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Growth response to thinning in two subtropical hardwood species

Kevin S. Glencross
Southern Cross University

Graeme Palmer
Southern Cross University

Marie-Chantale Pelletier

J Doland Nichols
Southern Cross University

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High-value wood resources

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CRC for Forestry

Researching sustainable forest landscapes

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COOPERATIVE RESEARCH CENTRE FOR FORESTRY
College Road, Sandy Bay, Tasmania
Private Bag 12, Hobart, Tasmania 7001 Australia

Contents

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Summary

The subtropical eucalypt plantation estate now comprises more than 100 000 hectares in north-east New South Wales (NSW) and south-east Queensland (Qld). If a significant portion of this resource is to be used for sawlog production, it is necessary to design effective silvicultural systems, particularly thinning procedures. A thinning trial was carried out at two sites in Qld and one in NSW, in plantations established by Forest Enterprises Australia. Each was planted with two species, *Eucalyptus dunnii* and *Corymbia citriodora* ssp. *variegata*. The original stocking density of the plantations at planting was 1000–1300 trees per hectare. When the trees were approximately seven years of age, three treatments were applied in randomised complete block designs: an unthinned control, and 500 and 300 stems per hectare residual stocking. Two years (24 months) after thinning, mean diameter increment was significantly greater in the thinned stands of both species for all trees in the plots, and for the largest 15 trees in each plot (equivalent to 250 trees per hectare). The greatest growth response was in the 300 stems per hectare treatment in both species.

Introduction

Subtropical eucalypt plantations represent about 12% of Australia's plantation eucalypts (Gavran and Parsons 2009). The first subtropical hardwood plantations were established on the NSW north coast in the late 1960s and 1970s by Australian Paper Mills. The main species planted were *Eucalyptus pilularis* and *E. grandis* (Sinclair 1991; Nichols *et al.* 2010). In the mid-1990s, government agencies in NSW and Qld initiated hardwood plantation programs on previously cleared land, with a view to supplementing future native-forest sawlog production. The rate of plantings accelerated after 2000 when private forestry companies, many using managed investment schemes (MIS), became active in the region. The main species planted have been *E. dunnii, Corymbia maculata* and *C. citriodora* spp. *variegata* (CCV) (Table 1) (Northern Rivers Private Forestry Development Committee 2005; Lee 2006; Nichols *et al.* 2010).

Table 1: Plantation areas in hectares (ha) of main eucalypt species in subtropical eastern Australia

Species	Hectares (ha)
Eucalyptus dunnii	32 076
Corymbia citriodora ssp *variegata* (CCV)	21 973
E. pilularis	18 033
E. grandis	9 895

Source: Adapted from Nichols *et al*. (2010)

Two species, *E. dunnii* and CCV, now account for just under half of the current subtropical estate (approximately 54 000 ha), despite little previous experience growing these species in plantations in subtropical Australia (Lee 2006; Smith & Brennan 2006; Nichols *et al*. 2010). Therefore, data from which to base silvicultural decisions are limited, and the impacts of thinning on growth, taper and canopy characteristics are not well understood. The rapid expansion of the subtropical plantation estate has also provided forest growers with some significant challenges in sourcing adequate improved genetic material and appropriate matching of species to site types. Some growers have experienced losses in production due to pests and diseases (Carnegie & Angel 2004; Carnegie 2007; Nichols *et al.* 2010).

Compared with other tree genera, *Eucalyptus* and *Corymbia* have a strong competitive ability in resource-limited situations (Florence 1996). However, species within these genera differ in their tolerance to competition for light, nutrients and water. Therefore, careful matching of species to sites and application of appropriate silviculture are critical to commercial success (West 2006). While the most shade-intolerant species have a strong tendency to self-thin, stand dominance and self-thinning can be delayed in more shade-tolerant species (Florence 1996).

Shade-intolerant, subtropical hardwood species have shown a tendency to self-prune lower branches, as light intensity declines due to inter-tree competition (Alcorn *et al.* 2008). Rates of occlusion of dead branches appear similar in pruned and unpruned trees in several subtropical species (Smith & Brennan 2006). Thus, if clear-wood production is a plantation objective, canopy dynamics and branch shedding characteristics can be exploited to initiate 'self-pruning' in some subtropical species (Kearney *et al.* 2007). However, if thinning is delayed, the loss of foliage and rise in crown height that may result from excessive inter-tree competition may reduce the ability of these taxa to respond rapidly to the release from competitive stress that thinning provides (Smith & Brennan 2006).

Thinning is generally carried out to release dominant trees by reducing competition, thus allowing the retained stems to have a greater share of site resources. Thinning is an important mechanism for forest managers to realise larger individual tree sizes within a reduced rotation length (West 2006). Thinning is also used to improve stand quality by removing defective trees before they become dominant. This is especially important in stands of unimproved stock where a high proportion of defective stems can be present (Binkley *et al.* 2002). As pointed out by Smith and Brennan (2006), the optimal thinning regime will involve a trade-off between fully utilising the site resources and maximising growth of the most commercially valuable individual trees in the stand. Therefore, the optimal thinning regime will maintain rapid increases in basal area, while limiting that growth increment to a relatively small number of commercially valuable trees.

Heavy thinning is associated with greater exposure to light, which can induce larger branch sizes and associated knot defects, and to wind damage, stem breakage and growth stresses (Medhurst & Beadle 2001; Smith & Brennan 2006). The high cost of thinning in the absence of adequate markets imposes further risks to stand profitability (Binkley *et al.* 2002; Montagu *et al.* 2003;). Therefore, decisions on timing and intensity of thinning must consider the impacts on stand growth and wood quality, as well as market availability and impacts on financial returns.

Commonwealth Government agencies and state government agencies in Qld and NSW have historically supported the production of sawlogs in plantations to supplement their supply from native forests (Commonwealth of Australia 1992). However, most of the recent subtropical hardwood plantation expansion has been established by private MIS companies, primarily for pulpwood (Nichols *et al.* 2010). Declining world pulp prices and the need for diversification have seen some shift to managing pulp plantations in Australia for solid and engineered wood products (Montagu *et al.* 2003).

The production of sawlogs and poles from plantations will require growers to meet minimum size specifications, depending on the intended end use (e.g. Australian Standards AS 2082). Wood processors generally pay a premium for larger logs with a higher proportion of clearwood free of defects (Nolan *et al.* 2005). The larger logs provide efficient processing for sawn wood, but will require longer rotations and silvicultural management from growers (Smith & Brennan 2006). The plantation industry will need to evaluate the costs of production and the economic returns from higher value, solid-wood products, to ensure the investment in silvicultural inputs is justified by the return (Nolan *et al*. 2005).

To produce sawlogs, an early pre-commercial thinning within the first three to five years of the rotation has been advocated to coincide with canopy closure (Gerrand *et al*. 1997). One of the major MIS forest growers in the subtropics, Forest Enterprises Australia Ltd (FEA), opted for later-age thinning regimes (FEA 2009), at approximately eight to 10 years of age, when a commercial pulp product may be generated, and where the cost of a pre-commercial thinning is avoided. However, thinning response typically declines with age (West 2006), so thinning at this relatively late stage is unlikely to maximise thinning response (Smith & Brennan 2006).

New processing technologies may provide an opportunity for the development of roundwood and engineered wood products from young plantation wood (McGavin *et al.* 2006). The assessment of young subtropical wood by McGavin *et al.* 2006 concluded that subtropical species may have a competitive advantage over softwood and temperate eucalypts, due to higher density and superior mechanical properties. The development of products from thinning material is a critical issue for forest growers in the subtropics, where pulpwood and residue markets are not well developed (Nichols *et al*. 2010).

The thinning treatments evaluated in this study are based on silvicultural regimes proposed by FEA, the owners of the study sites. FEA's intention was to provide commercial thinning for pulpwood at age 8–9 years and final harvest of small sawlogs and pulpwood at age 13–15 years (FEA 2009). The growth response was evaluated for different intensities of late-age commercial thinning in *E. dunnii* and CCV at two sites. The preliminary results presented in this report are part of an ongoing investigation by CRC for Forestry researchers, into the impacts of timing and intensity of thinning on crown development and associated stem and wood defects and wood properties, and the resulting value of plantations of these species. The final growth assessment conducted by the CRC in these trials will be completed in early 2012, and will look at growth and crown development three years after thinning.

Methods

Site description

Locations of the thinning trials were selected to represent contrasting site types within the plantation estate of FEA. in subtropical eastern Australia. For each species, two sites with known and similar management histories were chosen. The sites were Reids plantation at Ellangowan located 50 km south-west of Lismore in northern NSW, Barron plantation located 15 km south-west of Kingaroy in south-east Qld, and Tingoora plantation, located 40 km north of Kingaroy, Qld (Table 2). The NSW and Qld locations were selected to provide contrasting high-rainfall and low-rainfall sites respectively. Annual rainfall data recorded at both locations for the period 2001–10 is presented in Figure 1. The mean annual rainfall for this ten-year period at Ellangowan, 1096 mm, was close to the long-term average (97% of long-term mean rainfall), whereas at Kingaroy, the mean annual rainfall for 2001–10, 783 mm, was 23% below the long-term average.

Table 2: Summary information for the Reids (NSW), Barron and Tingoora (Qld) sites

Site	Location	Soil type	Mean annual rainfall (mm)	Mean daily min. temp. coldest month (ºC)	Mean daily max. temp. warmest month (ºC)	Lat (ºS)	Long (ºE)	Elevation (m asl)
Reids	Ellangowan, NSW	Kurosol	1096	6.6	31.3	29 02	153 05	52
Barron	Kingaroy, Qld	Ferrosol	783	4.0	29.6	26 34	151 45	465
Tingoora	Kingaroy, Qld	Ferrosol	783	4.0	29.6	26 22	151 48	449

Source: Bureau of Meteorology (BOM), 2011

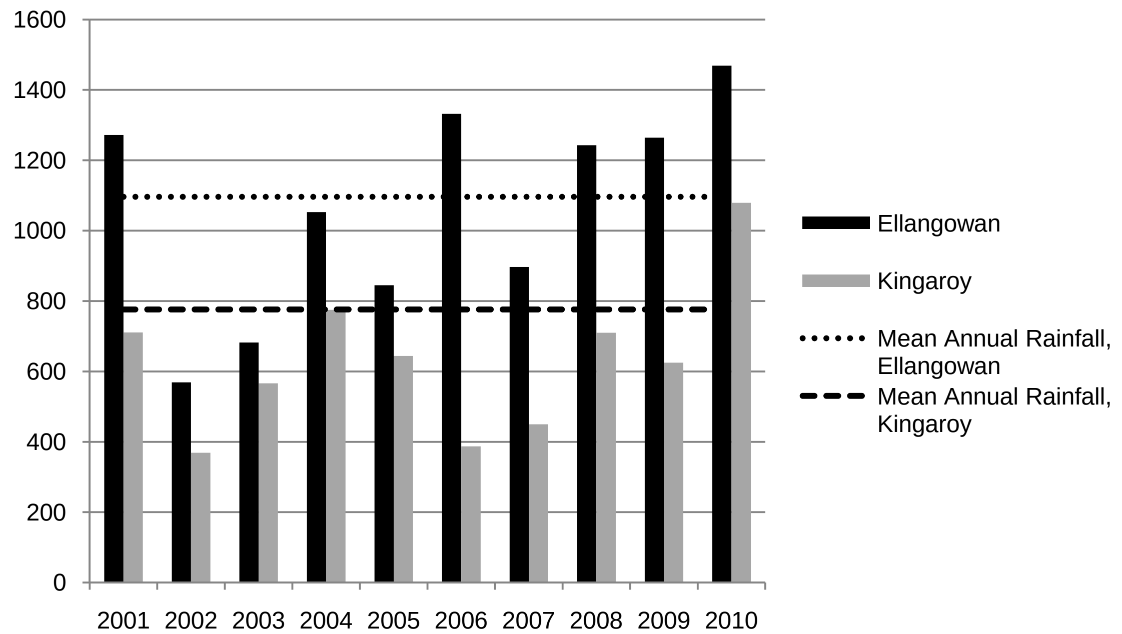


Figure 1: Mean annual rainfall (mm) and annual rainfall (mm) recorded at Ellangowan (NSW) and Kingaroy (Qld) for the period 2001–10. *Source*: BOM, 2011.

Plantations

Plantations at all sites were established in the summer of 2000–01. Prior to plantation establishment, planting rows were sprayed with glyphosate (4 l/ha as Roundup) then ripped to a depth of 0.6 m, cultivated and sprayed with Simazine® (2.5 kg/ha) and Duel® (1.5 l/ha) prior to planting. All sites were planted in February–March 2001 at 4 m × 2 m spacing. A post-planting fertiliser of 100 g of di-ammonium phosphate per tree was applied. Weed control spraying was conducted after planting using Verdict 520® (0.5 l/ha) and Verdict® (0.8 l/ha).

Trials

Thinning trials at Barrons (*E. dunnii*) and Tingoora (CCV) were established between October and December 2007, when the trees were six years and nine months old. The two trials at Reids (*E. dunnii* and CCV) were established between October and December 2008, when the trees were seven years and nine months old. Summary information for each plantation is presented in Table 3. For each trial, three thinning treatments (300 stems/ha, 500 stems/ha and an unthinned control—900 stems/ha) were applied in a randomised complete block design with four replicates. Treatment plots were square and 0.06 to 0.07 ha in size, with between 53 and 89 trees per plot in the unthinned control plots, depending on the stocking prior to thinning (Table 3). Each experimental plot was surrounded by a two-row buffer, to which the same thinning treatment was applied.

Table 3: Summary information for the *E. dunnii* and CCV plantations at Reids (NSW), Barron and Tingoora (Qld) at the time of thinning

Site	Species	Planting date	Age thinned	Stocking at planting	Stocking prior to thinning
Reids	*E. dunnii*	2001	7y 9m	1350	1270
Barron	*E. dunnii*	2001	6y 9m	1000	930
Reids	CCV	2001	7y 9m	1200	1050
Tingoora	CCV	2001	6y 9m	1100	950

Note: Stocking is stems/ha

Diameter over bark at breast height (DBH) of each tree was measured at 1.3 m immediately prior to thinning. The selection of trees to be retained was made on the basis of vigour, bole straightness, absence of visible defects and absence of large branches in the lower bole. The use of systematic thinning, for example, removal of every fourth row, was not appropriate, given the wide range of stem diameter and quality in each trial prior to thinning. The commercially valuable stems were not evenly distributed; therefore, the spacing of retained trees in the thinned plots was uneven. For the 500 stems/ha treatment, the actual stocking after thinning was set by retaining all trees judged to have the potential to grow on as final crop trees.

The DBH of all trees was measured at six-monthly intervals following thinning. This technical report presents results obtained up to approximately two and a half years after thinning. Measurement of the trials is ongoing.

Data analysis

Basal area (BA) per hectare was calculated by summing individual tree basal areas and dividing by the plot area. For each species at each site, 12 trees were selected to represent the range in DBH of the retained stems. Diameter over-bark and under-bark was measured, averaging values for the major and minor axis, at breast height, at the lowest dead branch, at the lowest green branch and at the base of the growing crown. Stem volume was then calculated assuming a cylindrical lower stem segment (below breast height), a conical topmost segment and linear taper for the intermediate segments. Regression models (polynomial with intercept at zero) were developed for each species and site to estimate stem volume over bark, using the variables DBH and height, with height the independent variable. Volume per hectare was calculated for each plot by summing predicted volumes for individual trees and converting to a per-hectare basis. In subsequent measurements, individual tree volumes of all trees in the plots were predicted from tree DBH and heights using the regression equation developed for each species–site combination.

Trends over time in DBH increment, BA increment and volume increment (expressed as mean annual volume increment, MAI) were calculated by subtracting the pre-treatment measurements from successive measurements. Both the mean DBH increment for all the experimental trees in the plots and the increment for the 15 trees in each plot with the largest DBH, equivalent to the largest 250 stems/ha, were calculated. At the Tingoora site, one plot of the 300 stems/ha treatment was heavily thinned, reducing the stocking to the equivalent of 200 stems/ha. The entire replicate (300, 500 and control plots) was excluded from the analysis of that site.

For each species at each site, the significance of the effects of thinning treatment on DBH increment and BA increment was examined using analysis of variance. Tukey's least significant difference analysis (LSD) was used to determine which individual treatment combinations differed significantly at $p<0.05$.

Results

Growth prior to thinning

The early years of these experimental plantations were characterised by below-average rainfall (Figure 1). Rainfall amounts increased at Reids, NSW from 2006 but lower-than-average rainfalls persisted at Barron and Tingoora, Qld until 2010 (Figure 1). Nevertheless, at the time of thinning, the survival rate was high (>90% for *E. dunni*, 94% and 92% at Reids and Barron respectively and, for CCV, 86% at both Reids and Tingoora).

Mean DBH just before thinning was less for both species at Barron and Tingoora than at Reids (Table 4). At Barron, MAI for *E. dunnii* was 6.7 m^3/ha. At Tingoora, MAI of CCV was 9.4 m^3/ha. At Reids, *E. dunnii* and CCV had MAIs of 16.7 and 12.6 m^3/ha respectively.

Change in mean DBH after thinning

The removal of 30 to 60% of the basal area resulted in large changes in the diameter distribution in the treated stands immediately after thinning (Table 4). The treatments were based on 'thinning from below' to remove the poorer quality stems. At both sites, the increase in DBH was greater for CCV than *E. dunnii*, and greater at Reids than at the Kingaroy sites. In the 300 stems/ha treatment, mean DBH of *E. dunnii* increased by 22% at Reids and 11% at Barron; mean DBH of CCV increased by 38% at Reids and 16% at Tingoora.

Table 4: Pre- and post-treatment stocking and tree size in E. dunnii and CCV thinning trials at Reids (NSW), Barron and Tingoora (Qld) plantations

		Pre-treatment			Post-treatment			
Trial	**Treatment**	**Stocking (stems/ha)**	**Mean DBH (cm)**	**BA (m^2/ha)**	**Stocking (stems/ha)**	**Mean DBH (cm)**	**BA (m^2/ha)**	**% BA reduction**
Reids	300	1238	13.3	18.6	365	16.2	9.1	51
E. dunnii	500	1159	13.5	18.3	585	15.9	14.0	23
	Control	1200	12.7	17.1		12.7	17.1	
Barron	300	852	12.4	10.4	376	13.8	6.1	41
E. dunnii	500	900	11.1	9.0	532	11.9	6.0	33
	Control	868	11.5	9.5		11.5	9.5	
Reids	300	943	13.4	15.9	275	18.5	7.4	53
CCV	500	1016	13.1	15.9	517	16.4	11.4	28
	Control	991	13.0	15.7		13.0	15.7	
Tingoora	300	884	12.2	11.7	271	14.2	4.8	59
CCV	500	880	11.6	10.8	500	12.7	6.9	36
	Control	896	11.7	11.3		11.7	11.3	

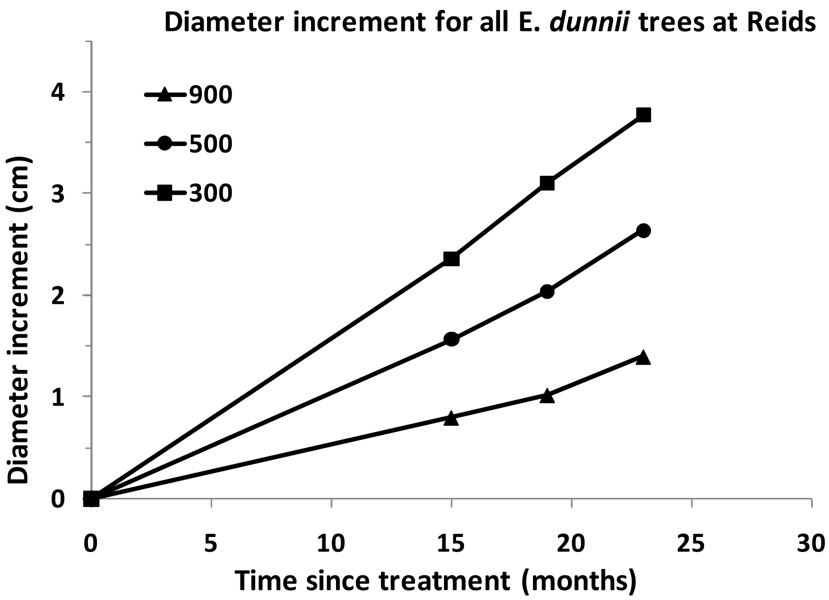
DBH increment 24 months after thinning, E. dunnii

At Reids, the unthinned treatment had a mean DBH increment of 1.4 cm over the 24-month period, compared with 2.7 cm and 3.8 cm for the 500 and 300 stems/ha treatments, respectively (Figure 2a). The equivalent increments for the largest 250 stems/ha were 2.3 cm, 3.1 cm and 4.1 cm, respectively (Figure 2c). For both the whole plot and largest 250 stems/ha, the DBH increment was significantly lower (p<0.01 at least) in the unthinned than the thinned treatments (Table 5).

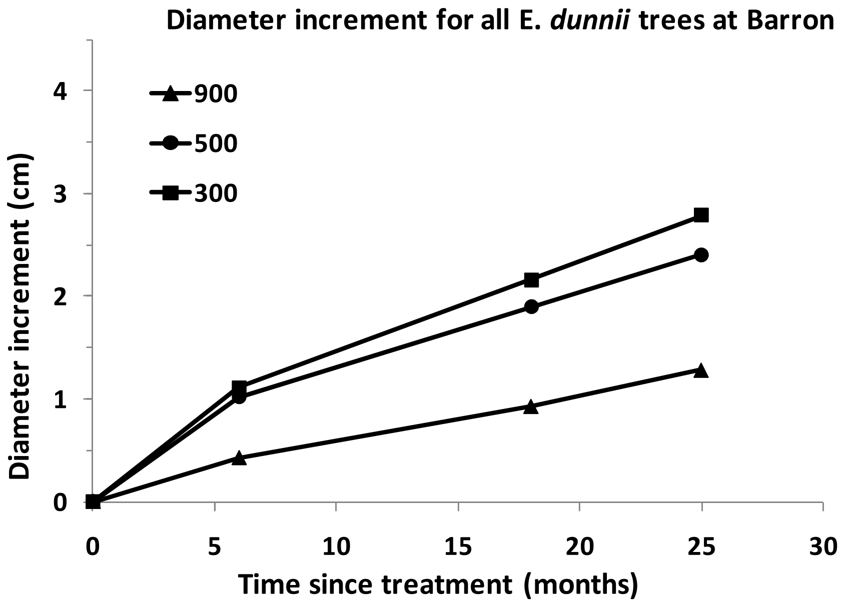
Table 5: Analysis of variance of diameter increment for each thinning trial, 24 months after thinning treatments were imposed, showing significance of difference between thinning treatments

Species		Site	Treatment d.f.	Residual d.f.	Variance ratio	*p*>F
E. dunnii	All trees	Reids	2	6	131.201	0.000
	Best 250	Reids	2	6	106.051	0.000
E. dunnii	All trees	Barron	2	6	33.885	0.000
	Best 250	Barron	2	6	22.517	0.000
CCV	All trees	Reids	2	6	40.264	0.000
	Best 250	Reids	2	6	8.545	0.008
CCV	All trees	Tingoora	2	4	66.742	0.000
	Best 250	Tingoora	2	4	39.916	0.000

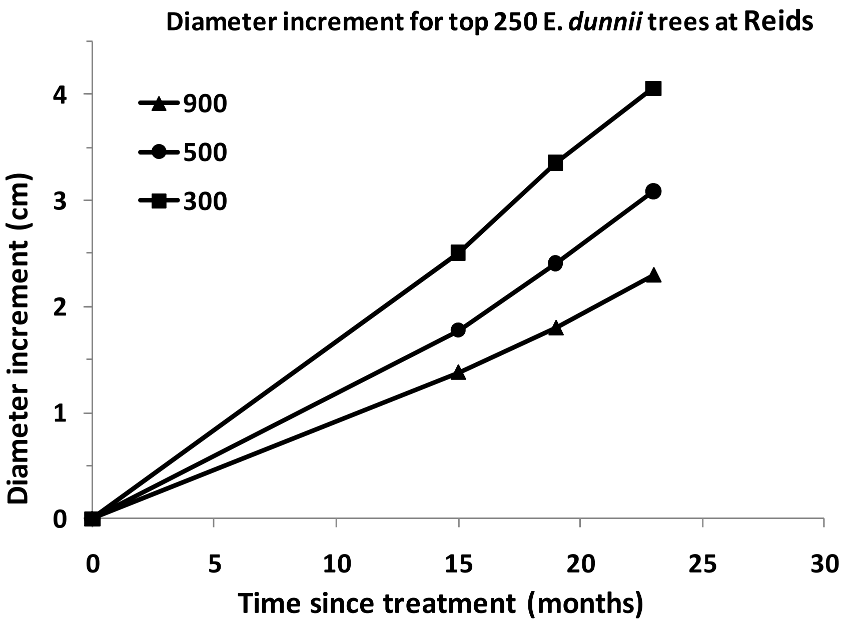
Similarly, at Barron, the DBH increment showed a significant growth response ($p<0.01$ at least) to thinning, compared with the unthinned control for the whole plot and largest 250 stems/ha; increments were 1.3 cm, 2.4 cm and 2.8 cm; and 1.9 cm, 2.9 cm and 3.2 cm respectively in the unthinned, 500 and 300 stems/ha treatments (Figures 2b, d).



(2a)


Diameter increment for all E. *dunnii* trees at Barron
4
3
2
1
0
Diameter increment (cm)
900
500
300
0
5
10
15
20
25
30
Time since treatment (months)

(2b)


Diameter increment for top 250 E. *dunnii* trees at Reids
4
3
2
1
0
Diameter increment (cm)
900
500
300
0
5
10
15
20
25
30
Time since treatment (months)

(2c)

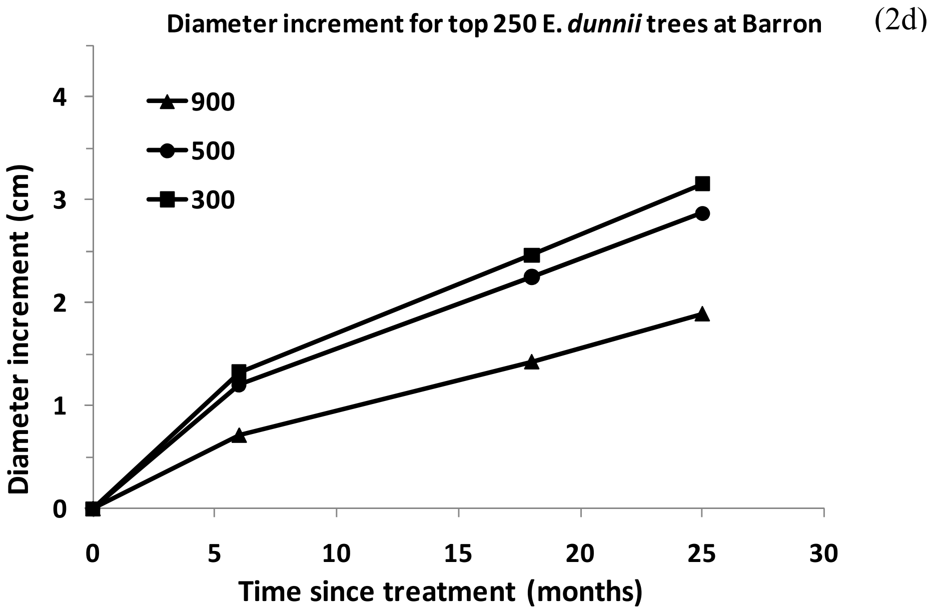
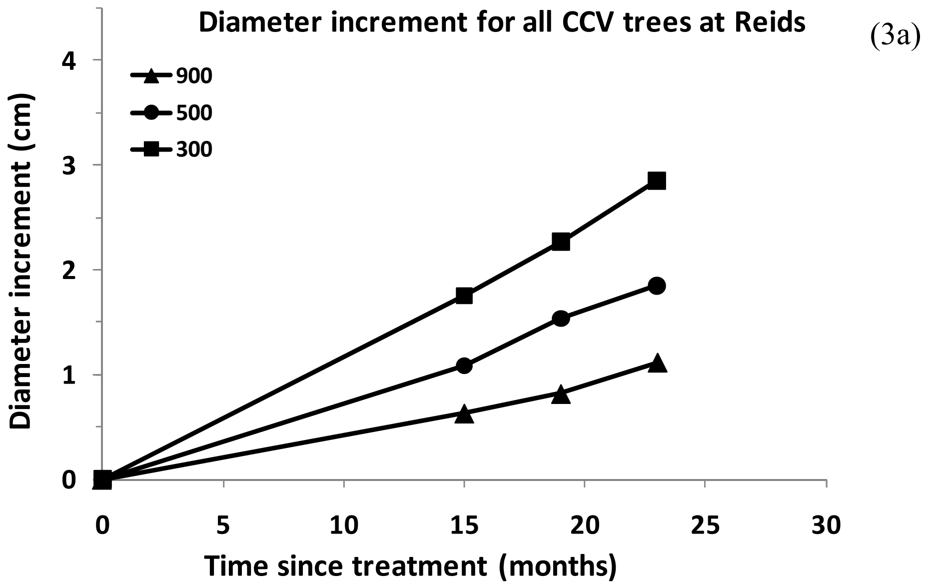


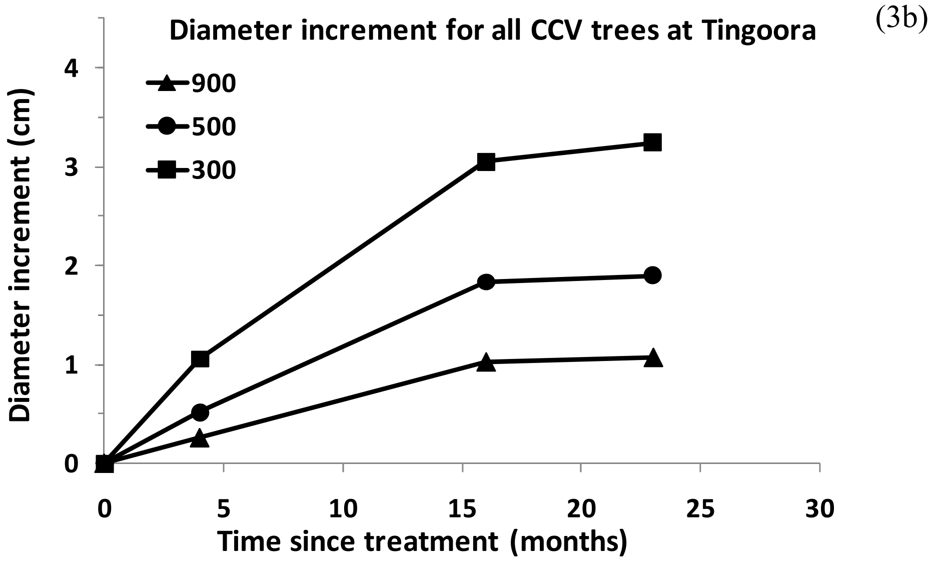
Figure 2: Diameter increment (cm) by treatment for *E. dunnii*: all (whole plot) trees at Reids (a) and Barron (b); top 250 stems/ha at Reids (c) and Barron (d)

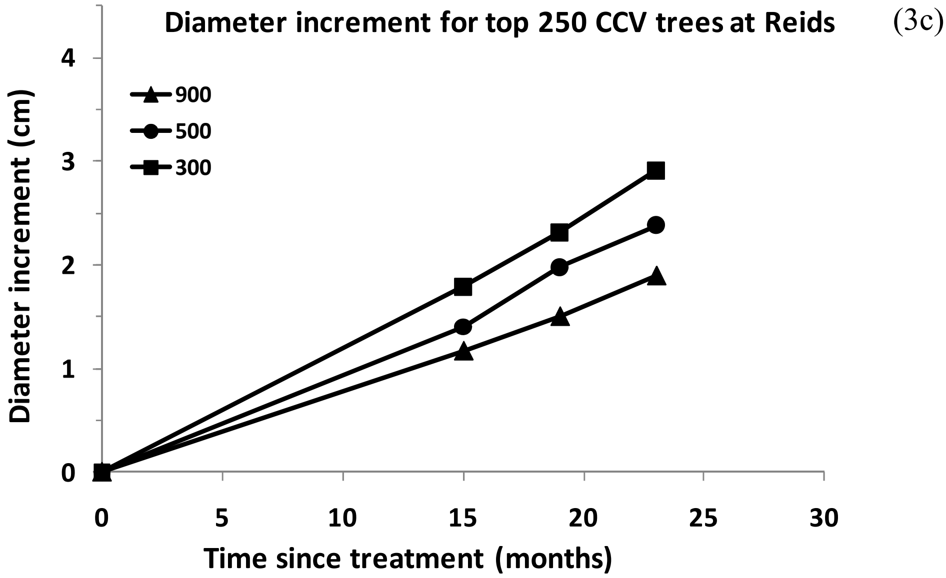
DBH increment over the 24 months after thinning, CCV

At Reids, DBH increment for CCV was significantly lower (p<0.001) in the unthinned than thinned treatments for the whole plot and the top 250 stems/ha (Table 5). For the whole plots the increments in the unthinned, 500 and 300 stems/ha treatments were, respectively, 1.1 cm, 1.9 cm and 2.9 cm (Figure 3a); for the top 250 stems/ha they were 1.9 cm, 2.4 cm and 2.9 cm (Figure 3c).

At Tingoora, the DBH increment for CCV was also significantly lower (p<0.001) in the unthinned than thinned treatments for the whole plot and the top 250 stems/ha (Table 5). For the whole plots, the increments in the unthinned, 500 and 300 stems/ha treatments were, respectively 1.1 cm, 1.9 cm and 3.2 cm (Figure 3b); and for the top 250 stems/ha, they were 1.8 cm, 2.4 cm and 3.5 cm (Figure 3d).







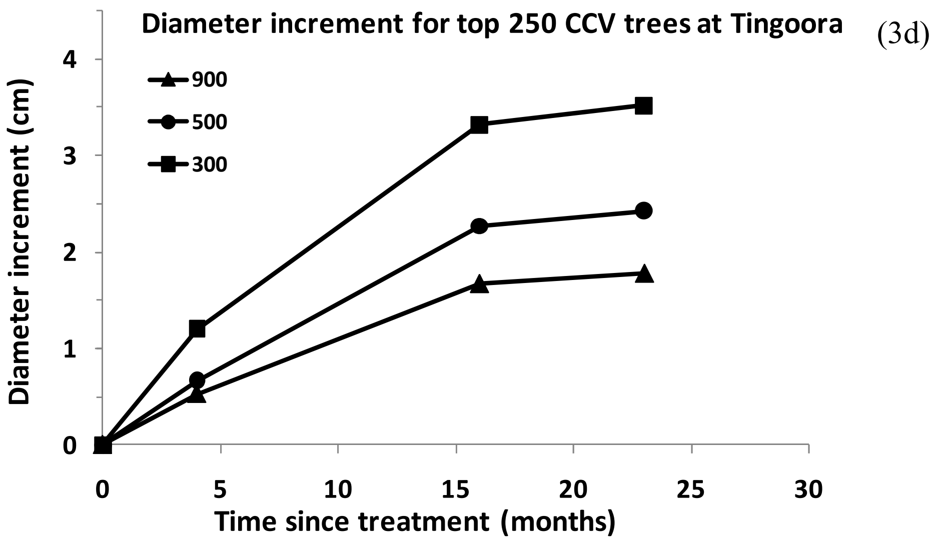


Figure 3: Diameter increment (cm) by treatment for *E. dunnii*: all (whole plot) trees at Reids (a) and Tingoora (b); top 250 stems/ha at Reids (c) and Tingoora (d)

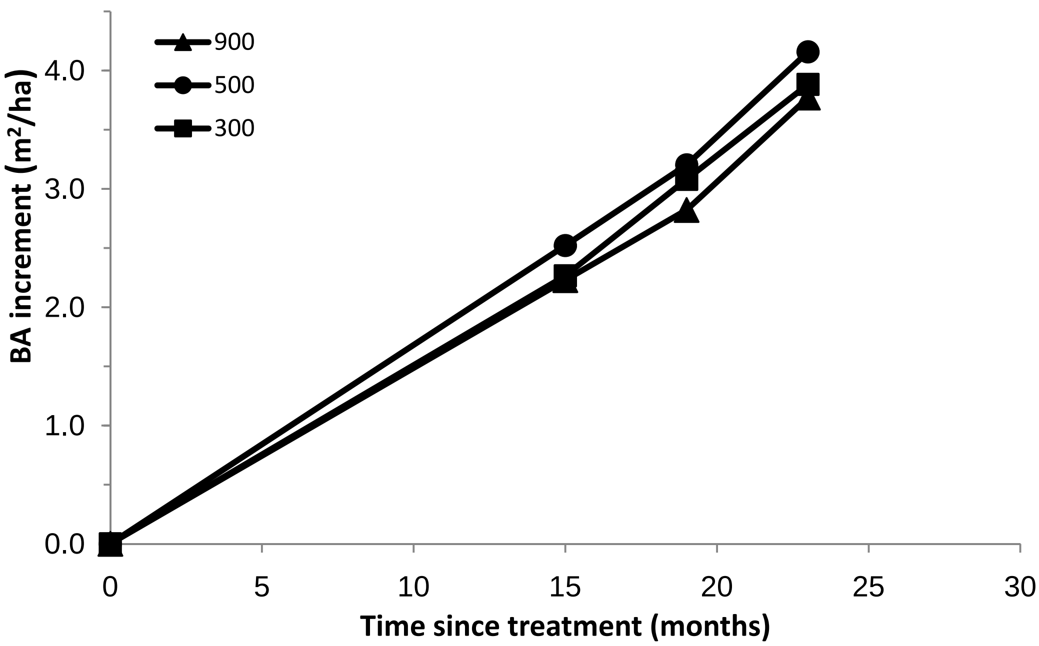
Basal area increment over the 24 months after thinning, E. dunnii

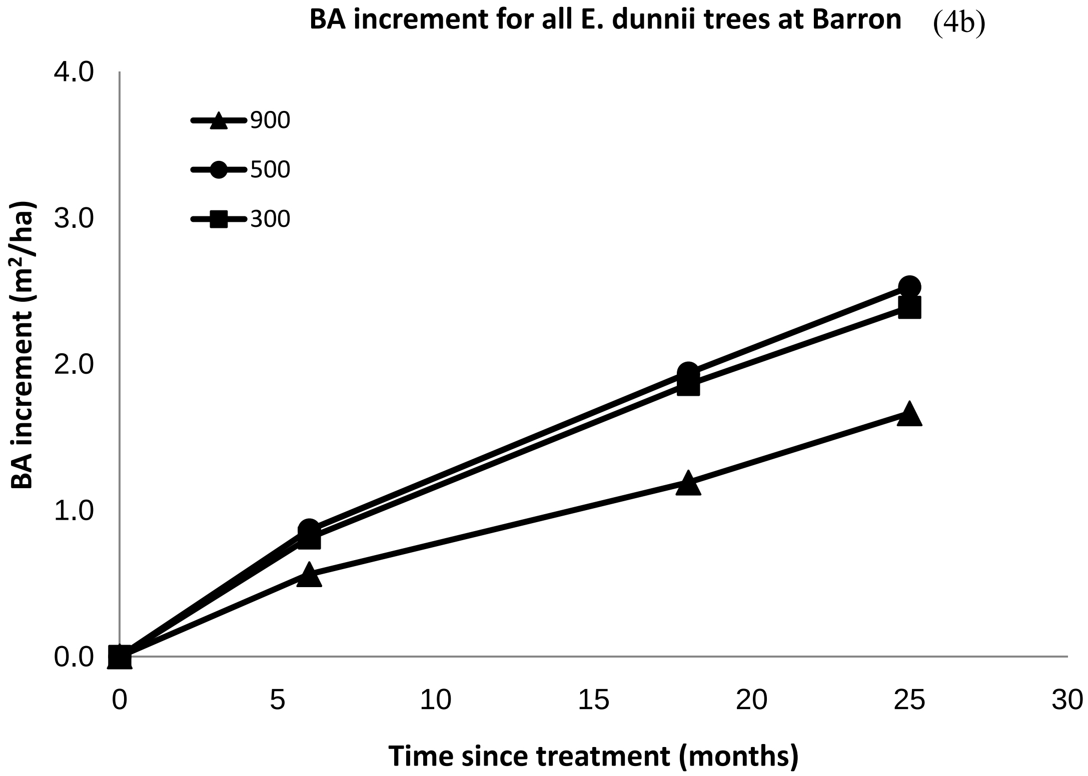
At Reids, basal area increment was significantly different ($p<0.05$) between treatments for the top 250 stems/ha but not for the whole plots; at Barron, basal area increment was significantly different for both whole plots and the top 250 stems/ha (Table 6). The basal area increment for whole plots in the unthinned control at Reids was 3.8 m^2/ha (Figure 4a); at Barrons it was 1.5 m^2ha (Figure 4b). The basal area increment for the top 250 stems/ha at Reids was 3.9 m^2/ha (Figure 4c). At Barron, basal area increment was significantly larger ($p<0.01$) in the thinned treatments than the unthinned control for whole plots trees and the top 250 stems/ha. In the 300 stems/ha treatment at Barron, the basal area increment of the top 250 stems/ha was 1.9 m^2/ha (Figure 4d); there were no significantdifferences between the 300 and 500 stem/ha treatments (Table 7).

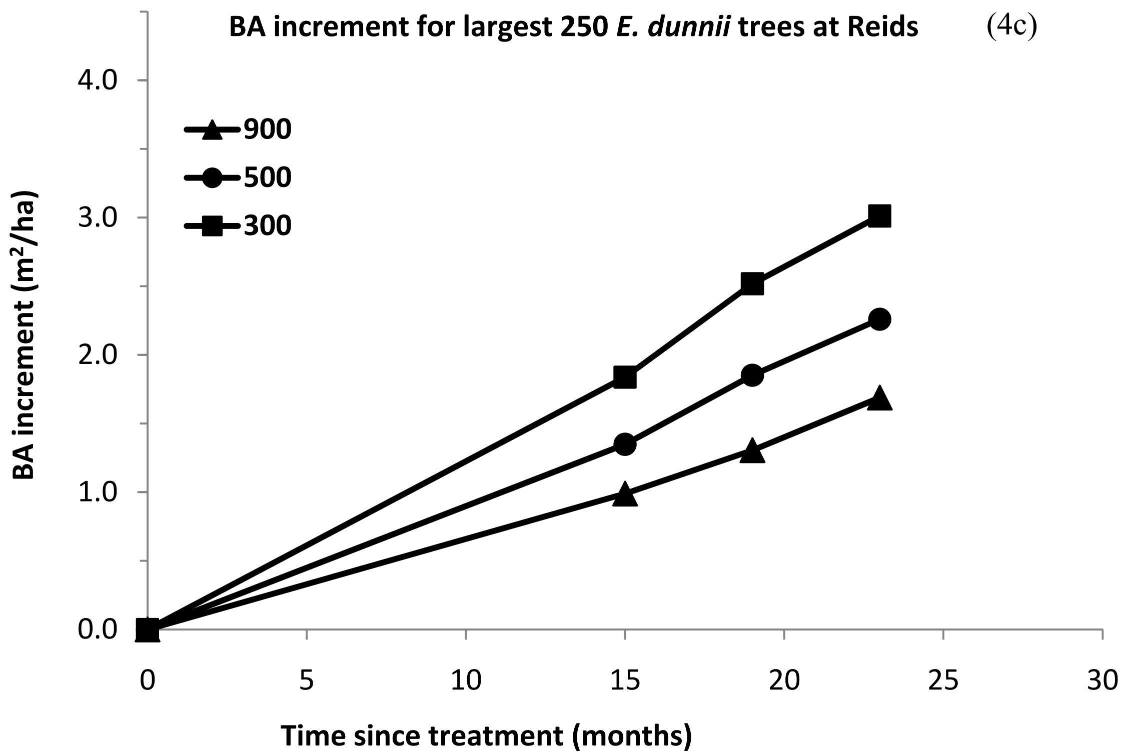
Table 6: Analysis of variance of basal area increment for each thinning trial, 24 months after thinning treatments were imposed, showing significance of difference between thinning treatments

Species		Site	Treatment d.f.	Residual d.f.	Variance ratio	*p*>F
E. dunnii	All trees	Reids	2	6	1.964	0.196
	Best 250	Reids	2	6	18.69	0.001
E. dunnii	All trees	Barron	2	6	8.428	0.009
	Best 250	Barron	2	6	34.472	0.001
CCV	All trees	Reids	2	6	0.148	0.864
	Best 250	Reids	2	6	6.664	0.017
CCV	All trees	Tingoora	2	4	1.206	0.363
	Best 250	Tingoora	2	4	13.033	0.007

BA increment for all *E. dunnii* trees at Reids (4a)




BA increment for all E. dunnii trees at Barron
(4b)
BA increment (m^2/ha)
Time since treatment (months)
900
500
300
0.0
1.0
2.0
3.0
4.0
0
5
10
15
20
25
30


BA increment for largest 250 *E. dunnii* trees at Reids
(4c)
BA increment (m^2/ha)
Time since treatment (months)
900
500
300
0.0
1.0
2.0
3.0
4.0
0
5
10
15
20
25
30

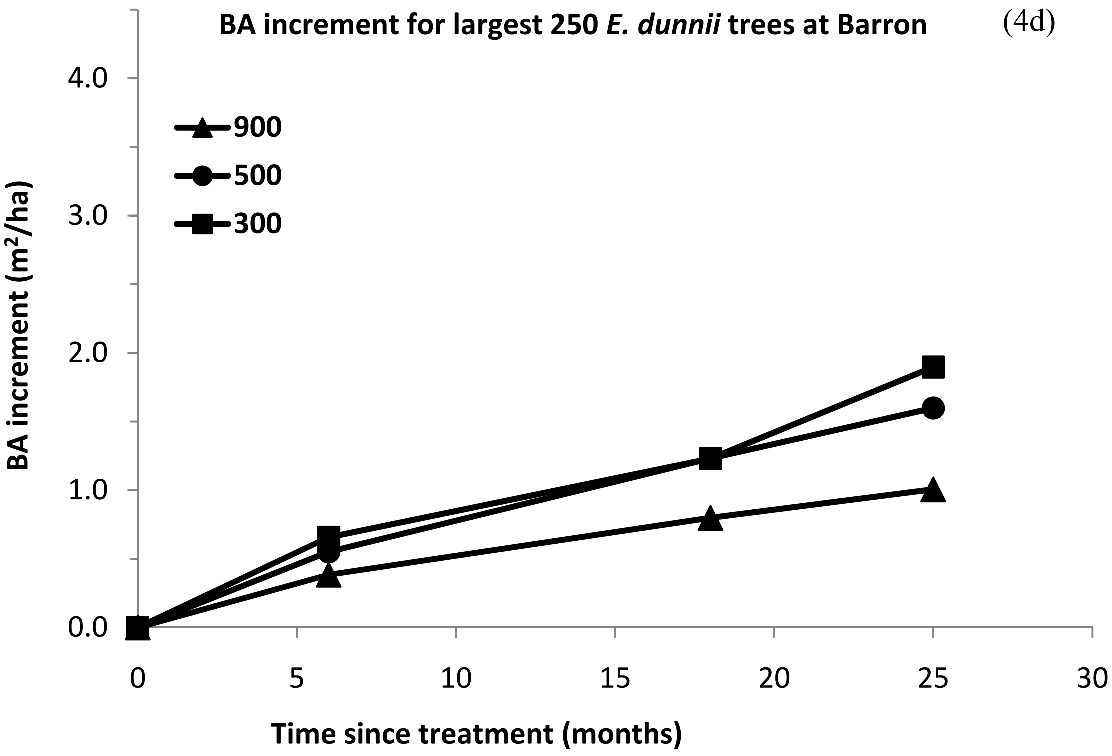


Figure 4: Basal area increment (m^2/ha) by treatment for *E. dunnii*: all (whole plot) trees at Reids (a) and Barron (b); top 250 stems/ha at Reids (c) and Barron (d).

Basal area increment after 24 months, CCV

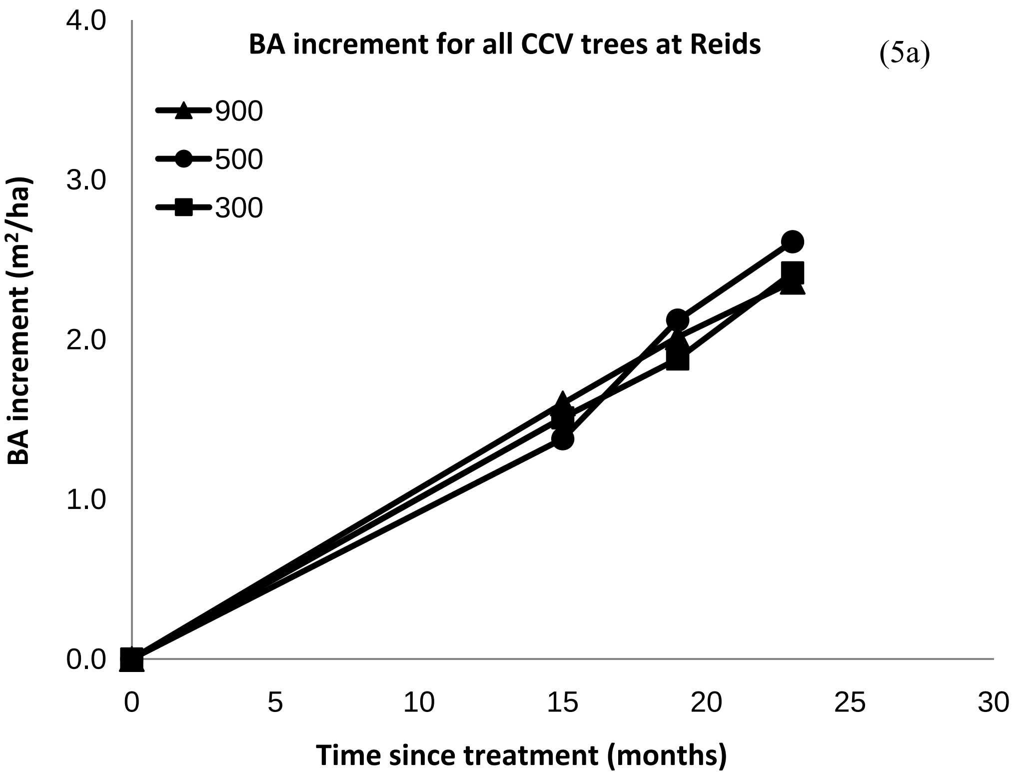
At both sites, the basal area increments were significantly different (p<0.02) for the top 250 stems/ha but not for the whole plots (Table 6). At Reids, the increments for the top 250 stems/ha in the 300 stems/ha treatment were significantly larger (p<0.05) than in the unthinned control; the 500 stems/ha treatment was not significantly different from the other treatments (Table 7; Figures 5a, 5c). At Tingoora, the increments for the top 250 stems/ha in the 300 stems/ha treatment were significantly larger (p<0.05) than in the unthinned control and the 500 stems/ha treatment (Table 7; Figures 5b, 5d).

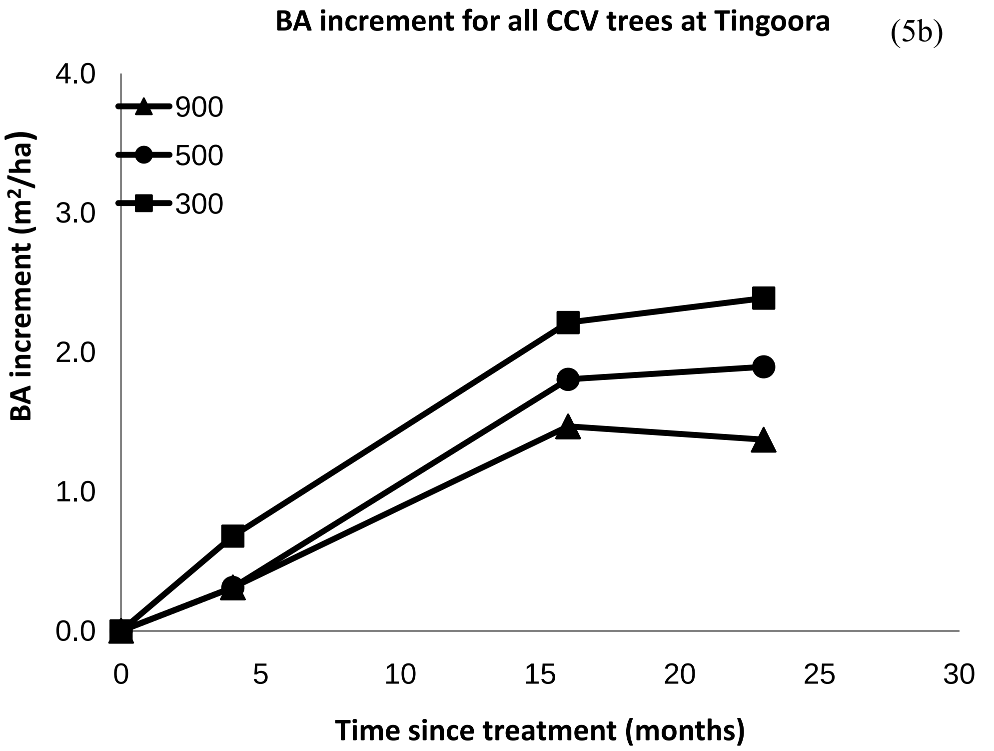
Basal area increment after 24 months, all trials

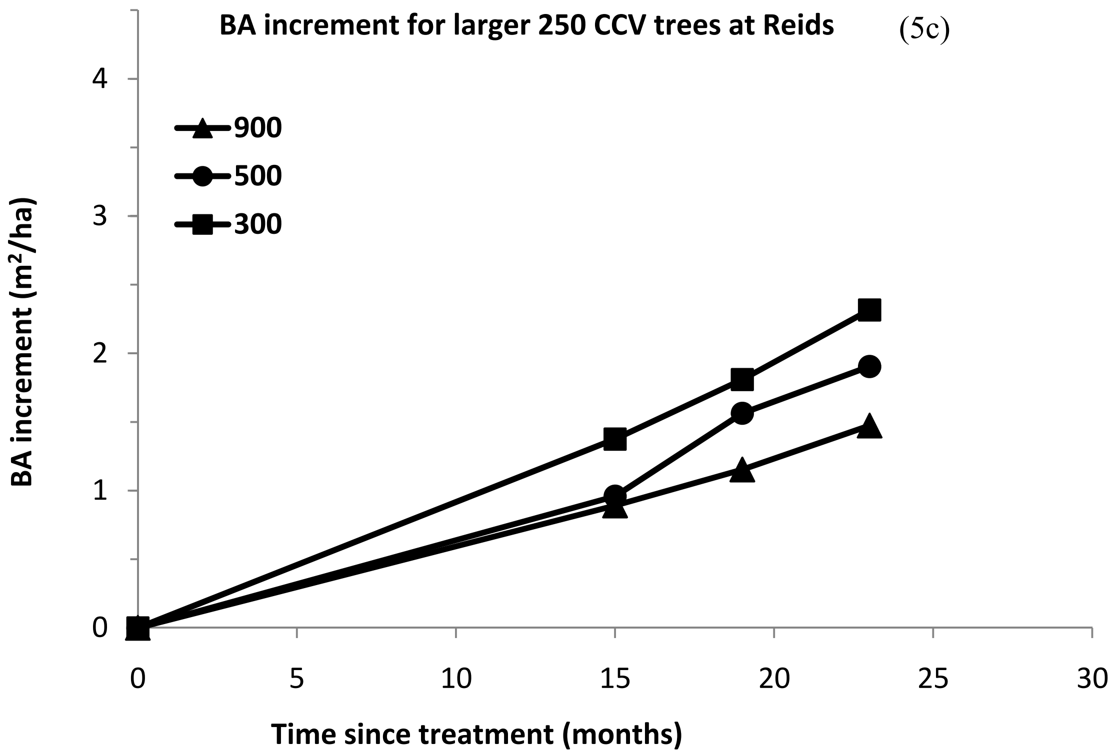
For whole plots, the largest basal area increment over the 24-month measurement period, 4.2 m^2/ha, was in the 500 stems/ha *E. dunnii* treatment at Reids (Table 7). For the top 250 stems/ha, the largest basal area increment over the 24-month period, 3.0 m^2/ha, was in the 300 stems/ha treatment at Reids (Table 7).

Table 7: Basal area increment (m^2/ha) for all trees and the largest 250 stems/ha in *E. dunnii* and CCV across all trials, 24 months after treatment. Values followed by the same letters are not significantly different (LSD α=0.05)

		Reids				Barron			
Species	**Treatment**	**Top 250 stems/ha**		**All trees**		**Top 250 stems/ha**		**All trees**	
E. dunnii	300	3.01	a	3.88	a	1.86	a	2.39	a
E. dunnii	500	2.26	b	4.16	a	1.6	a	2.53	a
E. dunnii	Control	1.69	c	3.77	a	1.0	b	1.66	b
		Reids				**Tingoora**			
CCV	300	2.31	a	2.42	a	2.16	a	2.39	a
CCV	500	1.92	a,b	2.61	a	1.28	b	1.89	a
CCV	Control	1.48	b	2.36	a	1.19	b	2.15	a




BA increment for all CCV trees at Tingoora
(5b)
900
500
300
BA increment (m²/ha)
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
25
30
Time since treatment (months)


BA increment for larger 250 CCV trees at Reids
(5c)
900
500
300
BA increment (m²/ha)
4
3
2
1
0
0
5
10
15
20
25
30
Time since treatment (months)

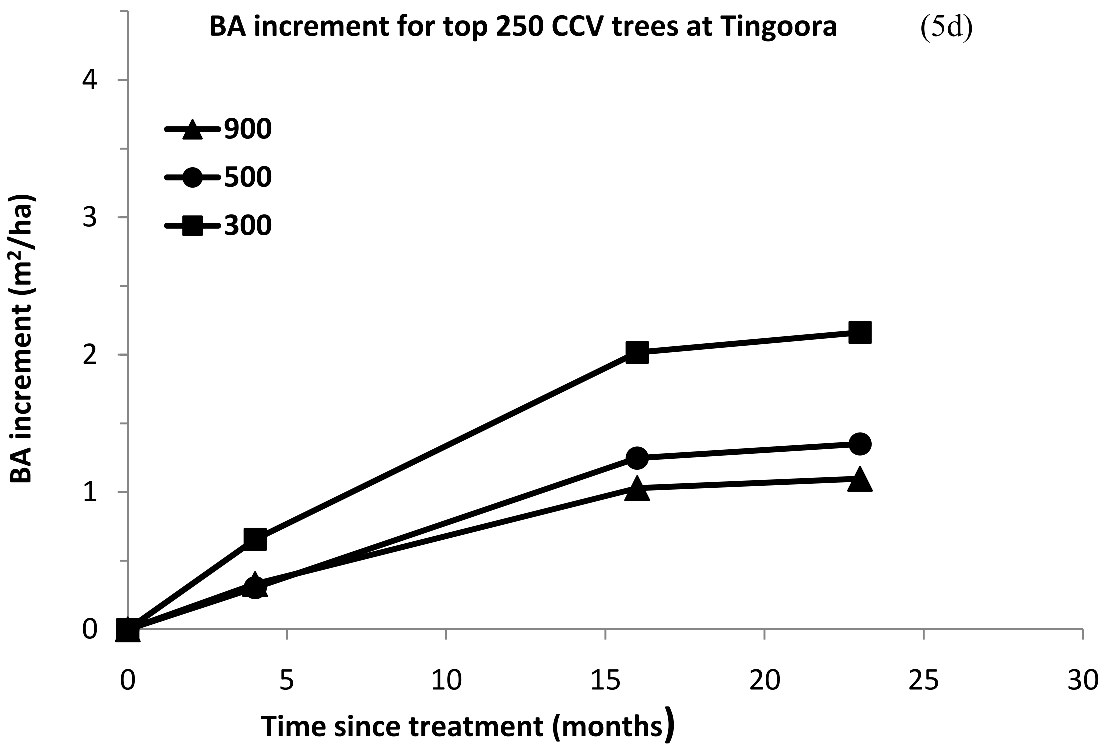


Figure 5: Basal area increment (m^2/ha) by treatment for *E. dunnii*: all (whole plot) trees at Reids (a) and Tingoora (b); largest 250 stems/ha at Reids (c) and Tingoora (d)

Discussion

At age seven to eight years, significant growth response to thinning was found in *E. dunnii* and CCV at two sites, within 24 months of treatment. A direct comparison of thinning response across sites is difficult because of biophysical and climatic differences. Previous work in subtropical eucalypt plantations would suggest that thinning at age seven to eight years is unlikely to be optimal for maximising the growth response (Smith & Brennan 2006). Nevertheless, diameter and basal area increments in this trial show that significant growth responses to thinning can be achieved at later ages in both relatively fast-growing (Reids) and slow-growing plantations (Barrons and Tingoora). The extent to which this growth in diameter increment can be sustained will be assessed through future measurements.

Solid-wood silvicultural regimes employ treatments that can produce the highest volume increment on the fewest possible trees, whilst not under-utilising site resources (Smith & Brennan 2006). To achieve this, solid wood growers often carry out an early, pre-commercial thinning (Nolan *et al.* 2005, West 2006) to ensure rapid early growth is concentrated on final crop trees. However, financial discount rates applied to forestry investments provide a disincentive to carry costs over the period of a rotation. Thus, the main MIS forestry company in the subtropics, FEA, was not planning any pre-commercial thinning. FEA anticipated a commercial thinning at eight to ten years would produce pulpwood from thinned material.

Unfortunately, the absence of a market for small logs, residue or pulp in the subtropics has left forest growers with limited prospects for thinning material (Nichols *et al.* 2010). There is a real need for new markets in small posts, poles and veneer logs. Developing sufficient log value will influence commercial returns in solid-wood production (Brown & Beadle 2008). Thinning has a significant role in improving log value, but it also provides opportunities to generate emerging products such as small veneer logs (<40 cm diameter) for composite products (Kennedy *et al.* 2010). The potential use of thinning material from subtropical plantations for rotary veneer peeling will be investigated as a part of this ongoing study.

Volume production rates per hectare (MAI) in the study sites are well below those considered to be commercially viable by Nolan *et al.* (2005), where an MAI of 20 m^3/ha is believed to be the minimum viable growth rate for solid-wood production. Lower rates of growth in this study can to some extent be attributed to the dry and hot climatic conditions in subtropical eastern Australia during the early stages of plantation establishment. Kingaroy, in particular, experienced extended periods of drought, with lower-than-average rainfall in almost every year of growth. Thinning coincided with especially dry conditions. The return to average or above-average rainfall in 2010 should assist future growth responses.

Prior to thinning at Reids, there were between-species differences in stand density, with 20% lower stocking in CCV than *E. dunnii*. The lower stocking appeared to be linked to shoot blight infection (*Quambalaria),* which has contributed to mortality and growth suppression of CCV across many subtropical sites (Nichols *et al* 2010). The reduction in stem numbers may have had some beneficial effects by reducing competition for resources among remaining trees.

Because log size is a key determinant of log value, rapid diameter increment of individual trees is important (Nolan *et al* 2005). Growth response of the largest trees in any stand is critical to determining the efficacy of thinning treatments in high-value, solid-wood production systems (Medhurst *et al.* 2001). In pulpwood regimes, the total volume production across all trees may be more important for growers. Since subtropical plantations are grown for both pulp and solid wood, this study is investigating the effects of thinning on larger trees, as well as all trees in a stand.

In CCV, a significant increase in diameter increment 24 months after thinning was found at both sites for both whole plots and the top 250 trees/ha. At Reids, the increase in DBH of the top 250 stems/ha in the 300 stems/ha treatment was 53% larger than in the unthinned control. At Kingaroy, for the same comparison, the DBH increment was 95% larger. Since CCV produces valuable sawn, pole and veneer products, the role of thinning will be particularly important in reducing rotation lengths and maximising high-value wood production.

For *E.* dunnii, the impact of thinning on DBH increment was similar for the top 250 stems/ha. At Reids, the increase in DBH of the largest 250 stems/ha in the 300 stems/ha treatment was 78% larger than in the unthinned control plots. At Kingaroy, for the same comparison, the DBH increment was 68% larger. Unlike CCV, the market for *E. dunnii* solid-wood products is not well developed, although Harwood *et al*. (2005) found that young plantation trees had good potential for sawn wood. The benefits of thinning *E. dunnii* may be even more important if an improvement in wood quality can be demonstrated.

High-intensity thinning may result in site resources being under-utilised immediately after thinning (Forrester *et al.* 2010). Basal area increment response was used in this study to determine if thinning treatments were resulting in site resources being underutilised. The results after 24 months indicated basal area increment was not significantly lower in thinned plots, indicating that site resources are being fully utilised even in heavy thinning treatments in the period after thinning. At Barrons, heavy thinning resulted in increased resource utilisation, with a 44% increase in basal area increment in the 300 stems/ha treatment compared with the unthinned control. A rapid growth response following thinning in temperate eucalypt plantations is indicative of a high degree of competition prior to thinning (Medhurst et al. 2001). Similarly, this rapid response across all trees in the thinned plots at Barrons may point to intense competition for site resources at the time of thinning.

Growth response to thinning has been found to vary greatly among species (West 2006). However, our results showed similar trends in diameter (DBH) and basal area increment in both species. Removing up to 60% of stand basal area had a positive impact on the larger, more commercially valuable trees in both species. The results in this trial are similar to others in temperate eucalypt plantations, where a later-age thinning also produced a growth response in *E. nitens* soon after treatment (Medhurst *et al.* 2001). These authors recommended a final stand density of 200 to 300 stems/ha to achieve an optimal basal area response.

The key findings of this study indicate that for both *E. dunnii* and CCV, a thinning intensity that reduces stand density to 200 to 300 stems/ha may provide the highest DBH and basal area response for the most commercially valuable trees. Thinning to 500 to 600 stems/ha also produced a thinning response, but this treatment requires the retention of trees of lesser commercial value. Higher levels of intra-specific competition in the 500 stems/ha treatment may, in time, reduce the extent of the growth response in this treatment.

Conclusions

In two widely planted subtropical species, *E. dunnii* and CCV, late-age thinning at age seven to eight years was found to result in significantly increased diameter growth of the retained trees, relative to an unthinned control, 24 months after treatment. A thinning operation that removed 50 to 60% of stand basal area was shown to produce a larger growth response for the most commercially valuable trees at each site than one that removed 20 to 30% of stand basal area. Thinning responses were observed at the productive, high-rainfall site and the less productive, low-rainfall site. Basal area increments in thinned treatments were not significantly different from unthinned controls, even when up to 50% of the basal area was removed, indicating that retained trees are efficiently utilising site resources in the initial period after thinning. Therefore, intensive thinning treatments can produce larger logs on crop trees without a significant loss in basal area production.

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