance and about the independence of samples at the plot scale, an approximation of the uncertainty of the predictions of regional biomass from allometric equations can be made.

The standard deviation (i.e. $\sqrt{\text{variance}}$) of the predicted value is usually obtained from output of the regression analysis. Confidence intervals (i.e. a quantitative estimate of uncertainty) of the predicted value for biomass is calculated from the product of the test statistic and the standard deviation. When biomass is estimated from an allometric equation of the logarithmic form, confidence intervals are calculated as the product of the test statistic (usually *t*-value) and the *ln*-transformed standard deviation, which is then added to or subtracted from the mean, prior to applying the exponential back-transformation. This results in an asymmetric distribution of the confidence intervals about the predicted value. Due to the non-equivalence of ln-transformed and linear standard deviations, in order to obtain upper and lower confidence intervals of the total single tree biomass from separate equations for each component, it is necessary to back-transform all the predictions of component biomass, sum these component biomasses, re-apply the transformation, add and subtract the product of the test statistic and sum of standard deviations for all components to the summed value and then once again apply the back-transform. This method is only approximate given that no covariance terms are calculated as explained below. Thus, it is not possible to compare directly studies where different forms of allometric equations have been used. Calculation of variance is considered here at each of the four levels of tree, plot, strata and region.

1. Calculation of total tree biomass is achieved by summing the component biomasses estimated from allometric equations. If it can be assumed that biomass components are independent, calculation of total variance of the sum of all components is equal to the sum of the component

variances (Item (1) Table 4). However, within any individual tree the component leaves, branches and bole are not likely to be independent (i.e. an increase in the predicted biomass of the tree bole is very likely correlated with an increase in branch biomass). Thus, the calculation of total variance should include covariance terms for correlation between various tree components. Generally, this information is not available from published studies in the literature because neither these statistics nor the original data are presented. Summing of component variances will be an overestimate. However, calculation of accurate error terms for the combined components is beyond the scope of this analysis; it is a research issue that requires further work. In some cases, an allometric equation for the total aboveground or total biomass has been calculated from the original data, hence this step in calculation of a total and variance is not required. The example calculations in the case study demonstrate the difference in total variance when calculated from the sum of component variances compared with an equation that gives total biomass and its variance. The main source of error variance in the prediction of biomass of individual trees using the allometric equation is due to precision, which is related to the variability of data around the regression line.

2. Total biomass of the plot is the basic measurement unit of biomass density (i.e. t ha^{-1}) used in the upscaling process and is independent of the number of trees measured or the size of the plot. Total biomass and variance at the plot level is calculated by summation of the biomasses and variances for all trees on the plot. The DBH of every tree on the plot is measured and tree biomass estimated predicted using the allometric equations, so the value of total biomass density is estimated without error from the summation process. Biomass density is calculated on a per hectare basis by dividing the sum of biomasses of all trees by the plot area. It is assumed that plot area is measured without error (Item (2) Table 4). The population variability, in terms of size distribution and number of trees in the plot, affects the total plot biomass and variance. The effect of population distribution was shown in Table 7.

3. Plots within a stratum represent a sample from the total population of possible plots within the stratum. Biomass density of the stratum is estimated from the mean of all sample plots and the estimate of stratum variance as the average of within plot variances (Item (3) Table 4). Confidence intervals for stratum mean biomass density decrease with an increase in the number of plots. It is likely that the largest source of error in stratum biomass density arises from inadequate sample number and unrepresentative distribution of plots within strata. The variance at this level represents the error of an inference about the mean value based on a sample.

4. Regions are divided into a number of contiguous strata. Variance in the estimation of biomass for the whole region is calculated as the sum of variances of all strata within the region. The estimate of stratum area is likely to contain some, and possibly considerable, error because the areal extent of homogenous vegetation units is measured by remote means (e.g. by interpretation of orthophoto or remote sensing data). With these techniques, identification of strata boundaries is less accurate than area measurements at the plot scale. The size of the error due to area may be small relative to the variability of biomass density within a stratum, but may be considerable for some vegetation types where boundaries between strata are difficult to discern. Thus, the error due to

miscalculation of strata areas is included in the calculation of regional biomass (Item (4) Table 4). The variance of regional biomass is derived from first order uncertainty analysis. This involves generating the first-order partial derivatives of the inferred value, M_R, with respect to A_S and M_S (Cieszewski *et al.* 1996). Thus, the total error is calculated as the sensitivity of M_R $(\frac{\partial M_R}{\partial M_S} = A_S)$ to error in M_S (σ^2_{Ms}) plus the sensitivity of M_R $(\frac{\partial M_R}{\partial A_S} = M_S)$ to error in A_S (). Where strata areas are known accurately (i.e. $\sigma^2_{As} = 0$), the second term on the right hand side of the variance equation disappears, thus simplifying the calculation of variance.

There are several assumptions required in estimating variances at each scale. Violation of any of these assumptions can introduce bias into the prediction of biomass.

1. The trees that were harvested to derive the allometric equation are representative of the population of trees for which biomass is predicted, in terms of size and form. In many studies, trees have been selected to be healthy, undamaged, dominant or co-dominant and so may not be truly representative of the population. A small, suppressed tree in a mixed-aged forest has different partitioning and total biomass compared with a small young tree in an even-aged forest. Selection of trees should be random or stratified random in order to meet the requirements for statistical analysis. Subjective selection of trees may introduce bias into the allometric equation when used for predicting biomass at the plot scale.

2. Individual trees in plots for which biomass is estimated belong to the same population from which the allometric equation was derived (ie there exists no bias in the application of the equation). Considering the scarcity of allometric equations and the limited range of trees from which they were derived, it is likely that some bias will be introduced in their application. One of the main factors required is the adequate sampling of large trees within plots. Large trees contribute a high proportion to biomass density but they are often sparsely distributed and hence under-represented within plots. For example, Brown *et al.* (1995) demonstrated that forest plots > 0.2 ha were highly likely to result in unrepresentative sampling of a forest stratum.

3. An adequate number, size and distribution of plots exist throughout each stratum such that estimates of plot mean and variance of biomass density are representative of each stratum. The adequacy of such a sampling strategy of inventory plots is beyond the scope of this work.

Heterogeneity of vegetation within strata and inadequate sampling strategies to ensure representative cover of the stratum by inventory plots is likely the greatest source of variance in the estimation of biomass. For example, Gertner and Kohl (1992) demonstrated the strong sensitivity of national forest inventories to bias due to heterogeneity of plot level estimations. The location of plot inventory data is biased towards productive forest types and it is likely that for large areas of woody vegetation, particularly for the open woodlands and low forests of large areas of Australia, there are insufficient numbers and distribution of sample plots to assume an unbiased representation of strata biomass density.

5. Strata represent vegetation types of sufficient homogeneity that they can be estimated by a mean value of biomass density. Mapping of development or growth stages of forests using aerial photo interpretation may be required to stratify forests to obtain relatively homogenous units as has been demonstrated in karri forest by Bradshaw and Rayner (1997).

Table 9: Summary of formulae used to upscale mean and variance of whole tree biomass derived from the application of allometric equations to DBH measurements for the purpose of estimating regional C stocks in forest biomass.

Symbols:

M_C = mass of component (t)

M_T = mass of tree (t).

M_P = total plot biomass density (t ha-^{1})

M_S = mean stratum biomass density (t ha-^{1})

M_R = regional biomass (t).

A_P = plot area (ha).

A_S = stratum area (ha).

$\sigma^2{}_{M_C}$ = variance of the component biomass

$\sigma^2{}_{M_T}$ = variance in a single tree biomass

$\sigma^2{}_{M_P}$ = variance of a plot biomass

$\sigma^2{}_{M_S}$ = variance of stratum biomass

$\sigma^2{}_{M_R}$ = variance of regional biomass

Scale	units	Inference Mean Value	Inference Variance
1. Within tree	t	$M_T = \sum_{i=1}^{C} M_{C_i}$ i^{th} component c = number of components in the tree	$\sigma^2{}_{M_T} = \sum_{i=1}^{C} \sigma^2 M_{C_i}$
2. Within plot	t ha^{-1}	$M_P = \dfrac{\sum_{j=1}^{n} M_{T_j}}{A_P}$ j^{th} tree within plot n = number of trees within the plot	$\sigma^2{}_{M_P} = \sum_{j=1}^{n} \sigma^2{}_{M_{T_j}} / A_P$
3. Within strata	t ha^{-1}	$M_S = \dfrac{\sum_{k=1}^{m} M_{P_k}}{m}$ k^{th} plot within stratum m = number of plots within the stratum	$\sigma^2{}_{M_S} = \dfrac{\sum_{k=1}^{m} \sigma^2{}_{M_{P_k}}}{m}$
4. Within region	t	$M_R = \sum_{l=1}^{o} A_{Sl} M_{Sl}$ l^{th} stratum within region o = number of strata within the region	$\sigma^2{}_{M_R} = \sum_{l=1}^{o} \left[\left(A_{Sl} \sigma_{M_{Sl}} + \sigma_{A_{Sl}} M_{Sl} \right) \right]^2$

CASE STUDY

Biomass density was calculated for Bago State Forest, a Hardwood Management Area on the south-west slopes of NSW between Batlow and Tumbarumba. This provides an example of the calculations of biomass and variance based on the above equations and the type of data that would be available.

The total area of the forest is 31485 ha, of which 11556 ha or 36.7% is *E. delegatensis*, which is used for production timber. There are 18 Permanent Growth Plots (0.1 ha) within the production part of the forest. Inventory plots and allometric relationships are not available for the non-productive forest types. The *E. delegatensis* forest is considered one stratum within the region of the whole State Forest. The forest is selectively logged and thinned, which results in variations in stocking and basal area. An allometric equation is available for *E. delegatensis* (record 19 in Table 2), with equations for wood, bark, branches, twigs, leaves and total aboveground in ln/ln form. Biomass was calculated for each component separately and the total, the mean and variance were corrected for bias in the back-transformation (Baskerville 1972). Biomass was also calculated from stem volume, wood density and an expansion factor. The usual height data available in forest inventory data is dominant height for the site. Stem volume was calculated from individual tree DBH, site height and a volume equation for *E. delegatensis* (Bi and Hamilton 1998). A relationship between DBH and height of individual trees exists for *E. delegatensis* in this region (Kris Jacobsen unpubl. data). This information was also used to estimate stem volume for individual trees. An average wood density for the species was used of 620 kg m^{-3} (Bootle 1981). An expansion factor for stem mass-to-total mass of 1.43 was used as recommended in the Greenhouse Challenge Workbook (1998).

Results of the calculated biomass density are given in Table 9 for each PGP plot and the stratum mean. There was little difference (1.8%) in the estimate of mean plot biomass between calculations based on the equation for total biomass or summation of the components. Biomass calculated from volume (using individual tree height) and density is 23% greater than that calculated from the allometric equation, and using volume (site height) the estimate is 60% greater. Use of site height rather than individual tree height resulted in an overestimation of biomass on most plots.

The average plot variance for the estimation of biomass from the summation of components had a coefficient of variation of 35%, compared with 27% based on the total biomass equation (Item 1, Table 4). This reduction in variance represents the effect of correlation among components. The variance associated with taking the mean of a sample of plots had a coefficient of variation of 48%. Thus the variance at the plot level was highest, but both sources of variance were large.

Table 10: Estimated biomass density calculated by four methods for individual permanent growth plots and the stratum mean at Bago State Forest (all trees in 0.1 ha plots)

	biomass derived from allometric equations				biomass derived from volume and density	
plot	**sum of components**		**total aboveground biomass**		**(site height)**	**(tree height)**
PGP	**biomass (t/ha)**	**Std.Dev. (t/ha)**	**biomass (t/ha)**	**Std.Dev. (t/ha)**	**biomass (t/ha)**	**biomass (t/ha)**
1	549.8	192.2	563.0	149.5	1045.3	704.2
2	241.6	84.7	244.9	65.0	530.0	312.5
3	281.4	98.4	288.1	76.5	442.9	358.6
4	446.0	155.7	459.5	122.0	725.3	548.9
5	237.1	83.0	241.6	64.1	412.3	307.9
6	639.2	223.3	655.4	174.0	1073.2	749.5
7	280.3	98.3	283.9	75.4	511.8	354.4
8	256.3	90.0	258.2	68.5	525.6	340.7
9	396.8	138.6	407.7	108.2	424.0	462.6
10	151.7	53.3	152.3	40.4	275.6	178.6
11	308.0	107.4	318.6	84.6	257.7	330.3
12	243.5	85.3	244.1	64.8	476.2	325.6
13	417.3	146.4	421.1	111.8	672.5	554.6
14	241.2	84.8	242.2	64.3	398.6	315.3
15	109.0	39.1	110.2	29.3	210.9	149.7
16	215.9	75.3	222.7	59.1	209.8	251.2
17	107.6	34.9	108.3	28.8	180.4	142.9
18	211.8	74.3	213.8	56.8	337.0	279.0
mean	**296.4**	**103.6**	**302.0**	**80.2**	**483.8**	**370.4**
std. dev.	**143.2**		**147.6**		**258.6**	**172.3**

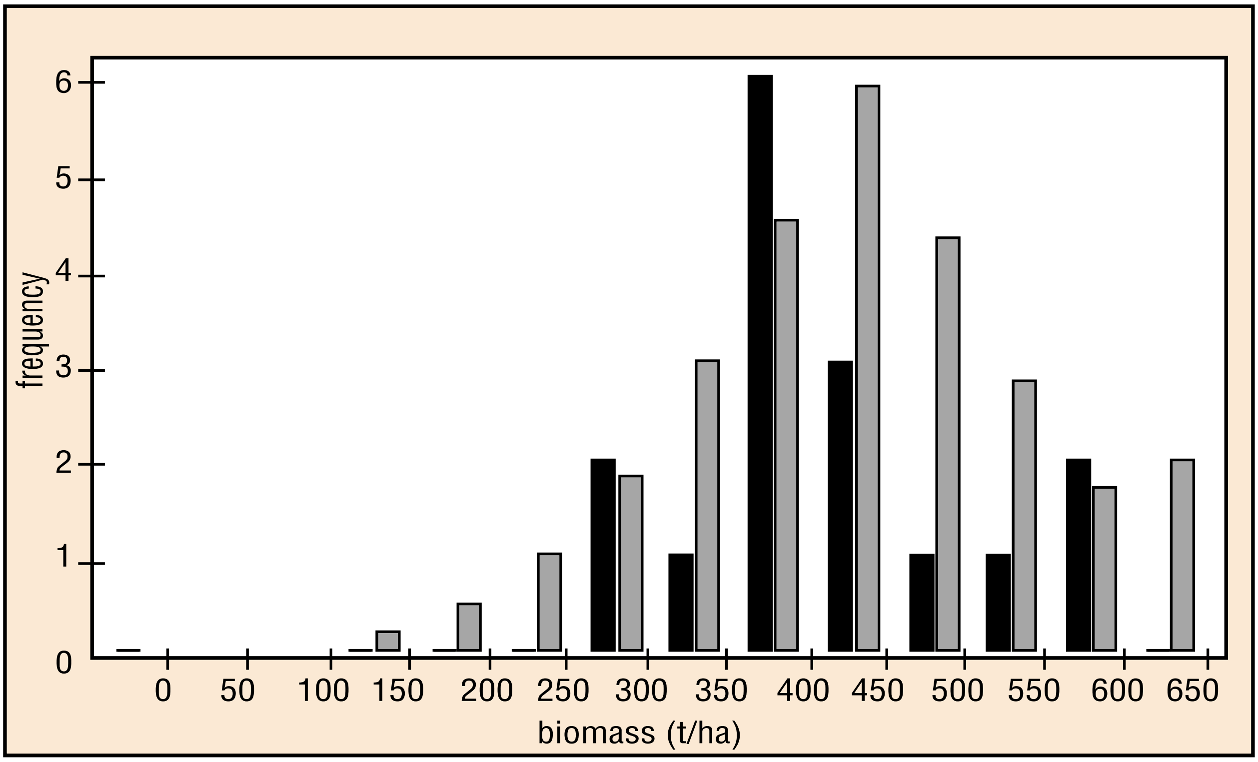


Figure 4: Frequency distribution of biomass density per plot for the 18 permanent growth plots (pale orange bars) compared with that of the theoretical normal distribution (pale blue bars).

The total biomass of the stratum was 4389 t with a variance of 1705 t, if the error associated with measurement of the stratum area is not included. The frequency distribution of biomass density per plot for the 18 plots was assessed to determine the goodness-of-fit to the normal distribution using the Komogorov-Smirnov Test (Siegel 1956). There was no significant difference from the normal distribution at $P<0.20$ (Figure 4). This result confirms the assumption that is required in the upscaling process, that the mean biomass density of the stratum comes from a normal distribution from the sample plots.

EXAMPLES OF VARIANCE ASSOCIATED WITH SPATIAL PREDICTION OF BIOMASS

An example of spatial variability in the estimation of forest biomass is given by Tajchman *et al.* (1996) for *E. regnans* forest in Victoria. Spatial variation was divided into random variability, which can occur at scales from single tree to regions, and variation related to topography, specifically aspect but can include soil, climate and site history. Biomass was estimated for 30 x 0.08 ha plots. Single plot biomass varied from –50% to +61% of the mean. The coefficient of variation was 24% for a sample of 20 or more plots, but increasingly higher for fewer plots. Variation due to aspect ranged from 593 t ha-1 on southern slopes to 383 t ha^{-1} on western slopes, a reduction of 34%.

Estimates of the error associated with applying allometric equations relating aboveground biomass to DBH have been calculated by Nelson *et al.* (1999) for estimates of tropical forest biomass. The average error of estimation for 8 species-specific equations was 10 – 15% based on 17 to 27 trees per species. When the data from all trees were combined to give a general equation for all species, the error of estimation was 20% using DBH, but was reduced to 15% using DBH and species-specific wood density.

Variances in the estimation of biomass at Bago State Forest are high compared with these examples. There is a high degree of heterogeneity in the forest because of disturbance from management practices. However, disturbance is common in eucalypt forests from both natural and management factors.

The strategy for estimating forest biomass recommended by Brown *et al.* (1989) is the use of data from forest inventories and application of general allometric equations for the vegetation type. This recommendation is based on estimates of tropical forest biomass at regional to global scales. They consider that this method will generally give unbiased estimates of a population when the trees are uniformly distributed by size classes and the inventory data is derived from well-designed forest surveys.

GAPS IN KNOWLEDGE AND IMPLICATIONS FOR ESTIMATION OF TOTAL BIOMASS

1. The allometric relationships available do not cover representative vegetation types across the continent, under represented types include rainforests, woodlands and shrublands. There is a bias towards production forest species and small trees.
2. The lack of data for large trees is a major limitation in the application of allometric equations in communities where they occur, particularly old-growth forests.
3. Belowground biomass is the major component of uncertainty in quantifying total tree biomass.
4. Not all trees are measured in inventories of production forests, there is usually a minimum DBH of 10 cm, often a maximum size measured, and non-commercial species may not be measured. This underestimates the total tree population.
5. Spatial inventory data of dimension measurements for individual trees is also biased towards production forests. Within these forest regions, inventory plots are often located only in commercial forest types.
6. Spatial prediction of biomass will have to use interpolation of limited data based on an understanding of processes that control production and partitioning of biomass. A major limitation to developing complete C budgets for forests is a poor understanding of factors controlling allocation of C from gross primary productivity to respiration, biomass increment, partitioning among biomass components, storage and secondary plant defensive chemicals. This information is also necessary to predict the capacity of systems to sequester C under scenarios of climate change and landuse management.
7. Improved methods are required to integrate site specific data into general response variables. The scale and criteria used for aggregating data can influence the analysis. Testing this variation will aid identifying the scale at which biomass information is most sensitively predicted by various biotic and abiotic factors.

STRATEGIC APPROACH FOR FURTHER RESEARCH

1. Strategic sampling and measurement of biomass of individual trees could be used to verify and calibrate existing allometric equations for a wider range of species and environmental conditions. Coefficients of the equation can be modified according to environmental and genetic factors that influence production and partitioning of biomass. The linear allometric equations would thus become response surfaces where biomass is a function of tree

attributes (e.g. diameter, height, density) and environmental attributes (e.g. available water and nutrients, temperature). Spatial prediction of biomass using allometric equations could then be based on relationships established between regression coefficients and environmental factors. Distribution of the environmental factors can be obtained from GIS databases for the region, for example moisture, radiation, and soil type.

2. Additional sampling of large trees is required to extend the range of application of existing equations, particularly in forest types where trees over 100 cm DBH occur.

3. Derivation of relationships between DBH and height would extend the application of allometric equations that require both variables, where inventory data for height is not available. In addition, height may be useful as a modifier to coefficients of the DBH variable to improve estimates from extrapolation of allometric equations to forest types of different forms.

4. Greater standardisation of inventory systems and variables measured across States would facilitate use of this information at the national scale. There is a need to collect additional inventory data in vegetation types where standard systems do not exist, such as non-productive forest types, reserves, young regrowth and woodlands. It is unlikely that a new system would be comprehensive and may have to be supplemented by deriving relationships between interpretation of remote sensing images and vegetation structure, characterised by growth form of trees, stocking and size distribution of stands.

5. More robust data is required on belowground biomass. This should be collected with the aim of improving understanding of the processes controlling partitioning and net C storage in root systems, so as to establish trends in the below-to-aboveground biomass rates in response to environmental conditions.

6. The most appropriate scales at which trends in allometric equations and below-to-aboveground biomass ratios are related to environmental conditions should be assessed, and then the most appropriate predictive variables identified at each scale. Division of woody vegetation into strata should be based primarily on structure or growth form rather than species.

7. Understanding of the physiological and ecological processes that govern partitioning of biomass will underpin a strategy for spatial prediction from site and species specific allometric equations. Implementation of a strategy for biomass estimation making best use of current information on allometrics requires an improved understanding of the processes and strategic experimental studies to define key variables and trends.

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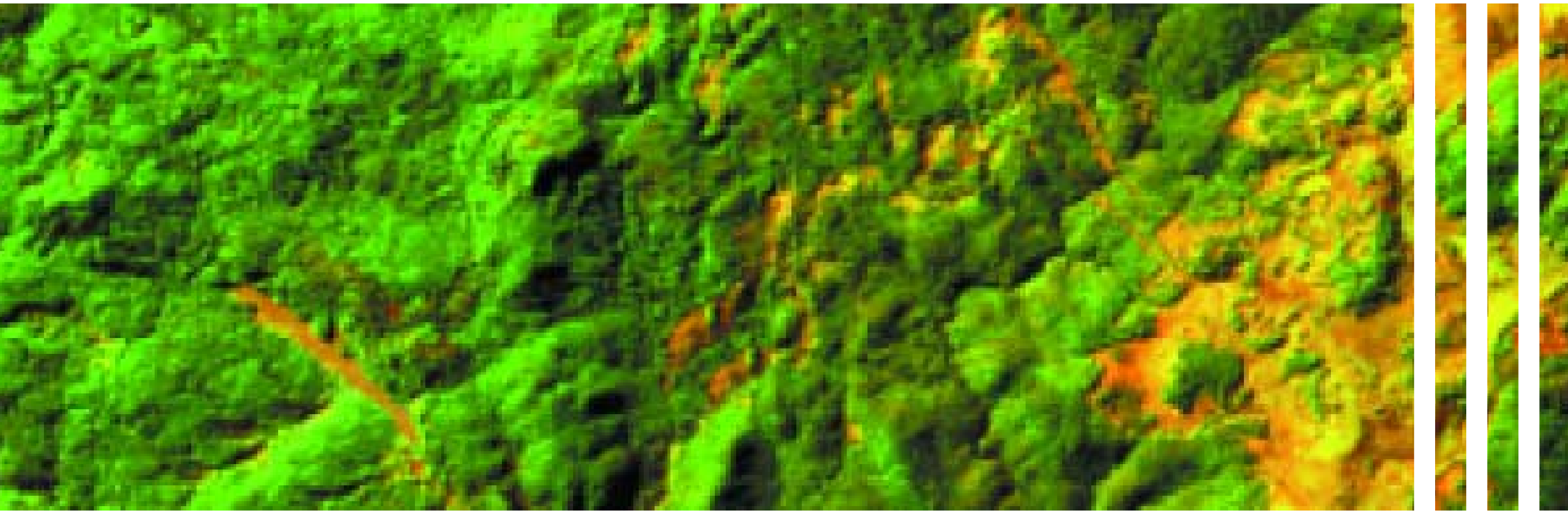

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