

Growth and carbon sequestration rates at age ten years of some eucalypt species in the low- to medium-rainfall areas of New South Wales, Australia

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Summary

This paper presents the results of a study of tree growth in farm forestry eucalypt plantations in the low- to medium-rainfall (450–700 mm y⁻¹) regions of New South Wales, Australia, in an attempt to estimate the productivity of the plantations. The species measured include *Eucalyptus camaldulensis*, *E. botryoides*, *E. globulus*, *E. albens*, *E. polyanthemos*, *E. microcarpa*, *E. melliodora*, *E. sideroxylon*, *E. crebra* and *Corymbia maculata*. At age 10 y, mean dominant height (100 tallest trees per hectare) ranged from 7.5 to 18.8 m, mean top basal area (thickest 100 stems ha⁻¹) from 1.5 to 9.2 m² ha⁻¹, volume from 9.5 to 125.9 m³ ha⁻¹, total above-ground biomass from 12.5 to 105.8 t ha⁻¹, and mean carbon density (above ground) from 11.2 to 35.2 t ha⁻¹.

Keywords: arid climate; plantations; growth; productivity; height; basal area; volume; farm forestry; environmental factors; eucalypts

Introduction

The establishment of plantations in landscapes prone to dryland salinity in Australia is one means of reducing the recharge that drives the salinisation process (George *et al.* 1999; Morris and Collopy 1999). Due to low growth rates, less established forestry infrastructure and greater distances to markets, commercial agroforestry in the low- to medium-rainfall region of Australia is unlikely to generate an economic return based on wood products alone (Zorzetto and Chudleigh 1999). However, packaging the environmental services such as carbon sequestration, salinity control and biodiversity enhancement that farm forestry provides with timber products may provide a means of attracting investment in reforestation in areas otherwise considered marginal for farm forestry (Grieve¹; Walsh *et al.* 2003).

Large areas of land that are potentially available for farm forestry in Australia do not suit most of the hardwood and softwood species that traditionally have been grown in plantations; hence species likely to succeed on low-rainfall sites have had little

or no commercial development (Ryan *et al.* 2002). As a result, empirical site assessment systems that are already developed to estimate site productivity for commercial species will have little direct utility for farm forestry. As most of the plantations that have been established in low- to medium- (450–700 mm y⁻¹) rainfall environments in New South Wales (NSW) are generally less than 15 y old, there are virtually no long-term growth data from which to develop robust empirical yield prediction models for various hardwood species. As a consequence, estimates of plantation productivity in low- to medium-rainfall areas generally rely on process-based models (e.g. 3-PG, ProMod) using data of varying quality, accuracy and resolution with a reliance on expert knowledge and opinion to calibrate and validate the models (Bugg *et al.* 2002; Ryan *et al.* 2002).

This difficulty in developing both empirical and process-based models to estimate productivity on unplanted land is not confined to Australia. In the United Kingdom (UK), changes in UK forest policy, combined with ongoing reforms of the Common Agricultural Policy, have led to suggestions that the area under forestry in the UK is likely to expand significantly over the next half-century (Bateman and Lovett 1998). As a result, considerable effort is being channelled into developing empirical models to predict growth of commercial species on unplanted land across diverse terrain in the UK, using a range of environmental attributes (e.g. Worrell and Malcolm 1990; Macmillan 1991; Bateman and Lovett 1998).

This study is concerned with the productivity of farm forestry plantations in the low- to medium-rainfall (450–700 mm y⁻¹) areas of NSW, Australia. Our objective was to examine the current productivity and carbon sequestration potential of eucalypt plantations along the western slopes and plains of NSW, using measurement data from permanent sample plots (PSPs) established in the latter half of 2002. We predict mean dominant height, mean top-basal area, stem volume and carbon sequestration potential at age 10 y for a range of eucalypt species. The results are then compared to other published estimates of the potential productivity of plantations in the low-rainfall areas of south-eastern Australia, and opportunities for improving estimates are discussed.

¹Grieve, A.M. (2003) An overview of the environmental service indices developed for use in the NSW Environmental Services Scheme, Environmental Markets Team. Forests NSW Internal paper, June.

Data and methods

Sampling strategy and study sites

The sampling strategy was aimed at eucalypt plantations that were 5 y of age or older and were a block planting no less than 2 ha in size. The size of the plantations ranged from 3 to 31 ha, and age from 5 to 14 y (Table 1). The sample plots were located at least 10 m from the boundary of each plantation to avoid possible edge effects. Plot sizes ranged from 0.04 to 0.16 ha, tree stocking from 175 to 1150 stems ha⁻¹ (Table 1), and the number of stems per plot from 16 to 76. Eighty-eight per cent of the plots had between 22 and 49 stems per plot. In each plot stem height and diameter at breast height over bark (dbhob, 1.3 m) were measured for each tree using a Vertex III hypsometer ultrasonic signal device and a diameter tape, respectively. In total, 73 sample plots were established across 12 properties (Table 1), providing 2908 individual tree measurements. Figure 1 shows the location of the 12 properties on which PSPs were established.

Measurement trees

Eucalyptus camaldulensis Dehnh. (river red gum) was the most common species planted, occurring on 6 of the 12 properties (Table 1) and providing 34% of the total number of tree measurements (Table 2). This species also had the greatest range

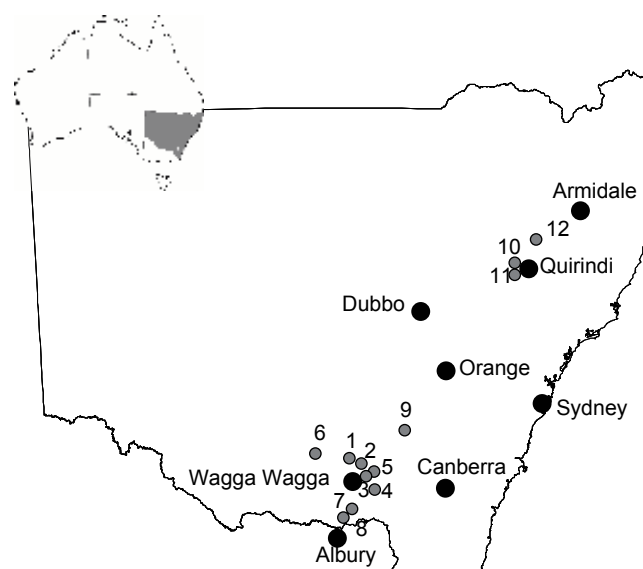


Figure 1. Location of the study properties and plantations in NSW, Australia. The numbers refer to the location ID shown in Table 1.

Table 1. Summary of the property names and locations, the age class, species mix, size and current stocking of the plantations, and the number and size of the measurement plots established in each of the plantations

ID	Property name	Location	Latitude (S) and longitude	Year planted	Species	Plantation size (ha)	No. plots	Plot size (ha)	Current stocking at 1.3 m (stems ha ⁻¹)
1	Avondale	Coolamon	34°47', 147°13'	1995	<i>E. camaldulensis</i> , <i>E. sideroxylon</i> , <i>E. microcarpa</i> , <i>E. melliodora</i>	6	9	0.04–0.07	420–1150
2	Fairfield	Marrar	34°52', 147°21'	1992	<i>E. camaldulensis</i>	4	4	0.05	830–960
3	Mona Vale	Ladysmith	35°11', 147°29'	1989	<i>E. melliodora</i>	3	3	0.06–0.1	290–640
4	Burnbank	Ladysmith	35°12', 147°38'	1994, 1996	<i>E. camaldulensis</i> , <i>E. botryoides</i> , <i>E. polyanthemos</i>	7, 4	8	0.06–0.13	350–910
5	Tufnell Park	Wantabadgery	35°01', 147°38'	1994	<i>C. maculata</i>	5	4	0.06–0.07	310–440
6	Rockdale	Narrandera	34°39', 146°28'	1990	<i>E. camaldulensis</i>	31	8	0.16	175–220
7	Old Carabobola	Culcairn	35°40', 147°10'	1990, 1991	<i>E. melliodora</i> , <i>E. albens</i> , <i>E. sideroxylon</i>	13, 6	5	0.06–0.09	480–730
8	Lindfield	Mullengandra	35°54', 147° 06'	1991	<i>E. globulus</i> , <i>C. maculata</i>	12	6	0.08–0.16	230–450
9	Hillcrest	Young	34°15', 148°19'	1988	<i>E. camaldulensis</i>	8	5	0.12–0.14	300–380
10	Connamara	Pine Ridge	31°32', 150°28'	1996	<i>E. sideroxylon</i> , <i>E. melliodora</i> , <i>E. albens</i>	5	5	0.09–0.12	330–470
11	Paringa	Pine Ridge	31°33', 150°29'	1996, 1997	<i>E. sideroxylon</i> , <i>E. crebra</i> , <i>E. melliodora</i>	14	12	0.05–0.1	390–770
12	Davidson	Attunga	30°57', 150°52'	1990	<i>E. camaldulensis</i> , <i>E. melliodora</i>	8	6	0.07–0.12	330–670

Table 2. The percentage of the total number of trees measured represented by each species and the year they were established

Species	Fraction of the total number of trees measured (%)	Year established
<i>E. camaldulensis</i>	34	1988, 1990, 1992, 1994, 1995, 1996
<i>E. melliodora</i>	17	1989, 1990, 1991, 1995, 1996,
<i>E. albens</i>	4	1996
<i>E. microcarpa</i>	5	1995
<i>E. polyanthemos</i>	7	1994
<i>E. sideroxylon</i>	10	1990, 1991, 1995, 1996
<i>E. crebra</i>	5	1997
<i>C. maculata</i>	6	1991, 1994
<i>E. botryoides</i>	8	1994, 1996
<i>E. globulus</i>	4	1991

in age class with plantations ranging from 6 to 14 y old (Table 2). The four box species *E. albens* Benth. (white box), *E. microcarpa* (Maiden) Maiden (grey box), *E. melliodora* Cunn. ex Schauer (yellow box) and *E. polyanthemos* Schauer (red box) collectively provided 33% of the total number of trees measured (Table 2) and occur on 8 of the 12 properties (Table 1). The box species ranged in age from 6 to 13 y, with only *E. melliodora* having more than one age class (Table 2). The ironbarks *E. sideroxylon* Cunn. ex Woolls (Mugga Mugga ironbark) and *E. crebra* F.Muell. (narrow-leaved ironbark) constituted 10% and 5% of the total number of trees measured, respectively (Table 2), with *E. sideroxylon* occurring on four properties and *E. crebra* on one. The former had an age class range of 6–12 y whilst the latter had one age class, 5 y. *Corymbia maculata* Hook. (spotted gum) occurred on two properties and provided 6% of the total number of measurements, with age classes of 6 and 11 y. *Eucalyptus botryoides* Smith (southern mahogany) and *E. globulus* Labill. subsp. *bicostata* (Maiden *et al.*) Kirkpatr. (southern blue gum) were each confined to one property and represent 8% and 4% of the total number of trees measured

respectively. The former species was 6 and 8 y of age, and the latter 11 y, at the time of measurement (Table 2). For modelling purposes, growth data for the four box species (*E. albens*, *E. microcarpa*, *E. melliodora*, *E. polyanthemos*) and the two ironbark species (*E. crebra*, *E. sideroxylon*) were combined into a box and ironbark group, respectively.

Site attributes: rainfall

Values of long-term mean annual rainfall (MAR) for each plantation obtained from interpolated daily rainfall and climate surfaces maintained by the Queensland Department of Natural Resources and Mines (Jeffrey *et al.* 2001), show that MAR across the measurement plots ranged from 459 to 678 mm (Table 3). These values, however, may not be a true reflection of the amount of rain received by each plantation since its establishment. Hence, for each plantation, an estimate of the MAR received by the plantation between the year it was established and the measurement date was calculated from the interpolated daily rainfall data (Table 3). Half of the properties (Avondale, Monavale, Rockdale, Old Carabobola, Lindfield and Davidson) received rainfall within ± 15 mm of the long-term annual mean. MAR at Connamara and Paringa was >100 mm above of the long-term average, whilst Tufnell Park received 40 mm less than the long-term average. The remaining three plantations — Fairfield, Hillcrest and Burnbank — received an additional 27 mm, 34 mm and 72 mm of rainfall annually respectively when compared to the long-term average (Table 3).

Modelling methods

Dominant height at age 10 y

The quantification of height growth in even-aged forest stands can be used for assessing the potential productivity of forest land (site quality). Dominant height is used in preference to measures such as volume because it is more easily measured and is relatively independent of variations in stand density and thinning treatments. In this study, dominant height is defined as

Table 3. Climatic data for each of the properties and plantations

Property	Long term MAR ^a (mm)	Actual ^b MAR received by the plantation (mm)	Difference between long-term MAR and actual MAR (mm)	Annual pan evaporation (mm)
Avondale	501	499	-2	1674
Fairfield	562	589	+27	1632
Mona Vale	647	658	+11	1568
Burnbank	578	650	+72	1626
Tufnell Park	569	529	-40	1585
Rockdale	459	455	-4	1715
Old Carabobola	630	620	-10	1532
Lindfield	678	693	+15	1442
Hillcrest	614	648	+34	1388
Connamara	625	727	+102	1788
Paringa	625	727	+102	1788
Davidson	618	615	-3	1836

^aMean annual rainfall

^bEstimated as described in text

the mean height of the trees in a plot which correspond to the 100 tallest trees per hectare.

Due to the very small number of suitable plantations in the region, the field measurement data in this study were collected from plots of differing ages. An attempt was made to 'normalise' the dominant height to a base age by projecting the data forward or backward to a base age of 10 y using a path-invariant projection equation. Ten years was chosen as the base age, as this was roughly the mid-point of plot ages and it minimised the average projection interval for the plots. An unpublished Forests NSW dominant height projection equation developed for *C. maculata* (Muhairwe²) was used to normalise the data (Equation 1 — coefficients not provided). The range of projection intervals between the initial age and the base age was between 0 and 5.6 y.

$$H_2 = \frac{B_0}{1 - (1 - B_0/H_1) \times (A_1/A_2)^{B_1}}, \quad (1)$$

where H_2 = mean dominant height at future age; H_1 = current mean dominant height (m); A_1 = current stand age (y); A_2 = future stand age (y); and B_0 and B_1 are coefficients.

Basal area increment model

Basal area for each plot at the time of measurement was calculated as the sum of the cross-sectional area of each tree (using dbhob) and dividing by the plot area. As with the dominant height data, the basal area data were normalised to a base age of 10 y using an unpublished Forests NSW basal area projection equation developed for *C. maculata* (Muhairwe²) (Equation 2 — coefficients not provided).

$$BA_2 = \exp \left(\ln(BA_1) \times \left(\frac{\text{age}_1}{\text{age}_2} \right)^{B_3} + B_4 \times \left(1 - \left(\frac{\text{age}_1}{\text{age}_2} \right)^{B_5} \right) \right), \quad (2)$$

where BA_1 and BA_2 are basal area at age₁ and age₂ respectively and B_3 , B_4 and B_5 are coefficients.

The error associated with using a single generic model is small due to the projection period being relatively short and the expectation that initial basal area is driving the growth predictions. For this study, the ranking of plots on the same footing was more important than accurate estimation of final yield.

Top basal area

A perennial problem with diameter or basal area per hectare measures is that they are intrinsically related to stocking. By definition, basal area is correlated with stems per hectare, especially with lower absolute numbers. To permit comparison among plots with differing stocking levels, the average basal area of the thickest 100 stems ha⁻¹ (top basal area) was calculated for each plot on the premise that it would be reasonably invariant to the effects of stocking. This approach is not ideal, as trees grown at high stocking levels will interact and tend to have lower diameters

than those of a similar age grown at lower stocking, but it does provide a first-order method of removing stocking as a factor when comparing basal area at age 10 y among plots.

Volume

The basal area for each tree projected to year 10 was estimated by adjusting the basal area at the time of measurement by the same proportion that the stand basal area changed (Equation 3):

$$B_2 = B_1 \times \frac{BA_2}{BA_1}, \quad (3)$$

where B_1 and B_2 is the individual tree basal area at ages 1 and 2 respectively and BA_1 and BA_2 are the stand basal areas at ages 1 and 2 respectively.

The height of each tree projected to year 10 was estimated in the same way using the ratio of dominant heights (H_2/H_1) multiplied by the tree height at time of measurement. The volume (V) of each tree was then estimated from height and diameter at age 10 y using the formula for the volume of a cone modified to account for the section of the tree between the base and 1.3 m (Equation 4). Tree volumes were then summed to obtain a plot volume:

$$V = 0.333 BA(H - 1.3) + 1.3 BA. \quad (4)$$

A cone rather than a more complex shape function was deemed an acceptable and conservative estimator of volume given the projection was to age 10 y and the lack of species-specific volume equations and taper functions.

Above-ground biomass

Total above-ground biomass (AGB) at age 10 y for each plot was estimated using the following general allometric equation for *E. pilularis* (Equation 5) published by Montagu *et al.* (2005). These authors demonstrated that the total aboveground biomass for *E. pilularis* from across a range of ages and growth forms was well estimated by the equation:

$$AGB = \exp(-3.270 + 2.707 \times \ln(\text{dbhob} + 1)) \times (0.971). \quad (5)$$

The diameters of all trees were converted to AGB using the above equation and the result expressed as tonnes per hectare. Total carbon was estimated assuming that the carbon content of AGB is 50%. The use of this general equation rather than species-specific equations was deemed acceptable for the purposes of this study, since reliable allometric equations for most of the species do not currently exist and the objective was merely to give an indication of the likely rates of biomass accumulation and carbon sequestration by plantings in this rainfall zone.

Results

Tree growth

The results of modelling dominant height and basal area to age 10 y for the various eucalypt species are shown in Figures 2 and 3. Figure 2 shows the trajectories of the growth curves for the range of site indices for *E. camaldulensis*, and has been provided mainly

²Muhairwe, C. (2003) Growth and yield models for eucalypt plantations. Unpublished Forests NSW internal report.

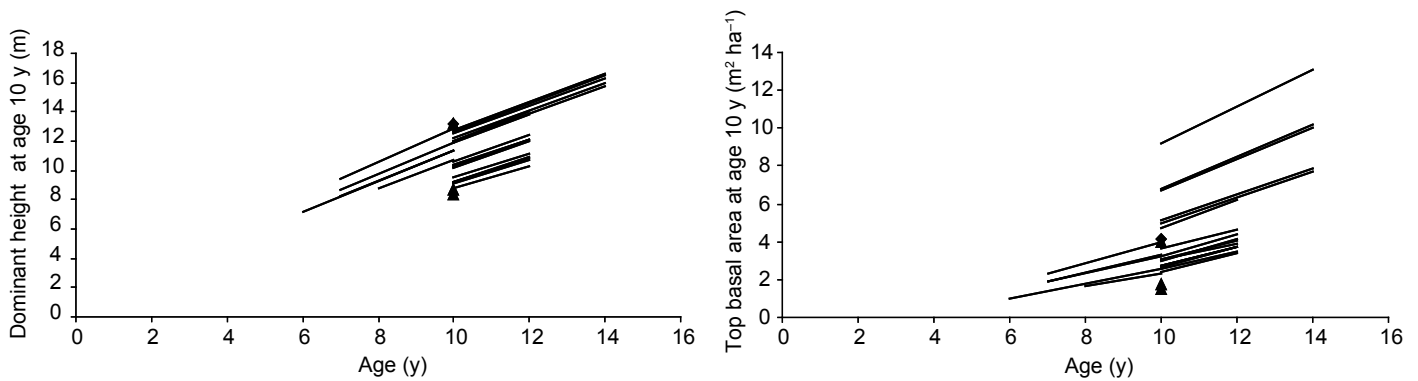


Figure 2. Mean dominant height and mean top basal area at age 10 y for *E. camaldulensis*. The symbols represent age 10 plots.

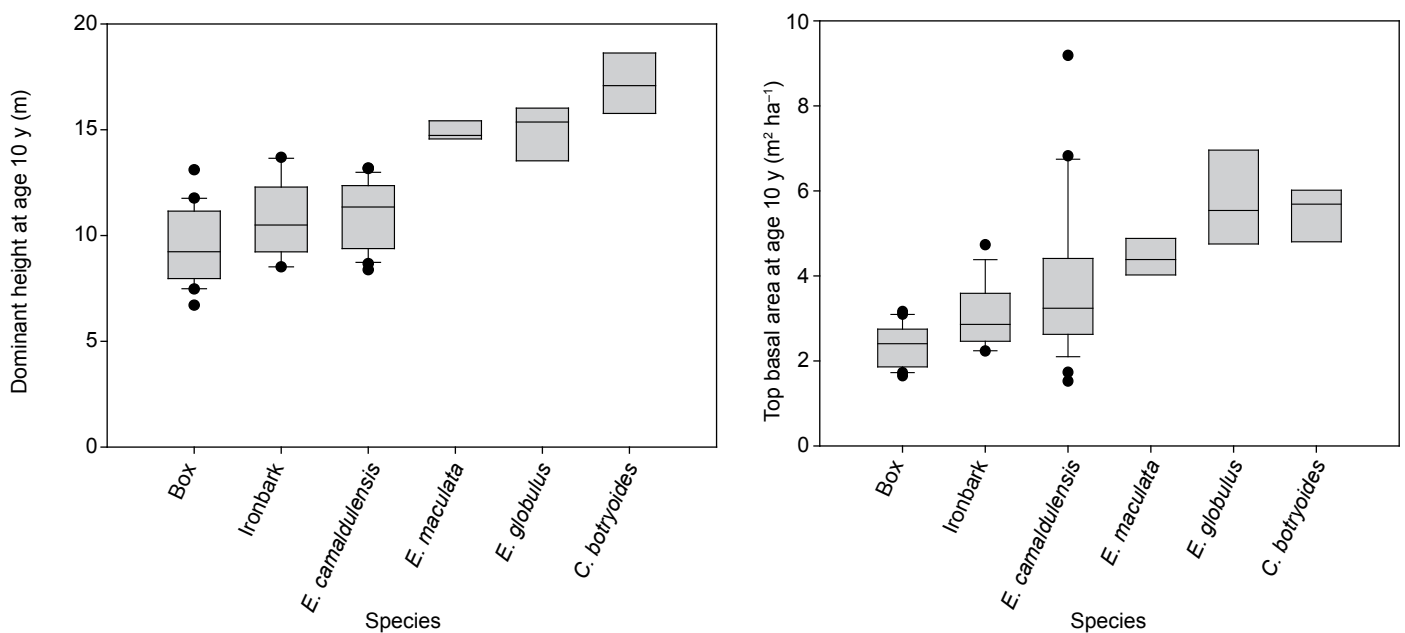


Figure 3. Boxplot of mean dominant height and mean top basal area at age 10 y for each of the tree species. The line across each boxplot denotes the median value, whilst the bottom and top of the boxplot are the 25th and 75th percentiles respectively. The whiskers denote the 10th and 90th percentiles.

as a visual check on the behaviour of the model. Dominant height was greatest for *E. botryoides*, *E. globulus* and *C. maculata*, and ranged from 14.1 to 18.8 m, 13.5 to 16 m and 13.9 to 16.0 m for these three species, respectively (Fig. 3). For the ironbark group, dominant height ranged from 8.5 to 13.7 m; for *E. camaldulensis*, 8.4 to 13.2 m; and for the box group, 7.5 to 13.1 m (Fig. 3).

Top basal area was greatest for *E. camaldulensis* and the most variable, ranging from 1.5 to 9.2 m² ha⁻¹. As with dominant height, top basal area was similar for *E. botryoides*, *E. globulus* and *C. maculata*, and ranged from 4.5 to 6.0 m² ha⁻¹, 4.8 to 7.0 m² ha⁻¹ and 4.0 to 6.7 m² ha⁻¹ for these three species, respectively. The ironbark group top basal area ranged from 2.2 to 4.7 m² ha⁻¹, followed by the box group with 1.6 to 3.1 m² ha⁻¹ (Fig. 3).

The estimates of volume attained at age 10 y for the various species show a high degree of variability, particularly for *E. camaldulensis* and *E. botryoides* which ranged from 13.3 to 87.9 m³ ha⁻¹ and 52 to 125.9 m³ ha⁻¹ respectively (Fig. 4). For the other species,

volume estimates ranged from 64.2 to 85.6 m³ ha⁻¹ for *E. globulus*, 40.9 to 65.7 m³ ha⁻¹ for *C. maculata*, 15.7 to 54.6 m³ ha⁻¹ for the ironbark group and 9.5 to 48.2 m³ ha⁻¹ for the box group. The large range in volume estimates for *E. camaldulensis* is due to five high-productivity plots (45.1 to 87.9 m³ ha⁻¹, see Fig. 4) in a single plantation (Hillcrest, Table 1) established in 1988 over a shallow water-table, where it is assumed the trees have had access to water additional to rainfall. The range in volume estimates for *E. camaldulensis* is greater than the difference in the volume estimates between the species and can be attributed largely to the range of site conditions where this species was planted. In contrast to *E. camaldulensis*, the box species — whilst planted on a similar range of sites — showed much less variation in their predicted growth. The volume estimates for *C. maculata*, which occurred on two sites, and *E. globulus* and *E. botryoides*, which occurred on one site each, need to be treated with caution, as the sites in question are not representative of conditions in the low- to medium-rainfall areas of NSW.

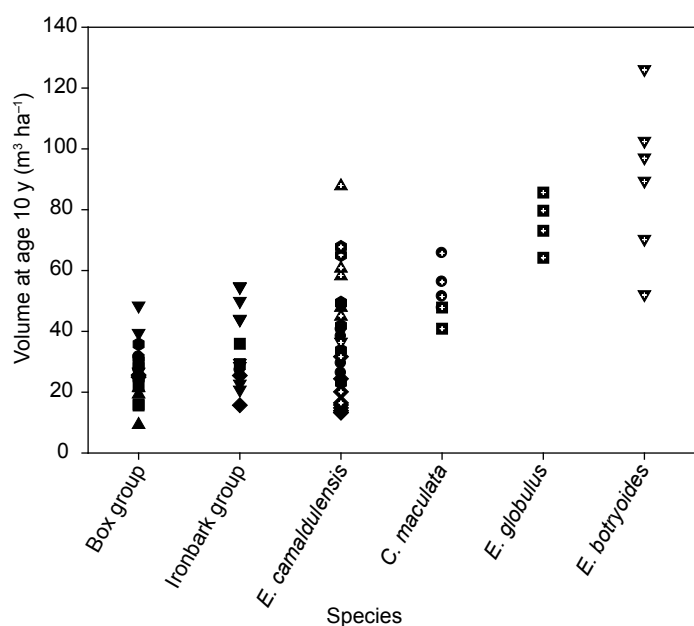


Figure 4. Scatterplot showing the range of volume estimates at age 10 y for each of the tree species. The symbols represent the different properties and plantations.

Biomass accumulation

Total AGB ranged from 12.5 to 40.7 t ha⁻¹ for the box species, 16.5 to 51.2 t ha⁻¹ for the ironbark species, 14.1 to 105.8 t ha⁻¹ for *E. camaldulensis*, 36.5 to 55 t ha⁻¹ for *C. maculata*, 54.8 to 74.8 t ha⁻¹ for *E. globulus* and 46.5 to 94.3 t ha⁻¹ for *E. botryoides* (Table 4). The mean annual biomass increment was 2 to 3.4 t ha⁻¹ for the box species, 2 to 3.6 t ha⁻¹ for the ironbark species, 2.2 to 6.7 t ha⁻¹ for *E. camaldulensis*, 3.8 to 4.7 t ha⁻¹ for *C. maculata*, 6.8 t ha⁻¹ for *E. globulus* and 7 t ha⁻¹ for *E. botryoides* (Table 4). Grierson *et al.* (1992) reported a biomass accumulation rate of 1.5–2 t ha⁻¹ y⁻¹ for box-ironbark communities in south-eastern Australia, a rate similar to that reported here for the box and ironbark species (2–3.6 t ha⁻¹ y⁻¹). The mean above-ground carbon density at age 10 ranged from 10.1 to 16.9 t ha⁻¹ for the box species, 10.1 to 18.1 t ha⁻¹ for the ironbark group, 11.2 to 33.7 t ha⁻¹ for *E. camaldulensis* and 19.1 to 23.3 t ha⁻¹ for *C. maculata*. For *E. globulus* and *E. botryoides*, mean above-ground carbon density at age 10 y was 33.8 t ha⁻¹ and 35.2 t ha⁻¹, respectively (Table 4).

Discussion

Wong *et al.* (2000) used an empirical modelling approach to estimate growth of six eucalypt species in south-eastern Australia, two of which — *E. botryoides* and *E. globulus* — were common to this study. For their lower-rainfall sites (600–699 mm y⁻¹) in the Gippsland region of eastern Victoria, their ranges of dominant heights at age 10 y for *E. botryoides* were 14–18 m on deep sands and 11–14 m on texture-contrast soils, a result similar to our estimate for this species (14–19 m). For *E. globulus*, their ranges of dominant heights at age 10 y were 13–16 m on deep sands and 14–17 m on texture-contrast soils, again a result similar to our estimate for this species (13–16 m). On their poorest sites (site index of 14, height (m) at age 10 y), *E. globulus* attained

a volume of 89 m³ ha⁻¹ and 81 m³ ha⁻¹ in trials in Victoria and South Australia respectively, which is within the range (64.2–85.6 m³ ha⁻¹) of our estimated volume at age 10 y for this species. Using these authors' South Australian growth projection for *E. globulus* with a site index of 14 m and 16 m at age 10 y (i.e. the range of dominant heights at age 10 for *E. globulus* in our study), stem volume for this species in our study at age 20 y is estimated to range from 167 to 232 m³ ha⁻¹, which equates to an MAI of 8.4–11.6 m³ ha⁻¹. The South Australian volume projection was chosen as it is derived from plantations receiving an MAR similar to that of the plantations in our study.

Booth *et al.* (2007) reported a minimum, mean and maximum site index (dominant height) value at age 10 y of 2.6 m, 14.7 m and 29.7 m respectively for the combined growth of *E. grandis* Hill ex Maiden (flooded gum), *E. globulus*, *E. saligna* Smith (Sydney blue gum), *E. camaldulensis* and *C. maculata*. Their samples were located on a wide range of sites across mainland south-eastern Australia, where annual rainfall varied from a minimum of 227 mm to a maximum of 1830 mm, with a mean of 745 mm. The much greater site index values reported by these authors are probably a reflection of the high rainfall and the irrigation of some sites. Nevertheless, the estimates of site index at age 10 y presented herein are consistent with previous studies.

Bugg *et al.* (2002) undertook a strategic assessment of land across NSW to determine its biophysical capability and suitability for growing softwood and hardwood plantations for wood production, carbon sequestration, salinity abatement and land rehabilitation. Using the process-based model 3-PG (Landsberg and Waring 1997) they assessed the biophysical potential of land to grow trees and defined six productivity classes based on stem volume at age 20 y. The potential productivity of *E. globulus* at age 20 y (8.4–11.6 m³ ha⁻¹ y⁻¹) presented herein equates to a productivity class 4 as defined by these authors. Areas of productivity class 4 are considered to be of low productivity (i.e. non-commercial growth rates) and unsuited for conventional plantations but sites where tree planting could provide environmental benefits. Given that the productivity of the other species in our study was either similar to or less at age 10 y than that of *E. globulus*, it is also unlikely that they will generate an economic return based on wood products alone.

Since our measurement in 2002, *E. globulus* has suffered considerable mortality (up to 50%) due to water stress caused by a prolonged drought, and thus will not achieve the volume growth estimated above. Dutkowski (1995) reported significant mortality (600 ha) in 3–6-y-old blue gum plantations in Western Australia due to water stress induced by a major drought in 1993–1994. Susceptibility to drought is an important consideration when matching species to sites in low-rainfall environments characterised by highly variable annual rainfall, and particularly for eucalypts with a water-use strategy similar to that of *E. globulus* (White *et al.* 2003). These authors suggest that whilst *E. globulus* is well adapted to short periods of water stress punctuated by rainfall events, it is particularly vulnerable to prolonged periods of water stress. On sites where water storage capacity is insufficient to buffer the deficit between summer rainfall and evaporative demand, the physiological traits that enable the rapid growth of this species render it vulnerable to drought death. As with *E. globulus*, the *E. botryoides* plantation

Table 4. Mean volume, total above ground biomass and carbon density at age 10 y, the range in biomass values and annual biomass increment for each of the tree species

Species	Property	Volume range (m ³ ha ⁻¹)	Mean above-ground biomass (t ha ⁻¹)	Mean annual biomass increment (t ha ⁻¹)	Biomass range (t ha ⁻¹)	Mean carbon density (t ha ⁻¹)	No. of plots
Box group (<i>E. melliodora</i> , <i>E. albens</i> , <i>E. macrocarpa</i> , <i>E. polyanthemus</i>)	Connamara	25.0–25.6	23.4	2.3	22.4–24.3	11.7	2
	Paringa	26.5–48.2	33.7	3.4	23.8–40.7	16.9	3
	Davidson	31.6	32.7	3.3	–	16.4	1
	Mona Vale	9.5–31.6	20.1	2.0	12.5–25.5	10.1	3
	Old Carabobola	15.6–29.6	23.2	2.3	17.7–34.0	11.6	4
	Avondale	24.5–31.3	27.3	2.7	24.0–31.3	13.7	4
	Burnbank	35.7	31.8	3.2	–	15.9	1
Ironbark group (<i>E. sideroxylon</i> , <i>E. crebra</i>)	Connamara	15.7–25.4	20.2	2.0	16.5–23.9	10.1	2
	Paringa	20.6–54.6	36.2	3.6	20.2–51.2	18.1	9
	Davidson	27.3	26.7	2.7	–	13.4	1
	Old Carabobola	27.2	30.1	3.0	–	15.1	1
	Avondale	29.2–35.9	35.9	3.6	32.5–39.4	18.0	2
<i>E. camaldulensis</i>	Connamara	24.4	22.3	2.2	–	11.2	1
	Davidson	26.3–40.6	33.7	3.4	26.4–42.8	16.9	4
	Avondale	33.8–49.4	42.2	4.2	34.8–47.8	21.1	3
	Burnbank	36.3	32.4	3.2	–	16.2	1
	Hillcrest	45.1–87.9	67.3	6.7	47.2–105.8	33.7	5
	Fairfield	23.1–67.7	42.3	4.2	23.9–62.9	21.2	4
	Rockdale	13.3	31.7	3.2	14.1–33.0	15.9	8
<i>C. maculata</i>	Tufnell Park	47.6–65.7	46.6	4.7	40.1–55.0	23.3	4
	Lindfield	40.9–47.8	38.2	3.8	36.5–39.9	19.1	2
<i>E. globulus</i>	Lindfield	64.2–85.6	67.6	6.8	54.8–74.8	33.8	4
<i>E. botryoides</i>	Burnbank	52.0–125.9	70.4	7.0	46.5–94.3	35.2	6

has also suffered high mortality due to water stress induced by the current drought in NSW. Whilst both of these species are by far the most productive in our study, they are also a high risk. On sites where sources of water additional to rainfall may be exhausted or unavailable, even for a short time, there is an obvious trade-off between production and risk when considering which species to plant.

Accurate estimates of tree growth rates in low- to medium-rainfall environments in Australia are essential to provide landholders and potential investors with reliable forecasts of the economic and environmental benefits of farm forestry. At present there is little information on the specific adaptations of different tree species and their potential growth rates across broad regions and particular sites in low-rainfall environments. A major limitation of this study and others (e.g. Wong *et al.* 2000; Booth *et al.* 2007) is the lack of comparable species trials planted using the same genetic material and establishment techniques over a wide range of conditions. This issue is currently being addressed through the establishment, by Forests NSW, of 50 dryland species demonstration trials across NSW covering the range of seasonal rainfall regimes in the state. The trials, planted in 2000, have been established using the same genetic material and establishment techniques in replicated blocks, each site being 2 ha in size (Barton and Parekh 2005). The species planted include *E. camaldulensis*, *E. sideroxylon*, *E. cladocalyx* F.Muell. (sugar gum), *E. argophloia* Blakely (Queensland western

white gum), *C. maculata*, *C. variegata* F.Muell. (spotted gum), *Pinus pinaster* Aiton (maritime pine), *Acacia mearnsii* DeWild. (black wattle) and two eucalypt hybrids.

The aim of the trials is to develop knowledge of species × site interactions and potential growth rates to improve the planning of afforestation for environmental and commercial benefits in the low- to medium-rainfall area of NSW (Ryan *et al.* 2005). The trials also provide the opportunity to undertake physiological measurements of key species to parameterise and validate physiological growth models that can simulate growth of farm forestry plantations across broader areas. This knowledge will be used to underpin decision support and risk analysis tools to guide tree planting in the low- to medium-rainfall environments of NSW.

Conclusions

This study shows that potential productivity varies within and between the eucalypt species measured. The more productive species *E. botryoides* and *E. globulus* showed early promise, but they have both suffered significant mortality due to prolonged water stress. For these species to remain productive in the low- to medium-rainfall zone, sources of water additional to rainfall are required. The productivity of *E. camaldulensis* varied considerably,

due largely to the range of site conditions on which it had been planted. On the better sites, its productivity overlapped that of *E. botryoides* and *E. globulus*. *C. maculata* and the ironbarks showed promise, and their productivity also overlapped that of *E. botryoides* and *E. globulus*. Whilst the results for *C. maculata* need to be treated with some caution due to a lack of replication across a range of site conditions, its performance along with that of *E. camaldulensis* and *E. sideroxylon* in other trials established in similar environments is consistent with that reported here (C. Barton unpublished). Of the species examined in this study, *E. camaldulensis*, *E. sideroxylon* and *C. maculata* present the best trade-off between production and risk when considering which species to plant in the low- to medium-rainfall areas of NSW. We must add a word of caution regarding *C. maculata*, based on experience within Forests NSW: this species is susceptible to frost damage when young, a problem that may in part be addressed by planting frost-tolerant provenances in frost-prone areas.

The recent establishment of replicated trials by both Forests NSW and the Australian Low Rainfall Tree Improvement Group, using similar establishment methods and genetic material, provides a great opportunity to augment the present work and improve estimates of potential productivity for a wider range of species across broad areas and specific sites. The information collected from these trials will assist in providing landholders and potential investors with tools for decision support and risk analysis to maximise the potential commercial and environmental outcomes from farm forestry plantations in the low- to medium-rainfall environments of NSW.

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