

## The effect of initial planting density on branching characteristics of *Eucalyptus pilularis* and *E. grandis*

Dean Kearney<sup>1</sup>, Ryde James<sup>2</sup>, Kelvin Montagu<sup>1,5</sup> and R. Geoff B. Smith<sup>3,4</sup>

<sup>1</sup>Land Management and Technical Services Division, Forests New South Wales, PO Box 100, Beecroft, NSW 2119, Australia

<sup>2</sup>Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia

<sup>3</sup>Land Management and Technical Services Division, Forests New South Wales, PO Box J19, Coffs Harbour, NSW 2450, Australia

<sup>4</sup>Corresponding author email: GeoffSm@sf.nsw.gov.au

<sup>5</sup>Present address: School of Environment and Agriculture, The University of Western Sydney

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### Summary

Branch-related defects can significantly decrease the quality of plantation eucalypt logs grown for solid-wood products. In this study we examined the effect of initial spacing on branching characteristics of 5-y-old plantation-grown *Eucalyptus grandis* and *E. pilularis* on the North Coast of New South Wales. For each sample tree all branches on the lower stem (the butt log, 0.3–6 m) were assessed for diameter, angle and condition. Trees were sampled in plots grown at four initial planting densities: 838 (3 m × 4 m), 1111 (3 m × 3 m), 1667 (3 × 2 m) and 3333 (3 m × 1 m) trees ha<sup>-1</sup>. The butt log of both species contained 55–70 branches, regardless of the initial density. Initial density did not affect branch formation, but it did affect the subsequent growth and persistence of branches. Lower initial density increased both the mean branch diameter and the number of large branches (>2.5 cm diameter) per tree in both species. Branch size also increased with height up the stem, but the rate of increase was not different between densities. A major difference between species was that *E. pilularis* had more small dead branches that had not been shed. A single spacing prescription is possible for both species because there was no difference between species in the relationship between large branches and density.

**Keywords:** plantations; stand density; branching; canopy; pruning; tolerance; dynamics; *Eucalyptus grandis*; *Eucalyptus pilularis*

### Introduction

The last decade has seen a rapid expansion in the rate of planting of eucalypts across Australia. In 2002 close to 50 000 ha of new plantings were established (BRS 2003), most of which were aimed at producing pulpwood. Plantings to produce high-value, solid-wood products have also increased rapidly, particularly in New South Wales (NSW), Queensland and Tasmania. The increase in planting is partly in response to the Commonwealth Government's 2020 Vision for increased plantation establishment (C of A 1997), but has also been driven by the restriction of timber harvesting in large areas of native production forest. Projected supply shortages

of high-quality hardwood logs throughout the Asia-Pacific region also provide a future target market for this resource (FAO 1999).

Sawing studies of a number of eucalypt species have clearly shown that branches are the major cause of defect in timber sawn from plantation-grown logs (Waugh and Rozza 1991; Waugh and Yang 1994; Yang and Waugh 1996a,b). Unlike native forests, where natural branch-shedding processes and long rotations can be relied on to produce high-quality logs, new plantations must produce high-quality wood within strict economic timeframes. This necessitates active and appropriate silviculture. The problem is not a new one for forest managers. Techniques such as pruning (e.g. Craib 1939) and control of branch size by planting density (e.g. Fenton 1971) have long been used to reduce branch-related defects in species such as *Pinus radiata*. The challenge is to determine how such techniques can be effectively applied to eucalypt species. The growth habits of eucalypts have been described extensively by Jacobs (1955) and more recently reviewed by Florence (1996). The major difference (of importance to silviculture) between pines and eucalypts is the natural tendency of eucalypts to rapidly shed their branches in closed-canopy conditions, and the complex process of occlusion of branch stubs following branch shedding. This process has been described by Jacobs (1955) as a series of progressive steps in which the branch dies and an abscission zone is formed where the xylem of the branch becomes blocked and subsequently brittle. With the growth of the stem the branch becomes more horizontal in orientation and is eventually shed by the pressure of stem growth, with part of the branch abscission zone remaining within the stem to be occluded by the continuing growth of the stem.

Studies of the response of branches to variation in planting density are comparatively rare. Sutton (1970) reported on measurements taken in New Zealand from eight spacing trials of *P. radiata*. There was a consistent trend of increasing branch size with reduced initial density. Neilsen and Gerrand (1999) found a similar trend in *E. nitens*. Both the mean diameter and the number of large branches (>36 mm diameter) increased at lower densities.

Large branches have implications for disease entry after pruning (Nielsen and Gerrand 1999) and are more persistent (Jacobs 1955). The rate of crown rise for *E. nitens* was slower than for both subtropical species in this study — *E. grandis* and *E. pilularis* (Montagu *et al.* 2003).

The branch size and shedding characteristics of subtropical eucalypts were expected to differ between species because of the species' differing degrees of shade tolerance, self-pruning and growth patterns. While neither of the two species investigated in this study can be described as shade tolerant, *E. grandis*, a member of the *Symphyomyrtus* sub-genus, is less tolerant than *E. pilularis*, a member of the subgenus *Monocalyptus* (Florence 1996). Growth patterns also differ — the annual volume increment for *E. grandis* may peak at an age as early as 6 y, whilst that for *E. pilularis* may peak at ages as late as 20 y (Florence 1996). It follows that within-species competition can be expected to occur at an earlier age for *E. grandis* and that this will in turn affect the way in which branches grow, are suppressed and are shed. Using silvicultural techniques to control branches involves either pruning them off or establishing stands at a density sufficient to cause early suppression and shedding; or some combination of both techniques (Nielsen and Wilkinson 1990). Before an effective prescription can be nominated for eucalypt plantations it is necessary to quantify the growth and branch habits of each species under conditions of varying planting density.

This paper reports on a study which quantified the effect of initial planting density on the branching characteristics of two contrasting eucalypt species, *E. pilularis* and *E. grandis*. We discuss ways in which defects in sawn timber resulting from branches might be minimised.

## Methods

### Site description

Spacing trials were established in 1994 of *E. pilularis* (Kennaicle Creek; 30°32'S, 152°49'E, 82 km from Coffs Harbour) and *E. grandis* (Hardacres; 30°09'S, 153°04'E, 25 km from Coffs Harbour). Prior to establishment the Kennaicle Creek site was used for extensive grazing and the Hardacres site was formerly a seed orchard for *P. taeda*. The seed source for the *E. grandis* trial was Wedding Bells seed orchard but that of the *E. pilularis* is unknown, although it would have been from a routine collection and not genetically improved. Both trials were established with trees planted into ripped lines. At the Kennaicle Creek location (*E. pilularis*), drought after planting and browsing by local fauna resulted in one of the three replicate blocks being destroyed. There was very little mortality in the remainder of the plots, ensuring the integrity of the spacing treatments. Both sites were of high quality (although Kennaicle Creek was the better); the soils were well drained and of relatively high fertility with mean annual rainfall of 1600 and 1250 mm respectively.

The two trials had a randomised complete block design with four initial density treatments, each replicated three times. All treatments were based on an inter-row spacing of 3 m. Treatments varied by the within-row distance between trees of 1, 2, 3 or 4 m; resulting in initial densities of 3333, 1667, 1111 and 838 stems ha<sup>-1</sup>, respectively. Although in the following account we relate differences between the two trials to the two species, it is

important to recognise that species effects are confounded with any site effects.

### Tree and branch measurement

When the trees were 5 y old, a total of 30 trees for *E. grandis* and 20 trees for *E. pilularis* were sampled from each of the four spacing treatments. Ten trees of good form were randomly selected within the central portion of each plot. For each tree, diameter at breast height, total height, diameter at 6 m, height of the base of the living canopy and dominance class were recorded. For each branch, branch height on the stem, branch diameter at the junction of the stem, branch angle with the stem and branch condition were measured. Branch condition was recorded as live, senescent, dead intact branch, stub or occluded. A 'senescent' branch was defined as one that supported only a few leaves of moribund appearance and where the bark showed formation of a brittle zone; a 'stub' was where only a branch stub was visible and 'occlusion' referred to an occluded branch whose location was still recognisable by external features of the bark. These attributes were recorded for all branches between heights of 0.3 and 6.0 m. The response of branch parameters to variation in density was tested using regression, and the significance of the relationship tested on the basis of  $P > |t|$ .

## Results

The *E. pilularis* sample trees were taller and had larger average diameter than the *E. grandis* trees (Table 1). For both species, there was a general trend for trees to be smaller (diameter at breast height, dbh) at higher initial densities, and for the green crown base to be higher at higher initial densities. The proportion of sample trees within each dominance class was not significantly different for the different spacings (Fisher's exact test  $df = 6$ , *E. grandis*  $P = 0.65$ , *E. pilularis*  $P = 0.38$ ). However, the number of dominant trees was greatest, and of sub-dominant trees least, in the *E. pilularis* lowest initial density treatment (833 trees ha<sup>-1</sup>). The number of trees of each dominance class sampled is given in Table 1.

### Branch frequency and distribution

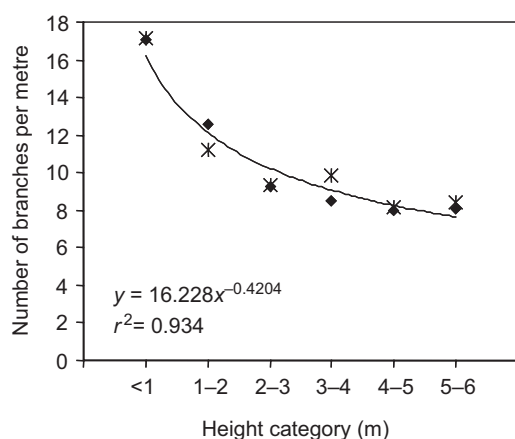
The range of mean branch numbers per butt log (i.e. to 6 m) recorded for the sample trees was not significantly different across treatments, for either species. (This was tested using the Tukey–Kramer HSD comparison function, SAS 1997). Within the range of initial densities examined, *E. grandis* and *E. pilularis* trees produced about 64 branches in the first 6-m length of merchantable stem. For both species, the number of branches per lineal metre of stem decreased as height increased up the stem (Fig. 1). In both species there were 17 branches m<sup>-1</sup> at the base of the tree, reducing to about 8 m<sup>-1</sup> at between 5 and 6 m in stem height. There was no difference in branch numbers, at any height, as a result of the planting density.

### Branch state

As the number of branches in each density treatment and species were not significantly different, branch condition could be compared directly. The greatest difference between the species

**Table 1.** Mean dbh, height and height to the base of the green crown of sample trees at age 5 y (standard deviations in brackets). 'Dominance' gives counts of dominant (D), codominant (C) and subdominant (S) trees sampled per experimental treatment

Species and initial density (stems ha <sup>-1</sup> )	Sample	Dominance D:C:S	Dbh (cm)	Height (m)	Green height (m)
<i>Eucalyptus grandis</i>					
833	30	7:21:2	13.2 (1.7)	16.7 (1.3)	7.0 (1.2)
1111	30	7:21:2	13.9 (1.8)	18.4 (1.8)	9.4 (1.6)
1667	30	3:26:1	12.6 (1.8)	18.6 (2.5)	11.1 (1.7)
3333	30	7:20:3	10.9 (1.3)	15.8 (1.5)	11.0 (1.4)
<i>E. pilularis</i>					
833	20	11:8:1	16.5 (2.0)	18.7 (2.2)	7.7 (2.1)
1111	20	6:12:2	15.7 (2.7)	18.3 (2.2)	10.2 (1.6)
1667	20	6:10:4	13.8 (2.5)	18.1 (2.3)	11.7 (2.2)
3333	20	6:9:5	12.1 (1.5)	17.7 (1.6)	12.1 (1.5)



**Figure 1.** Number of branches per metre with increasing height up the stem for *Eucalyptus pilularis* (diamond) and *E. grandis* (star). The species exhibit a similar reduction in branch numbers over the first 3 m. Above 3 m the number of branches stabilises in both species at about eight branches per metre. Initial planting density had no effect on branch number in either species.

was the greater number of dead branches in *E. pilularis* compared to a greater number occluded in *E. grandis* (Fig. 2). *Eucalyptus pilularis* was less efficient in shedding dead limbs. The proportion of branches that were still alive (or senescent) was very small in both species and was strongly related to planting density (Table 2; Fig. 2). The number of trees with no live branches in the butt log was greater in *E. pilularis* than in *E. grandis* in all but the 3333 trees ha<sup>-1</sup> treatment (Table 2).

### Branch size

Branch diameter was significantly affected by initial density and height up the stem, although these two factors explained only a small proportion of the total variation in average branch diameter. An analysis of covariance for each species showed branch size increased with height at a rate of about 1 cm m<sup>-1</sup> of height (*E. pilularis*  $P < 0.01$   $r^2 = 0.36$ , *E. grandis*  $P < 0.01$   $r^2 = 0.28$ ). Branch size was significantly greater at lower initial densities for both species, but the rate of increase in branch size with height was not significantly different between spacing treatments. The

difference in average branch diameter due to initial density was less than the increase due to height (<0.5 cm difference between the lowest and highest density for both species). Apart from the difference between spacing treatments the greatest difference in the distribution of branch diameter was the higher proportion of branches < 1 cm in diameter in *E. pilularis* than in *E. grandis*. In *E. grandis* the equivalent branches were occluded because the proportion of branches > 1 cm diameter was very similar for both species (Fig. 3).

Statistical parameters describing patterns in branch diameter were influenced by the large number of small branches. Patterns in large branches were therefore analysed separately as they were more persistent, had a greater effect on wood quality and showed a clearer response to density. Jacobs (1955) suggested that branches with a diameter > 2.5 cm may not be cleanly ejected by the usual process of branch shedding — therefore the number of branches per tree > 2.5 cm in diameter and the mean diameter of the largest branch per tree were tested. The number of branches per tree > 2.5 cm in diameter in each of the density treatments decreased exponentially for both species (Fig. 4). The number of large branches was related to the number of trees without large branches due to variation between trees. The variation between trees resulted in an increasing number of trees with no large branches in the lower 6 m of stem as initial planting density increased. This results in a linear increase in the number of trees without large branches, a relationship that is not significantly different between species (Fig. 5).

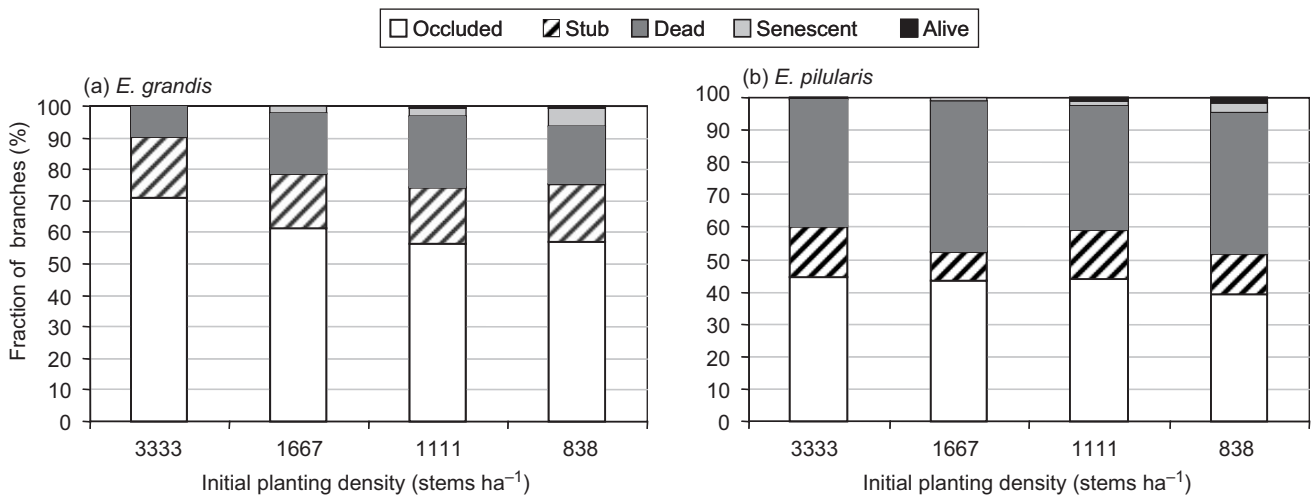
Branch size is not simply a function of density as larger (dominant and codominant) trees within a stand tend to have larger branches. Both spacing and tree diameter were found to be significant predictors of largest branch per tree. In both cases, however, although the models were highly significant, the  $r^2$  values were low (Table 3). Dominance class was not a significant predictor variable when tree diameter was included in the model.

Branch angle was related to branch shedding. Jacobs (1955) noticed that branches tend to be closer to horizontal when they were about to be shed, and where branches persist at a high angle they do not shed efficiently. High-angled branches were defined as those at an angle of 50° or more above the horizontal. The number of high-angled branches within the examined stem section

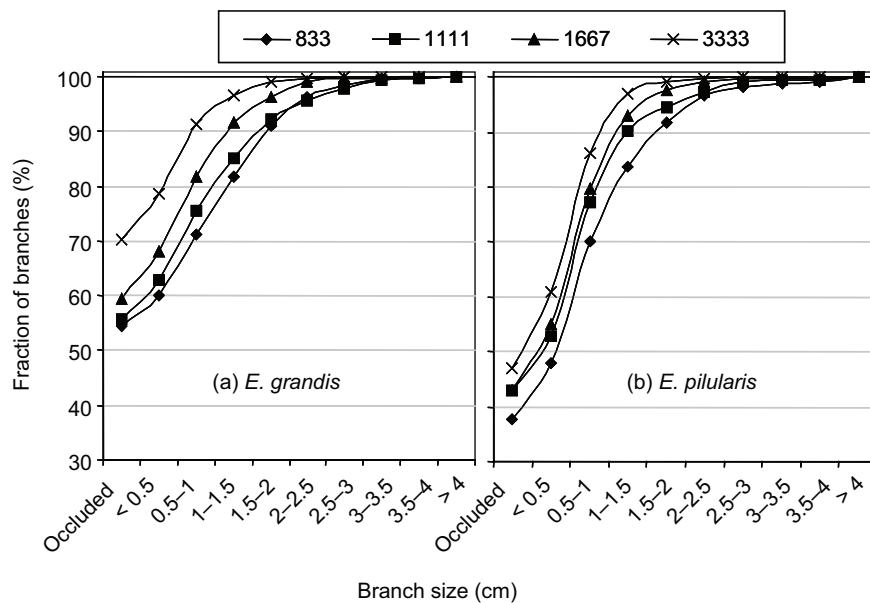
**Table 2.** Density of sample trees without any living or senescent branches below a height of 6 m at age 5 y, and the mean number of living or senescent branches per tree below a height of 6 m

Initial density (trees ha <sup>-1</sup> )	<i>Eucalyptus grandis</i>			<i>E. pilularis</i>		
	Density of trees (trees ha <sup>-1</sup> )		No. of living or senescent branches per tree	Density of trees (trees ha <sup>-1</sup> )		No. of living or senescent branches per tree
	Without*	With*		Without*	With*	
833	0	833	5.2	305	528	4.4
1111	148	963	3.3	556	556	2.4
1667	500	1167	2.6	889	778	1.9
3333	3000	333	1.0	2111	1222	1.5

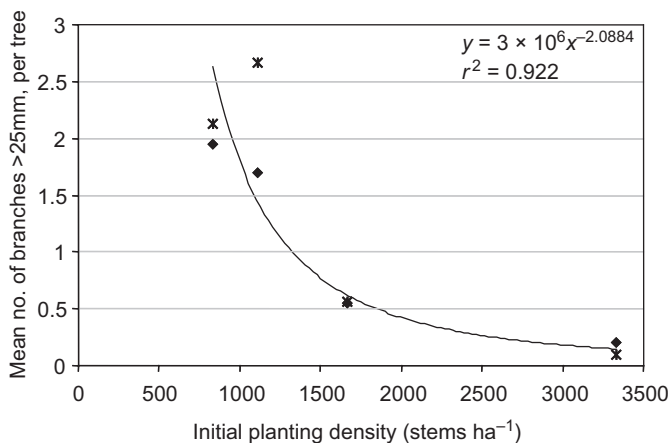
\*Living or senescent branches below a height of 6 m



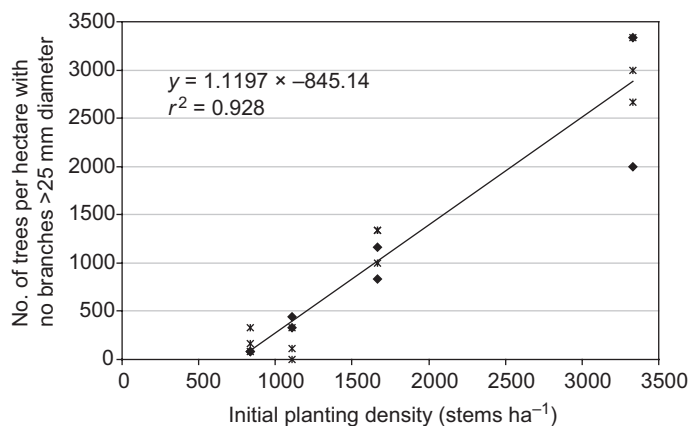
**Figure 2.** Branch condition in the lower 6 m of stem of *Eucalyptus pilularis* and *E. grandis* at four initial planting densities



**Figure 3.** Branch diameter distribution at age 5 y for *Eucalyptus pilularis* and *E. grandis* for each initial planting density. *E. grandis* produced more large branches at lower densities, evident as a separation of the distributions.



**Figure 4.** The number of branches with diameter >2.5 cm shows the same relationship for both species (*Eucalyptus grandis* — star; *E. pilularis* — diamond). The number decreases rapidly with initial planting density.



**Figure 5.** The number of trees per hectare with no large branches for *Eucalyptus grandis* (star) and *E. pilularis* (diamond) at four planting densities.

increased as the initial density decreased for *E. grandis* ( $P < 0.0001$ ,  $r^2 = 0.88$ ). The relationship for *E. pilularis* was not so clear ( $P = 0.053$ ,  $r^2 = 0.49$ ).

**Discussion**

When the major objective of establishing eucalypt plantations is to produce high-quality solid-wood products, the major cause of downgrade in the produce is knots and other branch-related defects. By quantifying the branching characteristics of two contrasting plantation eucalypt species and how they are modified

by stand density or spacing we have provided a basis for silvicultural regimes that maximise the production of high-quality wood. For both *E. grandis* and *E. pilularis*, the first 6-m log length will contain 64 ( $\pm 7$ , the standard deviation) branches, regardless of initial density. In both species the rate of branch initiation will reduce with height, from about 18 branches  $m^{-1}$  at ground level to about 8 branches  $m^{-1}$  at the top of the 6-m butt log. The reduction in branch number was associated with an increase in branch diameter, and this was also related to spacing such that the largest branches were found on trees at the lowest initial density (or those with the greatest growing space per tree). Initial planting density has no influence on the number of branches formed, but influences later development as the stand forms a canopy and neighbouring trees begin to compete and shade one another. The timing of onset of this process varies with initial spacing, wider spacings taking longer to form an effective canopy.

Initial planting density has a strong influence on the light environment of the tree canopy. At higher planting densities, branches are shaded earlier than at low densities. Any differences in branch properties between species could be expected to be an expression of differences in shade tolerance. Although each species was examined only on a single (and different) site, the two sites were of high quality. Other factors that affect canopy dynamics and branch development and that may limit growth (such as water or nutrient limitation) are unlikely to occur at a young age on such sites. *Eucalyptus pilularis* is generally more tolerant than *E. grandis* (Florence 1996), but both species had only a very small number of live branches. The similarities between the species found at the densities in this study suggest that tolerance doesn't have as large an effect on branching as may be evident at the much higher densities found in native forests. The main difference between the species was the rate of occlusion of small branches, and the process confirms Jacobs' (1955) description of eucalypt branch death and shedding under plantation conditions. At age 5 y, 57–71% of branches in *E. grandis* trees were found to be ejected or occluded — depending on spacing (Fig. 3). For *E. pilularis* only 40–47% were shed by the same age, and the influence of stand density was less pronounced. The two species demonstrated two important distinct steps in the process of self-pruning: crown rise (branch death) and the subsequent shedding of dead branches. *Eucalyptus pilularis* has rapid crown rise but less efficient branch shedding. *Eucalyptus grandis* crown rise is less efficient (live branches tend to persist) but dead branches are rapidly shed.

Although differences between species were observed in branch development, these would probably have few implications for stand management due to the variation between trees. The number of trees per hectare without large branches (>25 mm), for a given initial density, was similar in both species. Therefore if the best

**Table 3.** Regression results for mean largest branch per tree

Response variable — mean largest branch per tree	$r^2$	F
<i>E. grandis</i> : $0.04 + 0.26 \text{ SPACING}^\# + 0.12 \text{ dbhob}$	0.57	74 on 2,112 df
<i>E. pilularis</i> : $-0.35 + 0.33 \text{ SPACING}^\# + 0.14 \text{ dbhob}$	0.47	31 on 2,69 df

<sup>#</sup>SPACING = intra-row spacing in metres

trees in the stand are to be pruned or simply retained after a later thinning, any spacing prescriptions that aim for a sufficient density of trees without large branches would be applicable to both species. The spacing prescription would ideally require enough trees without large branches to be selected to fully occupy the site. This is usually in the order of 300 trees ha<sup>-1</sup> for pruning or 500 trees ha<sup>-1</sup> if an intermediate thinning is to take place for products such as poles. Our results suggest planting densities of >1250 trees ha<sup>-1</sup> would be necessary to achieve 500 trees ha<sup>-1</sup> of good quality at age 5 y (Fig. 5). Similar conclusions can be drawn regarding high-angle branches where similar relationships with stand density exist. The selection of trees without both high-angle and large branches, however, may require extra trees if these characteristics are independent of each other.

An apparent conundrum for selection is that the most desirable trees to be retained at thinning are typically the larger, dominant trees that have larger branches (Table 3). Within the stands at the lower three densities, a fairly constant number of trees per hectare have live branches (Table 2) and in stands at the lower two densities a fairly constant number per hectare have large branches (Fig. 5), suggesting that dominant trees develop according to the space available. The number of sample trees within each dominance class, however, was not significantly different between spacings, suggesting that there were more dominant trees at closer spacings. Therefore, trees were smaller at closer spacings (due to competition) but still had the same light regimes around the crown (dominance). So dominant trees within the closer-spaced treatments were smaller in dbh and therefore had smaller-diameter crowns and less live-crown depth (Table 1).

Until branches are shed, smaller tree diameter is an advantage for solid-wood products as this results in a smaller knotty core. It is the subsequent growth that forms the clear wood within the logs. The main question, then, is how trees will respond to release after growing at closer spacings and with smaller-diameter crowns, and at what age thinning will become necessary to avoid co-dominant trees without large branches becoming subdominant and suppressed within the stand. The productivity of *E. grandis* when grown primarily for pulp has been shown to be unaffected by the timing or intensity of thinning up to age 10 y (Schonau 1984). There are few data for the more tolerant *E. pilularis*.

As both these stands were derived from genetically unimproved stock, the conclusions may not be valid for improved or clonal stands where variation between trees would be expected to be much less. Branch characteristics are expensive to measure and so reporting of heritabilities for eucalypt species is uncommon (Raymond 2002). Heritability of branch thickness and angle may be very low (Whiteman *et al.* 1992), although a general visual estimate of branching gave medium heritabilities (Greaves *et al.* 2004). Given the variation between trees, if important branching characteristics are heritable they should be considered in tree improvement programs.

To produce high-quality wood products, silviculture must be aimed at reducing or eliminating knots and other branch-related defects (Donnelly *et al.* 2003; Montagu *et al.* 2003; Nolan *et al.* 2005). For plantations, economics may dictate a shorter rotation

than required for the natural branch-shedding process. The problem for the silviculturist is to find a cost-effective method of controlling the defects caused by branches.

Two solutions are commonly adopted in plantation management — encouraging the natural shedding of branches through planting densely, or pruning using techniques similar to those employed in softwood plantations. The application of pruning to plantation-grown eucalypt species is not as straight-forward as it is for pines. In *E. nitens*, the pruned stub can be ‘caught’ by stem growth and drawn out radially, leaving a trace of kino through potentially valuable clearwood (Gerrand *et al.* 1997). This has been observed by the authors in *E. grandis* in Australia and Argentina. This can be avoided if branches are pruned while they are living, when they tend to occlude in a more predictable manner similar to that of softwoods. The creation of a freshly cut stubs, however, can lead to an increase in the incidence of stem decay by providing entry points for decay organisms (Mohammed 2000).

The rapid rise of the base of the green crown, and hence branch mortality, may also complicate pruning regimes. The rate of occlusion of dead branches has been shown to be no different between pruned and unpruned branches in several sub-tropical species with contrasting crown dynamic behaviour (Smith *et al.* 2006). This is another reason to prune only live branches, although this may be difficult with rapid crown rise (Maree 1979; Montagu *et al.* 2003). It may be better to plant at lower densities to keep branches alive for pruning. Height to the base of crowns in *E. pilularis* was greater than in *E. grandis* in this study. The crown heights were influenced by the higher site quality of Kennaic Creek, where *E. pilularis* trees were larger and taller. Green crown length was not consistently different between species. Studies of crown rise over time are needed to understand the crown dynamics over the range of sites on which the species grow (Klootwijk 2001).

An alternative strategy to pruning is to plant at higher densities — thereby encouraging branch death and, in *E. grandis* at least, efficient shedding of the dead limbs — and to rely on the self-pruning of the species (Maree 1979; Bredenkamp *et al.* 1980; Schonau 1984). The effect of density on the height to the green crown was clear in this study (Table 1). The occlusion of dead branches must then be relied upon to create clear wood (Smith *et al.* 2006). The choice of a regime will require knowledge of changes in branch condition with time and particularly how the height of the base of the green crown changes with density and time (Klootwijk 2001) for these and other species. Although the spacings examined here were rectangular (with unequal dimensions within and between rows), this is not thought to have affected the conclusions, as other studies by Glass (1985) for *E. saligna* and Gerrand and Neilsen (2000) for *E. nitens* (plus unpublished data for *E. pilularis* held by the authors) indicate no effect of rectangularity within the range investigated in this study. Whether pruning or an alternative regime is the most appropriate silvicultural regime will depend on many factors, such as the crown dynamics of the species, as well as the ability of the market to utilise products of varying quality.

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