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## Allometric relationships and community biomass estimates for some dominant eucalypts in Central Queensland woodlands

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**Abstract.** Allometric equations are presented relating stem circumference to branch, leaf, trunk, bark, total above-ground and lignotuber biomass for *Eucalyptus crebra* F.Muell. (woodland trees), *E. melanophloia* Sol. Ex Gaerth. (both woodland and regrowth community trees) and *E. populnea* F.Muell. (woodland trees). There were no significant differences ( $P > 0.05$ ) between the slopes of individual lognormal regression lines plotting stem circumference against total above-ground biomass for *E. crebra*, *E. melanophloia* and *E. populnea*. Root-to-shoot ratios and leaf area indices were also determined for the stands contributing to each regression. The regressions were then applied to measured eucalypt stems in the associated plant community to give estimates of each stand's component (eucalypt tree fraction only) biomass per hectare. These eucalypt regressions were next applied to measured stems of each species on a total of 33 woodland sites in which these eucalypts individually contributed  $> 75\%$  of total site basal area. Above-ground biomass/basal area relationships averaged  $6.74 \pm 0.29 \text{ t m}^{-2}$  basal area for 11 *E. crebra* sites,  $5.11 \pm 0.28 \text{ t m}^{-2}$  for 12 *E. melanophloia* sites and  $5.81 \pm 0.11 \text{ t m}^{-2}$  for 10 *E. populnea* sites. The mean relationship for all sites was  $5.86 \pm 0.18 \text{ t m}^{-2}$  basal area. The allometric relationships presented at both individual tree and stand levels, along with calculated biomass : basal area relationships, enable ready estimates to be made of above-ground biomass (carbon stocks) in woodlands dominated by these eucalypts in Queensland, assuming individual stem circumferences or community basal areas are known. However, to document changes in carbon stocks (e.g. for Greenhouse Gas Inventory or Carbon Offset trading purposes), more attention needs to be placed on monitoring fluxes in the independent variables (predictors) of these allometric equations.

### Introduction

Sequestration of carbon in vegetation presents an opportunity to offset carbon dioxide emissions accumulating in the earth's atmosphere as a result of fossil fuel consumption. Usually such sequestration is associated with plantation forestry. However, in much of the world's savanna regions woody plants are presently increasing in size and/or number as a result of anthropogenic influences (Archer 1995; Idso 1995). Management effects include the introduction and confining of domestic livestock, together with changed fire regimes in these communities. Before the advent of Europeans and their livestock the vegetation was commonly maintained as a fire-mediated subclimax.

Such changes in management tend to favour woody plants, especially those with unpalatable leaves and/or thorns. This proliferation of woody plants has the potential to account for a significant proportion of the 'missing carbon sink' (Leemans and Zuidema 1995) identified in global  $\text{CO}_2$ -circulation models. In fact, Burrows *et al.* (1998) have suggested that c. 100 Mt of  $\text{CO}_2$  are sequestered annually in above-ground woody plant tissue over Queensland's 60 Mha of grazed woodlands.

An essential component of carbon sequestration (sink) estimation is the determination of biomass and growth in vegetation. Foresters traditionally derive timber biomass (volumes) 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, and the independent variable (predictor) in this regression is obtained from detailed inventory of study plots.

Emerging remote sensing techniques show promise for biomass estimation (Dobson *et al.* 1995) but it is likely to be some time before these techniques are sufficiently refined to detect short–mid-term (3–6-year?) changes in biomass stocks (Brown and Schroeder 1999), 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.

Allometric relationships for semi-arid woodland species in eastern Australia have been detailed by Burrows (1976) for mulga- (*Acacia aneura*) and mallee- (*Eucalyptus socialis*)

dominant sites, while Harrington (1979) presented a similar, but less comprehensive, set of relationships for a poplar box (*E. populnea*) community in the Cobar district (New South Wales). The present paper expands this data set to narrow-leaved ironbark (*E. crebra*) and silver-leaved ironbark (*E. melanophloia*) intact woodland and regrowth communities in Central Queensland, along with an additional poplar box site sampled at Dingo, also in this region. These new relationships are then applied to a range of eucalypt communities in which the independent variable (tree circumference 30 cm above ground) has been measured as part of ongoing studies of tree population changes in Queensland's grazed woodlands.

## Methods

### Plant community structure

Woody plant composition and structure were determined by using the Transect Recording And Processing System (TRAPS) methodology (Back *et al.* 1997, 1999). This involves the siting of permanently positioned transect lines within representative stands of each community. A normal layout comprises five parallel belt transects 100 m long arranged along a north–south axis, 25 m apart and with recordings made of all woody plants within a 2-m band either side of the transect line. In open or closed woodlands the length of the transects may be increased or decreased to include sufficient plants (> 30 for any particular target species/size class) for monitoring purposes. Each transect is contained within a minimum 300 × 300-m uniform buffer of similar vegetation.

The position of plants either side of the transect line is recorded with a graduated 2-m rule. By combining these observations with a tape drawn between permanently positioned steel posts, situated 50 m apart, all woody plants can be located over successive samplings within a notional 10 × 10-cm grid. The stem circumference of all trees and shrubs present in the belt is measured 30 cm above ground level (to include juveniles as well as mature individuals). Plant height (clinometer) and canopy measurements (vertical intercepts on the transect line) are also obtained. A fixed point photographic record is maintained at each recording by focussing back from the northernmost steel picket in each line.

### Determination of standing biomass relationships

Procedures followed were similar to those outlined by Burrows (1976). Dimensional analysis (allometry) was used to determine above-ground biomass of the dominant tree on each site. Regressions for estimating biomass were based on 20 stems for the *E. crebra* intact<sup>1</sup> woodland, 20 stems for *E. melanophloia* intact woodland, 43 stems for *E. melanophloia* regrowth and 22 stems for intact *E. populnea*. The independent variable chosen for all regressions was stem circumference—measured 30 cm above ground level to match that measured in the TRAPS transects.

Stems selected for harvest came from a destructive harvest area adjacent to, but not interfering with, permanent vegetation transects (TRAPS) established in each community type. Each stem harvested was visually assessed to be 'average' with respect to vigour and foliage cover for its particular size class. The stems were chosen in a stratified fashion to include the range of circumferences measured from the stand analysis. Each stem was cut off as close to ground level as practicable. To minimise loss of stem components the fallen stem and associated branches, leaves and fruits were placed on canvas tarpaulins for subsequent sorting.

Prior to sorting, the length of each stem from base to tallest branch tip and crown diameter, as represented by horizontal projection of the leaves on the canvas, was recorded. Fresh weights of the following components were obtained: live stem (>4, 1–4, <1 cm diameter), dead stem, dead bark, leaves and capsules. A tractor-mounted jib and electronic cattle scales were utilised to weigh large trunk billets. The live stem components were separated into wood and bark segments. A portion of each biomass component was retained for determination of dry weight (constant at 80°C) and nutrient analysis (not presented here).

Lognormal regressions were established for stem circumference,  $x$ , against dependent variables,  $y$ , representing each of the tree components indicated

$$\ln y = a + b \ln x.$$

Each transect line on the associated TRAPS transect was divided into 50 × 4-m segments ('quadrats') and the biomass for each component within the 'quadrat' was determined by applying the appropriate regression relationship to stem circumferences measured at 30 cm above ground therein. There were 8–15 such 'quadrats' in each sampled community. A bias in biomass estimates is introduced if antilogs of the previously transformed data are simply taken because the geometric mean rather than the true mean of the estimated value is obtained (Munro 1974). To avoid this problem the steps outlined by Beauchamp and Olson (1973) were adopted. A computer program was written to apply these corrections after prevalidation with the data provided by these latter authors as a test set. (A less robust but computationally simpler procedure which provides a correction multiple to apply to the predicted biomass derived from lognormal regression is given by Baskerville (1972). This procedure is not appropriate where the residual standard deviation of the lognormal regression equation is greater than, say, 0.6.)

Leaf subsamples collected from each stem were retained for leaf area determination. There were a minimum of 30 randomly chosen leaves per stem. Leaves were photocopied and the area of one side only of the photocopy calculated with an electronic planimeter. The measured leaves were then dried to constant weight at 80°C and a weight/area relationship was derived. This conversion was applied to the previously estimated leaf biomass to obtain a stand leaf area and leaf area index.

### Root mass

The biomass of living roots was estimated from soil cores and excavation of stem butts and lignotubers. Soil cores were taken to a depth of 1 m with a 120-cm steel tube of 4.35-cm internal diameter. The cores (60 for each *E. melanophloia* and *E. populnea* site, 40 for *E. crebra*) were positioned in a stratified random fashion over the detailed study (TRAPS) area in each community.

Each soil core was sectioned into 20-cm lengths to give five depth intervals (0–20, >20–40, >40–60, >60–80 and >80–100 cm). The sections were placed into individually labelled bags and returned to the laboratory for root separation. Each section was soaked in tap water and the roots were then washed free of soil while being retained on a fine sieve. Because of the low clay content of the soils detergent was not added to assist with soil dispersal. 'Live' root material (internally white and possessing some elasticity) only was collected. All root samples were dried to constant weight at 80°C.

A subsample of the root butts (lignotubers) of the stems selected for above-ground harvest was identified to cover the range of stem sizes in the transect recording belts. Either a back hoe or front-end loader was used to excavate these lignotubers and large roots. A minimum excavated volume of 1 m<sup>3</sup> of soil was removed along with the accompanying lignotuber and large lateral roots. It was necessary to excavate larger volumes of soil to extract the larger lignotuber systems. The exposed lignotuber and large roots were carefully brushed free of soil particles and the fresh weight was recorded. A subsample was retained for determination of moisture content. Regressions were then established between stem circumference and lignotuber (including excavated large

<sup>1</sup>Intact woodland is woodland not subjected to mechanical or chemical tree clearing for at least 30 years before the present sampling.

roots) weight in like manner to the above-ground fractions and similar estimation procedures were followed in applying these regressions to the TRAPS transect populations. Community biomass for above- and below-ground eucalypt components could then be estimated for each site contributing to the individual tree regressions.

#### Community biomass survey

Once the biomass regressions were established the TRAPS database (Back *et al.* 1997, 1999) was interrogated and 11 *E. crebra*, 12 *E. melanophloia* and 10 *E. populnea* sites were identified in which these eucalypts contributed >75% of total site basal area. Each of the communities selected had not been recently disturbed, e.g. subjected to tree clearing or thinning operations in the previous 30 years. The respective biomass regressions were then applied to the appropriate stem circumferences measured along these transects to obtain estimates of community biomass above-ground. Coarse lignotuber (including large root) weights were similarly derived from the predetermined relationships. Fine root biomass was established by assuming the same relationship of above-ground biomass to fine root weight occurred in the target TRAPS community as was recorded at the site where allometric regressions were determined for the particular species dominating that TRAPS. Finally, above-ground and above- and below-ground biomass/stand basal area relationships were derived to facilitate estimates of stand biomass where the more easily obtained stand basal area parameter is known or can be readily measured.

## Results

Dominant eucalypt structure, summarised from the relevant TRAPS transects, is presented for each eucalypt community in which biomass regressions were determined (Table 1). In all these cases the dominant eucalypt contributed >79% of total woody plant basal area for the stand.

Biomass regressions are presented along with parameters necessary to obtain unbiased estimates of yield when the relationships are applied to independently measured stem circumferences (Table 2). The associated biomass estimates for community tree components (Table 3) are derived from TRAPS recordings obtained in June 1996 for *E. populnea*, August 1996 for *E. melanophloia* sites and August 1997 for the *E. crebra* site. The total above-ground biomass of eucalypts only and estimates of community root biomass to 1-m depth are given for 33 communities in which these eucalypts individually

contributed >75% of total woody plant basal area (Table 4). Basal area of the dominant eucalypt in each stand and basal area/biomass relationships are also presented in the latter table.

## Discussion

Basal area integrates data on plant size and number to accurately reflect the contribution of each species to community biomass. The TRAPS program (Back *et al.* 1997, 1999) calculates individual species basal area (summed for a range of height classes—Table 1) from each plant's circumference. Field recording for TRAPS involves measurement of both stem circumference (or diameter) and height for each woody plant encountered.

Foresters often combine trunk diameter and height measurements as the independent variables in allometric relationships predicting timber yield (e.g. Madgwick *et al.* 1991). However, for the eucalypts studied here stem circumference alone accounted for 99% of total above-ground yield in *E. crebra* and *E. melanophloia*, 96% in *E. melanophloia* regrowth and 94% in *E. populnea*. These results are in accord with those of Hingston *et al.* (1981) for *E. calophylla* and *E. marginata*. Indeed the only variables for which stem circumference was a poor predictor of yield in the present study were capsule and dead wood weights (Table 2).

Laser altimetry (Tickle *et al.* 1998) is a recent development which enables rapid estimation of mean plant height over extensive areas. For this reason we examined the relationship between plant height and total above-ground biomass for the three eucalypt species in Table 2, as well as for *E. melanophloia* regrowth. This resulted in  $R^2$  values of 0.95, 0.95, 0.91 and 0.92 for *E. crebra*, *E. populnea* and *E. melanophloia* trees in intact woodland and *E. melanophloia* regrowth respectively, thus indicating that height alone is an adequate predictor of species yield for individual woodland eucalypt plants. However, to obtain an estimate of community biomass a knowledge of plant density and composition would also be required if this predictor were to be utilised on an individual tree basis.

**Table 1.** Basal area distributed by height class for the dominant eucalypts at each site sampled to establish allometric relationships

| Site                              | Species                             | Basal area ( $\text{m}^2 \text{ha}^{-1}$ ) for height class: |           |            |            |             |              | Total         |
|-----------------------------------|-------------------------------------|--------------------------------------------------------------|-----------|------------|------------|-------------|--------------|---------------|
|                                   |                                     | <0.5 m                                                       | 0.5–1.5 m | >1.5–4.0 m | >4.0–7.0 m | >7.0–10.0 m | >10.0–15.0 m |               |
| Kiauroo<br>(23°05'S, 149°20'E)    | <i>E. crebra</i> <sup>A</sup>       | 0                                                            | 0.06      | <0.01      | 0.05       | 0.18        | 1.43         | 7.81          |
| Summerdell<br>(23°45'S, 146°02'E) | <i>E. melanophloia</i> <sup>A</sup> | 0                                                            | 0.05      | 0.53       | 1.05       | 2.56        | 2.14         | 3.02          |
| Summerdell<br>(23°45'S, 146°03'E) | <i>E. melanophloia</i> <sup>B</sup> | 0                                                            | 0.16      | 1.05       | 0.37       | 0           | 0            | 0             |
| Wandobah<br>(23°39'S, 149°24'E)   | <i>E. populnea</i> <sup>A</sup>     | 0                                                            | <0.01     | 0.06       | 1.69       | 0.88        | 5.44         | 3.75          |
|                                   |                                     |                                                              |           |            |            |             |              | 11.80 (14.50) |

<sup>A</sup> Intact woodlands (see text).

<sup>B</sup> Three-year-old regrowth.

<sup>C</sup> Data in parentheses are total site basal areas for all woody species at each site.

**Table 2. Lognormal regressions for biomass components of selected species in Queensland woodlands**

Site details are given in Table 1 and in the text. All regressions are of the form  $\ln y = a + b \ln x$ , where  $x$  = stem circumference (cm) measured 30 cm above ground level,  $y$  = yield (kg). The residual standard deviation (RSD) and sum of squares of the deviations in  $x$  (SSD $x$ ) values are utilised in applying the antilogarithm correction factor (Beauchamp and Olson 1973) to estimating community biomass by using these regressions

|                                                                                              | <i>n</i> | <i>a</i> | <i>b</i> | <i>R</i> <sup>2</sup> | RSD   | SSD $x$ |
|----------------------------------------------------------------------------------------------|----------|----------|----------|-----------------------|-------|---------|
| <i>Eucalyptus crebra</i> intact woodland (stem circumference range at 30 cm: 8–202 cm)       |          |          |          |                       |       |         |
| Branches                                                                                     | 20       | –8.536   | 3.041    | 0.979                 | 0.436 | 17.456  |
| Total (above-ground)                                                                         | 20       | –6.505   | 2.756    | 0.987                 | 0.309 | 17.456  |
| Stem                                                                                         | 20       | –6.886   | 2.828    | 0.987                 | 0.317 | 17.456  |
| Bark                                                                                         | 19       | –7.942   | 2.766    | 0.991                 | 0.265 | 16.639  |
| Wood                                                                                         | 20       | –7.541   | 2.898    | 0.978                 | 0.427 | 17.456  |
| Trunk wood                                                                                   | 20       | –7.407   | 2.7      | 0.967                 | 0.492 | 17.456  |
| Trunk                                                                                        | 20       | –6.742   | 2.62     | 0.972                 | 0.435 | 17.456  |
| Capsules                                                                                     | 16       | –8.706   | 1.94     | 0.393                 | 1.241 | 3.702   |
| Leaf                                                                                         | 20       | –5.785   | 1.858    | 0.933                 | 0.492 | 17.458  |
| Lignotubers                                                                                  | 10       | –8.186   | 2.732    | 0.986                 | 0.311 | 7.451   |
| <i>Eucalyptus melanophloia</i> intact woodland (stem circumference range at 30 cm: 6–165 cm) |          |          |          |                       |       |         |
| Branches                                                                                     | 20       | –8.300   | 2.913    | 0.978                 | 0.406 | 15.385  |
| Total (above-ground)                                                                         | 20       | –6.553   | 2.726    | 0.991                 | 0.236 | 15.385  |
| Stem                                                                                         | 20       | –6.879   | 2.789    | 0.991                 | 0.245 | 15.385  |
| Bark                                                                                         | 20       | –7.865   | 2.702    | 0.989                 | 0.269 | 15.385  |
| Wood                                                                                         | 20       | –7.317   | 2.82     | 0.99                  | 0.261 | 15.385  |
| Trunk                                                                                        | 20       | –7.191   | 2.724    | 0.981                 | 0.354 | 15.385  |
| Capsules                                                                                     | 17       | –18.693  | 4.204    | 0.615                 | 1.819 | 4.49    |
| Leaf                                                                                         | 20       | –6.227   | 1.851    | 0.938                 | 0.442 | 15.385  |
| Lignotubers                                                                                  | 10       | –7.181   | 2.419    | 0.986                 | 0.249 | 5.81    |
| <i>Eucalyptus melanophloia</i> regrowth (stem circumference range at 30 cm: 4–43 cm)         |          |          |          |                       |       |         |
| Branches                                                                                     | 43       | –6.136   | 2.185    | 0.9                   | 0.521 | 21.021  |
| Total (above-ground)                                                                         | 43       | –5.097   | 2.3      | 0.96                  | 0.334 | 21.021  |
| Stem                                                                                         | 43       | –5.325   | 2.317    | 0.961                 | 0.336 | 21.021  |
| Bark                                                                                         | 43       | –6.394   | 2.262    | 0.961                 | 0.326 | 21.021  |
| Wood                                                                                         | 43       | –5.795   | 2.355    | 0.95                  | 0.389 | 21.021  |
| Trunk                                                                                        | 43       | –6.016   | 2.412    | 0.948                 | 0.403 | 21.022  |
| Capsules                                                                                     | 4        | –15.247  | 3.473    | 0.521                 | 1.01  | 0.184   |
| Leaf                                                                                         | 43       | –6.805   | 2.234    | 0.889                 | 0.569 | 21.021  |
| <i>Eucalyptus populnea</i> intact woodland (stem circumference range at 30 cm: 4.6–240 cm)   |          |          |          |                       |       |         |
| Branches                                                                                     | 22       | –5.554   | 2.344    | 0.925                 | 0.713 | 22.753  |
| Total (above-ground)                                                                         | 22       | –2.809   | 1.922    | 0.939                 | 0.525 | 22.754  |
| Stem                                                                                         | 22       | –3.327   | 2.006    | 0.91                  | 0.673 | 22.753  |
| Bark                                                                                         | 22       | –3.685   | 1.685    | 0.869                 | 0.703 | 22.752  |
| Wood                                                                                         | 22       | –3.428   | 1.979    | 0.916                 | 0.64  | 22.753  |
| Trunk                                                                                        | 22       | –2.873   | 1.761    | 0.9                   | 0.625 | 22.752  |
| Capsules                                                                                     | 20       | –9.985   | 1.932    | 0.619                 | 1.419 | 15.769  |
| Leaf                                                                                         | 22       | –3.491   | 1.259    | 0.806                 | 0.659 | 22.753  |
| Dead wood                                                                                    | 18       | –10.664  | 2.767    | 0.809                 | 1.225 | 13.278  |
| Lignotuber scrap                                                                             | 6        | –28.906  | 6.305    | 0.711                 | 2.18  | 1.175   |
| Lignotuber trunk                                                                             | 10       | –5.339   | 1.976    | 0.933                 | 0.679 | 13.103  |
| Lignotuber total                                                                             | 10       | –5.747   | 2.116    | 0.922                 | 0.782 | 13      |

A lognormal regression of stem circumference versus total above-ground biomass, obtained by combining the data sets for the three contrasting eucalypt species, reveals remarkable congruence (Fig. 1). There were no significant differences ( $P > 0.05$ ) between the slopes of all three individual lognormal regression lines plotting stem circumference against total above-ground biomass for *E. crebra*, *E. melanophloia* and *E. populnea*. These species, along with close allies, dominate

much of the grazed eucalypt woodlands in Queensland. Therefore, it should be possible to produce reasonably accurate estimates of standing biomass for dominant eucalypts in these communities as soon as a representative network of population transects (TRAPS) are established in them.

Hingston *et al.* (1981) found no significant differences in lognormal relationships between total above-ground dry weight and diameter at breast height for *E. calophylla* and

**Table 3. Biomass estimates for various 'live' components of the dominant eucalypts in selected Queensland woodlands**

Site details are presented in Table 1. Years in parentheses are the last recordings of population transects (TRAPS) to which the biomass regressions were applied. s.e. = standard error. Quadrat size = 50 m × 4 m for *Eucalyptus melanophloia* ( $n = 10$ ), *E. populnea* ( $n = 8$ ) and *E. crebra* ( $n = 15$ )

|                                                                     | Total biomass (t ha <sup>-1</sup> ) | s.e.  |
|---------------------------------------------------------------------|-------------------------------------|-------|
| <i>Eucalyptus crebra</i> intact woodland (1997)                     |                                     |       |
| Branches                                                            | 63.3                                | 15.5  |
| Leaf                                                                | 3.1                                 | 0.5   |
| Capsule                                                             | 0.4                                 | 0.06  |
| Trunk                                                               | 47.5                                | 10.5  |
| Total bark <sup>A</sup>                                             | 27.9                                | 6.4   |
| Total (above-ground)                                                | 113.3                               | 26    |
| —direct regression                                                  |                                     |       |
| Lignotubers (to 1 m depth)                                          | 18.6                                | 4.2   |
| Fine roots (to 1 m depth)                                           | 6.9                                 | 1.5   |
| Root : shoot ratio                                                  | 0.23                                | —     |
| Leaf area index                                                     | 1.2                                 | —     |
| (one side only) m <sup>2</sup> m <sup>-2</sup>                      |                                     |       |
| <i>Eucalyptus melanophloia</i> intact woodland (1996)               |                                     |       |
| Branches                                                            | 17.1                                | 4.1   |
| Leaf                                                                | 1.6                                 | 0.3   |
| Capsule                                                             | 0.7                                 | 0.2   |
| Trunk                                                               | 22.4                                | 5     |
| Total bark <sup>A</sup>                                             | 10.1                                | 2.3   |
| Total (above-ground)                                                | 41.4                                | 9.3   |
| —direct regression                                                  |                                     |       |
| Lignotubers (to 1 m depth)                                          | 5.9                                 | 1.2   |
| Fine roots (to 1 m depth)                                           | 4.8                                 | 1.2   |
| Root : shoot ratio                                                  | 0.26                                | —     |
| Leaf area index                                                     | 0.85                                | —     |
| (one side only) m <sup>2</sup> m <sup>-2</sup>                      |                                     |       |
| <i>Eucalyptus melanophloia</i> regrowth woodland—3 years old (1996) |                                     |       |
| Branches                                                            | 1.3                                 | 0.2   |
| Leaf                                                                | 0.8                                 | 0.1   |
| Capsule                                                             | 0.01                                | 0.002 |
| Trunk                                                               | 2.7                                 | 0.3   |
| Total bark <sup>A</sup>                                             | 1.2                                 | 0.1   |
| Total (above-ground)                                                | 4.8                                 | 0.5   |
| —direct regression                                                  |                                     |       |
| Lignotubers (to 1 m depth) <sup>B</sup>                             | 5.9                                 | 1.2   |
| Fine roots (to 1 m depth)                                           | 4.2                                 | 1     |
| Root:shoot ratio                                                    | 2.13                                | —     |
| Leaf area index                                                     | 0.33                                | —     |
| (one side only) m <sup>2</sup> m <sup>-2</sup>                      |                                     |       |
| <i>Eucalyptus populnea</i> intact woodland (1996)                   |                                     |       |
| Branches                                                            | 29.7                                | 4.8   |
| Leaf                                                                | 2.6                                 | 0.3   |
| Capsule                                                             | 0.1                                 | 0.02  |
| Trunk                                                               | 35.7                                | 4.7   |
| Total bark <sup>A</sup>                                             | 12.7                                | 1.6   |
| Total (above-ground)                                                | 70.3                                | 9.8   |
| —direct regression                                                  |                                     |       |
| Lignotubers (to 1 m depth)                                          | 9.5                                 | 1.4   |
| Fine roots (to 1 m depth)                                           | 10.1                                | 1.1   |
| Root : shoot ratio                                                  | 0.28                                | —     |
| Leaf area index                                                     | 0.8                                 | —     |
| (one side only) m <sup>2</sup> m <sup>-2</sup>                      |                                     |       |

<sup>A</sup> Included in trunk and branch totals.

*E. marginata* in south-west Western Australia. Likewise Senelwa and Sims (1998) suggested that woody biomass allometry does not differ significantly within the same genus, after their study of five species of juvenile (2–5-year-old) plantation eucalypts (*E. globulus*, *E. nitens*, *E. ovata*, *E. regnans* and *E. saligna*). This broader conclusion requires further testing in natural stands and over a wider age class range. However, the present data, and those in the literature, indicate that it may not be necessary to determine individual biomass regressions for all eucalypt species to obtain reliable biomass estimates in communities containing these species.

The accuracy of biomass estimates for the total community will be influenced by the contribution of codominants and understorey species to overall stand structure. In most cases the contribution of non-eucalypts to total community biomass is <20% in communities dominated by *Eucalyptus* or *Corymbia* spp.<sup>2</sup> Accordingly we identified currently positioned TRAPS sites (Fig. 2) where any of the eucalypts represented in Table 2 accounted for >75% of the total TRAPS transects woody plant basal area. The respective biomass regressions (Table 2) were then applied to the individual eucalypt circumferences within each transect site to give a cumulative community estimate of live tree biomass (Table 4, Fig. 3).

There are quite large variations in the total above-ground biomass of live eucalypt plants in the 'intact' woodlands sampled—mean  $71.38 \pm 6.49$  t ha<sup>-1</sup> (range 13.7–158.5 t ha<sup>-1</sup>) (Table 4). Yet the range of biomass encountered and size class distributions within each site (not presented) suggest that few of the sampled populations are in equilibrium.

The TRAPS program provides estimates of basal-area increment in monitored grazed woodland sites. For example, Burrows *et al.* (1998) found that in 47 sampled communities eucalypt trees had a mean basal area increment of  $0.21 \pm 0.03$  m<sup>2</sup> ha<sup>-1</sup> year<sup>-1</sup> over an average 9-year monitoring period, although in terms of carbon sequestration this needs to be balanced against losses due to tree deaths and subsequent decay, along with gains from ingrowth of newly established plants. Such net basal area change data can be combined with biomass/basal area relationships (Table 4) to determine the fluxes of carbon in the grazed woodlands over time.

These relationships can also be combined with readily estimated community basal areas (e.g. by Bitterlich stick, Grosenbaugh (1952), or prism sweep method, Dilworth and Bell (1971)) to give first pass estimates of biomass for standing eucalypts. Alternatively, community basal area estimates can be applied to stand allometric equations (e.g. Fig. 3) to obtain stand biomass. These approaches can thus facilitate the establishment of ground truth for calibrating spaceborne Synthetic Aperture Radar (SAR) sensors and other methods which are being proposed for remote sensing of biomass in woodlands (Witte *et al.* 1998).

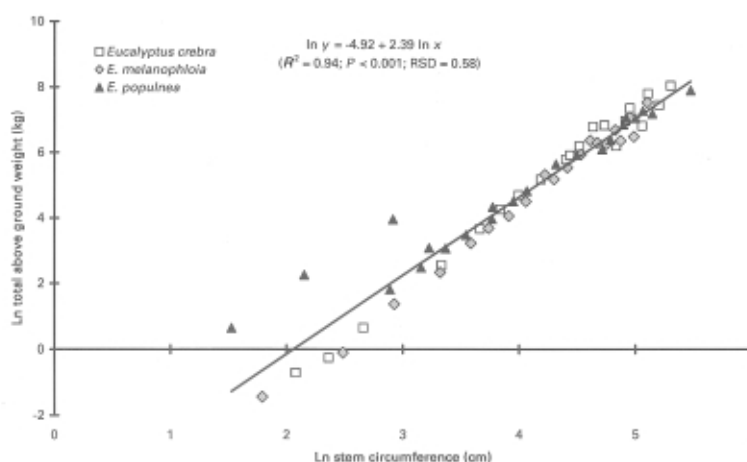
<sup>2</sup>However, this generalisation and conclusion would not apply to significant non-eucalypt communities (e.g. *Acacia aneura*, *A. cambagei*, and *Melaleuca viridiflora*).

**Table 4.** Mean biomass for *Eucalyptus* spp. at selected intact woodland sites in north-eastern Australia where the basal area of the dominant eucalypt exceeded 75% of total site basal area for all live woody plants (all values  $\pm$  s.e.)

|                                                            | Total above-ground<br>dry wt ( $\text{t ha}^{-1}$ ) | Total lignotuber<br>( $\text{t ha}^{-1}$ ) <sup>A</sup> (to 1 m) | Fine root dry wt<br>( $\text{t ha}^{-1}$ ) <sup>B</sup> (to 1 m) | Total biomass<br>( $\text{t ha}^{-1}$ ) above +<br>below ground<br>(to 1 m) | Basal area<br>( $\text{m}^2 \text{ ha}^{-1}$ )<br>( <i>Eucalyptus</i> spp.) | Above-ground/<br>basal area<br>relationship<br>( $\text{t m}^{-2}$ ) | Total above-<br>+ below-<br>ground/basal<br>area relationship<br>( $\text{t m}^{-2}$ ) |
|------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| <i>E. crebra</i> dominant sites<br>Mean ( $n = 11$ )       | 85.29 $\pm$ 15.60                                   | 14.06 $\pm$ 2.57                                                 | (5.23 $\pm$ 0.96)                                                | 104.58 $\pm$ 19.13                                                          | 12.38 $\pm$ 2.17                                                            | 6.74 $\pm$ 0.29                                                      | 8.27 $\pm$ 0.35                                                                        |
| <i>E. melanophloia</i> dominant sites<br>Mean ( $n = 12$ ) | 59.85 $\pm$ 8.67                                    | 7.58 $\pm$ 1.01                                                  | (6.92 $\pm$ 1.00)                                                | 74.35 $\pm$ 10.67                                                           | 11.54 $\pm$ 1.42                                                            | 5.11 $\pm$ 0.28                                                      | 6.35 $\pm$ 0.34                                                                        |
| <i>E. populnea</i> dominant sites<br>Mean ( $n = 10$ )     | 69.91 $\pm$ 6.72                                    | 10.08 $\pm$ 1.06                                                 | (10.04 $\pm$ 0.96)                                               | 90.03 $\pm$ 8.71                                                            | 12.12 $\pm$ 1.21                                                            | 5.81 $\pm$ 0.11                                                      | 7.47 $\pm$ 0.13                                                                        |
| Grand mean ( $n = 33$ )                                    | 71.38 $\pm$ 6.49                                    | 10.50 $\pm$ 1.07                                                 | (7.30 $\pm$ 0.65)                                                | 89.18 $\pm$ 7.99                                                            | 12.00 $\pm$ 0.93                                                            | 5.86 $\pm$ 0.18                                                      | 7.33 $\pm$ 0.22                                                                        |

<sup>A</sup>Some large lateral roots were excavated along with the lignotubers when determining the regressions on which these estimates are based.

<sup>B</sup>Fine root proportion of dry weight calculated as 14.36% of total above ground for *E. populnea* (based on Wandabah, Table 1), 11.57% for *E. melanophloia* (based on Summerdell) and 6.14% for *E. crebra* (based on Kiauroo). Fine root standard errors are only available for these core sites for each species. Species means and grand means for fine roots are based on these estimates. Note: Allometric equations on which these estimates are founded were determined for Wandabah, Summerdell and Kiauroo sites only. For a few of the remaining sites there were some stem circumferences outside of the range sampled (see Table 2) when determining the regression. In such cases the biomass ascribed to those trees was constrained to that estimated for the largest tree of the species regression set.

**Fig. 1.** Lognormal regression of stem circumference ( $x$  cm) measured 30 cm above ground v. total above-ground weight ( $y$  kg) for *Eucalyptus crebra*, *E. melanophloia* and *E. populnea* combined data. (Independent regressions for each species were not significantly different,  $P > 0.05$ .)

Remotely sensed methods show promise for biomass determination in woodlands but they are unlikely to identify the various fractional contributions (e.g. leaf, bark, branches, trunk) to total yield with the accuracy of allometric techniques (Table 3). Estimating root biomass also inevitably requires field sampling to establish relationships. Nevertheless, the root-to-shoot ratio across the three intact communities, based on root mass sampled to 1-m depth (Table 3), is quite consistent at 0.26 for *E. melanophloia*, 0.23 for *E. crebra* and 0.28 for *E. populnea*. Likewise these communities also exhibit similar leaf area indices—0.85, 1.20 and 0.80  $\text{m}^2 \text{ m}^{-2}$  respectively (Table 3)—falling within the expected range for ever-

green plant communities with evaporative coefficients below 0.06 (Specht and Specht 1989).

The dependent variable for many published and unpublished regressions developed by foresters is usually merchantable (commercial) timber volume. Expansion factors have been suggested to convert such volume estimates to above-ground biomass for the total tree (Brown and Schroeder 1999). These firstly utilise wood density values ( $\text{kg m}^{-3}$ ) to obtain merchantable timber weight and this is then multiplied by an expansion factor to obtain total aerial weight (to include branches, bark, leaves and other tree components). The Intergovernmental Panel on Climate Change (IPCC) currently suggests a

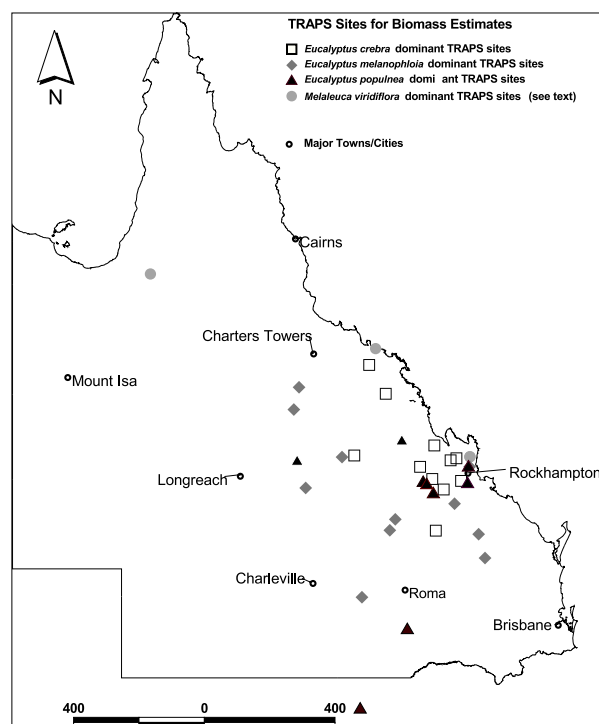


Fig. 2. Distribution of TRAPS sites for which biomass estimates were derived for *Eucalyptus crebra*, *E. melanophloia* and *E. populnea*.

default wood density of  $500 \text{ kg m}^{-3}$  and expansion factor multiple of 2 for 'unproductive' forests (IPCC 1997) to estimate the total above-ground biomass of forest trees.

The IPCC default wood density is completely inappropriate for Australian hardwoods, which have wood densities of  $c. 1000 \text{ kg m}^{-3}$  (see extensive data sets for Australian native trees 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 can be compared with calculated values for Queensland hardwoods sampled in the present study (Table 3). Appropriate expansion multiples (total above-ground biomass/trunk biomass) are 2.39 for *E. crebra*, 1.85 for *E. melanophloia*, 1.97 for *E. populnea* and 2.04 for *Melaleuca viridiflora*.<sup>3</sup> These values (mean 2.06) are in accord with the IPCC default value.

The mean above-ground live biomass of  $5.86 \text{ t m}^{-2}$  eucalypt basal area (Table 4) exceeds comparable values of  $4.79 \text{ t m}^{-2}$  for *Acacia aneura* (Burrows 1976) and  $4.97 \text{ t m}^{-2}$  basal area for *A. harpophylla* (Scanlan 1991). A mature *M. viridiflora*<sup>3</sup> stand had an above-ground biomass/basal area relationship of  $3.18 \text{ t m}^{-2}$  basal area. Regrowth communities would obviously have smaller values again, e.g. for the *E. melanophloia* regrowth site (*Eucalyptus/Corymbia* basal area  $2.47 \text{ m}^2 \text{ ha}^{-1}$ , Table 1) a corresponding above-ground biomass (Table 3)/basal area relationship is  $1.94 \text{ t m}^{-2}$ . However, the annual basal area growth increment for the regrowth site (growth from root suckers following tractor pulling of the standing trees) is greater than that of the adjacent 'mature' *E. melanophloia* stand (Burrows, unpubl. data). The latter has an above-ground biomass : basal

<sup>3</sup>Allometric and biomass data for *Melaleuca viridiflora* were obtained according to the same methodology as outlined in the present paper. These data are available from the senior author on request.

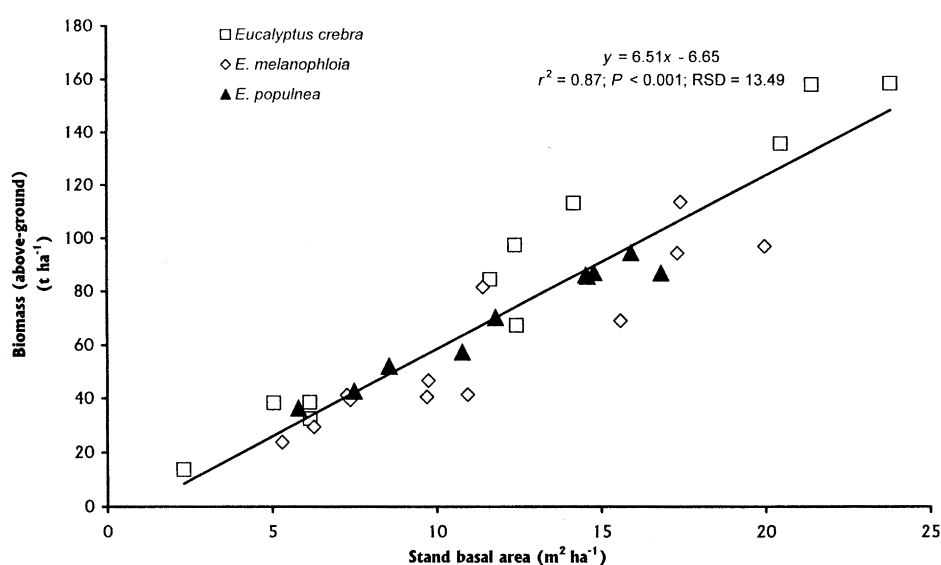


Fig. 3. Relationship between stand basal area ( $\text{m}^2 \text{ ha}^{-1}$ ) and standing above-ground biomass ( $\text{t ha}^{-1}$ ) of the dominant species for 33 stands dominated by either *Eucalyptus crebra*, *E. melanophloia* or *E. populnea*. Individual stand data are combined for the regression analysis.

area value of  $3.78 \text{ t m}^{-2}$  (cf. species mean of  $5.11 \text{ t m}^{-2}$ , Table 4) or 1.9 times that of the regrowth stand. This suggests that both stands may have similar biomass (and thus carbon) accretion rates (the product of annual basal area increment by biomass/basal area relationship), despite their structural differences.

Some caution needs to be exercised in applying biomass/basal area relationships to the total tree basal area of stands containing dominants of mixed genera or age, in order to estimate community biomass. Nevertheless, eucalypts tend to contribute more than 80% of total stand basal area in eucalypt-dominant communities (Burrows and Hoffmann, unpubl. data). This reinforces the utility of basal area: biomass conversion relationships to obtain estimates of stand biomass. Short to medium term (3–6-year?) changes in such biomass (carbon stocks) will also have to be measured with accuracy and precision if they are to be utilised for National Greenhouse Gas Inventory or Carbon Offset trading purposes. This suggests more attention now needs to be paid to monitoring changes in tree stem circumferences—the predictor variable utilised in the allometric relationships developed for estimating tree biomass in this paper. We are extending the TRAPS site network for this purpose.

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