Chapter 3. Fuelwood volume and weight relationships for five eucalypts in southern New England

3.1. Introduction

The formulation of mathematical expressions to calculate the volume or weight of individual trees from measures of their overbark diameter at breast height (DBH), height (HT) and crown dimensions is an essential step in the design of silvicultural guidelines for production forestry (e.g. allocation of timber quotas and appraisal of harvest rotations). There are two principal methods used in volume estimation. The more traditional 'direct' method is destructive in nature, where volume is estimated from a series of diameter measurements along the merchantable portion of the stem of a felled tree (Cailliez 1980; Corbyn *et al.* 1988; Shiver and Brister 1992). 'Indirect' methods are non-destructive and involve the measurement of standing trees with optical instruments such as relascopes or dendrometers (Wiant *et al.* 1992). More recent techniques such as importance sampling (Gregoire *et al.* 1986) and centroid sampling (Wood and Wiant 1990) estimate merchantable volume from a single measurement of the stem diameter of a standing tree, hastening the process of forest inventory and negating the need for volume tables (Wiant *et al.* 1992).

Of the various indirect techniques developed for estimating the volume of merchantable stemwood, none have yet been adapted to quantify the fuelwood biomass of trees, in which the volume of almost all above-ground woody material is required. Morse (1985a) estimated visually the fuelwood volume of standing eucalypts in the Canberra region using a simple optical calliper and ranging pole, recognising its limitations compared with the use of expensive dendrometers or destructive sampling. Pukkala and Pohjonen (1990) measured the stem diameter at various heights in *Eucalyptus globulus* fuelwood plantations in Ethiopia, calculating stem volume by integrating the taper curve of the stem.

The most reliable method for fuelwood biomass estimation is destructive sampling, a labour-intensive and costly method involving total tree harvesting and measurement of many stem and branch diameters to estimate total standing volume. Corbyn *et al.* (1988) used this approach to produce a series of volume tables for oak, ash and beech trees in southern England, in which the contribution to total fuelwood volume made by the stem and branchwood of various tree sizes was determined using DBH and HT as independent tree variables. Shiver and Brister (1992) developed tree volume functions for *E. saligna* in Kenya by harvesting and measuring several trees and relating volume to DBH and HT.

A more useful tool for fuelwood managers is the relationship between tree size and dry-weight (i.e. air-dry weight), in which calorific content can be applied directly to estimate fuel yield. Green-weight and volume are more useful from a fuelwood transportation and storage viewpoint, assisting managers in estimating the number of trips required for a harvesting operation and the amount of storage needed for air-drying. A number of destructive biomass studies have been carried out on eucalypt plantations outside Australia to determine dry-weight of individual fuelwood trees and stands. Ranasinghe and Mayhead (1991) assessed dry matter content in relation to age for an *E. camaldulensis* plantation in Sri Lanka. Madgwick *et al.* (1991) constructed a number of dry-weight equations based on DBH and diameter at the base of the live crown (DC) for four fast growing eucalypts in New Zealand by harvesting and weighing small plantation trees. Similar work has been undertaken by Frederick *et al.* (1985a,b) in New Zealand and Schönau and Boden (1982) in South Africa.

The removal of dead trees from rural holdings in the study region is exploitative. Trees are not replaced and accessible timber stocks appear to be depleting (Chapter 2). Regression equations expressing dependent variables in terms of easily recorded parameters such as DBH and HT offer the fuelwood industry a simple and convenient tool for quantifying the fuelwood biomass of individual trees in terms of dry-weight, green-weight and volume. Used as part of the double sampling procedure (Catchpole and Wheeler 1992), they play a pivotal role in compilation of forest inventory data from which silvicultural strategies can be developed. This chapter reports the development of a set of fuelwood-specific volume and weight equations for naturally occurring eucalypt species in southern New England.

3.2. Methods

3.2.1. Species notation

Five groups of eucalypt species indigenous to the New England region provide premium quality fuelwood. Unless otherwise stated, their common names are used throughout this chapter, and the following abbreviations are used in tables and figures :

- GB - grey box *E. moluccana* (also white box *E. albens*)
- IB - red ironbark *E. sideroxylon*
- RG - red gum *E. blakelyi*
- SB - stringybarks *E. caliginosa* and *E. laevopinea* (also blackbutt *E. andrewsii*)
- YB - yellow box *E. melliodora*

3.2.2. Tree harvesting and weighing

Overview

Stringybark is easy to handle and split and provides a medium-density fuelwood with good burning qualities (section 2.2.5). It comprises the most widespread and common group of eucalypt species in the study region, and is likely to play an increasing role in provision of fuelwood to Armidale. Yellow box is a high-density timber of premium combustion quality, forming a hot coalbed and generating ample heat.

It is not as abundant as stringybark and will play a lesser role in fuelwood production if reforestation programs are not pursued. A total of 52 live and 7 dead trees of two stringybark species (*E. laevopinea* and *E. caliginosa*) and 12 live and 5 dead *E. melliodora* were selected for tree harvesting in this study.

A destructive technique was adopted in which trees were selected, measured for allometric parameters (overbark diameter, tree height, height to first major branch, canopy height, canopy width and canopy breadth), felled and sectioned using a chainsaw, and weighed on site.

Site selection and sample size

Field operations were carried out at two sites (A and B) within the study region. The majority of work was undertaken at site A (part of site 65, Figure 2.1), 10 km north of Armidale at the University of New England's Field Laboratory, "Newholme". Site A comprises open eucalypt forest dominated by *E. laevopinea* with *E. melliodora, E. caliginosa, E. bridgesiana* and *E. dalrympleana*. Site B is situated on private land about 60 km west of Armidale (Figure 2.1) and contains open forest dominated by *E. caliginosa*, with *E. viminalis, E. melliodora* and *E. blakelyi*.

Initial sampling at site B was undertaken in conjunction with a farm fencing schedule in which 21 *E. caliginosa* trees were selected for fencing timber (posts, strainers, stays, rails). All trees were less than 50 cm DBH, the majority less than 30 cm DBH, and all possessed straight stems suitable for fencing. A total of 31 *E. laevopinea* trees at site A was selected using a stratified random technique, in which trees were selected randomly within distinct diameter classes. The method proved useful for small DBH classes (5-15, 15-25, 25-35, 35-45 cm), where at least five trees were chosen within each class. For large DBH classes, however, the ability to maintain randomness was affected by factors such as slope, rockiness, proximity to other trees, and risk of injury to personnel, and trees were chosen according to ease of felling and subsequent weighing, with the proviso that each possessed typical stem and branch form. Twelve *E. melliodora* trees were selected purely in terms of tree availability, accounting for the majority of accessible trees at site A.

Twelve dead trees (7 x *E. laevopinea* and 5 x *E. melliodora*) were felled and weighed to enable comparison of woody biomass in live and dead trees of the same species and diameter class. Selection of dead trees was based on tree form and time since mortality. Recently dead trees are relatively intact due to the initially high strength of stem and branches, a trait which may last up to 30 years whereas long-dead trees (> 50 years) show evidence of major branch loss and internal stem decay, rendering them unsuitable for fuelwood.

There is conjecture over the number of trees to be sampled in generating regression equations and volume and weight tables. For construction of regression equations using woodland trees in Somalia, Bird and Shepherd (1989) recommended enough trees be sampled to achieve a precision level within

10% of the mean biomass at the 95% confidence interval. This may be possible where a relatively large number of small trees or shrubs (< 30 cm DBH) can be felled, sectioned and weighed *in situ* in low woodlands or shrublands (Bird and Shepherd 1989; Tietema 1993; Grundy 1995) or young plantations (Madgwick *et al.* 1991). However, the cost of harvesting and measuring large trees (> 30 cm DBH) limits the number of trees sampled, and a compromise must be made between what is theoretically desirable and what is practical in terms of sampling (Applegate 1982). Further, there is little benefit in increasing sample size (using more time and labour) if the accuracy of the regression model is not in turn increased, or is so only marginally (Young 1976, cited in Applegate 1982). Stewart *et al.* (1979) sampled the above ground biomass of 11 *E. muellerana*, 10 *E. agglomerata* and 10 *E. sieberi* and Feller (1980) sampled six *E. regnans*, six *E. obliqua* and five *E. dives* in Victoria. Consistently high values of r^2 (> 0.85) for the various woody biomass components of each species were obtained in each case, negating the need for further sampling. The final number of sample trees used in this study (52 stringybark and 12 yellow box) was considered sufficient in light of both resources available and values of r^2 obtained (all > 0.80).

Pre-harvesting measurements

Using a diameter tape, DBH was measured to the nearest 0.5 cm, perpendicular to the stem, 130 cm above ground level (a.g.l.), and from the uphill side for trees on sloping terrain (Loetsch *et al.* 1973). Strips of shedding bark often required removal before DBH measurement, particularly in *E. melliodora*. HT was measured using a clinometer and 30 m tape. From a point (P1=0) directly under the highest part of the canopy (usually at the bole), the tape was extended horizontally to a point (P2) in which the sighting angle to canopy-top was 45°. After measuring the 'height to eye-level' (h) of the sighting person, tree height was measured as :

$$HT = P2 + h \qquad (3.1)$$

Crown area (also width or diameter) is the measure of lateral spread of a tree canopy, often used as an index of competition and relative stand density (Krajicek *et al.* 1961). Crown volume is a measure of the three-dimensional space occupied by a tree canopy, and can be used to indicate tree vigour and productivity. All heights and canopy dimensions were measured to the nearest 0.5 m. Height to the first major branch (HTB) and height to the base of the main canopy (HC) were also measured using a clinometer and tape. Crown height (CNHT) was subsequently calculated as :

$$CNHT = HT - HC \qquad (3.2)$$

Crown width (CNWDTH) and crown breadth (CNBRDTH) were measured perpendicular to each other using a 30 m tape at ground level.

Crown area (CNAREA) was simplified as :

CNAREA = CNWDTH * CNBRDTH 3.3

and crown volume (CNVOL) was calculated as :

CNVOL = CNAREA * CNHT 3.4

Figure 3.1 illustrates measurements of tree canopy. The inter-canopy spaces and three-dimensional curvilinear nature of the canopy periphery suggest that true crown volume is over-estimated by CNVOL, which is a hypothetical rectangular volume enclosing the canopy. Nonetheless, CNVOL is a surrogate for true crown volume (as is CNAREA for true crown area) when used in regressions to predict timber volume and weight.

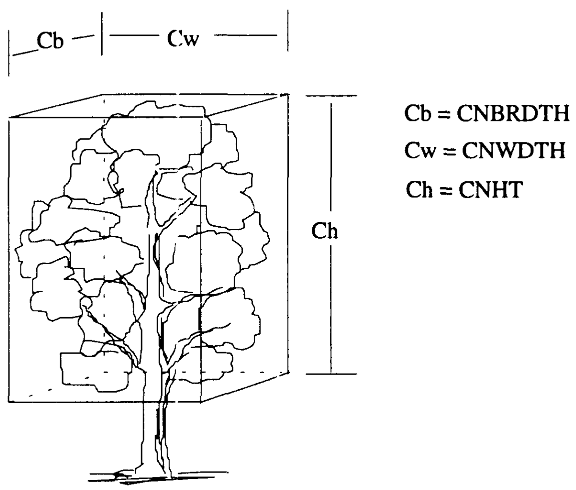

Figure 3.1. Canopy measurements required for calculation of CNAREA and CNVOL.

Tree weighing

Each tree was felled an average 80 cm above ground level and all branchwood less than 5 cm diameter was cut to remove canopy foliage. A minimum fuelwood diameter of 5 cm was considered appropriate because it corresponded roughly to the initiation of heartwood formation, and chainsaw operation became more hazardous and inefficient at smaller diameters. Trees were sectioned after canopy removal into 0.5 - 4 m lengths (depending on manoeuvrability) for weighing. Lengths were cut to fit within one of five major diameter categories: D1 = 5-15 cm; D2 = 15-25 cm; D3 = 25-45 cm; D4 = 45-65 cm; D5 = 65-95 cm. At site A, lengths were further classified as stemwood or branchwood. Each was placed on a set of portable electronic cattle scales and weighed to an accuracy of ± 0.5 kg. Smaller lengths were weighed simultaneously. The procedure continued until the entire tree had been weighed. Plates 3.1-3.3

show various stages of tree weighing and preparation. Sample discs were extracted from certain trees, stored in plastic bags (Plate 3.4) and returned to the laboratory for analysis of volume, moisture content and density (section 3.2.3).

Plate 3.1. Weighing a stem section of *E. melliodora* at site A.

Plate 3.2. Preparing a large *E. melliodora* stem for weighing at site A

Plate 3.3. Weighing small branches of *E. caliginosa* at site B.

An additional procedure was used at site A in which the length and small and large end diameters of each section were measured (Figure 3.2). Section volume (V_{sect}) was then calculated using the expression :

$$V_{sect} = \frac{\pi \cdot \left(L \cdot \left(D^2 + D \cdot d + d^2\right)\right)}{12} \quad \text{(Loetsch et al. 1973)} \quad \ldots\ldots \quad 3.5$$

where L = length of section (m)
D = large end diameter of section (overbark, m)
d = small end diameter of section (underbark, m)
V_{sect} = volume of section (m^3)

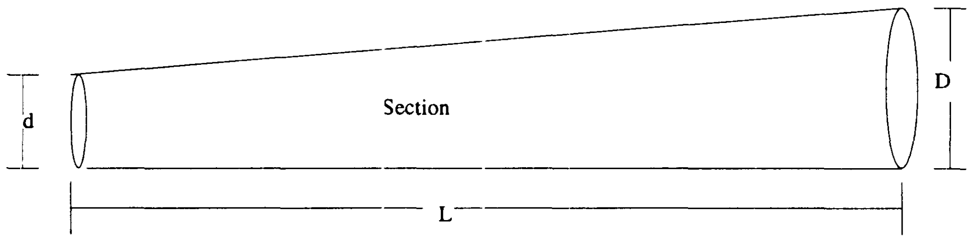

Figure 3.2. Measurements for stem and branch sections weighed at site A (D = diameter of large end; d = diameter of small end; L = length).

Dead trees were cut about 50 cm above ground. All timber was sectioned before weighing *in situ* using cattle scales. Bark was not weighed since it was absent from selected trees. Several discs were cut from the main stem of dead trees and returned to the laboratory for volume, moisture content and density analysis (section 3.2.3).

3.2.3. Disc analysis

A total of 132 cross-sectional timber 'discs' was cut from stemwood and branchwood of 42 sample trees for analysis of weight, volume, density and moisture content of wood and bark. The number of discs cut at each site, according to diameter class, branch/stem class, and species, is shown in Table 3.1.

Table 3.1. Number of discs sampled during tree mensuration.

	E. caliginosa [1]			*E. laevopinea* [2]		*E. melliodora* [2]	
DC (cm) [3]	Stem	Branch	NC [4]	Stem	Branch	Stem	Branch
5 - 15	6	-	5	19	13	11	10
15 - 25	7	-	-	19	4	10	6
25 - 45	1	-	-	10	1	6	2
45 - 65	-	-	-	1	-	1	-

1. Site B
2. Site A
3. diameter class
4. not classified as stem or branch

After cutting a disc, usually to a thickness of between 4 and 6 cm, wood shavings were scraped away and the sample placed (bark intact) into a plastic bag for storage in the shade before transportation to the laboratory (Plate 3.4). Once in the laboratory, the sample was removed from its bag (moisture loss during storage and transit was negligible) and immediately weighed on an electronic balance to an accuracy of 0.1 g. Overbark diameter was measured to an accuracy of 0.1 cm, and the disc classified into one of four diameter classes, 5-15, 15-25, 25-45, or 45-65 cm. The bark was sheared from the wood at the vascular cambium using a sharp knife and the green-weight of bark and wood weighed separately. Underbark diameter of the disc was also measured.

Plate 3.4. Storage of *E. laevopinea* discs at site A.

The volume of discwood was determined by water displacement. Water was poured into a large container until it flowed freely from a single outlet pipe. An equilibration time of at least 20 minutes was allowed, after which outlet flow was negligible. The discwood sample was then placed into the water for the same period of time and displaced water was collected from the outlet pipe in a receiving vessel. The volume of displaced water equalled the volume of discwood. The disc was reweighed to determine the volume of hydroscopic absorption during emersion. Although this absorption volume, measured as the difference in discwood weight before and after emersion, was usually small, it was added to the displacement volume to obtain a total volume for the disc wood sample, calculated to the nearest 0.1 cm^3. Bark volume (Bv) and timber to bark volume ratio (Tv : Bv) was then calculated using the relationship:

$$Bv = \frac{Tv \cdot \left(DOB^2 - DUB^2\right)}{DUB^2} \quad \text{........ 3.6}$$

where Bv = bark volume (cm^3)
Tv = wood volume (cm^3)
DOB = diameter of disc overbark (cm)
DUB = diameter of disc underbark (cm)

After volume estimation, wood and bark samples were placed in a drying oven at 95°C for 1 week. Larger discs were sectioned into small pieces (< 500 g) to assist drying. Samples were reweighed and moisture content (as a proportion of green-weight) was calculated as follows :

$$MC = \frac{100 \cdot (GWt - ODWt)}{GWt} \quad \text{........ 3.7}$$

where MC = moisture content (% of green-weight)
GWt = green-weight (g)
ODWt = oven dry-weight (g)

Assuming an air-dry moisture content of about 12% (Bootle 1983; FTS and UT 1989), dry-weight of wood and bark samples was also calculated :

$$DWt = ODWt + \left(\frac{12 \cdot (GWt - ODWt)}{MC}\right) \quad \text{........ 3.8}$$

where DWt = dry-weight (g)
GWt = green-weight (g)
ODWt = oven dry-weight (g)
MC = moisture content (%)

Green-density (GD) and air-dry density (ADD) ($g.cm^{-3}$) of all wood and bark samples were calculated using the expressions :

$$GD = \frac{GWt}{V} \quad \text{........ 3.9}$$

$$ADD = \frac{DWt}{V} \quad \text{........ 3.10}$$

where V = volume of sample (cm^3)

3.2.4. Tree weight, volume and density calculations

Calculations in this section pertain to woody biomass (timber and bark) ≥ 5 cm diameter (overbark), and values of dry-weight and density assume a moisture content of 12%.

Chainsaw volume and weight

To account for loss of woody biomass from chainsaw operation, the diameter at each cut was measured using a diameter tape or metre rule and a combined volume for all cuts calculated using the formula (chainsaw width was 0.8 cm) :

$$\text{Vcs} = \sum_{cs=1}^{n} \left(\frac{\pi \cdot (\text{Dcs}_c)^2}{5} \right) \quad \text{.......... 3.11}$$

where Vcs = volume of chainsaw cut (cm^3)
n = number of chainsaw cuts (c) in tree class
Dsc = diameter of each chainsaw cut

The following relationships were used to convert Vcs into timber and bark weights :

$$\text{Wtcs(t)} = \frac{\text{Tgd} \cdot \text{Vcs} \cdot (\text{Tv:Bv})}{(\text{Tv:Bv}) + 1} \quad \text{.......... 3.12}$$

$$\text{Wtcs(b)} = \frac{\text{Bgd} \cdot \text{Vcs}}{(\text{Tv:Bv}) + 1} \quad \text{.......... 3.13}$$

where
Wtcs (t) = weight of timber lost by chainsaw (g)
Wtcs (b) = weight of bark lost by chainsaw (g)
Tgd = GD of timber ($g.cm^{-3}$) (eq. 3.9)
Bgd = GD of bark ($g.cm^{-3}$) (eq. 3.9)
Tv : Bv = timber : bark volume ratio (calculated from eq. 3.6)
Vcs = volume lost by chainsaw (cm^3) (eq. 3.11)

Timber and bark weight

Total weight (Wt) within each diameter and stem or branch class was calculated by summing the individual weights of sections. These weights were subsequently partitioned into timber and bark components using the following expressions :

$$\text{Wt(t)} = \left(\frac{\text{Wtcs(t)}}{1000} \right) + \left(\frac{\text{Tgd} \cdot (\text{Tv:Bv}) \cdot \text{Wt}}{\text{Tgd} \cdot (\text{Tv:Bv}) + \text{Bgd}} \right) \quad \text{.......... 3.14}$$

$$Wt(b) = \left(\frac{Wtcs(b)}{1000}\right) + \left(\frac{Bgd \cdot Wt}{Tgd \cdot (Tv:Bv) + Bgd}\right) \qquad 3.15$$

$$DWt(t) = Wt(t) \cdot \left(\frac{Tdd}{Tgd}\right) \qquad 3.16$$

$$DWt(b) = Wt(b) \cdot \left(\frac{Bdd}{Bgd}\right) \qquad 3.17$$

where Wt (t) = green-weight of timber (kg)
Wt.(b) = green-weight of bark (kg)
DWt (t) = dry-weight of timber (kg)
DWt (b) = dry-weight of bark (kg)
Wtcs (t) = weight of timber lost by chainsaw (g) (eq. 3.12)
Wtcs (b) = weight of bark lost by chainsaw (g) (eq. 3.13)
Wt = weight of sections (kg) measured *in situ*
Tgd = GD of timber ($g.cm^{-3}$)
Bgd = GD of bark ($g.cm^{-3}$)
Tdd = ADD of timber ($g.cm^{-3}$)
Bdd = ADD of bark ($g.cm^{-3}$)
Tv : Bv = timber : bark volume ratio

Sections of deadwood were weighed separately from sections of greenwood in each diameter class for each tree. Bark had peeled away from the majority of deadwood sections, so calculation of timber/bark differences in weight and volume of deadwood was not necessary. It was assumed that deadwood had attained a moisture content of about 12%, and could thus be incorporated in the total within-class (and within-tree) dry-weight of seasoned timber. Measurement of weight and volume of deadwood was not undertaken separately for *E. caliginosa*, rather it was incorporated into the overall weight and volume assessment of greenwood.

Timber and bark volume

Timber and bark volumes within each class were calculated for each tree from results of disc analysis using the functions :

$$V(t) = \frac{Wt(t)}{1000 \cdot Tgd} \qquad 3.18$$

$$V(b) = \frac{Wt(b)}{1000 \cdot Bgd} \qquad 3.19$$

where V (t) = volume of timber (m^3)
V (b) = volume of bark (m^3)
Wt (t) = weight of timber (kg) (eq. 3.15)
Wt (b) = weight of bark (kg) (eq. 3.16)
Tgd = timber GD ($g.cm^{-3}$)
Bgd = bark GD ($g.cm^{-3}$)

Timber and bark volumes were also calculated from results of section volume analysis (eq. 3.5), providing an alternative estimation of volume :

$$V(t) = \frac{\left(\sum_{s=1}^{n} \left(V_{sect}\right)_s + Vcs\right) \cdot (Tv:Bv)}{\left((Tv:Bv)+1\right) \cdot 10^6} \quad \text{.......... } 3.20$$

$$V(b) = \frac{\sum_{s=1}^{n} \left(V_{sect}\right)_s + Vcs}{\left((Tv:Bv)+1\right) \cdot 10^6} \quad \text{.......... } 3.21$$

where	V (t)	= volume of timber (m^3)
	V (b)	= volume of bark (m^3)
	V_{sect}	= volume of section 's' (cm^3) (eq. 3.6)
	Vcs	= volume of chainsaw cuts (cm^3) (eq. 3.12)
	Tv : Bv	= timber : bark volume ratio
	n	= number of sections within class

Final within-class volumes for *E. laevopinea and E. melliodora* were calculated as the mean of equations 3.18 and 3.20 (timber) and equations 3.19 and 3.21 (bark). Since section volume was not measured for *E. caliginosa*, its volume estimation was based entirely on equations 3.18 and 3.19.

The volume of deadwood in *E. melliodora* and *E. laevopinea* was calculated by summing the volume of each dead section extracted from the tree. The majority of deadwood was incorporated in the 5-15 cm branchwood class. Chainsaw cuts required to partition dead sections from the main stem were accounted for in the calculations of chainsaw weight for green sections (eqs. 3.12-3.13).

Total tree weight and volume

For each *E. melliodora* and *E. laevopinea* tree, the diameter class totals of green-weight, dry-weight and volume of stemwood and branchwood were combined to obtain a standing green-weight, dry-weight and volume (Appendix VII). Within-class values of green and dry-density were calculated for each *E. laevopinea* and *E. melliodora* tree by dividing the weight of a class (e.g. stem timber) by its volume. Collective values of green and dry-density ($g.cm^{-3}$) were also calculated for each tree (Appendix VIII). Weight, volume and density estimation for *E. caliginosa* did not incorporate stem and branch components, although diameter classes were taken into account.

3.2.5. Statistical analysis

Single-variate regression analysis

Single-variate regression establishes the best-fitting relationship between a dependent biomass variable (e.g. volume) and a independent tree measurement, usually DBH. Least squares regression was undertaken for each above-ground biomass variable (GWt, DWt, V) according to the regression form :

Biomass variable = $a + c.(D)^2$ (Schönau and Boden 1982) 3.22

Independent variable D = (DBH-5) was used as a surrogate for DBH to express the majority of biomass variables in regression analysis since useful fuelwood does not begin to develop until stem DBH exceeds 5 cm. Diameter variable D = (DBH-15) was used to express branchwood biomass variables in stringybark (*E. laevopinea* and *E. caliginosa*), based on the observation that development of fuelwood-sized branches (≥ 5 cm diameter) in stringybark did not occur until acquisition of a stem DBH of 15 cm. Both terms were found to improve values of r^2 given the curvilinear nature of the regression equations.

Species comparisons

While volume and weight relationships are usually species-specific, similar weight and volume trends may exist between species, enabling construction of multiple-species regression functions such as those reported in New Zealand (Madgwick *et al.* 1991), Puerto Rico (Weaver and Gillespie 1992), Botswana (Tietema 1993) and Zimbabwe (Grundy 1995). The biomass of one species has sometimes been estimated using functions of another (Stewart *et al.* 1979; Applegate 1982).

The two stringybark species in this study (*E. caliginosa* and *E. laevopinea*) have a similar appearance. To test whether all stringybark data could be pooled for regression analysis, the slopes of regression functions for *E. caliginosa* were compared to the slopes of respective functions for *E. laevopinea* using a method incorporating Student's *t*-test (Zar 1984). A total of nine between-species tests were performed to compare the relationship of each dependent biomass variable (GWt, DWt, V) with transformed data of each independent variable (HT, DBH, CNVOL). To standardise the comparisons, all trees < 15 cm and > 50 cm DBH were eliminated from analysis, since *E. caliginosa* trees outside the range 15-50 cm were not sampled.

Multi-variate regression analysis

While it was feasible to apply the single-variate DBH models constructed from harvested trees to trees and stands of similar site quality and species, their application to dissimilar tree populations is unwise due to errors arising from differences in tree size and form. Multi-variate functions using determinants of tree form in addition to DBH were thus developed to account for site quality and species differences in tree weight and volume (Schönau and Boden 1982).

DBH and HT account for the greatest proportion of variability in tree volume (Avery 1975) and the majority of literature reports their use in generating weight and volume functions (Opie 1976; Feller 1980; Corbyn *et al.* 1988; Pukkala and Pohjonen 1990; Madgwick *et al.* 1991; Ravindranath *et al.* 1991; Weaver and Gillespie 1992). The 'combined variable' method of volume prediction (Spurr 1952) provides a powerful but simple linear expression of timber volume in the form :

$$V = a + b \cdot \left(DBH^2 \cdot HT\right) \quad \text{.......... 3.23}$$

Multiple stepwise regression was undertaken on tree data using independent variables DBH^2.HT (eq. 3.23) and HT-5 to determine the most appropriate function for each stemwood variable. The latter was used as a surrogate for HT to express biomass variables in multiple regression analysis since useful fuelwood does not begin to develop until tree height exceeds about 5 m. Independent variable CNVOL was included as a co-predictor in generation of branchwood and total weight functions. Various biomass studies report the use of crown variables for tree weight and volume prediction, particularly in bushy or heavily branching species in which crownwood contributes significantly to total biomass (Deshmukh 1992).

3.2.6. Allometric relationships of New England eucalypts

Measurements

To investigate allometric relationships within and between the five eucalypt species, a number of sample trees were selected at random from 87 of the 122 forest inventory sites (Figure 2.1) during point-quarter and horizontal sampling (Chapter 4), and measurements of DBH, HT and CNVOL conducted according to methods outlined in section 3.2.2. In cases where buttress taper extended above diameter height, mostly in large trees in the eastern sites, DBH was measured at the point in which buttress influence was minimal (between 130 and 180 cm a.g.l.), and where the bole swelled at diameter height (as a result of insect damage or stem malformation), DBH was measured at the narrowest point below the zone of swell. In multi-stem trees, or where a major branch junction occurred below 130 cm, more than one diameter measurement was necessary, and DBH was later calculated as :

$$DBH = \left(\sum_{i=1}^{n} (d_i)^2\right)^{1/2} \quad \text{.......... 3.24}$$

where i = number of stems; d_i = diameter of stem i.

The number of trees sampled for each species, and the sites and site quality classes in which they were sampled, are listed in Appendices IX and X. Trees were not sampled at sites 4, 21, 26-27, 29-30, 36, 41-45, 52-54, 56-59, 62, 64, 71, 73, 90-97, and 111-114 due to either time and resource constraints or lack of target species.

Site quality

Considerable heterogeneity in species composition and mean height of dominant trees was observed between sites, indicating the need for site quality indices. While soil factors such as parent material, structure, texture and depth are a major influence on site quality (Avery 1975), the majority of fertile basaltic soils in New England have been denuded of native forest and woodland for pastoral development, and remnant vegetation is largely confined to localised regions of shallow, low fertility soils derived from sediments and granites, often on steep, inaccessible and rocky terrain. This is indicative of many production forests in eastern Australia which occupy land unsuitable for crops or grazing (Braithwaite *et al.* 1993). FCNSW (1984) indicated that more than 90% of state forest on the Northern Tablelands occurs on sediments, with only a small area of Styx River State Forest confined to basalt-derived kraznozem soils.

Mean annual rainfall (MAR) was used as the main index of site quality, having been identified as the greatest influence on stand productivity in other Australian forests (e.g. Inions 1990). MAR was extracted from the BIOCLIM software (section 5.2.1) and used as an index of site quality according to the following classes : SQ1 > 1000; SQ2 = 950-1000; SQ3 = 900-950; SQ4 = 850-900; SQ5 = 800-850; SQ6 = 750-800; and SQ7 < 750 $mm.yr^{-1}$. Figure 3.3 presents a map of site quality distribution and Appendix XI shows an isohyet map of the study region.

HT-DBH regressions

Various regression expressions relating HT to DBH have been produced (Husch *et al.* 1971; Loetsch *et al.* 1973). While the second degree paraboloid $HT = a + b.(DBH) + c.(DBH)^2$ has proven satisfactory for fitting height curves in even-aged stands over a restricted range of DBH values (Loetsch *et al.* 1973), DBH of most trees in this study ranged from 5 to 100+ cm, indicative of uneven-aged stands. As a consequence, height values fitted by the above expression were found to decrease with increasing DBH beyond a critical value. The following hyperbolic functions (Loetsch *et al.* 1973) were considered more appropriate for application to the New England data because of their suitability for uneven-aged stands :

$$HT = \frac{(DBH)^2}{a + b \cdot (DBH) + c \cdot (DBH)^2} + 1.3 \qquad 3.25$$

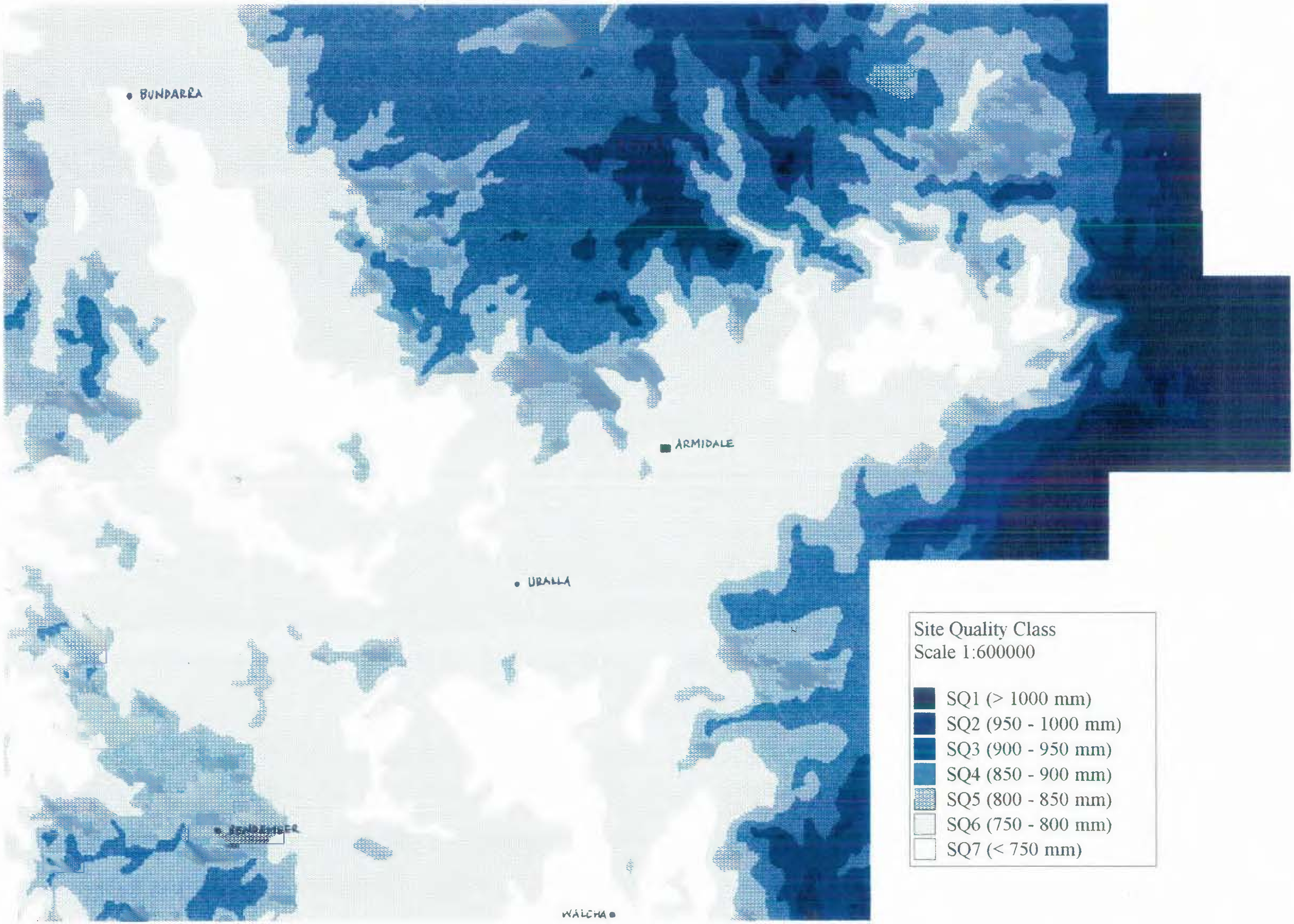

Figure 3.3. Distribution of site-quality classes in the study region (based on values of MAR derived by BIOCLIM).

$$HT = \frac{(DBH)^2}{\left(a + b \cdot (DBH)\right)^2} + 1.3 \qquad \text{3.26}$$

Equations 3.25 and 3.26 force the curve through co-ordinates DBH = 0 and HT = 1.3, whereas other functions ignore that HT is at least 1.3 m when DBH = 0 cm. They also exhibit a point of inflection at a low DBH value, reflecting the growth development curve of young trees and eliminating the over-estimation of HT at low values of DBH. Equation 3.26, known as Näslund's height curve, produced lower standard errors than equation 3.25, and was used to produce a set of HT-DBH curves for New England species. For the purpose of species comparisons and construction of regression equations, Näslund's height curve assumes the straight line form :

$$\frac{DBH}{(HT - 1.3)^{1/2}} = a + b \cdot (DBH) \qquad \text{3.27}$$

where $DBH / (Ht-1.3)^{1/2}$ = transformed dependent variable
DBH = independent variable

CNVOL-DBH regressions

The paraboloid function $Y = a + b.X^2$ approximated the general trend of CNVOL-DBH data and was found to yield values of r^2 similar to a logarithmic function $\log_e(Y) = a + b.\log_e(X)$. After testing the fit of both functions on the various crown relationships for each species, the logarithmic function, although representing the data very well at low to mid ranges of DBH, was found to grossly overestimate CNVOL at high values of DBH, and was thus discarded. The parabola was employed without a constant, adjusting the fit slightly to avoid negative values of CNVOL at low values of DBH.

$$CNVOL = c \cdot (DBH)^2 \qquad \text{3.28}$$

Inter-site and inter-species comparisons

Trees with similar taper and shape can be grouped together within specified localities (Avery 1975). This point is of particular relevance in New England where tree form and DBH-height-crown relationships within certain species groups are similar in areas of coexistence. New England blackbutt *E. andrewsii* is similar in appearance and possesses similar wood qualities to *E. laevopinea* (Bootle 1983), and is likely to have been mistaken for stringybark in regions in which they coexist. Yellow and grey box possess similar stem and branch characteristics, while the height and form of ironbarks in closed and open forests west of Armidale resemble those of adjacent stringybarks.

Student's t-tests of the type discussed in section 3.2.5 (Zar 1984) or analysis of covariance was undertaken on HT-DBH and CNVOL-DBH data to determine whether tree populations of different species and site quality were similar in height and form (transformed data were used; eqs. 3.27 and 3.28).

Whilst t-tests compared the slopes of two regression lines, analysis of covariance tested for significant differences between slopes of more than two lines using the F-statistic. Where covariance analysis concluded that slopes were not all equal, a 'multiple comparisons among slopes' test was employed using the q-statistic (Zar 1984). Single-variate regression functions were subsequently constructed within similar tree-SQ classes.

3.2.7. Site-specific regression functions for stringybark and yellow box

Allometric tree data (DBH, HT, CNVOL) collected for stringybark and yellow box at 123 sites throughout the study region were grouped into site quality classes. Weights and volumes of trees in each species-site quality class were computed using the multi-variate regressions developed at site A. Differences between the resultant set of values for DBH and weight or volume in each site quality class were tested for each species using covariate analyses (Zar 1984). Data sets that did not differ significantly ($P > 0.05$) were pooled and DBH regression functions derived for each.

The assumption underlying this approach was that multi-variate expressions derived from stringybark or yellow box trees at site A (SQ5) could be used to model weight and volume of respective trees from areas of different site quality; i.e. that relationships between fuelwood weight or volume and tree dimensions are similar across different site quality classes, and that tree taper is similar.

3.2.8. Regression functions for other fuelwood species

Background

An estimate of total dry-weight of standing trees for each fuelwood species is required for the purpose of forest inventory (Chapters 4-5). Because of inherent differences in dry-density and bark thickness between species, direct application of weight functions for stringybark and yellow box to other fuelwood species was not feasible. Since tree volume is independent of weight and timber : bark ratio, volume functions derived for stringybark and yellow box using overbark DBH were considered appropriate for adaptation to other species, given a number of assumptions (section 3.3.7). Independent volume equations were thus established for red gum, ironbark and grey box. These were subsequently converted to timber and bark dry-weight equations by measuring the average volumetric ratio of timber to bark and the dry-density of timber and bark for each species.

Timber : bark volume ratio

Direct measurements of overbark and underbark diameter (DOB and DUB) were undertaken during disc analyses for stringybark and yellow box (section 3.3.1) and tree stump analyses for all species (section 6.6.2). Results were used to generate estimates of the relative contribution of timber and bark surface area (m^2) to total area of cut surface (m^2). Due to the paucity of data for red gum and grey box, and a lack of data for yellow box surfaces > 50 cm, regression analyses of DUB on DOB were undertaken within three overlapping diameter classes : 5-25 cm; 5-55 cm; and 5-90 cm. The relationships for red gum, grey box and yellow box were subsequently extrapolated in proportion to changes in regression coefficients for stringybark and ironbark over the three classes (section 3.3.7).

Regression functions of the form DUB = a.(DOB) were used, where constant 'a' is the volumetric proportion of timber, and 'a : (1-a)' is the ratio of timber : bark in terms of cross-sectional area of cut and total within-tree volume (Figure 3.4).

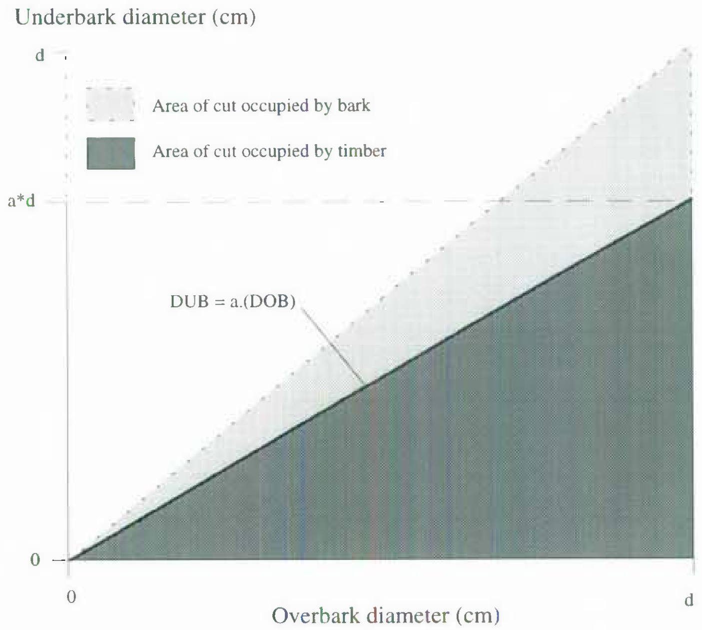

Figure 3.4. Standard DUB-DOB plot for fuelwood eucalypts.

Timber and bark density

The density of heartwood within any species is higher than that of sapwood (Wilkes and Heather 1983); the density of wood in mature trees is greater than that in young trees and saplings (Campbell and Hartley 1984); and the density of wood decreases with increasing tree height (Bamber *et al.* 1969; McKimm 1984; Hillis 1984; Ranasinghe and Mayhead 1991). It was beyond the scope of this project to partition timber density within individual trees and species, so average values of wood density reported by other authors were adopted for grey box, ironbark and red gum.

Red ironbark, as its name suggests, provides one of the densest timbers of all eucalypt species. Literature values for the dry-density of its timber are 1.06 $g.cm^{-3}$ (Gardiner 1989), 1.09 $g.cm^{-3}$ (Kingston and Risdon 1961), 1.13 $g.cm^{-3}$ (Bootle 1983) and 1.17 $g.cm^{-3}$ (Boland *et al.* 1992), where dry-density assumes a moisture content of 12% of green-weight. The density of younger trees (10-40 cm DBH) was found to range from 0.82 $g.cm^{-3}$ for sapwood to 0.99 $g.cm^{-3}$ for outer heartwood (Wilkes and Heather 1983). A dry-density of 1.10 $g.cm^{-3}$ was adopted for ironbark in this study (12% moisture content).

According to Kingston and Risdon (1961), Bootle (1983) and Boland *et al.* (1992), the dry-density of white box and grey box is 1.10 and 1.12 $g.cm^{-3}$ respectively. Wilkes and Heather (1983) reported the basic (oven-dry) density of sapwood and heartwood of younger white box (10-40 cm DBH). From their values, dry-density was calculated at 0.88 $g.cm^{-3}$ for sapwood, 0.98 $g.cm^{-3}$ for inner heartwood and 1.04 $g.cm^{-3}$ for outer heartwood. A dry-density of 1.05 $g.cm^{-3}$ was assumed for grey and white box in the study region.

Dry-density of young Blakely's red gum in the ACT was 0.85 $g.cm^{-3}$ (Groves and Chivuya 1989), somewhat less than the 0.98 $g.cm^{-3}$ for mature red gum (Boland *et al.* 1992) and 0.90 $g.cm^{-3}$ for mature river red gum *E. camaldulensis* (Bootle 1983). A value of 0.95 $g.cm^{-3}$ was assumed for the air-dry fuelwood of Blakely's red gum in this study.

Bark is a more heterogeneous material than wood and its anatomical components vary greatly in structure, hardness, density and chemical composition (Browning 1967). Cremer (1990) discussed the protective role of bark during fire, contrasting bark morphology within and between eucalypt species. The outer layers of stringybark, blackbutt and ironbark, and to a lesser extent grey box and yellow box, are rough and dead and offer greater protection from fire than the bark of red gum, which is thin and almost entirely alive. Outer bark formation in the former group is characterised by bark 'splitting' as it is retained in a dead state on the growing stem (Cremer 1990), thus producing the blocky, flaky or fibrous textures evident of the outer bark or rhytidome of such trees (Chattaway 1953). The density of rhytidome is usually less than the density of the inner bark from which it was formed such that the overall density of bark decreases with increasing volume of rhytidome on the stem.

The density of eucalypt bark has seldom been investigated. Attiwill (1979) and Stewart *et al.* (1979) calculated bark volume by analysing the cross-sectional area of cut discs, similar to the procedure used in section 3.3.1. Attiwill (1979) measured the dry-density of messmate stringybark *E. obliqua* bark in Victoria, and found a slight decrease in density as stem diameter increased. Values ranged from 0.20 to 0.27 $g.cm^{-3}$. Stewart *et al.* (1979) measured the basic density of bark in three eucalypt species in a mixed forest in eastern Victoria, obtaining quite different values for the stringybark species *E. agglomerata* and *E. muellerana* (0.61 and 0.39 $g.cm^{-3}$ respectively).

The bark of red ironbark is hard, ridged, deeply furrowed and persistent to the small branches (Boland *et al.* 1992). It is similar to the bark of the trunk and lower limbs of *E. sieberi*, the basic density of which is 0.65 $g.cm^{-3}$ (Stewart *et al.* 1979). Stewart *et al.* (1979) used weight functions of *E. sieberi* to establish that 76.4% of ironbark biomass (not including twigs and foliage) comprised wood on a dry-weight basis, the remainder comprising bark. This information was used in conjunction with the timber : bark volume ratio and timber density of ironbark, and the 0.82 $g.cm^{-3}$ dry-density of *E. sieberi* timber (Bootle 1983), to estimate the air-dry bark density of ironbark at about 0.64 $g.cm^{-3}$.

The rhytidome of grey box occurs on the main trunk and is thin, fibrous and held in small, finely compact tessellations (Brooker and Kleinig 1983; Boland *et al.* 1992). Red gum has virtually no rhytidome, the bark being smooth and shiny throughout, shedding annually from the trunk in thin ribbons. Since literature values of the density of bark in grey box or red gum were not found, the value obtained for yellow box was used for grey box (0.56 $g.cm^{-3}$), and a density of 0.60 $g.cm^{-3}$ was assumed for red gum.

Derivation of air-dry regression functions

Values of timber and bark dry-density and timber : bark volume ratios were used in conjunction with appropriate tree volume functions to derive dry-weight equations for the timber and bark components of grey box, ironbark and red gum. By comparing HT and CNVOL relationships with those of stringybark and yellow box, functions of dry-weight for the stem and branch components of grey box, ironbark and red gum were also derived.

3.3. Results

3.3.1. Disc analysis

Between-species comparison

Some 86 stringybark discs (67 *E. laevopinea* from site A and 19 *E. caliginosa* from site B) and 46 yellow box discs from site A were analysed for wood and bark attributes, the results of which are tabulated in Appendix XII.

Variation in the green and dry-densityand moisture content of the timber and bark of cut discs was tested between the two stringybark species using 2-tailed *t*-tests. The variables did not differ significantly between species except moisture content and green-density of bark, which were significantly lower in *E. caliginosa* (P = 0.003 and P = 0.019, respectively). Site B possesses a lower annual rainfall than site A (~750mm vs. ~840mm), and since sampling at both sites was undertaken during drought, the soil moisture deficit may have had a greater influence on bark moisture status than species. Stringybark data were thus pooled and tested against yellow box data using further 2-tailed *t*-tests (Table 3.2). The density of timber and bark and the moisture content of bark were significantly higher in yellow box, although moisture content of timber was higher in stringybark. Yellow box possessed a higher timber : bark volume ratio than stringybark, reflecting thicker bark in the latter.

Table 3.2. Differences in timber and bark variables between stringybark and yellow box using data from all sample discs.

Variable	SB Mean (n=86)	YB Mean (n=46)	*t*	P
Timber : bark volume ratio	1.9 ± 0.1	4.2 ± 0.2	- 10.938	< 0.001
Timber moisture content (%)	44.4 ± 0.4	34.5 ± 0.3	16.971	< 0.001
Bark moisture content (%)	44.3 ± 0.7	55.8 ± 0.4	- 11.019	< 0.001
Timber GD ($g.cm^{-3}$)	1.15 ± 0.01	1.23 ± 0.01	-4.761	< 0.001
Timber ADD ($g.cm^{-3}$)	0.78 ± 0.01	0.96 ± 0.01	-12.411	< 0.001
Bark GD ($g.cm^{-3}$)	0.63 ± 0.02	1.00 ± 0.02	-11.161	< 0.001
Bark ADD ($g.cm^{-3}$)	0.42 ± 0.01	0.56 ± 0.01	-7.211	< 0.001

Within-species comparison

One-factor analyses of variance (AOVs) and 2-tailed *t*-tests were used to test for within-species variation in density, moisture content and timber : bark ratios between stems and branches and between diameter classes for stringybark and yellow box (Tables 3.3 - 3.6). The moisture content and green and dry-density of timber were similar between the stem and branches of stringybark, although the green-density and moisture content of bark were significantly higher in branches (Table 3.3). Moisture content and green and dry-density of timber and bark did not vary significantly between the stems and branches of yellow box (Table 3.4).

Table 3.3. Differences in moisture content, green-density and air-dry density of the stems and branches of stringybark.

Variable	Stemwood Mean (n=59)	Branchwood Mean (n=16)	*t*	P	Pooled Mean
Timber moisture content (%)	44.3	44.1	- 0.175	ns	44.3 ± 0.4
Bark moisture content (%)	43.1 ± 0.9	47.3 ± 1.4	- 2.247	0.028	-
Timber GD ($g.cm^{-3}$)	1.13	1.14	- 0.305	ns	1.13 ± 0.01
Timber ADD ($g.cm^{-3}$)	0.77	0.77	- 0.359	ns	0.77 ± 0.01
Bark GD ($g.cm^{-3}$)	0.58 ± 0.02	0.66 ± 0.04	- 1.869	0.066	-
Bark ADD ($g.cm^{-3}$)	0.40	0.42	- 0.935	ns	0.40 ± 0.01

ns = not significant

Table 3.4. Differences in moisture content, green-density and air-dry density of the stems and branches of yellow box.

Variable	Stemwood Mean (n=28)	Branchwood Mean (n=18)	*t*	P	Pooled Mean
Timber moisture content (%)	34.8	33.9	1.483	ns	34.5 ±0.3
Bark moisture content (%)	55.3	56.6	-1.444	ns	55.8 ±0.4
Timber GD (g.cm^{-3})	1.24	1.23	0.426	ns	1.23 ±0.01
Timber ADD (g.cm^{-3})	0.95	0.96	- 0.495	ns	0.96 ±0.01
Bark GD (g.cm^{-3})	0.98	1.02	- 0.860	ns	1.00 ±0.02
Bark ADD (g.cm^{-3})	0.56	0.57	- 0.307	ns	0.56 ±0.01

ns = not significant

The effect of disc diameter on timber and bark characteristics varied markedly between the two eucalypt groups (Tables 3.5 - 3.6). Moisture content of timber and bark decreased with increasing diameter in stringybark, but not in yellow box. Green and dry-density of yellow box timber increased with increasing diameter, a trend reported in eucalypt studies elsewhere (Ranasinghe and Mayhead 1991), yet no significant change in timber density was observed between stringybark discs of varying diameter. Green-density of bark changed little with disc diameter in yellow box, yet in stringybark the green-density of bark was significantly lower in the 1525 cm diameter class than other classes. Dry-density of bark was not affected by disc diameter in either species, and the volume ratio of timber to bark increased with increasing disc diameter in both species.

Table 3.5. One-factor AOVs showing the effect of disc diameter on moisture content, green-density, air-dry density and timber : bark volume ratio for stringybark.

Variable	Diameter class (cm) 5 - 15 (n=43)	15 - 25 (n=30)	25 - 45 (n=12)	45 - 65 (n=1)	*F*-ratio	P	Pooled Mean
Timber : bark volume ratio	1.7 ± 0.1	1.8 ± 0.2	2.6 ± 0.3	2.9	4.170	0.008	-
Timber moisture content (%)	45.6 ± 0.9	43.5 ± 0.6	42.9 ± 1.1	40.4	3.323	0.024	-
Bark moisture content (%)	47.7 ± 0.9	41.5 ± 1.1	40.3 ± 1.4	34.5	10.089	< 0.001	-
Timber GD (g.cm^{-3})	1.15	1.15	1.17	1.16	0.094	ns	1.15 ± 0.01
Timber ADD (g.cm^{-3})	0.76	0.79	0.81	0.83	1.031	ns	0.78 ± 0.01
Bark GD (g.cm^{-3})	0.69 ± 0.01	0.55 ± 0.02	0.62 ± 0.05	0.65	3.298	0.015	-
Bark ADD (g.cm^{-3})	0.44	0.39	0.44	0.50	1.549	ns	0.42 ± 0.01

ns = not significant

Table 3.6. One-factor AOVs showing the effect of disc diameter on moisture content, green-density, air-dry density and timber to bark volume ratio for yellow box.

Variable	Diameter class (cm) 5 - 15 (n=21)	15 - 25 (n=19)	25 - 45 (n=8)	45 - 65 (n=1)	*F*-ratio	P	Pooled Mean
Timber : bark volume ratio	3.4 ± 0.2	4.4 ± 0.3	5.0 ± 0.4	9.8	13.043	<0.005	-
Timber moisture content (%)	35.0	34.2	33.9	34.4	0.781	ns	34.5 ± 0.3
Bark moisture content (%)	56.0	56.3	54.8	51.5	1.119	ns	55.8 ± 0.4
Timber GD (g.cm^{-3})	1.22 ± 0.01	1.24 ± 0.01	1.26 ± 0.01	1.29	3.721	0.018	-
Timber ADD (g.cm^{-3})	0.94 ± 0.01	0.97 ± 0.01	0.98 ± 0.01	1.00	2.529	0.07	-
Bark GD (g.cm^{-3})	0.99	1.00	1.00	1.00	0.029	ns	1.00 ± 0.02
Bark ADD (g.cm^{-3})	0.55	0.56	0.57	0.60	0.188	ns	0.56 ± 0.01

ns = not significant

Figure 3.5 shows the effect of species and diameter on dry-density of timber and bark. The density of timber and bark increased with increasing diameter in both species. Timber density of yellow box ranged from 0.94 to 1.0 g.cm^{-3}, about 22% higher than the respective values for stringybark (0.76 to 0.83 g.cm^{-3}). Density of bark ranged from 0.55 to 0.60 g.cm^{-3} in yellow box, an average 30% higher than corresponding values in stringybark (0.44 to 0.50 g.cm^{-3}). The dry-density of timber was about 70% greater than that of bark in yellow box, and about 82% greater than that of bark in stringybark.

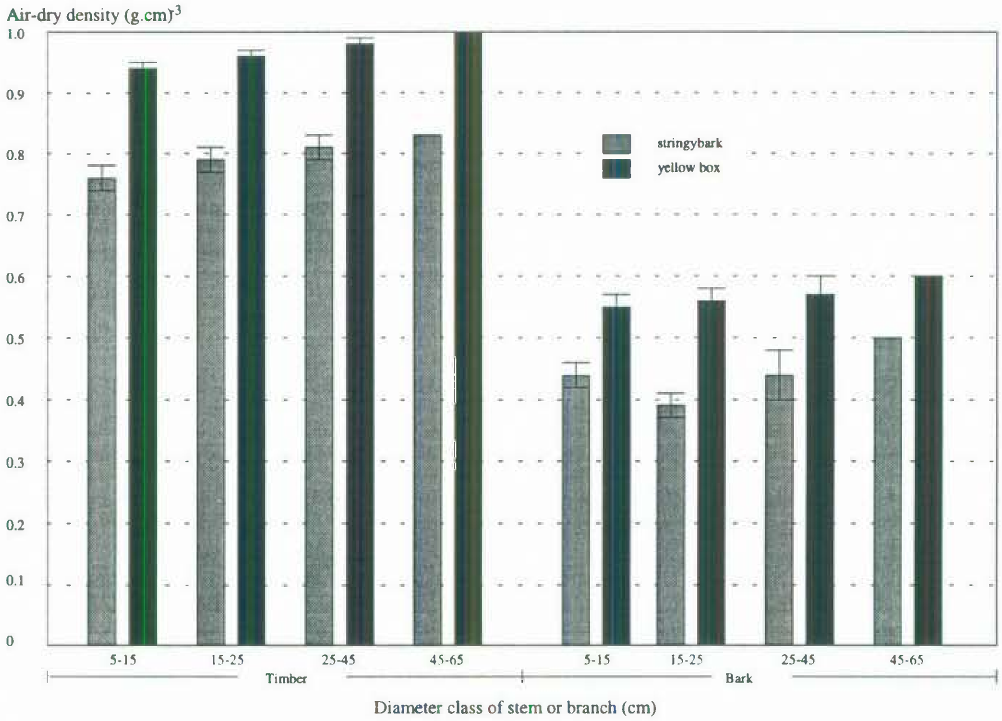

Figure 3.5. Air-dry density of timber and bark in stringybark and yellow box discs of different diameters (mean ± SE, sample sizes in Tables 3.5 and 3.6).

At 12% moisture content, the wood of stringybark and yellow box had a mean dry-density of 0.78 g.cm^{-3} and 0.96 g.cm^{-3}, respectively. These values are lower than reported by Boland *et al.* (1992) and Bootle (1983) for stringybark *E. laevopinea* and yellow box (0.86 and 1.10 g.cm^{-3}, respectively) and lower than that reported by Kingston and Risdon (1961) for yellow box (1.08 g.cm^{-3}). This is probably because the average underbark diameter of discs sampled in this study (13.0 cm for stringybark and 16.0 cm for yellow box) reflect fuelwood sized logs with a relatively high volume of lower-density sapwood, rather than sawlog sized logs with a greater volume of higher-density heartwood. The dry-density of yellow box was similar to that found in relatively young yellow box in the ACT (0.98 g.cm^{-3}; Groves and Chivuya 1989) and the density of stringybark *E. laevopinea* fell within the range reported by Hillis (1984).