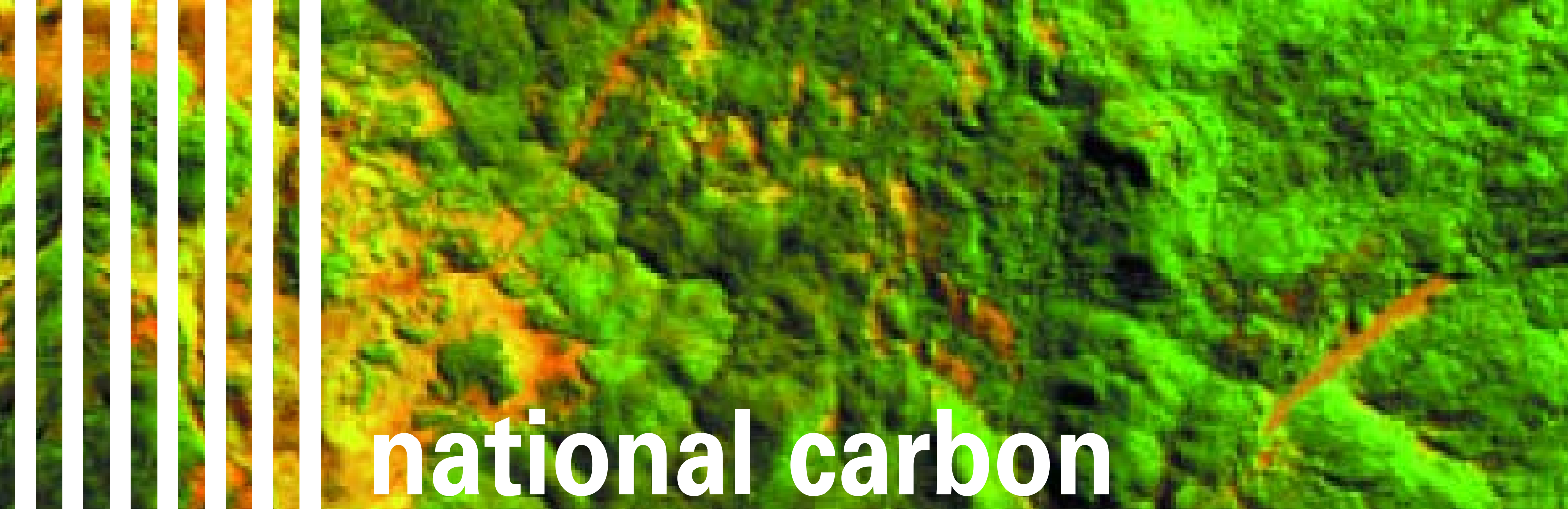

national carbon accounting system

technical report no. 5a

Review of Allometric Relationships for Estimating Woody Biomass for Queensland, the Northern Territory and Western Australia

Derek Eamus
Keith McGuinness
William Burrows

AUSTRALIAN
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Technical Report No. 5A

August 2000

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Explanatory note:

Unpublished allometric equations contained in this report should not be cited without acknowledging the original source of the data. All data from Burrows et al. and regressions from previously published papers can be cited as such. With the exception of the Kapalga data, which should be should be attributed to Werner and Murphy (1987), data for the NT should be cited as Eamus, McGuinness, O'Grady, Xiayang and Kelley, unpublished.

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TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

APPENDIX: Queensland Data Tables

SUMMARY

The determination of biomass and growth in vegetation is an essential component of the estimation of carbon sequestration. Biomass is often estimated using allometry. Thus, to help meet Australia's obligations under the Kyoto Protocol, the Australian Greenhouse Office commissioned the Northern Territory University to prepare a review of published and unpublished allometric relationships for trees growing in tropical Australia and Western Australia (WA). This report contains those relationships and associated statistical analyses and interpretations. The largest data set collated was for Queensland and the smallest for WA.

The following points summarise the results of this review:

1) Comparisons were made between paperbark swamps and savannas in the NT, Jarrah forests in WA, and experimental tree plantings and woodland sites in Queensland. The key finding was that within these very diverse ecosystems a single regression of Ln(Biomass) against Ln(Diameter at breast height) adequately described the allometric relationship for several of the dominant tree species within each ecosystem. However, a single relationship did not hold across the different ecosystems.

2) Data on eight species and four savanna sites were available for the Northern Territory. The species were *Erythrophloem chlorostachys, Terminalia ferdinandiana* and *Eucalyptus bleeseri, E. clavigera, E. miniata, E. papuana, E. porrecta* and *E. tetrodonta.* Regressions of above-ground biomass against tree height or diameter at breast height (DBH) were also obtained for paperbark swamps in the NT. For this, two species, *Melaleuca viridiflora* and *M. cajaputi*, were measured on the Magella Creek floodplain near Jabiru in Kakadu, NT.

3) Dr D. Hector, Queensland Forestry Research Institute, Gympie, Queensland made data for six species and two sites available. The species were: *E. camalduensis, E. argophloia; E. intertexta; Acacia colei; A. holosericea;* and *A. neurocarpa.* For two of the species at each site, individuals from different provenances were sampled.

4) Allometric equations for over two-dozen tree species growing in Queensland were obtained. Principal species included *E. crebra, E. diversicolor, E. melanophloia, E. obliqua, E. populnea, E. resinifera, E. grandis, E. marginata, Pinus radiata, A. aneura* and *A. harpophylla.*

5) Allometric equations were obtained for the following species growing in WA: *E. marginata; E. calophylla; Banksia grandis; E. diversicolor; Bossiaea laidlawiana; Trymalium spathulatum; Chorilaena quercifilia; Lasiopetalum floribundum; Pimelia clavata; A. puchella; Hibbertia cuneformis; E. maculata; E. calophylla;* and *E. resinifera.*

6) Three species, *E. miniata, E. tetrodonta* and *T. ferdinandiana*, were compared at a single site, Howard Springs, in the NT. For these species, Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 96% of the variation in biomass. Neither the slope nor intercept differed among the species at the site.

7) At a second NT site, Humpty Doo, six species were compared: *E. bleeseri; E. chlorostachys*; *E. miniata; E. porrecta; E. tetrodonta;* and *T. ferdinandiana*). For these species, Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 97% of variation in biomass. The slope of this relationship did not differ among species at this site, but the intercepts did.

8) At a third NT site, Kapalga, three species were compared: *E. miniata; E. tetrodonta;* and

E. papuana. For these species, Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 95% of the variation in biomass. The slopes differed among species, making a statistical comparison of intercepts questionable.

9) At Katherine, the last NT site, only two species, *E. miniata and E. tetrodonta*, were compared. For these species, Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 98% of the variation in biomass. Neither the slope nor intercept of this relationship differed among the species at this site.

10) Two species, *E. miniata and E. tetrodonta,* account for more than 80% of standing biomass in savannas around Darwin. For a comparison of these species at multiple sites, Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 94% of the variation in biomass. The slope of the relationship between Ln(DBH) and Ln(Biomass) was not the same for both species at all sites. More precisely, the slope of the relationship for one of the species at one or more of the sites differed from that of the other at one or more sites.

11) For both tree height and tree DBH regressed against biomass, there were no significant differences between the two paperbark species measured near Jabiru. Consequently, a single combined regression for both species adequately described the data.

12) Importantly, an interspecific comparison of all NT species except *E. caligera* and the paperbarks, showed that Ln(DBH) was highly correlated with Ln(Biomass) and accounted for 95% of the variation in biomass. The slope of the relationship between Ln(Biomass) and Ln(DBH) did not differ among species. Nevertheless, since there were some differences among sites for some species in the relationship between Ln(Biomass) and Ln(DBH), the results of this analysis must be interpreted cautiously.

13) There was a good relationship between Ln(DGH; Diameter at ground height) and Ln(Biomass) for all 6 species at the experimental AZI site in Queensland. Further, there was no significant difference among species in either the slope or the intercept.

14) There were no significant differences between the slopes of the individual lognormal regressions of stem circumference against total above-ground biomass for *E. crebra, E., melanophloia* and *E. populnea* at another site in Queensland. When community basal area or individual stem circumferences are sufficiently known, these allometric relationships enable accurate estimates of above-ground biomass of woodlands dominated by any of the three species.

15) The allometric regressions for Jarrah (*E. marginata*) and Marri (*E. calophylla*) at a site in WA did not different significantly from each other.

16) Using models of the form Ln(Biomass) = A * Ln(DBH) + B to predict biomass for plants of known DBH requires back-transformation from the logarithmic scale to the arithmetic. The resulting estimates of biomass will usually be too low, often by a large amount. Indeed, uncorrected estimates of biomass derived from least squares regression on double logarithmically transformed observations should not be used. In most instances the correction suggested by Baskerville (1972) will be adequate. In situations where error variance (or residual standard deviation) is high, say, greater than 0.6, Beauchamp and Olson's (1973) *Y1* estimator should be considered.

17) Analyses of the NT data revealed differences in the relationship between Ln(DBH) and Ln(Biomass) among some species and sites. This indicates that a single, simple equation will not produce accurate estimates of biomass for all species at all sites. However, it does not follow that the use of simple equations will produce grossly inaccurate predictions. It is quite possible for differences among species, and sites, to be significant, even highly so, but small. The degree of statistical 'significance' (i.e., the p-value associated with the test) is not a simple function of the magnitude, or importance, of differences among species or sites. The p-value is influenced by the magnitude of such differences (bigger differences will result in smaller p-values), but it also depends on the variability in the data and the number of replicate individuals sampled. Two separate investigations were done. In the first, results for the eucalypt species (with the exception of *E. clavigera*) sampled in the NT were used. Predictions were made using an equation derived for all eucalypts, and using equations derived for the individual species and sites (Table 4). The second investigation used three species common in Queensland – *E. crebra, E. melanophloia* and *E. populnea* – and was based on results from Burrows *et al.* (submitted). Overall, the difference among methods in predictions of *total biomass across all species and sites* was fairly small. Using species and site specific equations gave a total above ground biomass of 287 026 kg. Using species specific equations gave a value only 2.3% smaller. The use of a common Eucalypt equation resulted in an error of only 1.1%.

18) Errors involved in using a common equation in the Qld scenarios were greater than those observed in the NT results. Overall, the use of the common equation overestimated biomass by nearly 16%, a sizeable error (Table 10; Figure 12). The errors for the individual species ranged from an underestimate of 11% for *E. crebra* to an overestimate of 42% for *E. populnea*.

19) It is extremely important to remember that these results apply only to the particular mix of sites, species and sizes used. For instance, in the calculations done here, the sizes of the individuals were evenly distributed between the smallest and largest DBHs actually measured. However, if larger trees predominated at a site the error involved in using a common equation would probably be greater.

20) It is difficult, if not impossible, to determine the consequences of using common equations without information about the size and species distribution of the populations for which predictions are to be made.

21) Expansion factor decreases non-linearly with increasing size of the trees in a woodland. When expansion factor is plotted as a function of quadratic stand diameter (QSD), differences between regions and life zones disappear (Brown *et al.* 1989). Expansion factors are large for forests with small QSDs and decline to an asymptote of 1.5 – 2.0 when QSD is greater than 30 cm (Brown *et al.* 1989). However, there is no single expansion factor that can be applied to all forests within a given life zone or region. Therefore, application of universal expansion values should be avoided. The IPCC (International Panel for Climate Change) default expansion factor multiple for unproductive forests was compared with calculated values for two Queensland hardwoods (Burrows *et al.* 1999). The appropriate expansion multiples

were 2.38 for *E. crebra* and 1.85 for *E. melanophloia*. In this case these figures are similar to the IPCC default value, but this cannot always be assumed to be the case.

22) The IPCC default wood density is completely inappropriate for Australian hardwoods, which have wood densities of c. 1 000 kg m^{-3}. Extensive data sets are available in Boland *et al.* (1992) and Cause *et al.* (1989).

23) Large trees can significantly skew regression equations. The use of R^2 to evaluate the amount of variation explained by a regression is frequently made. However, R^2 gives a large weighting to observations with large values. Cumulative percentage deviation (ratio between total estimated and observed weight of sample trees) has been used to select the best regression function. However, this can also be overly influenced by the accuracy of determining the weight of very big trees. Consequently, Overman *et al.* (1994) used an average of the absolute percentage deviation:

$$\delta \text{ Biomass} = \sum_{n=1}^{n} \frac{[(DW'-DW)/DW]*100}{n}$$

where DW' is estimated dry weight and DW is observed dry weight. This measure gives equal weight to observations of different magnitudes.

24) It is apparent that there are some significant tropical ecosystems not represented in the data currently available. Some examples include rainforests (of which there are 1500 patches in the NT alone), paperbark (*Melaleuca* spp.) swamps (only one study at one site), riparian forests, *Allosyncarpia* forests and mangroves (of which there are more than 11 000 km^2 in tropical and sub-tropical Australia).

25) For future studies, laser altimetry enables rapid determination of tree height over large areas. When tree height was used in regression instead of DBH, Burrows *et al.* (1999) found R^2 values greater than 0.91 for four species. Clearly such an approach, when coupled with ground-based determinations of tree density and species composition, allows rapid estimates of above-ground biomass.

CARBON SEQUESTRATION

Carbon dioxide emissions from fossil fuel burning and deforestation are causing significant increases in the atmospheric concentration of CO_2 (IPCC 1995). This is predicted to cause significant long-term changes in global climate and weather patterns. One option to mitigate these increases is to absorb increasing amounts of CO_2 into long-lived vegetation, that is, trees. In Australia, where a significant proportion of the continent is suitable for such sequestration of carbon into vegetation, there is the potential to offset emissions of CO_2.

An essential component of carbon sequestration (sink) estimation is the determination of biomass and growth in vegetation. Foresters traditionally derive timber biomass by employing allometry (dimensional analysis) techniques. An easily measured parameter (e.g., diameter at breast height, often combined with plant height) is regressed against harvested plant component weights. The independent variable (predictor) in this regression is obtained from detailed censusing of study plots.

In the future, remote sensing techniques are likely to contribute to large-scale estimations of biomass (Dobson *et al.* 1995). However, it is likely to be some time before these techniques are sufficiently refined to detect short-mid term changes in biomass stocks, as would be required for National Greenhouse Gas Inventories or carbon offset trading. In any event, such techniques will always require validation against ground-based measurements. Recent investigations using RADAR techniques and biomass relationships yielded regressions that were clearly unusable (O'Grady *et al.* unpublished).

ALLOMETRICS

The estimation of biomass in woody ecosystems, such as woodlands, forests, savannas and mangroves, is required for a number of reasons. Foresters are interested in yield of wood (stem volume) as a function of age, stand density and other factors. Ecologists require information about stand biomass for a variety of reasons because of its relevance to nutrient turnover, stand structure and function, competition studies and a range of other topics. Ecophysiologists have used biomass as indicators of atmospheric and soil pollution input and forest health. More recently, governments have realised that there is a potential for woody ecosystems to store carbon and thereby contribute to mitigation strategies to offset carbon emissions.

Regressions between stem diameter and height (on log-log plots) have been used to investigate biomechanical constraints, near neighbour effects and allometrics of trees (Henry and Aarssen 1999). Elastic similarity and constant stress models of biomechanical functioning of tree stems predict that stem diameter should scale as the 3/2 or 2nd power of height (O'Brien *et al.* 1995; Sterck and Bongers 1998). Most studies using static data – measurements at one point in time – reveal that diameter scales with height as a power greater than one. However, confounding influences of near neighbours, which reduce light availability and wind exposure, are rarely investigated on diameter-height relationships. Consequently, forestry studies commonly assume, incorrectly, that static data can be used to predict the dynamic growth trajectory of trees (Henry and Aarssen 1999). In fact, the 'age-dependent' scaling effect (Niklas 1995) in allometric relationships is probably a function of near neighbour effects (Henry and Aarssen 1999). Indeed, Henry and Aarssen (1999) conclude that, because of near- neighbour effects, it is not yet possible to categorically state that as trees grow, they add stem diameter faster than height.

Brown and Lugo (1982, 1984) estimated the total above- and below-ground biomass of tropical forests (open and closed canopy) world-wide. In the first estimate, they reviewed the literature of published biomass estimates, derived either from destructive harvests alone or destructive harvests and subsequent allometric regression. They calculated a weighted average total above-ground biomass of

282 Mg ha^{-1} for closed forests (range from 144 - 513 Mg ha^{-1}; weighted carbon density of 124 t ha^{-1}) and 55 Mg ha^{-1} (range 28 - 82 Mg ha^{-1}) for open tropical forests. In their later study, data from countries reporting to the Food and Agriculture Organisation of the United Nations (1981) were used, along with typical wood densities and expansion factors, which convert total above-ground biomass to commercial yield. This later estimate yielded 150 Mg ha^{-1} and 50 Mg ha^{-1} for closed and open forests, respectively. It is clear that for closed forests, different methods of calculation can result in very different estimates of biomass. Two additional studies gave weighted estimates of 114 t ha^{-1} (Olson *et al.* 1978) and 165 t ha^{-1} (Ajtay *et al.* 1979). This disparity in estimate results in significant problems for those charged with verifying biomass estimates as part of the Kyoto Protocol.

Part of the problem in estimating biomass on large scales is the use of data derived from studies that were not designed to provide data for this purpose (Brown *et al.* 1989). In addition, sampling frequency and sampling area are generally extremely limited. The use of forest volume inventories, which are generally more extensive and frequently measured, are likely to be of high value in this regard (Brown *et al.* 1989). However, for much of the Australian tropical native vegetation, forest volume inventories are absent.

Tropical forests offer a wide range of species composition, forest structure and stand densities. Classifications of tropical woody ecosystems vary from the simple to complex. Only two classifications were used by the Food and Agriculture Organisation, namely ‘open’ or ‘closed’ forests, depending on canopy structure. In contrast, Specht’s classification of Australian woody systems recognises five divisions of canopy cover, usually reduced to two (namely open and closed), and three divisions of tree height plus four divisions of shrub height. The presence / absence of sclerophyllous leaves is a further sub-division for shrubs. Consequently, tall closed forests fall at one end of the tree-dominated spectrum while low open woodland falls at the other, with 13 divisions between. For shrub-dominated vegetation types, closed scrub and dwarf open heathland or shrubland represent the two extremes.

To determine standing biomass for Australia, it is not realistic to attempt to destructively measure throughout all these biomes. An alternative approach is to establish whether allometric relationships with wide-scale applicability can be established for dominant life-forms. It may be possible to apply three or four allometric relationships that have sufficient confidence and robustness to adequately describe the relationship between a relatively easily measured parameter, such as diameter at breast height (DBH) and biomass, for all of the woody ecosystems of tropical Australia. Brown *et al.* (1989) applied analyses to 5300 trees from 43 independent plots in four countries. They developed regression equations to estimate above-ground biomass as a function of DBH, tree height, wood density and Holdridge tropical life zone. Analysis of covariance indicated that a single regression could be applied to each of two of the three life zones examined (dry life zone and wet life zone). The third zone (wet-dry transition or moist zone) was not amenable to such a reductionist approach. Clearly, the potential for a reductionist approach in Australia should be investigated.

AIMS

The aims of this consultancy are to provide: (a) a comprehensive literature review of allometric equations for woody biomass; and (b) an analysis of implications for these equations on biomass estimations for national greenhouse reporting. The analyses should include a statement of our current understanding and deficiencies in knowledge of biomass estimates, a consideration of the potential for using generic regressions for above-ground biomass, and recommendations on strategic approach to further research.

This presentation of the collated data and its analysis is divided into two main sections. In the first section, the Northern Territory and Queensland data is analysed, and in the second section the equations for the regressions of biomass and tree circumference are presented. Finally, there is a discussion of some of the issues pertaining to the application of regression data.

DATA COLLATION - SUMMARY OF SPECIES, SITES AND DATA AND DESCRIPTION OF ANALYSES

NORTHERN TERRITORY

Savanna

Data on eight species and four sites were available for the Northern Territory. The species are: *E. bleeseri, Erythrophloem chlorostachys, E. clavigera, E. miniata, E. papuana, E. porrecta, E. tetrodonta*, and *T. ferdinandiana.*

The sites were: Howard Springs (12° 40’ S, 132° 39’ E), located about 35 km east-south-east of Darwin; Humpty Doo (12° 30’ S, 131° 15’ E), located about 45 km east-south-east of Darwin; Kapalga (12° 35’ S, 132° 52’ E), located about 200 km east of Darwin; and Katherine (14° 40’ S, 132° 39’ E), located about 300 km south-south-east of Darwin.

Approximate mean annual rainfall is 1800 mm yr^{-1} for Darwin and Humpty Doo, 1350 mm yr^{-1} for Kakadu and 1000 mm yr^{-1} for Katherine.

Sources of data are as follows:

- Howard Springs data – collected by Derek Eamus, Chen Xiayang, Georgina Kelley and Tony O’Grady;
- Humpty Doo – collected by Derek Eamus, Chen Xiayang and Georgina Kelley;
- Katherine – collected by Chen Xiayang; and
- Kakadu – collected by Professor Pat Werner.

Because these four sites differ significantly in mean annual rainfall they provide a good comparative test of the applicability of single or multiple regressions in allometric data.

Data for a total of 150 trees were available, but most of these were for *E. miniata* (n = 49) and *E. tetrodonta* (n = 45), with fewer than 15 individuals of each of the other species being sampled (Table 1). *E. clavigera* was not considered further because only one tree was sampled.

Table 1: Summary of numbers of observations on eight species at four NT sites

Species	Howard Springs	Humpty Doo	Kapalga	Katherine	Sub–total
E. bleeseri	0	8	0	0	8
E. chlorostachys	1	13	0	0	14
E. clavigera	1	0	0	0	1
E. miniata	21	8	14	6	49
E. papuana	0	0	12	0	12
E. porrecta	0	8	0	0	8
E. tetrodonta	10	13	14	8	45
T. ferdinandiana	5	8	0	0	13
Sub–total	38	58	40	14	150

The first step in the analyses of these data was to test the following three null hypotheses:

- H_{01}: The relationship between Ln(Biomass) and Ln(DBH) is similar for all species at a site.
- H_{02}: The relationship between Ln(Biomass) and Ln(DBH) is similar for two species at all four sites.
- H_{03}: The relationship between Ln(Biomass) and Ln(DBH) is similar for all species, disregarding sites.

These hypotheses were tested using analysis of covariance (ANCOVA). First, it was tested whether the slopes of the relationships between Ln(Biomass) and Ln(DBH) were the same for different species. If the slopes were the same, then it was tested whether the intercepts were the same. In the general case, if the slopes of relationships being compared in an ANCOVA differ, then tests of the equality of intercepts can lead to invalid conclusions (Huitema 1980). Thus, when slopes differed, the individual relationships were calculated and reported (see Huitema 1980).

The double logarithmic transformation was used because, as discussed earlier, this successfully linearised the relationships. Prior to doing these analyses, Cochran’s test was used to determine if variances were equal; they were in all cases.

Because all eight species were not observed at all four sites, several sets of analyses were required to test these hypotheses. Analyses were done separately for each site, using all species represented by five or more individuals: three species at Howard Springs; six species at Humpty Doo; three species at Kapalga; and two species at Katherine. An analysis was also done using the two species – *E. miniata* and *E. tetrodonta* – available at all sites. Finally, an analysis was done comparing all species except *E. clavigera*, for which there was only one individual, disregarding sites.

Paperbark forest

Regressions of tree height or DBH against above-ground biomass were obtained for *Melaleuca viridiflora* and *M. cajaputi* on the Magella Creek floodplain near Jabiru in Kakadu, NT. Fifteen trees were sampled for each species. Fresh weight was recorded for each tree (see Finlayson *et al.* 1993 for further details). The distinctiveness, or otherwise, of the regressions for the two co-occurring species of paperbark were tested for both tree height and tree DBH as correlates of biomass using an F-ratio test (Finlayson *et al.* 1993).

QUEENSLAND FORESTRY RESEARCH INSTITUTE (QFRI)

Dr D Hector, Queensland Forestry Research Institute, Gympie, Queensland made data for six species and two sites available. The species were: *E. camalduensis* (n = 17), *E. argophloia* and *E. intertexta* (n = 17), *A. colei*, *A. holosericea* and *A. neurocarpa*. For two of the species at each site, individuals from different provenances were sampled.

The sites were: Noonbah (24°12’S, 143°18’E), about 160 km SE of Longreach in Queensland, and AZI, the former Arid Zone Research Institute at Longreach (23° 45’S, 144°27’E). Mean annual rainfall for the Noonbah site is 349 mm and for the AZI site is 395 mm.

Data for a total of 67 trees were available, but most of these were for *E. camaldulensis* (n = 17) and *E. intertexta* (n = 17) with fewer than 10 individuals of each of the other species being sampled (Table 2).

Table 2. Summary of numbers of observations on six species at two Queensland sites. Approximately half of the individuals in the species *E. camaldulensis* and *E. intertexta* were from different provenances (Petford and Tennant Creek, and NT and Qld, respectively): the numbers from each provenance are shown in parentheses.

Species	Noonbah	AZI	Subtotal
A. colei	2	6	8
A. holosericea	2	5	7
A. neurocarpa	2	7	9
E. camalduensis	4 (2, 2)	13 (5, 8)	17
E. intertexta	4 (2, 2)	13 (7, 6)	17
E. argophloia	2	7	9
Sub–total	16	51	150

The first step in the analyses of these data was to test the following hypothesis. Note that diameter at ground height (DGH), not at breast height, was measured in this study:

- H_{01}: The relationship between Ln(biomass) and Ln(DGH) is similar for all species at a site.

This analysis was only done for the AZI site, since only 2-4 individuals of each of the species were sampled at the Noonbah site. Since some individuals were of known provenance, there was also the opportunity here to test if this significantly affected relationships. Thus, the following hypothesis was also tested for the two species with sufficient data – *E. camaldulensis* and *E. intertexta*:

- H_{02}: The relationship between Ln(biomass) and Ln(DGH) is similar for all provenances.

These hypotheses were tested using the same procedures employed for the first data set. An ANCOVA was used to test whether the slopes of the relationships between Ln(biomass) and Ln(DGH) were the same for different species (or provenances). If the slopes were the same, then the intercepts were compared. The double logarithmic transformation was used because this successfully linearised the relationships.

Because all species were not observed at all sites, and provenance information was only available for two species, several sets of analyses were required to test these hypotheses. One analysis was done compared relationships for all species at the AZI site: as noted above, there were too few samples for such a comparison to be done at the Noonbah site. Two analyses were then done to compare relationships for samples from the two provenances available for *E. camaldluensis* and *E intertexta*. These analyses used data from the two sites pooled, to increase the number of replicates available.

QUEENSLAND

There is a large volume of data available for trees growing in Queensland. Allometric relationships are available for more than two dozen species, including *E. crebra*, *E. diversicolor*, *E. melanophloia*, *E. obliqua*, *E. populnea*, *E. resinifera*, *E. grandis*, *E. marginata*, *P. radiata*, *A. aneura* and *A. harpophylla* (see Appendix for full list).

For many species, biomass allocation to component parts of the tree (stem, bark, branch and leaf) were available. For regressions of total above-ground biomass on DBH, R^2 are typically > 0.9.

WESTERN AUSTRALIA

Allometric data for tree species growing in Western Australia were collected through a search of the published literature. Three studies were identified.

From the first study (Hingston *et al.* 1981), allometric equations were obtained for the following species – *E. marginata* (Jarrah), *E. calophylla* (Marri) and *Banksia grandis* – growing approximately 80 km south of Perth in a Jarrah forest 1.5 km north of Dwellingup. Mean annual rainfall is about 1200 mm. Ten trees of all species were sampled destructively.

From the second study (Grove 1988), regressions of above-ground biomass were obtained for the following species: *E. diversicolor*, *B. laidlawiana*, *T. spathulatum*, *C. quercifilia*, *L. floribundum*, *P. clavata*, *A. puchella* and *H. cuneformis*. The site was 30 km south west of Manjimupp in WA. Mean annual rainfall is about 1300 mm. DBH was measured at either 30 cm, 130 cm or 3 cm height, depending on tree diameter. See section 4.0 for clarification.

Finally, from Ward and Pickersgill (1985), allometric relationships were obtained for the following species: *E. maculata*, *E. calophylla*, and *E. resinifera*. Only *E. calophylla* is native to WA. The study involved two sites in the Darling Range and destructive harvest of between eight and 11 trees. The study was undertaken to assess biomass and nutrient distribution on a mine rehabilitation site, and included young (7.5 yr) plantation trees.

DATA

STATISTICAL ANALYSES OF NT AND QFRI DATA

Analyses of Northern Territory data

Howard Springs

The three species compared at this site were *E. miniata*, *E. tetrodonta* and *T. ferdinandiana*. For these species, Ln(Biomass) was highly correlated with Ln(DBH), with this relationship accounting for 96% of the variation in biomass (r = 0.98, n = 36, p < 0.01). Neither the slope (F = 0.21, df = 2, 30, p > 0.05) nor intercept (F = 1.76, df = 2, 32, p > 0.05) of this relationship differed among the species at this site. The relationship for all species is shown below (Figure 1).

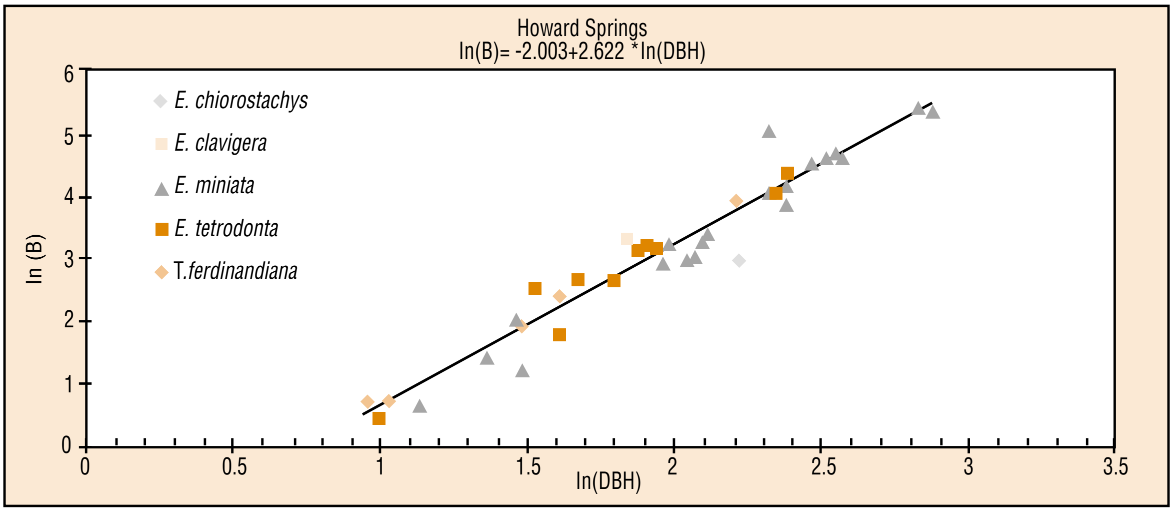

Figure 1: Relationship at Howard Springs between Ln(Biomass) and Ln(DBH) for five species (n = 38). The line plotted accurately represents the relationships for all species, since these did not differ in slope or intercept.

Humpty Doo

The six species compared from the Humpty Doo site were *E. bleeseri*, *E. chlorostachys*, *E. miniata*, *E. porrecta*, *E. tetrodonta*, and *T. ferdinandiana* (Table 3). For these species, Ln(Biomass) was highly correlated with Ln(DBH), with this relationship accounting for 97% of the variation in biomass ($r = 0.99$, $n = 58$, $p < 0.01$; Figure 2). The slope of this relationship did not differ among species at this site ($F = 1.10$, df = 5, 46, $p > 0.05$), but the intercepts did ($F = 8.39$, df = 5, 51, $p < 0.001$). It is evident from the results, that *E. bleeseri* and *E. tetrodonta* have intercepts which are similar and slightly higher than those of all the other species.

Table 3: Mean Ln(Biomass) and Ln(DBH), for species compared at Humpty Doo.

Also shown are the mean Ln(Biomass) values for each species, adjusted for differences in Ln(DBH). A higher adjusted mean indicates a higher intercept, and vice versa.

Species	Mean Ln(Biomass)	Adjusted mean	Mean Ln(DBH)
E. bleeseri	3.767	3.774	2.306
E. chlorostachys	2.661	3.347	2.053
E. miniata	4.027	3.371	2.553
E. porrecta	3.955	3.262	2.567
E. tetrodonta	3.350	3.631	2.204
T. ferdinandiana	3.072	3.447	2.169

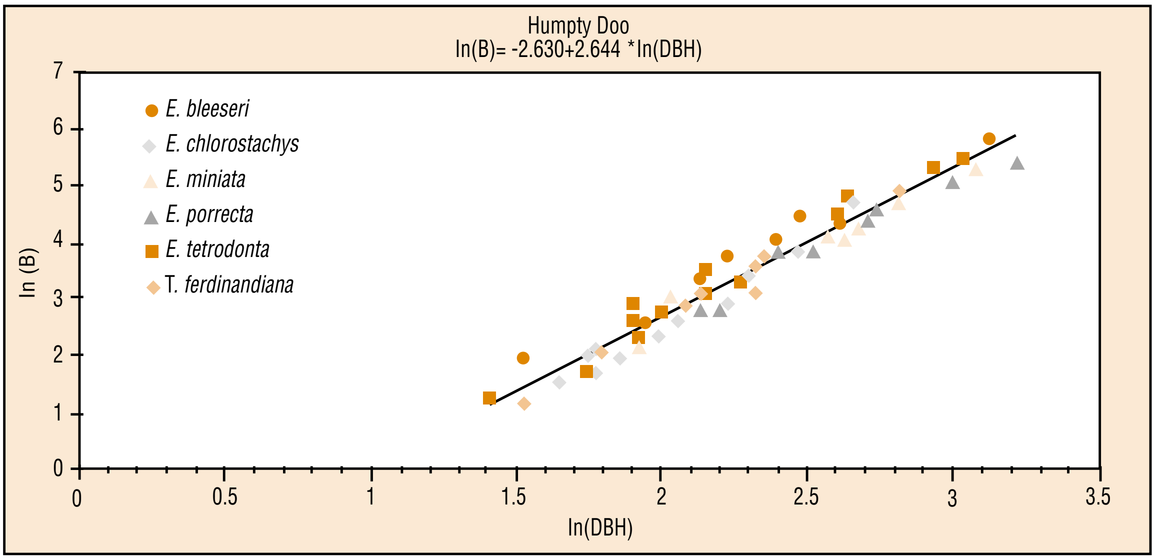

Figure 2: Relationship at Humpty Doo between Ln(Biomass) and Ln(DBH) for six species (n = 58). The line plotted accurately depicts the slope of the relationships but not the intercept: the latter differed among species.

Kapalga

The three species compared at this site were *E. miniata*, *E. tetrodonta* and *E. papuana*. For these species, Ln(Biomass) was highly correlated with Ln(DBH), with this relationship accounting for 95% of the variation in biomass (r = 0.98, n = 40, p < 0.01; Figure 3). Analysis indicated that the slopes differed among species (F = 7.32, df = 2, 34, p < 0.05), making a statistical comparison of intercepts questionable. The obvious difference among the species was that *E. papuana* had a lower intercept and a higher slope.

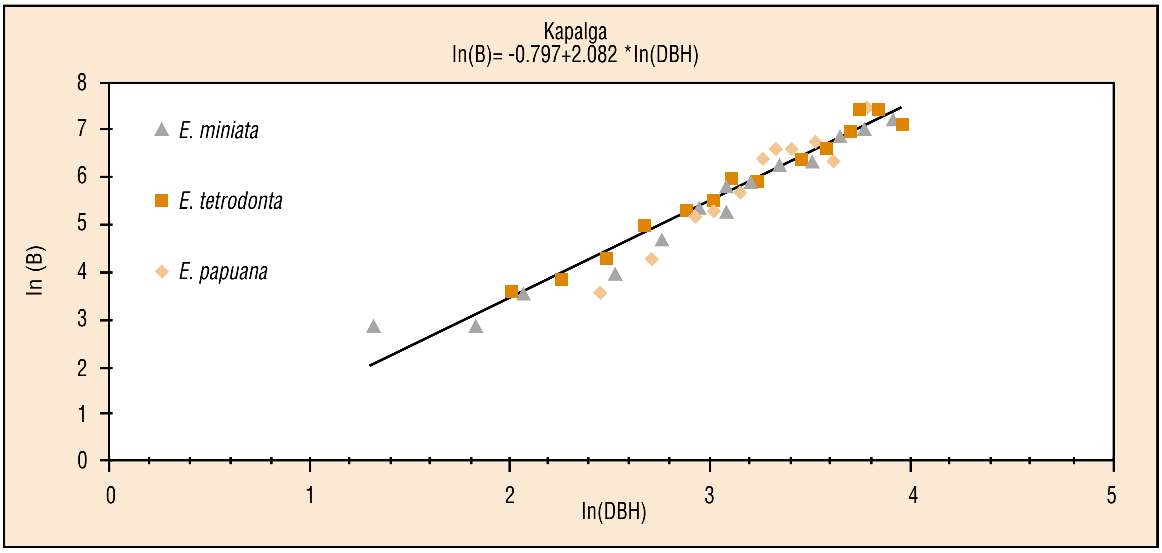

Figure 3: Relationship at Kapalga between Ln(Biomass) and Ln(DBH) for six species (n = 40). The line plotted is for reference only and does not accurately represent the relationships of the species.

Katherine

Only two species were compared at this site: *E. miniata* and *E. tetrodonta*. For these species, Ln(Biomass) was highly correlated with Ln(DBH), with this relationship accounting for 98% of the variation in biomass (r = 0.99, n = 14, p < 0.01; Figure 4). Neither the slope (F = 0.15, df = 1, 10, p > 0.05) nor intercept (F = 0.13, df = 1, 11, p > 0.05) of this relationship differed among the species at this site.

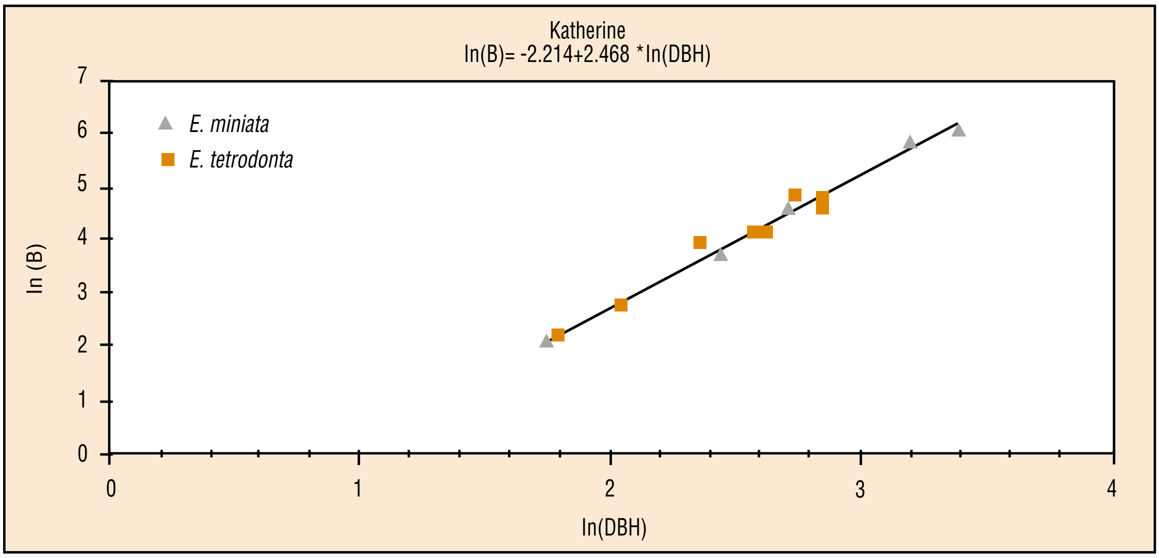

Figure 4: Relationship at Katherine between Ln(Biomass) and Ln(DBH) for two species (n = 14). The line plotted accurately depicts the relationship at this site because this did not differ between species.

Analyses of all data on *E. miniata* and *E. tetrodonta*

For these species, Ln(Biomass) was highly correlated with Ln(DBH), and accounted for 94% of the variation in biomass ($r = 0.97$, $n = 94$, $p < 0.01$). The slope of the relationship between Ln(Biomass) and Ln(DBH) was not the same for both species at all sites ($F = 6.66$, $df = 7, 78$, $p < 0.001$). More precisely, the slope of the relationship for one of the species at one or more of the sites differed from that of the other at one or more sites. Additional tests are required to determine what specific differences exist, but further detail on this point is probably not of great interest. Even without such tests, some points are evident from the results of this and previous analyses (Figure 5). The slope of the relationship at Kapalga differed markedly from that observed at the other three sites. Also, on the basis of previous analyses, at Humpty Doo the intercept was higher for E. tetradonta than for *E. miniata*.

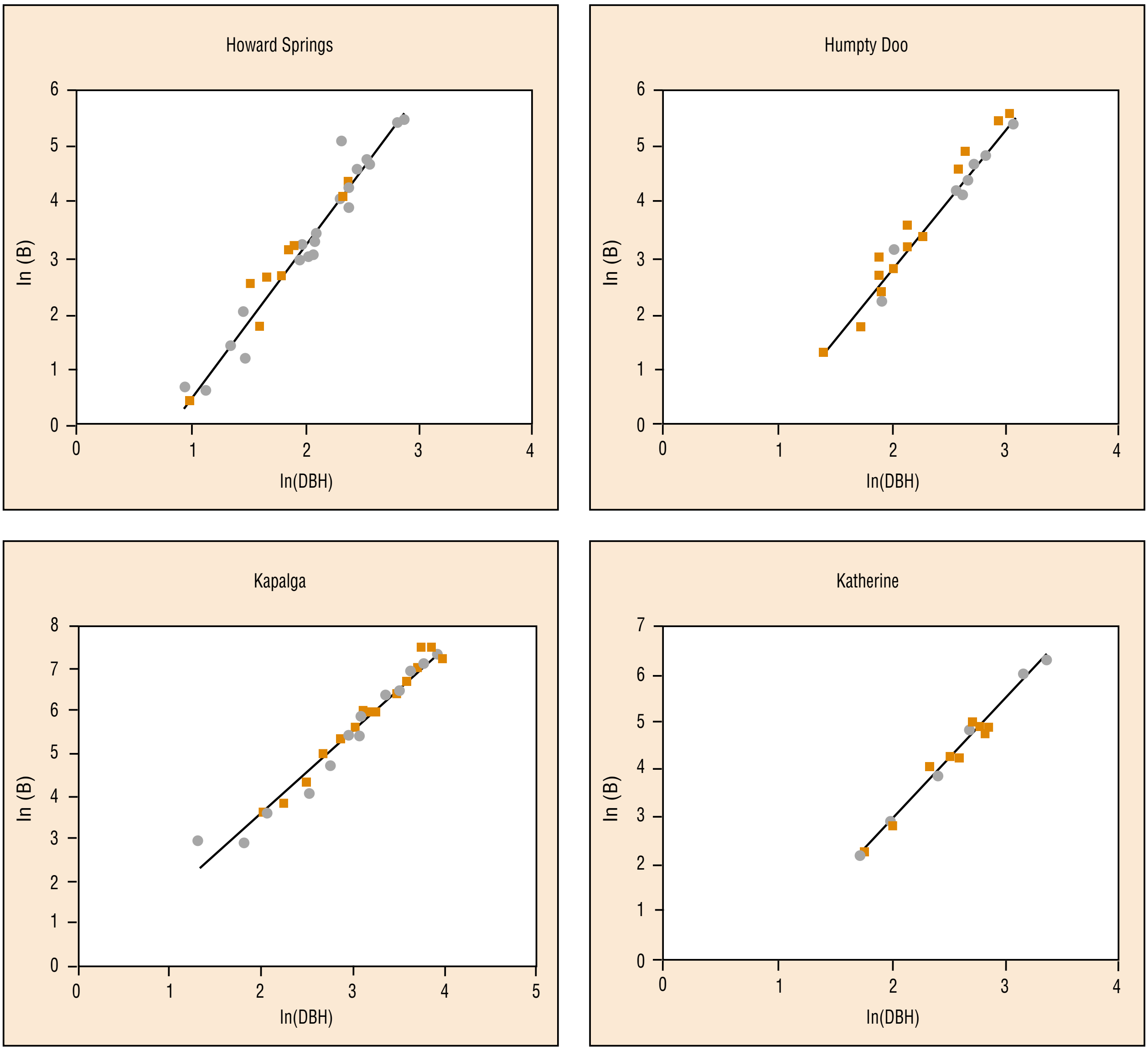

Figure 5: Relationship between Ln(Biomass) and Ln(DBH) for *E. miniata* (circle) and *E. tetradonta* (square) at all sites. The lines plotted are for reference only and do not accurately represent the relationship for the two species at all sites.

Analyses of all species except *E. clavigera*

Since it has already been shown that there were some differences among sites for some species in the relationship between Ln(Biomass) and Ln(DBH), the results of analyses comparing species ignoring sites must be interpreted cautiously (see below). In any case, Ln(Biomass) was highly correlated with Ln(DBH), with this relationship accounting for 95% of the variation in biomass ($r = 0.97$, $n = 149$, $p < 0.01$). The slope of the relationship between Ln(Biomass) and Ln(DBH) did not differ among species ($F = 1.55$, $df = 6, 135$, $p < 0.05$) but the intercept did ($F = 5.96$, $df = 6, 141$, $p < 0.001$). Without further tests, which are not likely to be particularly informative, it is not possible to state which species differed, although the results are broadly similar to those reported earlier for Howard Springs (Figure 1). Given the differences among sites noted above, the precise nature of differences among species would probably depend on which particular sites were sampled.

Table 4: Mean Ln(Biomass) and Ln(DBH), for all species. Also shown are the mean Ln(Biomass) values for each species, adjusted for differences in Ln(DBH). A higher adjusted mean indicates a higher intercept, and vice versa.

Species	Mean Ln(Biomass)	Adjusted mean	Mean Ln(DBH)
E. bleeseri	3.767	4.048	2.306
E. chlorostachys	2.686	3.533	2.065
E. miniata	4.138	4.053	2.462
E. papuana	5.880	3.993	3.229
E. porrecta	3.955	3.623	2.567
E. tetrodonta	4.084	4.014	2.456
T. ferdinandiana	2.636	3.882	1.895

Analyses of data from Paperbark swamps in the NT

For both tree height and tree DBH, there were no significant differences in the regressions between species. Consequently, a single combined regression for both species adequately describes the data (Table 5).

Table 5. Regressions are of the form: Log (FW) = a*Log (DBH or Ht) – b. From Finlayson *et al.* (1993).

Species	a	b	R^2
M. viridiflora (DBH)	2.338	0.561	0.987
M. cajaputi (DBH)	2.256	0.502	0.965
Combined (DBH)	2.266	0.502	0.984
M. viridiflora (Ht)	3.168	1.077	0.977
M. cajaputi (Ht)	3.018	0.941	0.538
Combined (Ht)	3.018	0.941	0.929

Analyses of Queensland Forestry Research Institute data

Former Arid Zone Institute Research (AZI) site, Longreach

There was a good relationship between Ln(Biomass) and Ln(DGH) for species at AZI ($r = 0.92$, $df = 49$, $p < 0.001$). There was no significant difference among species in either the slope ($F = 1.34$, $df = 5, 39$, $p > 0.05$) or intercept ($F = 1.53$, $df = 5, 44$, $p > 0.05$) of the relationship between these two variables (and see Figure 6).

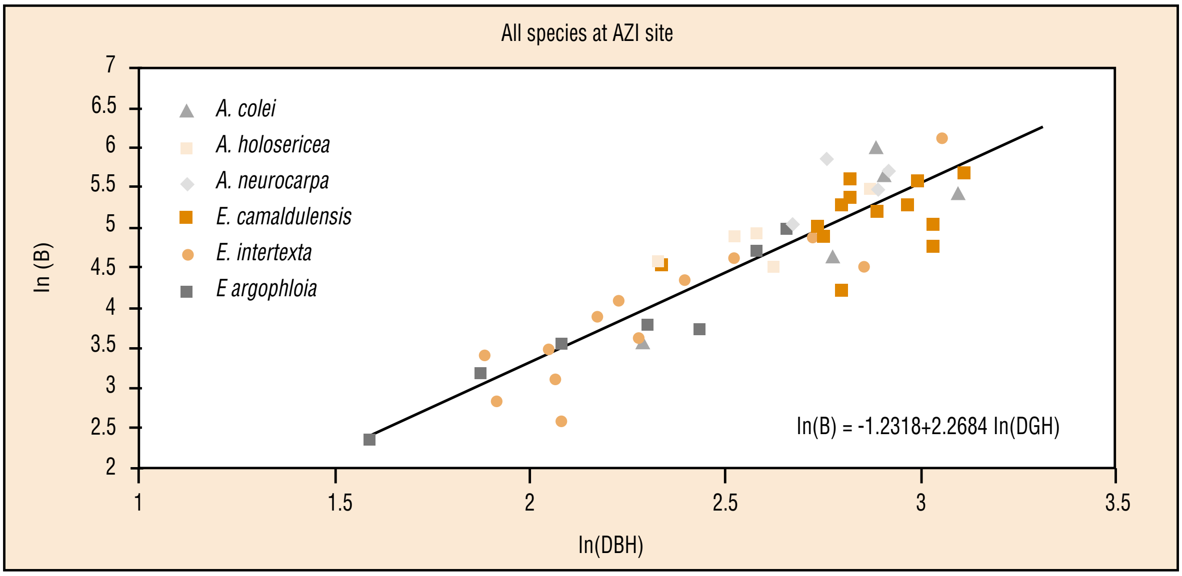

Figure 6: Relationship at AZI between Ln(Biomass) and Ln(DGH) for six species (n = 51).

Comparison of provenances

There was a moderate relationship between Ln(Biomass) and Ln(DGH) for *E. camaldulensis* from the two provenances ($r = 0.58$, $df = 17$, $p < 0.05$). There was no significant difference among provenances in either the slope ($F = 0.18$, $df = 1, 13$, $p > 0.05$) or intercept ($F = 0.76$, $df = 1, 14$, $p > 0.05$) of the relationship between these two variables. There was a good relationship between Ln(Biomass) and Ln(DGH) for *E. intertexta* from the two provenances ($r = 0.88$, $df = 17$, $p < 0.001$). As for *E. camaldulensis*, there was no significant difference among provenances in either the slope ($F = 0.52$, $df = 1, 13$, $p > 0.05$) or intercept ($F = 0.58$, $df = 1, 14$, $p > 0.05$) of the relationship between these two variables.

Summary of analyses of NT and QFRI data

At two of the sites – Howard Springs and Katherine – the relationship between Ln(Biomass) and Ln(DBH) did not differ among the species compared (*E. miniata*, *E. tetrodonta* and *T. ferdinandiana* at Howard Springs; *E. miniata* and *E. tetrodonta* at Katherine). This suggests that a common relationship might hold for at least two widespread species – *E. miniata* and *E. tetrodonta*. Howard Springs and Katherine were, however, the two sites with fewest individuals sampled and results from other sites, and all sites combined, contradict this conclusion.

The Queensland Forestry data, within which no significant differences of any kind were found, also had few replicates. For *E. miniata* and *E. tetrodonta*, the relationship between Ln(Biomass) and Ln(DBH) differed between the species and among the sites. Some differences among species also existed at the other sites (Humpty Doo and Kapalga).

It is important to note, however, that, despite these differences among species and sites, the simple relationship with Ln(DBH) – or Ln(DGH) – accounted for over 95% of the variation in Ln(Biomass) in all situations (see Table 6). Thus, much of the variation among individuals in biomass can be predicted simply from DBH.

Table 6: Summary of relationships between Ln(Biomass) and Ln(DBH) for NT and QFRI species († indicates that the independent variable is Ln(DGH)). For completeness, relationships for species pooled across all available sites are given, together with relationships for individual sites where analyses indicated differences. In this table n is the number of individuals; a and b are the constants for the regression equation; R2 is the percentage of the variation in Ln(Biomass) explained by the relationship; and RSD is the Residual Standard Deviation, required for corrections using the Baskerville (1972) procedure. Sites: HS = Howard Springs; HD = Humpty Doo; KAP = Kapalga; KAT = Katherine. The equation is of the form: Ln(Biomass) = B*(LnDBH) + A.

Species	n	a	b	R^2	RSD
A. colei (range: 9.9 mm – 22.2 mm)†					
Noonbah and AZI	8	–1.968	2.573	0.678	0.460
A. holosericea (range: 9.8 mm – 17.6 mm)†					
Noonbah and AZI	7	0.923	1.529	0.704	0.226
A. neurocarpa (range: 14.5 mm – 27.5 mm)†					
Noonbah and AZI	9	1.008	1.583	0.707	0.231
E. argophloia (range: 4.9 mm – 17.8 mm)†					
Noonbah and AZI	9	–1.114	2.198	0.949	0.240
E. camalduensis (range: 10.4 mm – 22.5 mm)†					
Noonbah and AZI	17	1.615	1.214	0.334	0.345
E. intertexta (range: 6.6 mm – 21.3 mm)†					
Noonbah and AZI	17	–1.338	2.332	0.773	0.446
E. bleeseri (range: 4.6 cm – 22.7 cm)					
Humpty Doo	8	–1.990	2.497	0.977	0.196
E. chlorostachys (range: 4.6 cm – 14.7 cm)					
Humpty Doo	14	–3.201	2.851	0.974	0.180
E. miniata (range: 2.6 cm – 50.0 cm)					
HS, HD, KAP, KAT	49	–1.447	2.269	0.941	0.395
Kapalga	14	–0.342	1.925	0.980	0.311
HS, HD, KAT	35	–1.844	2.426	0.929	0.382
E. papuana (range: 11.7 cm – 44.2 cm)					
Kapalga	12	–3.130	2.790	0.941	0.288
E. porrecta (range: 7.5 cm – 24.9 cm)					
Humpty Doo	8	–2.511	2.512	0.984	0.150
E. tetrodonta (range: 2.7 cm – 52.8 cm)					
HS, HD, KAP, KAT	45	–1.681	2.348	0.964	0.323
Kapalga	14	–0.758	2.083	0.980	0.189
HS, HD, KAT	31	–1.729	2.351	0.920	0.350
T. ferdinandiana (range: 2.6 cm – 16.7 cm)					
HS, HD	13	–1.653	2.263	0.927	0.367
All eucalypts in NT and QRFI data sets (range: 2.6 cm – 52.8 cm)					
HS, HD, KAP, KAT	137	–1.820	2.383	0.974	0.375

REGRESSIONS EXTRACTED FROM QUEENSLAND DATA SETS

The amount of data available for Queensland species is very large. Data are available (see Appendix) for several dozen species, including a wide range of Eucalypts, Acacias, Pines and other genera. For many species, biomass allocations to stem, branch, bark and leaves are available. Diameter at various heights (30 cm, 130 cm) and tree heights have been used in the regressions.

There were no significant differences between slopes of individual lognormal regression lines of stem circumference against total above-ground biomass for *E. crebra*, E., melanophloia and *E. populnea*. The allometric relationships enable accurate and quick estimates of above-ground biomass of woodlands dominated by these species to be made, provided community basal area or individual stem circumferences are sufficiently known.

REGRESSIONS EXTRACTED FROM WESTERN AUSTRALIAN DATA SETS

The regressions for Jarrah (*E. marginata)* and Marri (*E. calophylla)* were found to be not significantly different from each other (Hingston *et al.* 1980) (also see Table 7).

Because of the divergence of heights used when measuring stem diameter in other studies (3 cm, 30 cm, 130 cm), and because the raw data are not readily available, it is not possible to undertake further analyses of the regressions for WA data.

Table 7: A summary of the regressions available for tree species growing in WA. Regression is of the form Ln(Dry Weight) = A*Ln(DBH) +B.

Species	a	b	R^2	Author
Jarrah	2.84	– 3.680	0.994	Hingston et al. (1981)
Marri	2.74	– 3.370	0.982	"
Banksia grandis	2.50	– 2.260	0.963	"
Karri measured at 30 cm height	2.107	4.501	0.99	Grove (1988)
Karri measured at 130 cm height	2.128	5.146	0.99	"
B. laidlawiana measured at 30 cm height	2.70	4.998	0.99	"
B. laidlawiana measured at 3 cm height	2.814	4.268	0.99	"
T. spathulatum measured at 30 cm height	2.722	4.284	0.99	"
T. spathulatum diameter measured at 3 cm height	2.795	3.849	0.99	"
Chlorilaena quercifolia diameter measured at 3 cm height	2.665	4.187	0.96	"
L. floribundum diameter measured at 3 cm height	2.663	4.267	0.98	"
P. clavata diameter measured at 3 cm height	3.164	3.027	0.98	"
A. pulchella measured at 3 cm height	2.992	4.445	0.97	"
H. cuneiformis measured at 3 cm height	2.681	3.591	0.93	"
E. maculata – site 1	2.47	– 2.51	0.95	Ward and Pickersgill (1985)
E. calophylla – site 1	2.04	– 1.54	0.99	"
E. resinifera – site 1	2.44	– 2.54	0.97	"
E. maculata – site 2	1.87	– 1.1	0.98	"
E. calophylla – site 2	1.64	– 0.92	0.89	"
E. resinifera – site 2	1.74	– 1.12	0.98	"

DISCUSSION OF STATISTICAL METHODS

CORRECTION FACTORS

Testing correction factors

Frequently, the allometric relationship between plant biomass and some linear measure of size (e.g. DBH) is well described by the model:

$$Biomass = a(DBH)^{b} \qquad \text{Equation 1}$$

As indicated elsewhere in this report, R^2 values for such models are usually greater than 0.85 and often exceed 0.95. In most studies, this equation is transformed, by taking the logarithms of both biomass and DBH, before being applied to the data, to give the linear model:

$$Ln(Biomass) = a + bLn(DBH) \qquad \text{Equation 2}$$

There are two major advantages from using the transformed model. First, it can be easily fitted using standard least-squares regression procedures. Second, it is usually the case that variability in the dependant variable (biomass) increases with DBH, violating an assumption required for tests of significance. The logarithmic transformation of the dependent variable usually corrects this problem.

Using models of the form of Equation 2 to predict biomass for plants of known DBH requires back-transformation from the logarithmic scale to the arithmetic. The resulting estimates are likely to be biased unless corrected. Baskerville (1972) describes the problem thus:

> "When logarithmic transformation is used, it is usually desirable, indeed necessary, to be able to express estimated values of *Y* in arithmetic (i.e., untransformed) units. However, the conversion of the unbiased logarithmic estimates of the mean and variance back to arithmetic units is not direct. This results from the fact that if the distribution of Ln(*Y*) at a given *X* is normal, then distribution of *Y* cannot be normal but will certainly be skewed. In fact, if the distribution is normal in logarithms, the solution…for a given X_i and the determining of the antilogarithm of Ln(Y_i) yields the median of the skewed arithmetic distribution rather than the mean (Brownlee 1967; Finney 1941)!"

Expressing it slightly differently:

> "…a bias is inherent in this procedure because the largest values are compressed on the logarithmic scale and thereby tend to have less 'leverage' than small values in making such an estimate."

In any case, the result is that estimates of biomass made by simple back-transformation will usually be too low, often by a large amount (Baskerville 1972; Beauchamp and Olson 1973). Baskerville (1972) and Beauchamp and Olson (1973) suggest methods for correcting this problem. Beauchamp and Olson (1973) list the five estimators of *Y* (biomass): (1) *Y* EST is the biased estimate obtained by back-transforming; (2) *Y0* EST is the, also biased, estimate provided by Baskerville (1972); (3) *Y1* EST and (4) *Y2* EST are approximations to the unbiased estimator, and (5) *Y3* EST. Equations for the first four of these estimators, those most commonly used in practice and explored further here, are given below.

$$Y\ \text{EST}=Biomass=e^{(\hat{\beta}_0+\hat{\beta}_1 x_i)} \qquad \text{Equation 3}$$

where $\hat{\beta}_0$ and $\hat{\beta}_1$ are the intercept and slope, respectively of the linear regression obtained from logarithmically transformed observations, and x_i is the DBH for which an estimate of biomass is required.

$$Y0\ \text{EST}=Biomass=e^{(\hat{\beta}_0+\hat{\beta}_1 x_i+\hat{\sigma}^2/2)} \qquad \text{Equation 4}$$

where terms are defined as above and $\hat{\sigma}^2$ is the variance given by:

$$\sigma^2 = \sum_{i=1}^{n}(y_i-\hat{y}_i)^2 / (n-2) \qquad \text{Equation 5}$$

$$Y1\ \text{EST}=e^{(\hat{\beta}_0+\hat{\beta}_1 x_i+\hat{\sigma}^2/2)}\left\{1-\frac{\hat{\sigma}^2(2\O+\hat{\sigma}^2)}{4n}\right\} \qquad \text{Equation 6}$$

where Ø is given by:

$$\O = \sum_{i=1}^{n}(x_i-x)^2 / \sum_{i=1}^{n}(x_i-\bar{x})^2 \qquad \text{Equation 7}$$

$$\text{Y2 EST} = e^{(\hat{\beta}_0+\hat{\beta}_1 x_i+\hat{\sigma}^2/2)}\left\{1-\frac{\hat{\sigma}^2(2\varnothing+\hat{\sigma}^2)}{4n}+\frac{(\hat{\sigma}^2)^2\left[(\hat{\sigma}^2)^2+2(16/3+2\varnothing)\hat{\sigma}^2+4\varnothing^2 16\varnothing\right]}{32n^2}\right\} \qquad \text{Equation 8}$$

The calculation of estimates from *Y*0 EST (Equation 4) is straightforward, using the output of standard statistical packages, but the calculation of *Y*1 EST and *Y*2 EST is considerably more involved. Consequently, it is important to know the extent to which these three estimates differ in practice and, therefore, the value of undertaking the more elaborate calculations. In discussing the results obtained for sample data, Beauchamp and Olson (1973) themselves note that '*Y*0 EST is already a much closer approximation to *Y*3 EST' and that '*Y*1 EST and *Y*2 EST are not even plotted because they could not be distinguished [from *Y*3 EST] on the present scale of plotting'.

Procedure for testing correction factors

The performance of the various estimates was tested by calculating and comparing them for sets of simulated data. The simulated data were based on the observations for *E. miniata* in the Northern Territory at all sites *except* Kapalga (see Analyses of NT Data for further information). This data set included observations for 35 trees from 2.6 - 29.8 cm in DBH, and from 1.9 - 427.8 kg in biomass. The equation calculated for the real data was:

$$Ln(Biomass) = -1.84+2.43\text{x}Ln(DBH) \qquad \text{Equation 9}$$

The R^2 for this relationship was 0.93 and the variance was 0.146. The relationship simulated was:

$$Ln(Biomass) = 0 + 2.5\text{x}Ln(DBH)+\varepsilon_i \qquad \text{Equation 10}$$

The ε_i were random, normally distributed errors with variances of 0.15, 0.30, 0.45 or 0.60. Because bias in *Y* EST increases with variance, simulations with these different variances were done (Beauchamp and Olson 1973). The values selected cover the range often seen (see tables elsewhere in this report).

For each of the DBHs in the original data, new Ln(Biomass) observations were generated using Equation 10. A linear regression was fitted to the resulting pairs of observations and *Y* EST, *Y*0 EST, *Y*1 EST and *Y*2 EST calculated by the formulae above. This process was repeated 2000 times for each variance and the averages of all four estimates calculated. This gave reliable results. For example, the average $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\sigma}^2$ for the simulations with $\hat{\sigma}^2=0.60$ were 0.013, 2.494 and 0.597, respectively. In addition, the averages of the actual Ln(Biomass) were calculated for comparison with the estimates.

Results and discussion of the tests for correction factors

The results of the simulations were in accord with the conclusions of Baskerville (1972) and Beauchamp and Olson (1973): Y EST consistently underestimated the true mean biomass, often by a considerable amount (Figure 7). As indicated by Beauchamp and Olson (1973), Baskerville's (1972) estimator consistently overestimated the true mean biomass, although rarely by much.

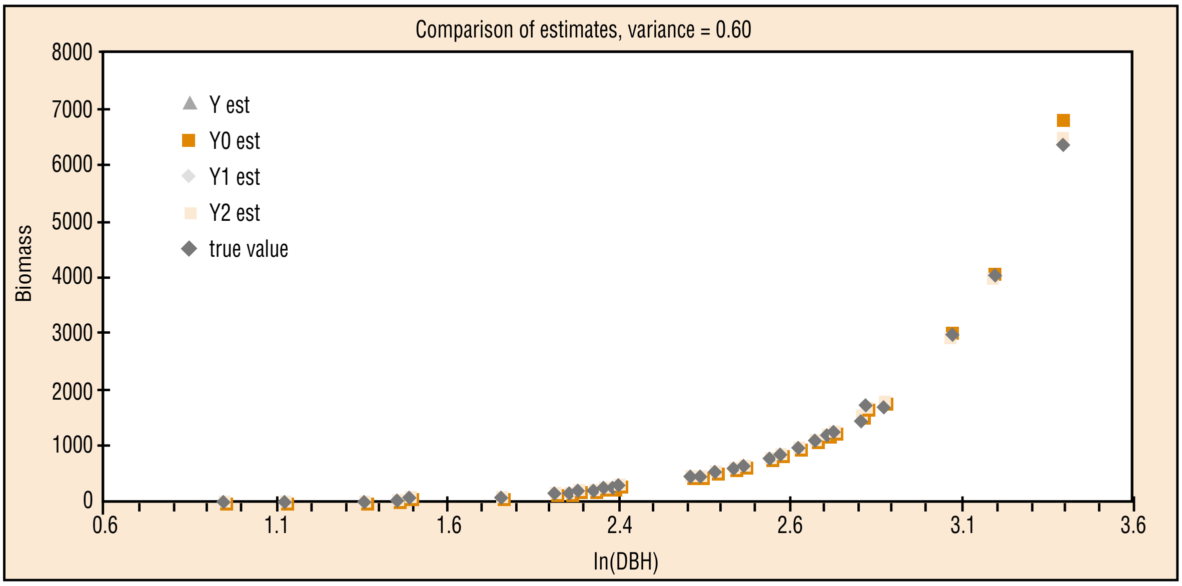

Figure 7: Performance of different estimators of biomass in simulations with variance = 0.60. Y EST, the simple back–transformation of Ln(Biomass), consistently underestimates the true biomass by a large amount and Y0 EST, Baskerville's (1972) suggestion, consistently overestimates it slightly.

A clearer indication of the performance of the different estimators is gained by examining the ratio of the estimated biomass to the true biomass (see Figures 8, 9 and 10).

Table 8: Mean ratio of estimated biomass to true biomass for the four estimators examined at each of the four variances simulated.

	Var = 0.150 SD = 0.387	**Var = 0.300 SD = 0.548**	**Var = 0.450 SD = 0.672**	**Var = 0.600 SD = 0.775**
Y EST	0.932	0.869	0.809	0.754
Y0 EST	1.004	1.009	1.014	1.020
Y1 EST	1.000	1.000	0.999	0.999
Y2 EST	1.000	1.000	1.000	1.000

The poor performance of *Y* EST was evident in these results and it is clear that these uncorrected estimates were quite unreliable. As indicated by Beauchamp and Olsen (1973), *Y*1 EST and *Y*2 EST were virtually indistinguishable. Since *Y*1 EST is somewhat easier to calculate than *Y*2 EST, it seems reasonable to adopt either it or *Y*0 EST.

It is clear that the use of *Y*0 EST involves the introduction of a bias, but this is not substantial and should be balanced against the greater complication, and therefore chance for error, involved in the calculation of *Y*1 EST. The greatest bias observed in the simulations was only 2% (Table 8) – about 130 kg for a tree of 6500 kg.

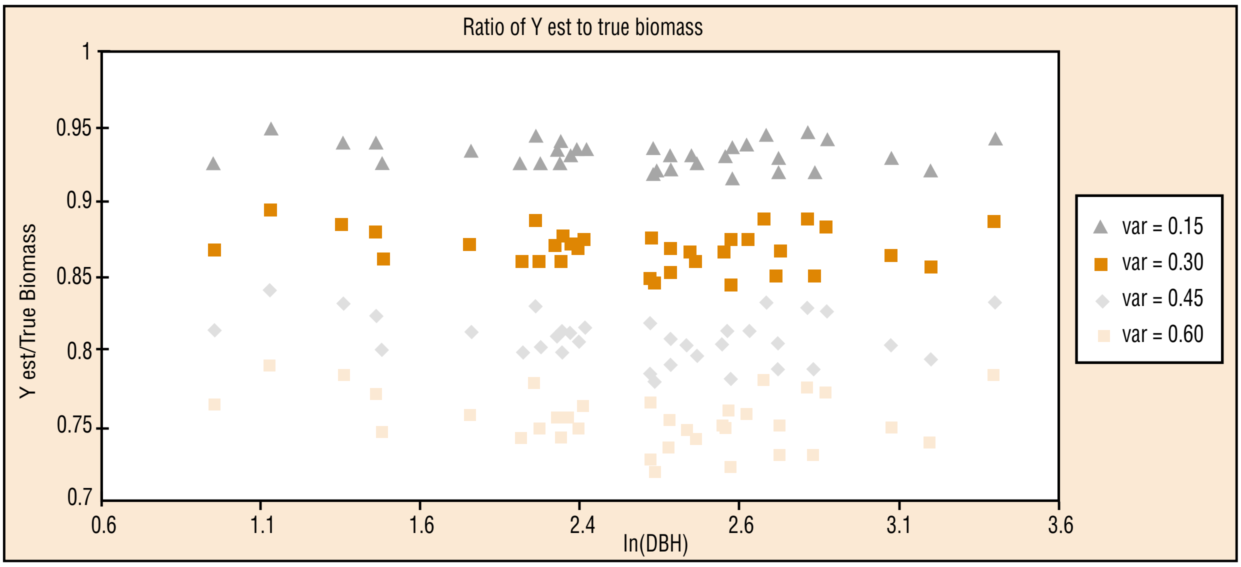

Figure 8: Performance of Y EST in simulations.

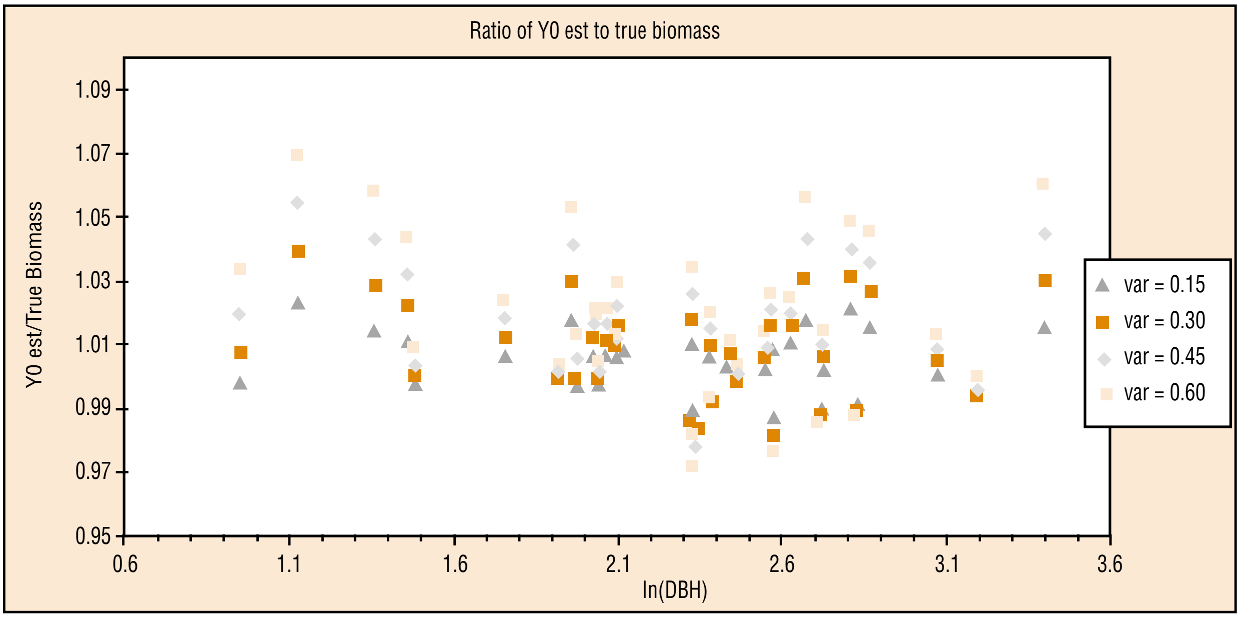

Figure 9: Performance of Y0 EST in simulations.

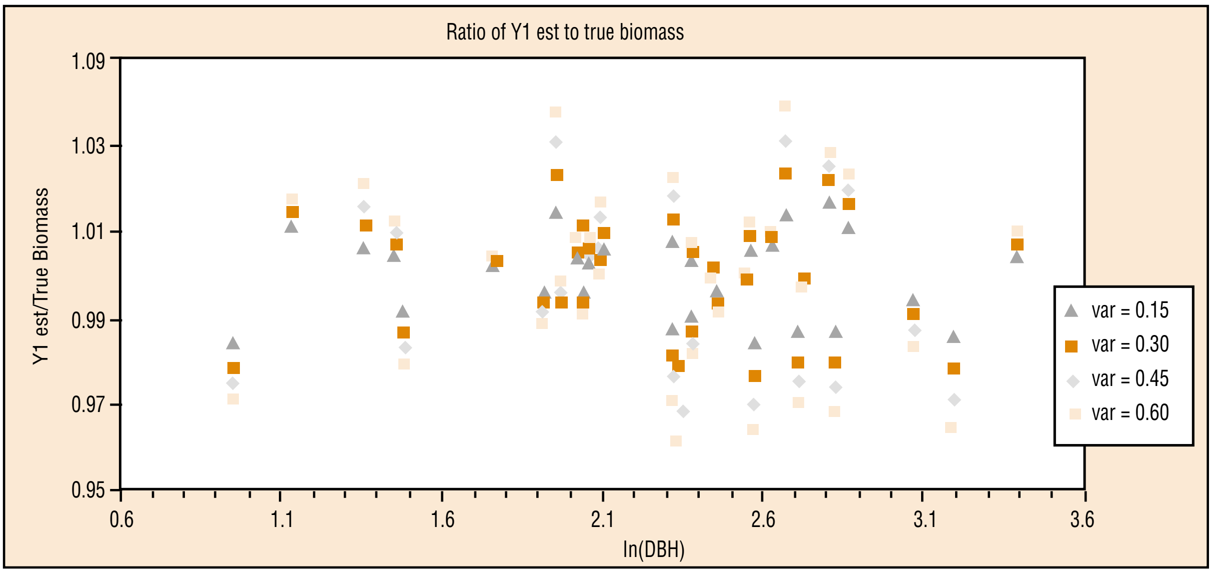

Figure 10: Performance of Y1 EST in simulations. Results for Y2 EST were virtually identical.

Conclusions of the tests for correction factors

Uncorrected estimates of biomass derived from least squares regression on double logarithmically transformed data are likely to be seriously biased and should not be used. In most instances the correction suggested by Baskerville (1972) will be adequate and is to be preferred because of its computational simplicity. The information required to employ this procedure in biomass predictions is presented in this report where appropriate. In situations where error variance (or residual standard deviation) is high, say, greater than 0.6, Beauchamp and Olson's (1973) *Y*1 estimator should be considered.

EXAMINATION OF ACCURACY OF PREDICTION

Introduction

One methodological aspect of the accuracy of predictions of biomass has already been discussed: the use of corrections for the bias inherent in the use of least squares regression with logarithmically transformed data. It must be emphasised again that some correction should be used and that, generally, the Baskerville (1972) method is recommended.

A second aspect concerns the importance of using the most appropriate equation. Analyses of the NT data revealed differences among some species, and sites, in the relationship between Ln(Biomass) and Ln(DBH). This indicates that a single, simple equation will not produce accurate estimates of biomass for all species or all sites. It is *not*, however, necessarily the case that the use of simple equations will produce grossly inaccurate predictions. It is quite possible for differences among species, and sites, to be significant, even highly so, *but small*. The *degree* of statistical "significance" (i.e., the p-value associated with the test) is not a simple function of the *magnitude*, or importance, of differences among species or sites. The p-value certainly is *influenced* by the magnitude of such differences (bigger differences will result in smaller p-values) but it also depends on the variability in the data and the number of replicate individuals sampled. These last two points also mean that failing to detect a difference among species or sites does not mean that no difference exists: if may be that too few replicates have been taken, given the variability observed.

One way to investigate the accuracy of different equations is to use them to predict biomass for some situations and compare the results. This procedure was done here.

Procedure for assessing of accuracy of prediction

Two separate investigations were done. In the first, results for the eucalypt species (with the exception of *E. clavigera*) sampled in the NT were used. Predictions were made using an equation derived for all eucalypts, and using equations derived for the individual species and sites (Table 4). The second investigation used three species common in Queensland – *E. crebra*, *E. melanophloia* and *E. populnea* – and was based on results from Burrows *et al.* (submitted).

In the first investigation, fifty different DBH values were randomly generated for each of the six eucalypts (*E. bleeseri*, *E. chlorostachys*, *E. miniata*, *E. papuana*, *E. porrecta*, *E. tetradonta*) at each of the four sites (Howard Springs, Humpty Doo, Kapalga, Katherine). The DBH values were constrained to fall within the range observed for that species (e.g., 2.6 - 50.0 cm for *E. miniata*) and values were only generated for sites at which more than one individual of each species had been sampled (e.g., DBH values for *E. papuana* were only generated for Kapalga). The biomass of each individual was then estimated using (a) the common eucalypt equation, (b) the common equation for that species, and (c) the equation for that species at that particular site. In all cases, predictions were made using Baskerville's (1972) correction. The individual values were summed and compared (see Table 9).

The second investigation used a very similar procedure but had some slight modifications because of the information available. Again, fifty different DBH values were randomly generated for each of the three species but, in this case, this was done for four hypothetical sites: one site which had all species in equal numbers, and three other sites, each which had only one of the species. Again, the DBH values were constrained to fall within the range observed for that species (see Burrows *et al.* submitted). The biomass of each individual was then estimated using (a) a common eucalypt equation, and (b) the specific equation for that particular species (equations in Burrows *et al.* submitted). Again, predictions were made using Baskerville's (1972) correction. The individual values were totalled and compared (see Table 10).

Results and discussion of accuracy of prediction

First investigation: NT

The three different methods of predicting biomass gave fairly similar results in terms of total biomass for each species, both for each site and overall. In some cases, the most accurate method, using species and site specific equations, predicted slightly higher biomass (e.g., *E. miniata* at Howard Springs), in other cases, slightly lower (e.g., *E. tetradonta* at Howard Springs). The same was true of totals for the other sites.

Table 9: Biomass predicted at each NT site using different combinations of equations.

	Number of species	Common equation	Species equation	Species–site equation
Howard Springs	3	56 809	55 755	59 949
Humpty Doo	6	75 125	71 767	75 742
Kapalga	3	94 431	96 580	90 320
Katherine	2	57 493	56 444	61 013
TOTAL		283 859	280 548	287 026
% of Species–site		98.9	97.7	100.0

Overall, in this instance the difference among methods in predictions of *total biomass across all species and sites* was fairly small (Table 9; Figure 11). Using species and site specific equations gave a total of 287 026 kg. Using species specific equations gave a value only 2.3% smaller. The use of a common eucalypt equation resulted in an error of only 1.1%.

Second investigation: Qld

The errors involved in using a common equation in the Qld scenarios were rather greater than those observed in the NT results. Overall, the use of the common equation overestimated biomass by nearly 16%, a sizeable error (Table 10; Figure 12). The errors for the individual species ranged from an underestimate of 11% for *E. crebra* to an overestimate of 42% for *E. populnea*.

Table 10: Biomass predicted for each Qld species using different combinations of equations.

	Number of species	Common equation	Species equation
All species	3	146 428	128 297
E. crebra	1	51 041	57 507
E. melanophloia	1	21 717	17 142
E. populnea	1	81 877	57 652
TOTAL		301 063	260 598
% of Species–site		115.5	100.0

Conclusions of accuracy of prediction

It is extremely important to remember that these results apply only to the particular mix of sites, species and sizes used. For instance, in the calculations done here, the sizes of the individuals were evenly distributed between the smallest and largest DBHs actually measured. If larger trees predominated at a site, however, the error involved in using a common equation would probably be greater.

For these reasons, it is difficult, if not impossible, to determine the consequences of using common equations without information about the size and species distribution of the populations for which predictions are to be made.

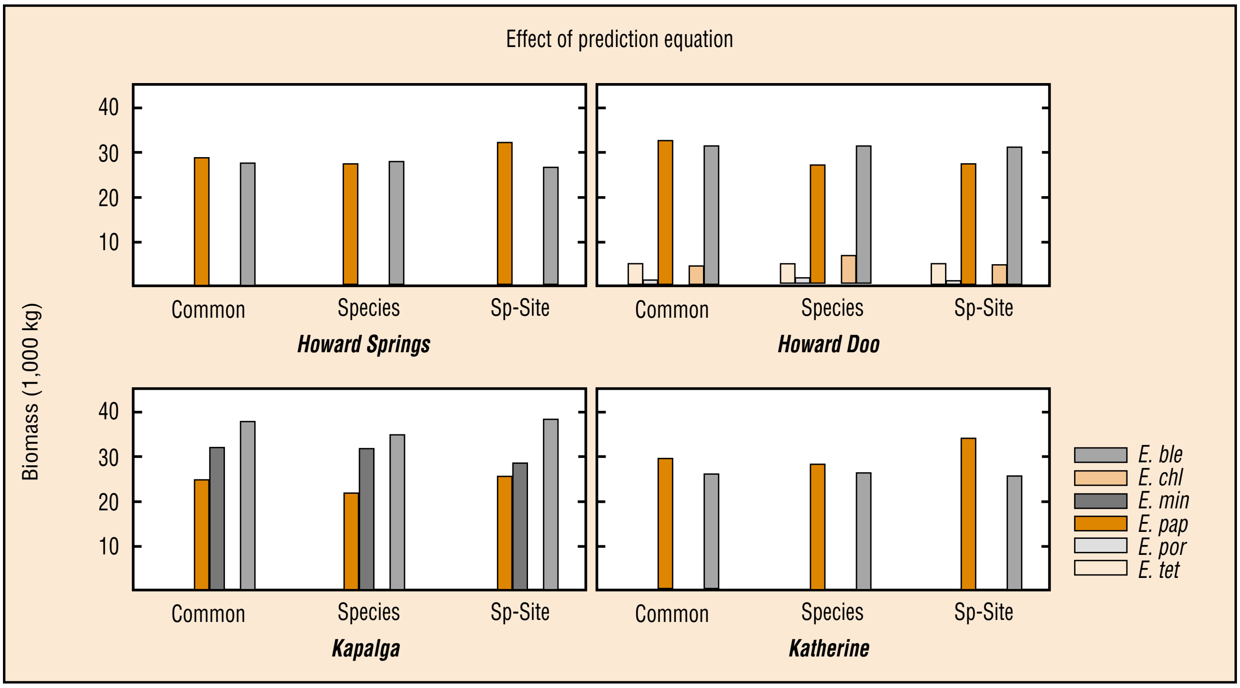

Figure 11: Total biomass of 50 randomly generated trees of each species at each NT site. The results for each site show the biomass predicted using a common equation for all eucalypts, a species-specific equation and a species and site specific equation. Data were only generated for species actually sampled at each particular site.

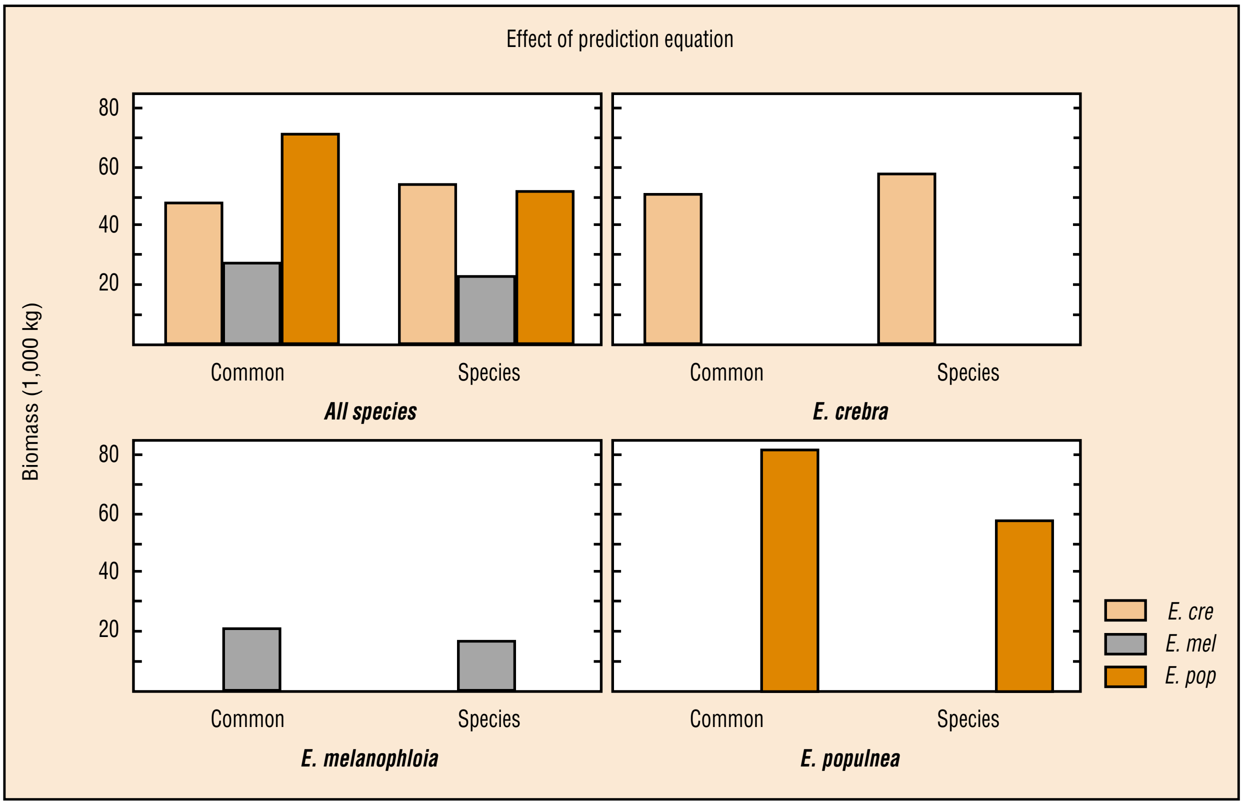

Figure 12: Total biomass of 50 randomly generated trees, of each species at each Qld site. The results for each site show the biomass predicted using a common equation for all eucalypts, a species–specific equation and a species and site specific equation. Data were only generated for species sampled at each site. Note that the ‘sites’ were, in this instance, hypothetical constructs.

GENERAL DISCUSSION OF ANALYTICAL METHODS

Correction factors

Usually, for natural stands of various size classes, the weight of a plant component can be plotted against some dimension, for example, basal stem circumference, to give a straight line on a double-log plot. Thus, it has been expedient to calculate regressions as linear in the logarithms of the variables, and to transform back to arithmetic units by determining the antilogarithms for the expansion of the stand table to biomass (Baskerville 1972). However, statistical aspects of the treatment are subject to question (Zar 1968; Hafley 1969; Baskerville 1972; Beauchamp and Olson 1973). In particular, because the geometric mean rather than the true mean of the estimated value is obtained, bias is introduced by simply taking antilogs of the previously transformed data (Munro 1974). This has resulted in a systematic underestimation of biomass whenever the logarithmic transformation has been used (Baskerville 1972).

Mathematical procedures which counteract this bias have been known for some time (Finney 1941), but are rarely applied in ecological work (Baskerville 1972). In the present study the steps outlined by Beauchamp and Olson (1973) are recommended, although many authors (e.g., Scanlan 1991, Ter-Mikealian and Korzukhin 1997) prefer Baskerville's (1972) procedure because of its computational simplicity.

Dimensional analysis, as outlined, is appropriate for tree and tall shrub vegetation. However, where it is difficult to easily measure a suitable independent variable on which regressions may be based, this method is limited. This is particularly true of small, multi-stemmed shrubs. In such vegetation the use of 'average' shrub techniques and stand enumeration seems unavoidable unless the more labour intensive total harvest of shrubs is employed.

Forest application of 'average tree' methods, and their attendant errors, have been discussed by Attiwill (1966) and Ovington *et al.* (1967). To minimise likely errors in the use of such techniques in shrub communities, it seems advisable to stratify populations into species size classes. 'Average' shrubs can then be selected within each size class as a basis for determination of stand biomass.

In the present study, some measure of stem diameter (measured at breast height, at 30 cm height, or as a circumference) was a very good predictor of total biomass. Indeed, for all species, circumference alone accounted for more than 90 % of above-ground biomass. In many cases, 95+% of variation in biomass was accounted for by circumference. It is important to note, however, that there are three measures of diameter in the data provided here. First, in the TRAPS data provided by Burrows, a diameter measure at 30 cm height was used. Second, the NT data are based on a diameter measured at a nominal breast height of 1.3 -1.5 m. The QFRI study of 6 species measured at two sites used diameter at ground level because such young (9 months) trees were studied. It is important that future modelling is specific about which diameter is used.

In a lognormal regression of *E. crebra*, *E. melanophloia* and *E. populnea* (Burrows *et al.* 1999), there was no significant difference in the slopes of the three species. These species, along with close allies, dominate much of the grazed eucalypt woodlands in Queensland. Similarly, for the three species at Howard Springs (*E. tetrodonta*, *E.miniata* and *T. ferdinandiana*), neither the slope nor intercept of the relationship between DBH and biomass differed among the species. For the six species studied at Humpty Doo (*E. bleeseri*, *E. chlorostachys*, *E. miniata*, *E. porrecta*, *E. tetrodonta*, and *T. ferdinandiana*), the slopes of the relationship between DBH and biomass did not differ among species, but the intercepts did. It is evident from the results that *E. bleeseri* and *E. tetrodonta* have intercepts that are similar and slightly higher than those of all the other species.

For Kapalga, some variation was observed. Analysis indicated that the slopes and intercepts for *E. miniata* and *E. tetrodonta* were similar but that *E. papuana* differed in slope and intercept. The latter species had a lower intercept and a higher slope than *E. miniata* and *E. tetrodonta* (Figure 3).

For Katherine, which is significantly drier than Humpty Doo, Howard Springs and Kapalga, the two eucalypts (*E. tetrodonta*, *E. miniata*) were found to have the same slope and intercept. *E. tetrodonta* and *E. miniata* dominate the woody species of the Top End of the NT savannas. It is likely that a single simple relationship can be used for this pair of species. O'Grady *et al.* (1999) have shown that these two species account for about 62% of the total basal area but 79% of the standing biomass of the open forest around Darwin.

Hingston *et al.* (1981) found no significant difference in the lognormal relationships between total above-ground biomass and DBH for *E. calophylla* and *E. marginata* in south-west Australia. In addition, after they studied 5 species of juvenile (2-5 y) plantation eucalypts (*E. globulus, E. nitens, E. ovata, E. regnans* and *E. saligna*), Senelwa and Sims (1998) concluded that woody biomass allometry does not differ significantly within the same genus.

Expansion factors

Foresters have developed many of the published and unpublished regressions available for tree species. In these cases the dependent variable is usually merchantable (commercial) timber volume. Expansion factors have been suggested to convert such volume estimates to above-ground biomass for the total tree. These utilise wood density values (kg m^{-3}) to obtain merchantable timber weight and this is then multiplied by an expansion factor to obtain total aerial weight (to include branches, bark and leaves). The IPCC currently suggests default wood density of 500 kg m^{-3} and expansion factor multiple of 2 for 'unproductive' forests.

The IPCC default wood density is completely inappropriate for Australian hardwoods, which have wood densities of c. 1000 kg m^{-3}. Extensive data sets are available in Forest Trees of Australia (Boland *et al.* 1992) and Queensland Timbers: Their Nomenclature, Density and Lyctid Susceptibility (Cause *et al.* 1989).

The IPCC default expansion factor multiple for unproductive forests was compared with calculated values for two Queensland hardwoods (Burrows *et al.* 1999). In this case, the appropriate expansion multiples were 2.38 for *E. crebra* and 1.85 for *E. melanophloia*, similar to the IPCC default value. Brown *et al.* (1989) estimate expansion factors of 1.74, 1.95 and 1.57 for undisturbed primary forest in wet, wet-dry transition and dry forests, respectively. These are comparable to estimates of 1.25 to 1.82 for temperate forests (Johnson and Sharp 1983).

Quadratic stand mean diameter (QSD) is a useful index for describing the average size of trees in a stand and is readily available from many forest inventories (Brown *et al.* 1989). The QSD is calculated thus:

$$\mathrm{QSD} = \sqrt{\{(\Sigma D^2)/n\}} = \sqrt{\{(BA/n)*(4/\pi)\}}$$

where BA = basal area and D = diameter.

Expansion factor decreases non-linearly with increasing size of trees in a woodland. When expansion factor is plotted as a function of QSD, differences between regions and life zones disappear (Brown *et al.* 1989). Expansion factors are large for forests with small QSDs and decline to an asymptote of 1.5-2.0 when QSD > 30 cm (Brown *et al.* 1989). However, there is not a single expansion factor that can be applied to all forests within a given life zone or region. Therefore application of universal expansion values should be avoided.

There is much uncertainty in the magnitude of the carbon flux arising from tropical forest deforestation. This is partly because of the uncertainty in estimates of biomass density (or organic carbon density, expressed as mass per unit area; Brown and Lugo 1984). There have been several estimates of tropical forest carbon density.

Whittaker and Likens (1973) estimated carbon densities as between 160 and 200 t ha^{-1} for two tropical forest types recognised in their study. In contrast, Brown and Lugo (1982) estimated C densities of tropical forests to be in the region 40-185 t ha^{-1}. These estimates are significantly different. This is partly because the database upon which such estimates are made is very small. In addition, many life zones are not represented in the data.

An alternative method of calculating carbon densities is to use standing timber volumes. Such data are relatively readily available across a broader geographical spread. The challenge is to find the relationship between standing biomass and standing wood volume. Brown and Lugo (1984) used this approach and concluded that the mean ratio of total biomass to stemwood volume was 1.6. However, it appears that this applies only to closed forests, and the ratio tends towards 3 or more for open forests.

PROBLEMS IN DATA COLLECTION

To accurately estimate total biomass of entire vegetation assemblages it is necessary to know the contribution of all the dominant woody species to total standing biomass. For the open forest savannas of the Top End of the NT, two species (*E. tetrodonta* and *E. miniata*) account for 79% of the standing biomass (O'Grady *et al.* 1999). Inclusion of five other species accounts for 98% of the total biomass (O'Grady *et al.* 1999). In the study of Burrows *et al.* (1999), the contribution of non-eucalypts to total biomass is less than 20%. However, in non-eucalypt dominated vegetation this is clearly untrue, but it is possible that in such vegetation types, knowledge of three or four species would account for more than 70% of the standing biomass.

Predictions of biomass that are made outside of the actual range of the data used to generate the regression equation should be avoided whenever possible. This is especially true for extrapolations into the region of large trees, where errors can be significant.

Destructive sampling gives accurate measures of biomass at a given point at a given time, but is costly and time-consuming, especially if biomass is to be partitioned into components (stem, branch, leaf and bark). Unless sampling occurs with sufficient replication and attention to a sampling scheme that incorporates all the variability, the precision of destructive sampling generally decreases as the spatial heterogeneity of the vegetation increases. Because of cost considerations, such sampling is rarely undertaken.

Destructive sampling of trees with single stems is usually undertaken along with a measure of stem diameter (basal, or DBH). Such measures are relatively easy and cheap to make and good correlations are obtained for single-stemmed species. However, for small shrubs, or multi-stemmed species, the use of DBH is problematic. A 'mean tree' approach may be appropriate in such cases. Nevertheless, Clough *et al.* (1997) have shown that linear log-log relationships for multi-stemmed mangrove trees can be obtained and it is likely that their approach can be modified for other multi-stemmed species.

There is variation between studies in the height at which stem diameter is measured. Thus, data on diameter included in this review was measured at a height of 3 cm, 30 cm or 130 cm. In addition, dry weight and fresh weight have both been used. The use of different measures clearly prevents easy comparison between studies.

MODELLING AND STATISTICAL CONSIDERATIONS

Different types of regression models have been used in the past to determine biomass from a range of tree parameters – usually DBH, tree basal area, tree height, wood density and a combination of these. Saldarriaga *et al.* (1988) found significantly improved regressions when data were divided into three DBH size classes. Jordan and Ehl (1978) included wood density because this was very variable in their forests (in the Amazon). In a study of mature lowland forests in Colombia, Overman *et al.* (1994) compared nine different regression models, and determined that the standard model of:

$$\text{biomass} = A(\text{DBH})^B + C$$

yielded a typically non-linear relationship which could be linearised by a simple transformation to DBH^2 to yield the model:

$$\text{biomass} = A(\text{DBH})^2 + C.$$

The problem of heterscedasticity (increase in variance with larger values of DBH) can be addressed by transforming both biomass and DBH as log transforms. These transforms were used in the present study.

The addition of more terms to the regression model can often improve the accuracy of biomass predictions. Two typical additions are tree height and wood density. However, the improvement is relatively small. Given the significant increase in the amount of work required to obtain tree height and wood density, it is probably not cost effective to add these variables to the model. For example, in the study by Overman *et al.* (1994):

$$\text{Ln(biomass)} = A * \text{Ln}(\text{DBH}^2 * \text{Ht} * D)$$

where Ht and D are tree height and wood density respectively, only increased the R^2 from 0.97 to 0.99, compared to the simpler model

$$\text{Ln(biomass)} = A * \text{Ln}(\text{DBH}^2).$$

Large trees can significantly skew regression equations. Frequently, R^2 is used to evaluate the amount of variation explained by a regression. However, R^2 gives a large weighting to observations with large values. Cumulative percentage deviation – the ratio between total estimated and observed weight of sample trees – has been used to select the best regression function (Saldarriaga *et al.* 1988). However, Overman (1989) showed that this was also overly influenced by the accuracy of determining the weight of very big trees.

Consequently, Overman *et al.* (1994) used the following:

$$\delta\ \text{Biomass} = \sum_{n=1}^{n} \frac{[(DW'-DW)/DW]*100}{n}$$

where DW’ = estimated dry weight and DW is observed dry weight. This measure, an average of the absolute percentage deviation, gives equal weight to observations of different magnitudes.

Models using DBH and height suffer from co-linearity of independent variables. Models using DBH in an untransformed state suffer from heteroscedasticity and this can be best overcome by using log transforms. Models using wood density can significantly improve the accuracy of the models but the improvement is unlikely to warrant the increased cost and effort required. However, it is likely that if a single, or at best, a few, regressions are required to adequately describe biomass of tropical Australia, then wood density is probably going to be required. Thus, Deans *et al.* (1996) observed that, compared to a number of other regressions, the multi-species, pan-tropical biomass equation of Brown *et al.* (1989) consistently overestimated biomass. However, if wood density was taken into account, predictions from different regressions converged. It is possible that this is true for tropical Australia too.

Values of the intercepts for many regressions in the literature are non-zero. Often they are negative, which means that estimates of biomass for small trees are in serious error. One way of removing this is to force the regression through zero. Alternatively, the biomass of trees 1.3 m tall (ie. the height used to measure DBH) can be accurately determined and this value can be subtracted from all biomass measurements used in the regression (Deans *et al.* 1996). Then the regression can be used and this value added to all predictions subsequently derived. Using this approach improved the regression equations obtained by Deans *et al.* (1996).

RESEARCH RECOMMENDATIONS

GENERAL RESEARCH RECOMMENDATIONS

1) Remotely sensed data are likely to be of increasing importance and relevance in the near future. Recently obtained synthetic aperture radar data for the NT show that leaf area index and tree basal area can be determined, after suitable ground-truthing, for savannas and presumably other vegetation types. However, the regressions with biomass were poor. It is likely that this technology will provide the most efficient means of large-scale (thousands of hectares) estimates of biomass, but the importance of good, high-resolution ground-truthing cannot be overstated. Applying this technology to all the major ecosystems of tropical Australia will be possible, but costly. Further, its use for closed forests and terrain that is not flat is more problematic than its application to sparse savanna vegetation on flat terrain.

2) A major source of error in calculating total C stored in vegetation is the component present below-ground. Compared to above-ground assessments, relatively few studies have been undertaken in Australia. It is likely that approximately 30-50 % of the total biomass in tropical Australian vegetation is located below ground. This estimate requires testing. Brown and Lugo (1982) provide a range of root to shoot ratios of between 0.03 and 0.81, with an average in moist tropical forests of about 0.25. Sanford and Cuevas (1995) give values for topical forests on podsols and tropical deciduous montane, lowland and rainforests of 0.6, 0.33, 0.18 and 0.12, respectively. Deans *et al.* (1996) found a ratio of 0.3 -0.36 for the semi-deciduous moist forest in the Cameroon. As a site becomes drier – for example, along the moisture gradient that exists inland through savannas of the NT) – partitioning to roots increases. Recent studies in the NT suggest an approximate 50% allocation to root biomass.

3) Global ecology is the study of relationships between variables that can be applied across a range of ecosystems or across a wide geographical range. For example, Reich *et al.* (1997) talk of the global convergence of plant functioning and find similar inter-specific relationships between leaf structural attributes and leaf function / plant growth. The idea that there is an almost universal relationship between tree density, or LAI, or other attributes such as standing biomass, and variables such as water and nutrient availability, seems worthy of further study.

An example of a Global Ecological Modelling approach is that of Baldocchi and Meyers (1998), who developed a simple relationship between leaf area index and a knowledge of foliar N content (N) and the ratio of rainfall to equilibrium evaporation rate (P / E_{eq}). This relationship appeared to apply to a large range of ecosystems around the world, including boreal, temperate and tropical evergreen ecosystems. Seasonally dry forests were absent from their analyses, but it is likely to be applicable there also.

The Baldocchi and Meyers equations were applied to savannas. For a range of seasonally dry forests, there is a significant relationship between $[N] * P / E_{eq}$ and LAI or tree density. Thus, for savannas of north Australia, covering a rainfall gradient of almost 1500 mm, and for other sites in Africa, tree density (which is highly correlated with leaf area and stem volume) or LAI can be predicted ($R^2 = 0.98$) from the following equation:

$$\text{Tree density} = [N] * P / E_{eq}$$

where

[N] is foliar Nitrogen content in mg g^{-1},

P = annual precipitation, and

E_{eq} = annual equilibrium evaporation.

Foliar N content provides a simple, albeit crude, estimate of nutrient availability and is highly correlated with assimilation rate (Eamus and Prior 1999), while the term P / E_{eq} is a surrogate measure of water availability. The $[N] * P / E_{eq}$ relationship for tree density and LAI may be easier to use than recently developed models based upon plant available moisture and plant available nutrients, since the required data are far more available.

Such relationships between foliar nutrient content (which is related to nutrient availability) and the ratio of rainfall to equilibrium evaporation (which is related to water availability) may be applicable to all ecosystems within Australia and may provide a means of modelling standing biomass. Clearly a significant amount of work is required to test this, but the application of a theoretical model to biomass could prove insightful and inexpensive.

4) There is an inverse relationship between log(plant mass) and log(population density). This appears to hold for both within and between species. Previous speculations on factors behind possible relationships between mass and stand density have been *a posteriori*, after statistical analyses of data. However, empirical patterns are subject to variance through choice of data set, data quality and type of analyses. In addition, the confidence limit around regressions in log-log plots allow a number of slopes to be applied, with major impacts upon the output. In a recent theoretical analysis, Franco and Kelly (1998) show that there is an *a priori* reason for believing there is a common inter-species relationship between log(biomass) and log(density), with a slope of -1/3, rather than the often assumed -1/2 relationship. This relationship should be investigated for Australian tree species as it could provide a simple method for large-scale assessments. Similar theoretical considerations are discussed by Enquist *et al.* (1998), who also conclude that a -1/3 relationship between total biomass and maximum plant density should exist because of mechanisms underlying resource use and tree size.

5) It is apparent that there are some significant tropical ecosystems not represented in the data currently available. Some key examples include rainforests (of which there are 1500 patches in the NT alone), paperbark (*Melaleuca* spp.) swamps (only one study at one site), riparian forests, *Allosyncarpia* forests and mangroves (of which there are more than 11,000 km^2 in tropical and sub-tropical Australia). It is clear that these gaps should be filled. This could be done relatively cheaply, although access to rainforests and monsoon vine forests such as *Allosyncarpia* forest, to undertake destructive harvests, is likely to be politically difficult. The Department of Lands, Planning and Environment are currently undertaking a mangrove forests biomass study in the NT. Data will not be available in the short-term. No data was located for tropical WA and this is clearly a major omission.

6) Wood density should be measured in a number of key species so that it is possible to determine whether inclusion of this parameter significantly improves the regressions, and whether its inclusion will significantly reduce the number of equations required to adequately describe tropical Australian biomass.

7) Effort should be made to determine the ratio of wood volume to total biomass, for tropical forests of Australia.

8) It is clear that for the NT, around Darwin, at the wet-end of the rainfall gradient that exists between Darwin and Newcastle Waters, a single regression is adequate to describe the biomass present in savannas. Errors introduced in the use of a single regression are sufficiently small to make this approach justified. Similar conclusions were made by Burrows *et al.* (1999) for Queensland sites dominated by *E. crebra*, *E. melanophloia* and *E. populnea*. There are insufficient data sets readily available to allow any statements to be made for WA species, although it is likely that similar conclusions can be drawn. This point requires confirmation.

9) The NT and Queensland have a number of permanent forest/woodland mensuration plots. However, this may not be true for WA. In addition, it is unlikely that such plots are adequately distributed in all major biomes. Such permanent

plots, with appropriate measurements over time, are of primary importance if allometric relationships are to be used to estimate biomass.

Laser altimetry enables rapid determination of tree height over large areas. When tree height was used in regression instead of DBH, Burrows *et al.* (1999) found R^2 values of larger than 0.91 for four species. Clearly, such an approach, when coupled with ground-based determinations of tree density and species composition, would allow rapid estimates of above-ground biomass.

SPECIFIC RESEARCH RECOMMENDATIONS

Well-designed and well-funded research programs are needed to tackle the following issues:

1) What is the below-ground allocation of biomass in all major tropical ecosystems? These ecosystems include savannas, riparian, mangrove, rainforest and monsoon vine forests such as *Allosyncarpia* and paperbark ecosystems.

2) What are the above-ground allometric relationships for all of the above, except savannas?

3) Collation of data into a GIS for all of northern Australia, which can be attempted now. The CRC for Tropical Savannas is currently compiling a vegetation map (digital) at 1: 2 $x10^6$ scale. This will represent the only consistent digitised vegetation coverage map for tropical Australia that can be used, when coupled to vegetation structure attributes and allometric equations, to estimate above-ground biomass. The next step is to incorporate TRAPS sites in Queensland and monitoring sites in the NT managed by the NT Bushfires Council and the Department of Lands, Planning and Environment, into the vegetation attributes tables. This will clearly identify areas where monitoring, both spatially and in terms of biomes represented, is currently insufficient. Tropical WA is clearly poorly represented in the available data.

4) In close linkage with the development of the GIS and monitoring system outlined in (3), development of a coupled model of fire scars for tropical Australia and C emissions through fires. Dr Gary Cook at the CSIRO Berrimah Research laboratories of the Division of Wildlife and Ecology has developed a model of carbon losses through fire for the NT, and the Bushfires Council of the NT uses satellite imagery to map fire extent and severity every dry season. The AGO may wish to consider mechanisms by which such approaches could be combined.

5) Application of laser altimetry to NT and WA sites to establish the validity of the technique for large-scale estimates of above-ground biomass.

6) Determination of root to shoot ratios for dominant species in key ecosystems in the NT and WA are required to extend knowledge from above-ground to total biomass.

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APPENDIX: QUEENSLAND DATA TABLES

Table A1: Biomass and allometric regression equations for a number of Queensland tree species.

Description	n	Range[A] (cm)	a	b	R^2	RSD
***Acacia* spp. (Birk and Turner 1992) Coff's Harbour (30°08'S, 153°07'E)** **x = dbhob (cm) $Y = a x^b$**						
Total (kg)	4		2.1484	0.4921	0.987	
***A. aneura* (Burrows et al. 1999) (26° 25'S, 146° 13'E)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Phyllode weight (kg)	65	1.8–86.0	1.9746	1.8568	0.96	0.381
Stem (kg)	32	1.8–86.0	–5.2193	2.3908	0.98	0.347
Wood (kg)	32	1.8–86.0	–5.4189	2.3901	0.98	0.347
Bark (kg)	32	1.8–86.0	–6.9297	2.3946	0.98	0.346
Root butt (kg)	8	17.3–61.5	1.2231	2.1214	0.95	0.225
***A. aneura* Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	19	0.2–3.5 [B]	–2.589	2.116	0.941	0.476
Wood (kg)	19	0.2–3.5 [B]	–1.736	2.404	0.941	0.5448
***D. decurrens* (Ward and Koch 1996)** **x = DBHOB (cm)**						
Total (kg)	3		–1.58	2.32	1.00	
***A. harpophylla* (Scanlan 1991)** **$Y = e^{(a + b Lnx)}$; where x = shoot height (cm)**						
Leaf (g)	29	60–320 [B]	–2.840	1.629	0.60	0.702
Branch (g)	29	60–320 [B]	–4.056	1.805	0.69	0.633
Stem bark (g)	29	60–320 [B]	–8.332	2.579	0.82	0.629
Stem wood (g)	29	60–320 [B]	–8.009	2.621	0.87	0.544
All stem (g)	29	60–320 [B]	–7.490	2.611	0.86	0.560
Total (g)	29	60–320 [B]	–4.303	2.150	0.86	0.558
***A. harpophylla* (Scanlan 1991)** **$Y = e^{(a + b Lnx)}$; where x = circumference at 30 cm (mm)**						
Leaf (g)	29	60–320 [B]	–3.284	2.042	0.91	0.330
Branch (g)	29	60–320 [B]	–3.818	2.092	0.90	0.358
Stem bark (g)	29	60–320 [B]	–7.235	2.809	0.94	0.339
Stem wood (g)	29	60–320 [B]	–6.436	2.747	0.92	0.409
All stem (g)	29	60–320 [B]	–6.083	2.774	0.94	0.360
Total (g)	29	60–320 [B]	–3.568	2.384	0.96	0.249
***Banksia aemula* (Westman and Rogers 1977)** **$\text{Log10 } Y = a + b \text{ Log}_{10}x$; where x = DBH (cm)**						
Stem wood (g)	10	19.4–44.0 [B]	1.9053	2.3113	0.8630	0.2983
Stem bark (g)	10	19.4–44.0 [B]	2.1232	1.4262	0.4476	0.2554
Live branch wood + bark (1° + 2°) (g)	10	19.4–44.0 [B]	0.6271	2.8366	0.5432	0.4618
Terminal twigs (3°) + leaves (g)	10	19.4–44.0 [B]	–0.5988	3.4250	0.4199	0.6338

[A] Range in circumference unless otherwise stated

[B] Height Range

Table A1 ***continued***

Description	n	Range[A] (cm)	a	b	R^2	RSD
Total above-ground (g)	10	19.4–44.0 [B]	1.7231	2.5924	0.9624	0.3168
Root crown (g)	9	19.4–44.0 [B]	0.7099	2.7153	0.8082	0.3458
Tap root (g)	9	19.4–44.0 [B]	4.8591	−0.4588	0.0480	0.2398
Lateral roots (g)	9	19.4–44.0 [B]	0.3266	3.0369	0.9003	0.3654
Total below-ground (g)	9	19.4–44.0 [B]	1.5319	2.4530	0.9312	0.2910
Current fruits (g)	9	19.4–44.0 [B]	0.8632	1.9744	0.2570	0.4457
Older fruits (g)	9	19.4–44.0 [B]	1.1825	1.9519	0.2830	0.4201
x = lateral root basal diameter (cm)						
Lateral root (g)	34	19.4–44.0 [B]	1.1839	2.2777	0.8064	1.3020
x = primary branch basal diameter (cm)						
Live branch wood + bark (1° + 2°) (g)	26	19.4–44.0 [B]	2.6709	1.4472	0.7327	0.6038
Dead branch wood + bark (1° + 2°) (g)	12	19.4–44.0 [B]	2.1708	1.0756	0.4316	0.5678
Terminal twigs and leaves (g)	28	19.4–44.0 [B]	2.3169	1.3978	0.3306	0.8480
x = tertiary branch basal diameter (cm) **Y = a +b Log$_{10}$x; where x = DBH (cm)**						
Tertiary branch wood + bark (g)	14	19.4–44.0 [B]	1.0771	2.0738	0.8742	1.0331
Tertiary branch terminal twigs and leaf (g)	13	19.4–44.0 [B]	0.9539	1.1329	0.6740	0.6665
Older leaves (g)	14	19.4–44.0 [B]	0.6524	1.3697	0.6626	0.7836
Total terminal branch	14	19.4–44.0 [B]	1.3815	1.8614	0.8538	0.9381
Current fruit (g)	4	19.4–44.0 [B]	1.5167	0.6992	0.8226	0.5008
Cassia nemophila **Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	19	0.6–2.0 [B]	−1.867	2.286	0.865	0.392
Wood (kg)	19	0.6–2.0 [B]	−1.310	3.297	0.884	0.494
Dodonaea viscosa **Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	40	0.2–2.0 [B]	−3.940	2.492	0.792	0.9823
Wood (kg)	40	0.2–2.0 [B]	−3.275	3.380	0.884	0.922
Eremophila bowmanii **Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	18	0.2–1.8 [B]	−3.236	2.586	0.903	0.5448
Wood (kg)	18	0.2–1.8 [B]	−0.259	3.522	0.941	0.5448
Eremophila mitchelli **Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	18	0.6–5.0 [B]	−2.612	2.532	0.828	0.6914
Wood (kg)	18	0.6–5.0 [B]	−1.790	3.002	0.922	0.545
Eremophila mitchellii **Trees > 4.0 m (Harrington 1979)** **LnY = a + b Lnx; where x = diameter at 30 cm (cm)**						
Leaf (kg)	18	0.6–5.0 [B]	−4.453	2.257	0.903	0.529
Wood (kg)	18	0.6–5.2 [B]	−3.89	2.623	0.960	0.392
Eucalyptus **spp[C] intact woodland (Burrows et al. 1999)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Total above-ground (kg)	62	4.6–240	−4.92	2.39	0.94	0.58

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[c] Combination of *Eucalyptus crebra, Eucalyptus melanophloia* and *Eucalyptus populnea.*

Description	n	Range[A] (cm)	a	b	R^2	RSD
***E. crebra* intact woodland (Burrows *et al.* 1999) (23° 05' S; 149° 20' E)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Branches (kg)	20	8–202	–8.536	3.041	0.979	0.436
Total above-ground (kg)	20	8–202	–6.505	2.756	0.987	0.309
Stem (kg)	20	8–202	–6.886	2.828	0.987	0.317
Bark (kg)	19	8–202	–7.942	2.766	0.991	0.265
Wood (kg)	20	8–202	–7.541	2.898	0.978	0.427
Trunk wood (kg)	20	8–202	–7.407	2.700	0.967	0.492
Trunk (kg)	20	8–202	–6.742	2.620	0.972	0.435
Capsules (kg)	16	8–202	–8.706	1.940	0.393	1.241
Leaf (kg)	20	8–202	–5.785	1.858	0.933	0.492
Lignotubers (kg)	10	10.6–202	–8.186	2.732	0.986	0.311
***E. diversicolor* (Grove and Malajczuk 1985)** **Ln Y = a + b Lnx; where x = diameter (cm)**						
Total (kg)			4.77	2.47	0.99	
36yr old trees (kg)[D]			3.98	2.74	0.98	
***E. maculata* (Ward and Koch 1996)** **x = DBHOB (cm)**						
Total above-ground (kg)	6		–2.55	2.49	0.98	
***E. maculata* (Ward and Pickersgill 1985)** **Site A, x = DBHOB (cm)**						
Total above-ground (kg)	10	2–24.5[E]	–2.51	2.47	0.95	
***E. maculata* (Ward and Pickersgill 1985)** **Site B, x = DBHOB (cm)**						
Total (kg)	11	2.0–11.5[F]	–1.10	1.87	0.98	0.182
***E. melanophloia* intact woodland (Burrows et al. 1999) (23° 45' S; 146° 02' E)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Branches (kg)	20	6–165	–8.300	2.913	0.978	0.406
Total above-ground (kg)	20	6–165	–6.553	2.726	0.991	0.236
Stem (kg)	20	6–165	–6.879	2.789	0.991	0.245
Bark (kg)	20	6–165	–7.865	2.702	0.989	0.269
Wood (kg)	20	6–165	–7.317	2.820	0.990	0.261
Trunk (kg)	20	6–165	–7.191	2.724	0.981	0.354
Capsules (kg)	17	6–165	–18.693	4.204	0.615	1.819
Leaf (kg)	20	6–165	–6.227	1.851	0.938	0.442
Lignotubers (kg)	10	12–165	–7.181	2.419	0.986	0.249
***E. melanophloia* regrowth (Burrows et al. 1999) (23° 45' S; 146° 02' E)** **LnY = a + b Lnx; where x = circ at 30 cm (cm)**						
Branches (kg)	43	4–43	–6.136	2.185	0.900	0.521
Total above-ground (kg)	43	4–43	–5.097	2.300	0.960	0.334
Stem (kg)	43	4–43	–5.325	2.317	0.961	0.336
Bark (kg)	43	4–43	–6.394	2.262	0.961	0.326
Wood (kg)	43	4–43	–5.795	2.355	0.950	0.389
Trunk (kg)	43	4–43	–6.016	2.412	0.948	0.403
Capsules (kg)	4	4–43	–15.247	3.473	0.521	1.010
Leaf (kg)	43	4–43	–6.805	2.234	0.889	0.569

[D] Hingston, personal communication 1984.

[E] DBH Range

[F] Range is diameter of stems in cm

Table A1 ***continued***

Description	n	Range^{A} (cm)	a	b	R^{2}	RSD
E. obliqua **(Feller 1980)** **Y = a + b LnD; where D = DBH (cm)**						
Stem wood (kg)	6	5–100 ^{E}	–631.2	287.4	0.93	45.8
Stem bark (kg)	6	5–100 ^{E}	–195.6	89.1	0.93	13.6
Y = a + b D^{2}H; where D = DBH (m) and H = tree height (m)						
Branches (kg)	6	5–100 ^{E}	–1.7	13.4	0.84	7.4
Leaves (kg)	4	5–100 ^{E}	0.9	1.7	0.95	0.5
LnD^{2}H = a + b D where D = DBH (cm) and H = tree height						
LnD^{2}H	6	5–100 ^{E}	–3.14	13.02	0.86	0.57
E. populnea **intact woodland (Burrows et al. 1999) (23° 37' S; 149° 25'E)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Branches (kg)	22	4.6–240	–5.554	2.344	0.925	0.713
Total above-ground (kg)	22	4.6–240	–2.809	1.922	0.939	0.525
Stem (kg)	22	4.6–240	–3.327	2.006	0.910	0.673
Bark (kg)	22	4.6–240	–3.685	1.685	0.869	0.703
Wood (kg)	22	4.6–240	–3.428	1.979	0.916	0.640
Trunk (kg)	22	4.6–240	–2.873	1.761	0.900	0.625
Capsules (kg)	20	4.6–240	–9.985	1.932	0.619	1.419
Leaf (kg)	22	4.6–240	–3.491	1.259	0.806	0.659
Dead wood (kg)	18	4.6–240	–10.664	2.767	0.809	1.225
Lignotuber scrap (kg)	6	4.6–240	–28.906	6.305	0.711	2.180
Lignotuber trunk (kg)	10	4.6–240	–5.339	1.976	0.933	0.679
Lignotuber total (kg)	10	4.6–240	–5.747	2.116	0.922	0.782
E. populnea **(Harrington 1979)** **LnY = a + b Lnx; where x = diameter of tree at 30 cm (cm)**						
Leaf (kg)	20		–1.011	1.275	0.792	0.199
All wood (kg)	20		–0.518	1.850	0.884	0.199
Rough bark wood (kg)	20		–1.104	1.972	0.884	0.199
Smooth bark wood (kg)	20		–0.270	1.216	0.865	0.199
Twig (kg)	20		–2.081	1.171	0.723	0.199
E. resinifera **(Ward and Koch 1996) Mean DBH = 17.7cm** **x = DBHOB (cm)**						
Total above-ground (kg)	4	some > 30 cm	–2.37	2.40	0.99	
E. resinifera **(Ward and Pickersgill 1985) Site A** **LnY = a + b Lnx; where x = DBHOB (cm)**						
Total above-ground (kg)	8		–2.54	2.44	0.97	
E. resinifera **(Ward and Pickersgill 1985) Site B** **LnY = a + b Lnx; where x = DBHOB (cm)**						
Total (kg)	10	2.0–11.5	–1.12	1.74	0.98	0.182
E. signata **(Westman and Rogers 1997)** **Log$_{10}$ Y = a + b Log$_{10}$ x; where x = DBH (cm)**						
Stem wood (g)	23	23.6–63.3^{E}	3.8936	0.9802	0.7992	0.1501
Stem bark (g)	23	23.6–63.3^{E}	3.1686	0.8266	0.7090	0.1344
Live branch 1° + 2° (g)	19	23.6–63.3^{E}	4.0366	0.7398	0.0697	0.3717
Twigs (3°) + leaf (g)	23	23.6–63.3^{E}	2.3980	1.3675	0.1892	0.4303
Total above-ground (g)	19	23.6–63.3^{E}	4.4284	0.8336	0.3272	0.1931

Description	n	Range^{A} (cm)	a	b	R^2	RSD
Root crown (g)	11	23.6–63.3 ^{E}	2.1266	1.8332	0.5446	0.3180
Tap root (g)	11	23.6–63.3 ^{E}	3.8606	0.3919	0.0269	0.3061
Lateral roots (g)	11	23.6–63.3 ^{E}	4.0405	0.5856	0.4238	0.3553
Total below-ground (g)	11	23.6–63.3 ^{E}	2.4005	1.9034	0.7157	0.2880
x = lateral root basal diameter (cm)						
Lateral root (g)	66	23.6–63.3 ^{E}	1.4259	2.3064	0.8317	1.2910
x = primary branch basal diameter (cm)						
Live branch wood + bark (1° + 2°) (g)	37	23.6–63.3 ^{E}	1.4736	2.3875	0.8501	0.4048
Dead branch wood + bark (1° + 2°) (g)	39	23.6–63.3 ^{E}	1.6890	1.6529	0.3238	0.5403
Twigs (3o) + dry leaves (g)	35	23.6–63.3 ^{E}	0.1475	2.8535	0.6691	0.5588
x = tertiary branch basal diameter (cm) $Y = a + b \text{ Log}_{10} x$						
Tertiary branch wood + bark (g)	25	23.6–63.3 ^{E}	1.3057	2.1153	0.7056	1.0253
Tertiary branch terminal + leaf (g)	25	23.6–63.3 ^{E}	1.1711	1.5796	0.6839	0.8133
Older leaf (g)	21	23.6–63.3 ^{E}	0.7217	1.5440	0.5417	0.7866
Total tertiary branch (g)	33	23.6–63.3 ^{E}	1.7606	1.9034		
Fruits (g)	13	23.6–63.3 ^{E}	–0.1736	1.2285	0.2704	0.5064
E. umbra subsp. umbra **(Westman and Rogers 1977)** **$\text{Log}_{10} Y = a + b \text{ Log}_{10} x$; where x = DBH (cm)**						
Stem live wood (g)	16	19.6–56.1 ^{E}	2.6770	1.7188	0.9467	0.2805
Stem live bark (g)	16	19.6–56.1 ^{E}	1.7726	1.8284	0.9526	0.2973
Live branch (1° + 2°) (g)	11	19.6–56.1 ^{E}	1.6306	2.2143	0.6162	0.4076
Twigs and leaves (3°) (g)	16	19.6–56.1 ^{E}	1.8424	1.6842	0.7762	0.3033
Total above-ground (g)	11	19.6–56.1 ^{E}	3.1609	1.5850	0.8987	0.2411
Root crown (g)	9	19.6–56.1 ^{E}	2.0967	1.8197	0.6823	0.4211
Tap root (g)	9	19.6–56.1 ^{E}	2.5949	1.2644	0.3919	0.3860
Lateral roots (g)	9	19.6–56.1 ^{E}	4.6264	0.0992	0.1490	0.3160
Total below-ground (g)	9	19.6–56.1 ^{E}	2.8854	1.5668	0.7123	0.3548
x = lateral root basal diameter (cm)						
Lateral root (g)	50	19.6–56.1 ^{E}	1.5352	2.1787	0.9197	0.9260
x = primary branch basal diameter (cm)						
Live branch wood + bark (1° + 2°) (g)	26	19.6–56.1 ^{E}	1.6439	2.2596	0.8136	0.5395
Dead branch wood + bark (1° + 2°) (g)	24	19.6–56.1 ^{E}	1.7731	0.6944	0.4516	0.5103
Terminal twigs (3°) = leaves (g)	27	19.6–56.1 ^{E}	2.0260	1.5004	0.4761	0.4602
x = tertiary branch basal diameter (cm) $Y= a + b \text{ Log}_{10} x$						
Tertiary branch wood + bark (g)	67	19.6–56.1 ^{E}	1.2871	1.3290	0.2959	0.6749
Tertiary branch terminal twigs + leaves (g)	68	19.6–56.1 ^{E}	1.2871	1.3290	0.2959	0.6749
Older leaves (g)	56	19.6–56.1 ^{E}	0.6273	1.5827	0.3795	0.6502
Total terminal branch (g)	85	19.6–56.1 ^{E}	1.7968	1.8736	0.7123	0.6616
Geijera parviflora **Shrubs less than 4.5 m high (Harrington 1979)** **$\text{Ln}Y = a + b \text{ Ln}x$; where x = height (m)**						
Leaf (kg)	9	0.6–4.5 ^{B}	–2.206	3.079	0.985	0.476
Wood (kg)	9	0.6–4.5 ^{B}	–1.784	3.442	0.960	0.457
Geijera parviflora **Trees > 4.0 m (Harrington 1979)** **$\text{Ln}Y = a + b \text{ Ln}x$; where x = diameter at 30 cm (cm)**						
Leaf (kg)	9	3.85–7.02 ^{B}	–2.156	1.614	0.656	0.280
Wood (kg)	9	3.85–7.02 ^{B}	–2.028	2.119	0.865	0.631

Table A1 ***continued***

Description	n	Range[A] (cm)	a	b	R^2	RSD
Mallee[G] intact woodland (Burrows *et al.* 1999) (33° 53'S, 146° 30'E) **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Leaf (kg)	29	2.5–55.2	2.6963	1.4296	0.88	0.349
Wood and bark (kg)	29	2.5–55.2	2.0216	2.4321	0.98	0.240
Wood (kg)	29	2.5–55.2	1.5967	2.5145	0.98	0.247
Bark (kg)	29	2.5–55.2	1.2250	2.0719	0.96	0.265
Capsule (kg)	25	12.4–55.2	–3.0863	2.8318	0.59	0.937
Seed weight (kg)	25	12.4–55.2	–7.3759	2.8515	0.59	0.944
Dead bark (kg)	29	2.5–55.2	–10.0764	1.8905	0.83	0.563
Total weight (kg)	29	2.5–55.2	–4.1671	2.2620	0.98	0.213
Dead wood[H] (kg)	28	5.6–55.2	–695.61	85.755	0.63	736.7
Mallee[I] regrowth (Burrows *et al.* 1999) app. (33° 53'S, 146° 30'E) **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Leaf (kg)	30	1.8–23.2	0.8392	2.1884	0.94	0.382
Wood and bark (kg)	30	1.8–23.2	1.4366	2.5661	0.99	0.151
Wood (kg)	30	1.8–23.2	1.1721	2.5887	0.99	0.147
Bark (kg)	30	1.8–23.2	–4.3421	2.4707	0.99	0.198
Capsule (kg)	26	5.1–23.2	–6.5518	4.4611	0.65	1.469
Seed weight (kg)	24	6.7–23.2	–7.6961	3.3173	0.70	0.860
Dead wood (kg)	30	1.8–23.2	–0.1168	1.9767	0.64	1.017
Dead bark (kg)	24	5.2–23.2	–3.5051	2.8426	0.53	1.150
Total weight (kg)	30	1.8–23.2	1.9943	2.4780	0.99	0.165
M. viridiflora **intact woodland (Burrows et al. 1999) (22° 57' S; 150° 32' E)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Branches (kg)	20	6.0–414.5	–8.468	2.932	0.966	0.413
Total above-ground (kg)	20	6.0–414.5	–6.520	2.666	0.987	0.230
Stem (kg)	20	6.0–414.5	–6.823	2.724	0.988	0.229
Bark (kg)	20	6.0–414.5	–6.993	2.329	0.943	0.432
Wood (kg)	20	6.0–414.5	–7.429	2.820	0.983	0.276
Trunk (kg)	20	6.0–414.5	–7.109	2.635	0.981	0.277
Capsules (kg)	18	6.0–414.5	–4.327	0.883	0.134	1.199
Leaf (kg)	20	6.0–414.5	–6.046	1.742	0.843	0.565
Dead wood (kg)	20	6.0–414.5	–10.947	2.776	0.908	0.666
Lignotuber total (kg)	10	14–123	–8.316	2.568	0.988	0.202
Myoporum deserti **Shrubs less than 4.5 m high (Harrington 1979)** **LnY = a + b Lnx; where x = shoot height (m)**						
Leaf (kg)	17	0.2–2.0 [B]	–1.535	2.449	0.846	0.6914
Wood (kg)	17	0.2–2.0 [B]	–0.998	3.030	0.923	0.643

Eucalyptus spp. **(Madgwick *et al.* 1991)**

Stems	70	LnWs = –1.5325 + LnB + LnHt; where Ht = 1.24Hm, B = basal area (m^2/ha^{-1}), Hm = mean height (m), S.D. = 0.057
	37	LnWs = –1.3205 + LnD +LnB + LnHt,; where D = density (Mgm^{-3}), S.D = 0.062
Live branch	40	LnWb = LnB – 0.7985; where S.D. = 0.21
	36	LnWb = 0.01 + 1.00LnB – 0.31 LnHt; where S.E. = 0.35
	68	LnWb = 1.14 + 0.64 LnB – 0.47 LnHt; where S.E. = 0.33
Leaf	102	LnWf = 0.2231 + (LnB)/2; where S.D = 0.44

[G] *Eucalyptus socialis/E. dumosa* combined

[H] Linear Regression on stem circumference

[I] *Eucalyptus socialis – e. gracilis – E. leptophylla* combined

Description	n	Range^{A} (cm)	a	b	R^2	RSD
***E. grandis* (Turner 1986) Coffs Harbour (30°18'S, 153°0'E)[J]**						
Total (kg m^{-2}) (biomass/basal area)	21	Y = 2.559 + 0.3538 Age; where Age (years), S.E. = 2.2			0.994	
Total (kg m^{-2}) (biomass/basal area)	21	Y = −5.597 + 5.289 LnAge, S.E.=1.9			0.980	
***E. grandis* (Birk and Turner 1992) Coffs Harbour (30°08'S, 153°07'E)** **Y = ax^{b}; where x = DBHOB (cm)**						
Foliage (kg)	24	5–35 [E]	2.9606	8.988E–4	0.846	
Branch (kg)	24	5–35 [E]	3.5072	4.248E–4	0.872	
Bark (kg)	24	5–35 [E]	2.0897	0.0772	0.936	
Sapwood (kg)	24	5–35 [E]	1.9664	0.2839	0.896	
Heartwood (kg)	24	5–35 [E]	3.3626	2.546 E–3	0.942	
Total tree (kg)	24	5–35 [E]	2.3229	0.2214	0.966	
Stem volumes x = diameter BH (cm) (Westman and Rogers 1977)						
E. signata						
Stem volume (m^3)	12		3.3249	1.4856	0.5155	0.2620
Stem wood volume (m^3)	12		3.2084	1.5476	0.5041	0.2703
E. umbra* subsp. *Umbra						
Stem Volume (m^3)	11		3.3140	1.4419	0.6757	0.3042
Stem wood volume (m^3)	11		3.2802	1.3952	0.6273	0.3058
Banksia aemula						
Stem volume (m^3)	10		2.4317	2.1456	0.8724	0.2614
Stem wood volume (m^3)	10		2.0943	2.3088	0.8630	0.2828
***Corymbia maculata,* Queensland 1997 (Margules Pöyry P/L 1998)[K]**						
	97	10–80+	9.1944	–0.1167	0.84	
***E. fibrosa spp. Fibrosa*, Queensland 1997 (Margules Pöyry P/L 1998)[K]**						
	53	10–60	6.6654	0.0645	0.78	
***E. acmenoides*, Queensland 1997 (Margules Pöyry P/L 1998)[K]**						
	70	10–80+	6.8421	–0.0845	0.89	
***E. crebra*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	44	10–70+	5.4780	0.0205	0.75	
***E. pilularis*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	75	10–80+	9.2615	0.0092	0.93	
***E. gummifera*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	45	10–70+	8.3067	–0.1640	0.88	
***Lophostemon confertus*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	37	10–80+	6.2756	0.1347	0.81	
***Angophora floribunda*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	56	10–80+	9.3406	–0.2645	0.86	

[J] relationships from Bradstock (1981) original data

[K] Margules Pöyry P/L 1998 equations are in the form of V = aBA + b, where V = total merchantable stem volume under bark (including residual wood fibre) m^3) and BA = Basal area at breast height (m^2)

Table A1 ***continued***

Description	n	Range^A (cm)	a	b	R^2	RSD
***E. microcorys*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	35	10–90+	8.1847	0.0569	0.87	
***Syncarpia glomulifera*, Queensland 1997 (Margules Pöyry P/L 1998) [K]**						
	21	10–70+	6.3991	–0.0164	0.83	
***E. pilularis,* Fraser Island ,Wabby 1982. (Applegate 1982)** **$\text{Log}_{10}\ Y = a + b\ \text{Log}_{10}\ X$; where Y is in (kg) and x = DBHOB (cm)**						
Leaf dry weight DW (kg)	7	13–23	–2.8318	2.9433	0.878	0.1383
Supportive branches DW (kg)	7	13–23	–3.3126	3.4449	0.853	0.2015
Canopy branches DW (kg)	7	13–23	–3.4172	3.2404	0.874	0.1736
Live branches DW (kg)	7	13–23	–3.2580	3.4673	0.718	0.2743
Total branches DW(kg)	7	13–23	–3.258	3.4673	0.718	0.2743
Leaf + supportive branches + canopy branches DW (kg)	7	13–23	–2.8267	3.2879	0.8878	0.2151
Leaf + branches + fruit DW (kg)	7	13–23	–2.8350	3.2953	0.8881	0.2152
Bark DW (kg)	7	13–23	–0.9163	1.7574	0.969	0.0399
Sapwood DW (kg)	7	13–23	–1.4924	2.3926	0.9586	0.0897
Heartwood DW (kg)	7	13–23	–1.3876	2.3451	0.8937	0.1485
Stem DW(kg)	7	13–23	–0.8406	2.2228	0.923	0.0813
Total above-ground DW (kg)	7	13–23	–1.013	2.4351	0.911	0.0959
Roots DW (kg)	3	13–23	–2.6206	3.1487	0.999	0.0156
Total tree DW (kg)	3	13–23	–1.1589	2.6064	0.991	0.0439
***E. pilularis*, Fraser Island (McKenzie 1982)**						
Leaf dry weight DW (kg)	9		–3.8701	3.1618	0.878	0.1952
Supportive branches DW (kg)	9		–4.7252	4.0744	0.900	0.2256
Canopy branches DW (kg)	9		–4.217	3.5169	0.877	0.2076
Live branches DW (kg)	9		–4.2629	3.8811	0.901	0.213
Dead branches DW (kg)	8		–1.3482	1.2604	0.200	0.4301
					not significant	
Total branches DW(kg)	9		–3.7375	3.5724	0.865	0.2336
Leaf + supportive branches + canopy branches DW (kg)	9		–4.0087	3.7704	0.910	0.1965
Leaf + branches + fruit DW (kg)	9		–3.5814	3.5202	0.882	0.2140
Bark DW (kg)	9		–.9806	2.5336	0.974	0.0685
Sapwood DW (kg)	9		–1.7635	2.3990	0.936	0.1043
Heartwood DW (kg)	9		–1.4595	2.6447	0.982	0.0586
Stem DW(kg)	9		–1.2253	2.5911	0.986	0.0503
Total above-ground DW (kg)	9		–1.3086	2.6803	0.986	0.0534
Roots DW (kg)	4		–2.1516	2.6864	0.989	0.073
Total tree DW (kg)	4		–1.0356	2.527	0.996	0.0402
***E. intermedia* Fraser Island, Wabby 1982. (Applegate 1982)** **$\text{Log}_{10}\ Y = a + b\ \text{Log}_{10}\ x$; where Y is in (kg) and x = DBHOB (cm)**						
Leaf dry weight DW (kg)	4		–3.6181	3.3261	0.962	0.0966
Live branches DW (kg)	4		–4.4442	4.1854	0.870	0.2376
Dead branches DW (kg)	9		–4.9137	3.6669	0.708	0.6203
Total branches DW(kg)	4		–4.5443	4.2691	0.870	0.2417
Leaf + supportive branches + canopy branches DW (kg)	4		3.8634	3.8888	0.967	0.1050
Leaf + branches + fruit DW (kg)	4		–3.9366	3.9500	0.966	0.1093
Bark DW (kg)	4		–1.1717	2.0207	0.994	0.0222
Sapwood DW (kg)	4		–0.7662	1.7249	0.928	0.0706
Heartwood DW (kg)	4		–4.1843	4.1743	0.975	0.0976

Description	**n**	**Range^A (cm)**	**a**	**b**	**R^2**	**RSD**
Stem DW(kg)	4		–1.1234	2.319	0.991	0.0320
Total above-ground DW (kg)	4		–1.4044	2.6018	0.999	0.0086
Bruguiera gymnorrhiza **(Clough and Scott 1989) Hinchinbrook Island (18° 16’ S, 146° 13’ E), Murray River (18° 04’ S, 146° 02’ E), Daintree River (16° 16’ S, 145° 25’ E)** **$\mathrm{Log}_{10} Y = a + b\ \mathrm{Log}_{10} x$; where Y is in (kg) and x = DBHOB (cm)**						
Leaf DW (kg)	17	2–24	–1.1679	1.4914	0.854	1.57
Branch DW (kg)	17	2–24	–1.5012	2.2789	0.926	1.60
Stem DW (kg)	17	2–24	–0.6482	2.1407	0.977	1.29
Total DW (kg)	17	2–24	–0.7309	2.3055	0.989	1.19
B. parviflora **(Clough and Scott 1989) Hinchinbrook Island (18° 16’ S, 146° 13’ E), Murray River (18° 04’ S, 146° 02’ E), Daintree River (16° 16’ S, 145° 25’ E)** **$\mathrm{Log}_{10} Y = a + b\ \mathrm{Log}_{10} x$; where Y is in (kg) and x = DBHOB (cm)**						
Leaf DW (kg)	16	2–21	–1.5716	1.407	0.621	2.32
Branch DW (kg)	16	2–21	–1.9403	2.4639	0.885	1.88
Stem DW (kg)	16	2–21	–0.8661	2.4037	0.992	1.18
Total DW (kg)	16	2–21	–0.7749	2.4167	0.993	1.17
Ceriops targal var. australis **(Clough and Scott 1989) Hinchinbrook Island (18° 16’ S, 146° 13’ E), Murray River (18° 04’ S, 146° 02’ E), Daintree River (16° 16’ S, 145° 25’ E)** **$\mathrm{Log}_{10} Y = a + b\ \mathrm{Log}_{10} x$; where Y is in (kg) and x = DBHOB (cm)**						
Leaf DW (kg)	26	2–18	–1.93	2.1294	0.927	1.42
Branch DW (kg)	26	2–18	–1.7061	2.5516	0.938	1.47
Stem DW (kg)	26	2–18	–0.8333	2.3393	0.977	1.24
Total DW (kg)	26	2–18	–0.7247	2.3379	0.989	1.16
Rhyzophora apiculata/stylosa **(Clough and Scott 1989) Hinchinbrook Island (18° 16’ S, 146° 13’ E), Murray River (18° 04’ S, 146° 02’ E), Daintree River (16° 16’ S, 145° 25’ E)** **$\mathrm{Log}_{10} Y = a + b\ \mathrm{Log}_{10} x$; where Y (kg) and x = DBHOB (cm)**						
Leaf DW (kg)	?	?	–1.8571	2.1072	0.857	1.59
Branch DW (kg)			–1.8953	2.6844	0.912	1.57
Stem DW (kg)			–1.0528	2.5621	0.991	1.14
Root DW (kg)			–2.1663	3.1353	0.968	1.32
Total DW (kg)			–0.9789	2.6848	0.995	1.11
Xylocarpus granatum **(Clough and Scott 1989) Hinchinbrook Island (180 16’ S, 1460 13’ E), Murray River (180 04’ S, 1460 02’ E), Daintree River (160 16’ S, 1450 25’ E)** **Log10 Y = a + b Log10 x; where Y is in (kg) and x = DBHOB (cm)**						
Leaf DW (kg)	15	3–17	–2.238	2.3966	0.951	1.39
Branch DW (kg)	15	3–17	–2.3315	3.0975	0.959	1.47
Stem DW (kg)	15	3–17	–1.0879	2.4624	0.988	1.18
Total DW (kg)	15	3–17	–1.0844	2.5883	0.994	1.13
E. drepanophylla **(Chris Balerna pers. Comm. 1998) Townsville** **$Y = a(x^2H)^b$; where Y is in (kg) and x = DBHOB (cm) and H = total height of tree (m)**						
Above-ground biomass DW (kg)	4		0.0569	0.931	0.9992	0.072R
Mixed pioneer and secondary successional rainforest species (e.g. *Darlingia darlingiana* and *Alphitonia petriei*) (Maycock 1998) Mt Spec and Mt Fox , North Queensland **$Y = a[x^2H]^b$; where x = DBHOB (cm) and H = total height (m)**						
Above-ground biomass (kg)	150	24 yr old recolonised site	83	0.786	?	?

Table A1 ***continued***

Description	n	Range^A (cm)	a	b	R^2	RSD
Eremophia gilesii **(Carter and Johnston 1986), Charleville (26.25, 146.13)** **W = a + bV; where W = fresh wt (g) and V = canopy volume (m^3)**						
Total fresh weight (g)	32		4.79	955.4	0.89	
E. grandis **(Bradstock 1981)** **Log_{10} Y = a Log_{10} x + b; where x = DBHOB (cm) (F value instead of R^2 (not given))**						
Mill Site					**F**	
Branch (g)	5		2.02	1.93	313.35	0.032
Foliage (g)	5		2.17	1.60	34.55	0.110
Bark (kg)	5		2.66	–2.12	42.38	0.118
Sapwood (kg)	5		2.47	–1.47	240.98	0.045
Everingham's II						
Branch (g)	4		2.77	0.95	413.54	0.045
Foliage (g)	4		2.42	0.97	470.50	0.045
Bark (kg)	4		1.36	–0.69	67.32	0.063
Sapwood (kg)	4		2.98	–1.86	71.06	0.127
Taylors						
Branch (g)	4		1.35	2.54	3.02	0.184
Foliage (g)	4		1.66	1.76	3.982	0.195
Bark (kg)	4		2.80	–2.22	265.50	0.045
Sapwood (kg)	4		2.76	–1.53	44.21	0.100
Nieshs II						
Branch (g)	4		2.59	0.97	86.63	0.095
Foliage (g)	4		1.99	1.39	72.79	0.084
Bark (kg)	4		3.10	–2.57	85.80	0.114
Sapwood (kg)	4		2.91	–1.81	138.32	0.084
Heartwood (kg)	4		2.75	–1.79	2622.94	0.017
Nieshs I						
Branch (g)	4		1.84	1.93	8.69	0.224
Foliage (g)	4		2.97	–0.04	23.04	0.221
Bark (kg)	4		3.21	–2.56	194.83	0.084
Sapwood (kg)	4		2.81	–1.62	189.18	0.071
Heartwood (kg)	4		5.00	–4.58	22.55	0.378
Holmes						
Branch (g)	4		2.53	0.90	304.66	0.055
Foliage (g)	4		2.67	0.23	102.48	0.100
Bark (kg)	4		2.81	–2.26	376.19	0.055
Sapwood (kg)	4		2.16	–0.99	11.91	0.071
Heartwood (kg)	4		3.20	–2.14	93.98	0.123
Everingham's I						
Branch (g)	6		3.64	–0.53	343.56	0.063
Foliage (g)	6		3.59	–0.95	54.45	0.152
Bark (kg)	6		2.48	–1.73	119.76	0.118
Sapwood (kg)	6		2.47	–1.29	154.75	0.100
Heartwood (kg)	6		2.95	–1.98	369.55	0.078
Boyd's Deviation						
Branch (g)	5		2.58	0.105	52.56	0.105
Foliage (g)	5		1.99	1.20	29.77	0.110
Bark (kg)	5		2.65	–1.97	208.92	0.084
Sapwood (kg)	5		2.62	–1.45	97.54	0.123
Heartwood (kg)	5		3.00	–1.59	317.93	0.078
Combined total (kg) (R^2 = 0.9646)	36		3.12	–1.77	1077.73	0.017

Description	n	Range^A (cm)	a	b	R^2	RSD
***E. marginata* (Hingston *et al.* 1981)** **LnY = a + b lnx; where x = DBH (cm)**						
Total above-ground	10		–3.68	2.84	0.994	
***E. calophylla* (Hingston *et al.* 1981)** **LnY = a + b Lnx; where x = DBH (cm)**						
Total above-ground	10		–3.37	2.74	0.982	
***Banksia grandis* (Hingston *et al.* 1981)** **LnY = a + b Lnx; where x = DBH (cm)**						
Total above-ground	16		–2.26	2.50	0.963	
***Casuarina spp.* (Chen 1988)** **$Y = a D^b$; where D = diameter at breast height (cm)**						
Trunk area			2.429	2.183	0.958	
Branch volume			2.133	2.315	0.905	
Fresh weight (g)						
Trunk			493.980	1.876	0.932	
Branch			41.329	2.694	0.882	
Foliage			12.683	2.321	0.761	
Roots			65.083	2.360	0.936	
Dry weight (g)						
Trunk			203.587	2.001	0.93	
Branch			17.400	2.749	0.875	
Foliage			3.060	2.323	0.698	
Roots			29.891	2.352	0.907	
$Y = a (D^2H)^b$; where D = diameter at breast height (cm), H = tree height						
Trunk area			0.617	0.952	0.969	
Branch volume			0.504	1.007	0.972	
Fresh weight (g)						
Trunk			150.813	0.819	0.946	
Branch			7.508	1.177	0.900	
Foliage			2.800	1.021	0.784	
Roots			14.501	1.032	0.953	
Dry weight (g)						
Trunk			56.948	0.875	0.946	
Branch			3.009	1.203	0.892	
Foliage			0.659	1.026	0.725	
Roots			6.614	1.030	0.927	
***P. radiata* (Baker *et al.* 1984)** **LnY = b LnD + a; where D = DBHOB (cm) R^2 calculated from untransformed residuals RSD column is error mean square**						
Needles (kg)	46		–3.365	1.893	0.78	0.1501
Live branches (kg)	46		–4.727	2.459	0.81	0.1612
Total branches (kg)	62		–4.332	2.413	0.88	0.1002
Stem wood (kg)	62		–2.399	2.342	0.98	0.0376
Stem bark (kg)	62		–3.863	0.9243	0.99	0.0110
Total stem (kg)	62		–2.201	2.320	0.98	0.0352

Table A1 ***continued***

Description	n	Range[A] (cm)	a	b	R^2	RSD
LnY = b LnDc + a; where Dc = stem diameter over bark at the base of the live crown (10cm below point of emergence form the stem of the lowest live branch) (cm), R^2 calculated from untransformed residuals RSD column is error mean square						
Needles (kg)	21		–3.779	2.192	0.97	0.0370
Live branches (kg)	21		–5.090	2.785	0.96	0.1414
Total branches (kg)	21		–4.530	2.717	0.94	0.1107
LnY = b Ln(D2h) + a; where D = DBHOB (cm) and h = total height of tree, R^2 calculated from untransformed residuals RSD column is error mean square						
Stem wood (kg)	62		–3.632	0.9243	0.99	0.0110
Stem bark (kg)	62		–4.946	0.8478	0.88	0.0529
Total stem (kg)	62		–3.415	0.9146	0.98	0.0120

Table A2: Forestry regressions (current DPI forestry plantation bole volume equations supplied by Eric Keady, pers. comm.).

Description	n	Range (cm)	a	b	c	d	R^2	RSD
Vanclay and Shepherd 1983 **$V = a + bA + cT + dAT$; where V = total stem volume (m^3), A = sectional area breast height over bark and T = total height (m)**								
***Araucaria cunninghamii* Imbil 1973**								
Total bole volume	2675		–0.015088	–1.79465	0.00252	0.44261		
***A. cunninghamii,* Yarraman 1972**								
Total bole volume	2548		0.011234	–3.29225	0.0014796	0.50291		
***P. caribaea var.* hondurensis, Queensland 1974 (Density = 0.5)**								
Total bole volume	807		0.028558	–2.65295	0.00015006	0.41133		
***P. elliottii var. elliottii*, Beerburrum 1973**								
Total bole volume	1125		–0.013452	–0.19897	0.00021398	0.38866		
***P. elliottii var. elliottii*, Warwick 1981**								
Total bole volume	450		–0.03593	–1.4456	0.0068484	0.41895		
***P. patulai,* Queensland 1982**								
Total bole volume	899		–0.37585	–1.11051	–0.0037408	0.44819		
***P. radiata,* Queensland (excluding Gambubal) 1982**								
Total bole volume	587		0.0013045	–1.51255	0.0027483	0.36371		
***P. taeda,* Beerburrum 1973**								
Total bole volume	1043		–0.012912	0.0107	0.00079288	0.38477		
***P. taeda,* Warwick 1981**								
Total bole volume	233		0.050406	–1.9463	–0.0039837	0.50535		
QDF Research Report 1985 Unknown locations **$V = (a + bL + cL^2)(BA + 0.023)$; where V = commercial log volume (m^3), L = log length (m) and BA = basal area at breast height or above buttress (m^2)**								
High volume species (e.g., *Agathis robusta, Argyrodendron realatum, Ceratopelalum succirubrum)*								
Log volume			–0.3031	0.8006	–0.008972			
Medium volume species (e.g., *Cardellia sublimis, Argyrodendron polyandrum, Flindersia brayleyana, Elaeocarpus grandis, Beilschmiedia bancroftii*)								
Log volume			–0.4098	0.7756	–0.01027			
Low volume species (e.g., *F. pimenteliana, Doryphora aromatica, F. bourjotiana*)								
Log volume			0.03692	0.6379	–0.005208			
QDF Research Report 1979 **$V = a + b\,BA + c\,H + d\,BAH$; where V = merchantable volume (m^3), BA = basal area (m^2), H = average height of 25cm DBH tree**								
***Callitris glaucophylla* generalised equation**								
Merchantable volume		20–30	0.061722	–1.74794	–0.012030	0.55228		2% [L]

[L] 95% confidence limit range on volume estimates based on groups of 500 trees

Table A3: Unpublished allometric equations for Australian trees.

Description	n	Range[M] (cm)	a	b	R^2	RSD
***A. nilotica* Burrows *et al.* unpublished** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Total above-ground (kg)	20	1.2–60.5	–4.082	2.092	0.954	0.472
Roots (kg)	5	6.1–60.5	–6.753	2.356	0.986	0.268
***E. laevopinea* (Chilcott 1999 unpublished) LnY =b LnBA + a, BA=basal area(m^2), SE**						
Total (includes roots) (kg)	31	5–85 [N]	9.19	1.27	0.99	0.19
Stem wood (kg)	19	5–85 [B]	8.49	1.25	0.97	0.24
Stem bark (kg)	19	5–85 [B]	7.31	1.26	0.98	0.17
Branch wood (kg)	19	5–85 [B]	7.57	1.43	0.92	0.64
Branch bark (kg)	19	5–85 [B]	5.84	1.18	0.82	0.82
Dead (kg)	30	5–85 [B]	1.76	0.92	0.62	1.03
Roots (kg)	3	18–79.5 [B]	7.22	–1.16	0.99	0.06
***E. laevopinea* (Chilcott 1999 unpublished) Y = b (BA) + a, BA=basal area(m^2), SE**						
Twigs (kg)	30	5–85 [B]	1.29	401.1	0.97	11.78
Leaves (kg)	29	5–85 [B]	–6.25	308.8	0.86	14.0
Buds and fruit (kg)	25	5–85 [B]	0.35	29.78	0.76	1.95
***E. melliodora* (Chilcott 1999 unpublished) Y = b (BA) + a, BA=basal area(m^2), SE**						
Twigs (kg)	7		–9.51	1016.97	0.99	6.79
Leaves (kg)	7		2.68	280.18	0.96	3.63
Buds and fruit (kg)	6		–0.75	98.58	0.89	2.32
Total (includes roots) (kg)	7		–69.5	10037.3	0.97	120.3
Stem wood (kg)	5		–62.16	4824.06	0.97	27.5
Stem bark (kg)	5		–34.9	1707.90	0.99	4.9
Branch wood (kg)	5		–106.0	3633.78	0.93	24.0
Branch bark (kg)	5		–34.66	1138.98	0.95	6.22
Dead (kg)	7		–1.73	117.89	0.76	4.31
***F. dissosperma* understorey of intact woodland (Burrows *et al.* unpublished)** **LnY = a + b Lnx; where x = circumference at 30 cm (cm)**						
Total dryweight (kg)	19	5.3–78.7	–5.614	2.610	0.986	0.247
Leaf (kg)	19	5.3–78.7	–6.555	2.132	0.928	0.475
Branches (kg)	19	5.3–78.7	–7.275	2.862	0.954	0.503
Trunk (kg)	19	5.3–78.7	–5.784	2.388	0.977	0.296
Wood (kg)	19	5.3–78.7	–5.988	2.635	0.986	0.250
Bark (kg)	19	5.3–78.7	–7.953	2.727	0.979	0.320
Stem (dead and live) (kg)	19	5.3–78.7	–5.853	2.648	0.987	0.243
Dead stem (kg)	15	5.3–78.7	–11.812	3.215	0.673	1.286
Live stem (kg)	19	5.3–78.7	–5.861	2.651	0.985	0.263
Roots (kg)	10	5.3–78.7	–9.342	3.050	0.980	0.381

[M] Range in circumference unless otherwise stated

[N] DBH Range cm

Table A4: Unpublished forestry regressions for Australian trees.

Description	n	Range (cm)	a	b	c	d	R^2	RSD
QDPI Forestry total Volume equations **V = a (DBH^b)(H^c); where V = total stem volume (m^3), DBH = diameter breast height over bark (cm) and H = total tree height (m)**								
***P. caribaea* variety hondurensis, Esk/Pechey 1995**								
Total volume	415	13–51	1.82E–05	2.07753	1.027584			
***P. caribaea* variety hondurensis, Toolara–Tuan 1995**								
Total volume	254	15–42	2.20E–05	1.992762	1.055168			
***P. caribaea* variety hondurensis, Byfield 1995**								
Total volume	338	13–44	5.72E–06	2.129475	1.311913			
***P. caribaea* variety hondurensis, Beerburrum 1997**								
Total volume	268	15–44	2.24E–05	1.9559	1.104			
***P. caribaea* variety hondurensis, Cardwell 1998**								
Total volume	221	12–46	2.56E–05	1.826359	1.185286			
***P. taeda*, Beerburrum 1995**								
Total volume	1122	12–65	1.88E–05	1.972362	1.186818			
***P. taeda*, Inland 1995**								
Total volume	273	12–65	1.93E–05	1.970646	1.181826			
***P. patula*, Passchendaele 1995**								
Total volume	468	13–64	2.71E–05	1.870152	1.215732			
***P. patula*, Pechey 1998**								
Total volume	313	16–50	2.41E–05	1.9325	1.1705			
***P. radiata*, Passchendale 1995**								
Total volume	629	13–73	2.77E–05	1.829565	1.178094			
***P. radiata*, Gambubal 1995**								
Total volume	143	18–70	3.75E–05	1.991258	0.912937			
***P. elliottii* variety *elliottii*, Tuan–Toolara 1995**								
Total volume	1675	12–46	1.08E–05	1.998368	1.315615			
***P. elliottii* variety *elliottii*, Byfield 1995**								
Total volume	636	12–43	1.19E–05	2.110127	1.16058			
***P. elliottii* variety *elliottii*, Inland 1995**								
Total volume	172	15–63	2.74E–05	1.852668	1.213549			
***P. elliottii* variety *elliottii*, Beerburrum 1997**								
Total volume	306	16–44	1.23E–05	2.1325	1.135			
***A. bidwillii*, Queensland 1995**								
Total volume	272	12–37	3.33E–05	1.871796	1.147687			

Table A4 ***continued***

Description	n	Range (cm)	a	b	c	d	R^2	RSD
P. elliottii var elliottii **X** ***P. caribaea*** **var** ***hondurensis*****, Queensland 1995**								
Total volume	288	12–34	2.17E–05	1.767575	1.344753			
A. cunninghamii, **Imbil 1995**								
Total volume	440	12–58	3.04E–05	1.978354	1.042016			
A. cunninghamii, **Yarraman 1995**								
Total volume	396	12–61	2.13E–05	1.909342	1.224394			
A. cunninghamii, Murgon 1995								
Total volume	573	13–53	3.21E–05	1.868055	1.139184			

Table A5: Densities of Australian tree species (from Boland *et al.* 1992).

Species	Density (kg m^{-3})
Agathis robusta	435–480
A. cunninghamii	530
Argyrodendron polyandrum	800–850
*Beilschmiedia spp.**	500–700
Callitris spp.	688
Ceratopelalum spp	630–690
Doryphora spp.	590
*Elaeocarpus spp.**	400
E. umbra subsp umbra	960
F. bourjotiana	640
F. brayleyana	575
F. pimenteliana	575
*P. patula**	450
*P. caribae**	510

*** Brown (1997)**

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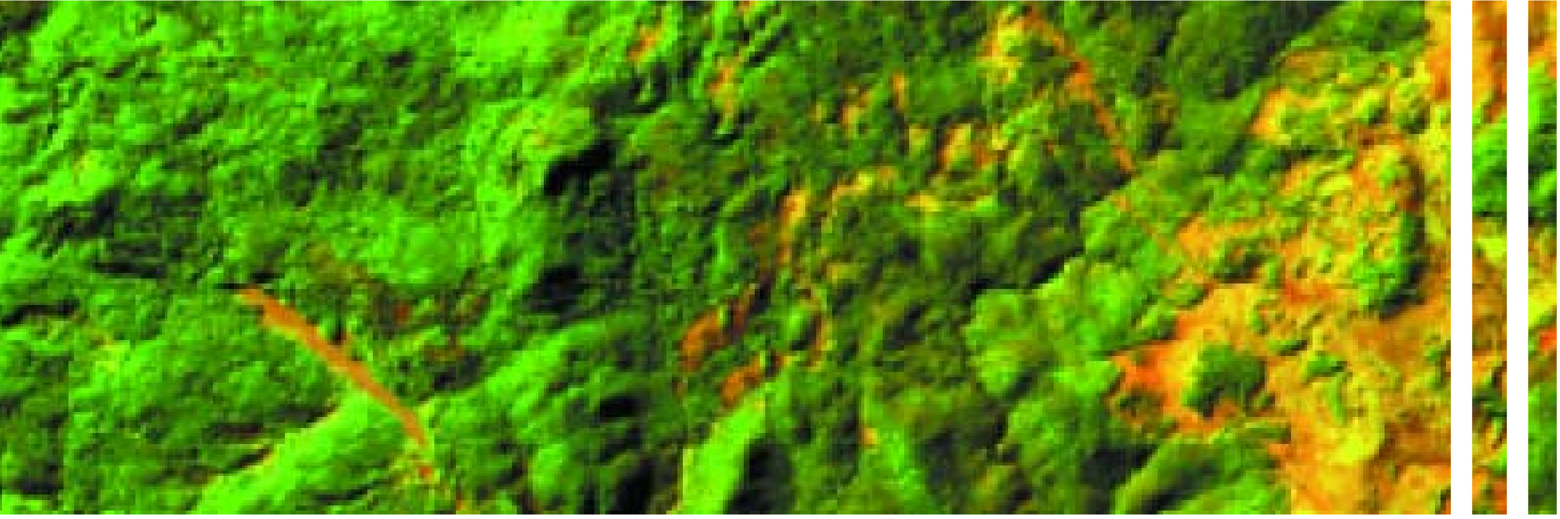

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