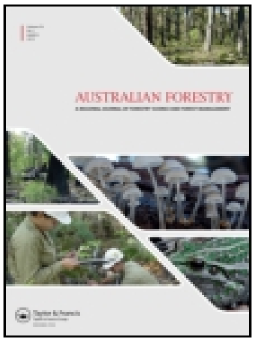

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The influence of site quality on timing of pruning in *Eucalyptus pilularis* and *Eucalyptus cloeziana* plantations

Philip J. Alcorn[1,8], David I. Forrester[2,3,4], R. Geoff B. Smith[5,6], Dane S. Thomas[5,7], Ryde James[1], Adrienne B. Nicotra[8] and Jürgen Bauhus[2]

[1]Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia
Email: phibibert@hotmail.com; Ryde.james@anu.edu.au
[2]Chair of Silviculture, Freiburg University, D-79085 Freiburg, Germany
Email: david.forrester@waldbau.uni-freiburg.de; Juergen.bauhus@waldbau.uni-freiburg.de
[3]Department of Forest and Ecosystem Science, The University of Melbourne, 500 Yarra Boulevard, Richmond, Victoria 3121, Australia
[4]Cooperative Research Centre for Forestry, Private Bag 12, Hobart 7001, Australia
[5]Forests NSW, PO Box J19, Coffs Harbour, NSW 2450, Australia
Email: dane.thomas@sa.gov.au; smith.rgb@gmail.com
[6]Forest Science Centre, School of Environment, Science and Engineering, SCU, Lismore, NSW 2480, Australia
[7]South Australian Research and Development Institute (SARDI), Climate Applications, GPO Box 397, Adelaide, SA 5001, Australia
[8]Research School of Biology, The Australian National University, Canberra, ACT 0200, Australia
Email: Adrienne.nicotra@anu.edu.au

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Summary

Maximising the production of knot-free (clear) wood can be achieved by early removal of branches from the lower crown. Ideally, this is carried out without reducing stem growth or the competitive status of the pruned tree. The decision surrounding the time to prune in *Eucalyptus* species is influenced by stem- and branch-diameter development, the rate of branch senescence and ejection on the lower stem, the timing of canopy closure and the proportion of leaf area that can be removed before growth is reduced. In this study, the effect of site quality on stem, branch and crown development was examined in 1.5- to 6.5-y-old *Eucalyptus pilularis* Sm. and *E. cloeziana* F.Muell. trees from plantations across north-eastern New South Wales, Australia. Results from 27 plantations established on former pastures showed that site quality influenced height, diameter growth, and live-crown rise in both species, but it influenced maximum branch diameter in *E. cloeziana* only. Using regression relationships and threshold values for stem, branch and crown variables considered critical to determine the timing of pruning, decision matrices for low (0–2.9 m), high (0–5.5 m), and multiple (0–2.9 m then 2.9–5.5 m) pruning regimes were developed to provide a practical guide to identify the age at which stands could be considered for pruning. For *E. pilularis* the rate of branch senescence will strongly influence the timing of pruning, while in *E. cloeziana* the timing of pruning will largely be driven by branch diameter growth on high-quality sites and branch senescence on medium- and low-quality sites.

Keywords: pruning; branches; crown; architecture; *Eucalyptus pilularis*; *Eucalyptus cloeziana*

Introduction

In the sub-tropical region of New South Wales, Australia, the establishment of plantations for solid-wood products has preceded much in-depth knowledge of how to treat stands silviculturally to ensure that high-quality clear-wood is produced. Increasing the density of stands to restrict branch development and induce early natural branch shedding reduces individual tree growth and may not maximise clear-wood production in two commercially important eucalypt species, *E. pilularis* Sm. and *E. cloeziana* F.Muell. (Alcorn *et al.* 2007). On the other hand, increased stand density may be an alternative to pruning if branch stub occlusion occurs at a similar rate for pruned live branches and naturally-shed dead branches, and if the costs of pruning outweigh any reduction in clear-wood yield due to increased competition resulting from higher stockings to control branching (Smith *et al.* 2006, 2010). When this is not the case, wider spacings should be combined with artificial pruning to maintain growth rates (to maximise clear-wood production) while improving wood quality and removing the uncertainty associated with natural branch-shedding processes (Alcorn *et al.* 2007).

Maximising clear-wood production is achieved by early pruning of branches from the lower stem to confine knot and knot-related defects to a small core of 10 (Bruskin 1999) to 15 cm stem diameter (Gerrand *et al.* 1997b; Pinkard and Beadle 1998b; Dickinson *et al.* 2000). In *Eucalyptus* species, this requires timing of pruning operations to strike a balance between achieving sufficient tree height that the leaf area removal has little negative influence on stem growth, yet preempting crown rise to avoid branch death before pruning (Wiseman *et al.* 2006) and minimising the area of pruning wounds by pruning branches while they are small and alive (Gerrand *et al.* 1997a; Pinkard *et al.* 2004). Pruning dead branches can cause branch stubs to become trapped in outer sapwood with the consequence that they are carried outward by the expanding tree, leaving a kino trace that degrades clear-wood timber (Gerrand *et al.* 1997a; Neilsen and Pinkard 2000). Dead pruned stubs may also provide an entry point for diseases (Smith *et al.* 2006). As a consequence, this may mean that those eucalypt species in which lower branches senesce rapidly owing to the rapid rise of the base of the live crown require pruning at a young age. Average stem diameter, height and branch size are positively related (for a given age) to site fertility, and canopy closure can occur earlier on more productive sites (Cromer *et al.* 1993). Therefore, if pruning is to achieve comparable results across a range of sites, the effects of site quality on crown development must be considered. However, most previous studies have reported the relevant aspects of crown dynamics only for single sites.

Pruning live branches reduces the photosynthetic area of tree crowns and can thereby reduce tree growth. Pruning experiments in a range of eucalypt species, including *E. pilularis* and *E. cloeziana*, have shown that removing less than 50% of the live-crown length will minimise impacts on tree growth and maintain the pruned stem's competitive status within the local neighbourhood (Alcorn *et al.* 2008; Forrester *et al.* 2010). Trees can maintain growth, despite losing half of the length of their live crown, by up-regulation of photosynthesis, rapid re-building of the crowns or changes in leaf morphology, and increased light- and water-use efficiencies of the remaining crown (Pinkard and Beadle 1998a, c; Pinkard 2003; Pinkard *et al.* 2004; Forrester *et al.* 2010, 2012b, 2013). Timing pruning to coincide with canopy closure may reduce the impact of pruning on tree growth (Pinkard 2002). Following canopy closure, the lower branches will become shaded and contribute proportionally less carbon to tree growth than before canopy closure or after thinning (Henskens *et al.* 2001; Medhurst and Beadle 2005). Pruning too soon before canopy closure (or in thinned stands) is likely to remove more-efficient foliage, leading to greater proportional losses in carbon assimilation (Forrester *et al.* 2012b, 2013).

Minimising the size of the occlusion zone between branch stubs and the clear wood is essential to achieving a small knotty core diameter with respect to log size. In current silvicultural regimes for pruning of eucalypts, the aim is to restrict the radial extent of occluded branch stubs to a maximum tree core diameter of 15 cm (Gerrand *et al.* 1997a; Dickinson *et al.* 1998). Since clear-wood is produced only following the occlusion of branch wounds, minimising the size of branches and their associated branch collars (swelling retained on the stems following pruning) will reduce the occlusion zone and restrict the diameter of the knotty core (O'Hara 2007). The close relationship between stem size and branch size reported for *E. globulus* and *E. nitens* (Neilsen and Gerrand 1999; Henskens *et al.* 2001; Pinkard and Neilsen 2003) means that early pruning will remove branches while they are smaller, with smaller branch collars, than later-age pruning.

From a wood quality perspective, the removal of large live branches is undesirable in *Eucalyptus* species. Studies in *E. nitens* have shown that the incidence and severity of fungal decay is very high in branch stubs greater than 30 mm in diameter, and in fact increases exponentially with the size of the pruning wound (Mohammed *et al.* 2000). Similarly, studies in *E. delegatensis* have shown that large pruning wounds result in greater risk of decay (Gadgil and Bawden 1981). For this reason, pruning prescriptions for eucalypts generally recommend avoiding pruning trees with branches larger than 25 mm (Gerrand *et al.* 1997a) or 30 mm (Gadgil and Bawden 1981) in diameter within the pruned zone.

Pruning prescriptions are not well developed for sub-tropical eucalypt plantations in north-eastern New South Wales, although it is generally agreed that for the production of high-quality veneer and clear-wood sawlogs the central knotty core should not exceed 15 cm diameter at breast height (1.3 m) for target stem diameters at harvest of 50–60 cm (Gerrand *et al.* 1997a; Dickinson *et al.* 2000). The current pruning prescription has been developed using height to crown-depth relationships, with little examination of how the development of branch size, stem size or crown will affect the timing of pruning. For this reason, there is a need to provide pruning recommendations based on current log sizes required for veneer production (stump height of 0.3 m and plywood log length of 5.2 m) in sub-tropical Australia (James 2001).

The objective of this research was to analyse how site quality and differences between species influence crown development and crown architecture, and how this should be considered to determine the timing of pruning. This was done by quantifying relationships between stand age and site quality, and important crown architectural traits (branch size, height of the lowest live branches, crown length) and stem diameter.

Methods

Study area and tree selection

Plots were established in 27 unpruned stands across the north-eastern region of New South Wales between Gloucester in the south and Lismore in the north (Table 1). The stands were in plantations selected on age class, species planted, stocking density and site information (aspect, elevation, position on slope). The aim was to sample the younger plantation age classes (17–80 months), containing *E. pilularis* and/or *E. cloeziana* at initial planting densities of 1000–1250 trees ha^{-1}. For each plantation site, stands that appeared visually different in height were mapped and separated into areas of a different site quality.

Trees were randomly selected from each plantation. To be selected, trees had to be considered potential crop trees by satisfying form and dominance selection criteria (Table 2). Around each of these trees a measurement plot was established that contained three by three trees, including the central measurement tree and eight neighbouring trees. All plots were at least four rows from the outside of the plantation to avoid edge effects. For each central measurement tree, height (h_T), stem diameter (d) at 0.3, 1.3 and 2.9 m above the ground, height of

Table 1. Summary of site details for *E. pilularis* (EP) and *E. cloeziana* (EC) plantations surveyed in north-eastern New South Wales

Site name	Approx. location	Longitude	Latitude	Mean annual rainfall (mm)*	Mean max. and min. temperature (°C)*	Age at assessment (months)	Species
Crab Tree	Coffs Harbour	153°6′13″	30°8′2″	1487	13.1–23.7	30	EP
Taylor	Bowraville	152°44′48″	30°38′17″	1421	12.4–23.6	31&43	EP/EC
Woodcock	Wauchope	152°34′27″	31°25′58″	1366	12.2–23.2	58	EP/EC
Mid-coast Water	Taree	152°29′1″	31°52′27″	1205	12.6–23.8	30	EP/EC
Glady	Wingham	152°19′32″	31°45′6″	1189	12.1–23.6	43	EP/EC
Maslens	Wingham	152°3′13″	31°49′38″	1059	11.3–23.4	32	EP/EC
Loughlan	Nabiac	152°11′5″	32°3′18″	1109	11.3–22.9	54	EP/EC
Brady	Nabiac	152°9′13″	31°3′10″	1064	11.7–23.3	54	EP/EC
Wilson	Gloucester	152°1′18″	32°13′41″	1091	11.5–23.2	55	EP
Paterson	Nabiac	152°11′56″	32°0′1″	1107	11.4–23.0	55	EP/EC
Byrne	West Kempsey	152°28′30″	30°52′42″	1179	12.1–23.7	44	EC
Sommerville	Casino	153°5′3″	28°46′60″	1285	13.1–24.4	17	EP/EC
Morrow	Lismore	153°26′15″	28°44′27″	1599	14.3–24.6	71&79	EP/EC
Gray	Bonalbo	152°40′34″	28°43′45″	1087	12.0–24.0	43	EP
Smith	Bonalbo	152°37′32″	28°34′32″	1020	11.9–24.0	17&42	EC
Gurranang	Grafton	153°1′30″	29°27′23″	1110	13.5–24.7	41	EP
Hourne	Grafton	153°0′49″	29°29′30″	1097	13.4–24.3	29	EP/EC
Zuells	Grafton	153°1′6″	29°30′59″	1127	13.3–24.5	20&30	EP/EC
Barcoongerie	Grafton	153°11′43″	29°55′12″	1299	13.6–24.1	18	EP
Coombs	Birdwood	152°19′14″	31°21′53″	1280	11.9–23.6	69	EP/EC
Baker	Byabarra	152°35′9″	31°30′51″	1349	12.4–23.4	68	EP/EC
Great Lakes Council	Nabiac	152°23′19″	32°8′33″	1149	12.4–23.4	79	EP/EC
Attikin	Wooton	152°17′44″	32°16′39″	1157	12.2–23.3	78	EP/EC
Mitchell	Krambach	152°9′31″	32°2′8″	1159	10.7–22.4	67	EP/EC
James	Krambach	152°9′4″	32°2′57″	1079	11.5–23.2	67	EP/EC
Latimore	Mount George	152°2′17″	31°52′44″	1074	11.0–23.1	54	EP/EC
Southgate	Coffs Harbour	153°1′2″	30°6′36″	891	12.8–23.4	70	EP/EC

*interpolated data from modelled climate surfaces ANUCLIM and ANUSPLIN (Kesteven *et al.* 2004)

Table 2. Criteria for random tree selection

Criterion	Details
Canopy dominance	Dominant or co-dominant in the stand
Health and vigour	Free of insect attack and disease. Healthy crown with a capacity for future growth
Straightness	Lean less than 12.5 cm from the base of the tree at breast height
	Butt sweep deviation no more than 8 cm in the first 3 m of stem
Branching	Absence of double or multiple leaders in the top of the tree
Stem defects	Must have a single leader, free of broken tops and wood damage

the lowest live branch on the stem and height of the live crown (h_L) were recorded. All diameters presented are overbark, unless stated otherwise. The base of the live crown was defined as the height of the lowest branch contained within a geometrically regular crown envelope (Soares and Tomé 2001). The diameter (30 mm from the stem junction) of the largest live and dead branch between 0 and 5.5 m stem height was recorded for each central measurement tree. Data were collected in September 2005 from 92 central measurement trees (49 *E. pilularis* and 43 *E. cloeziana*). The trees surrounding the central measurement tree were measured for h_T, and the mean dominant height (MDH) was calculated as mean height of the largest four trees surrounding the central measurement tree.

Data analysis

A site index function, based on the height growth model of McDill and Amateis (1992), was used to rank *E. pilularis* sites using MDH, age and established coefficients for MDH (Charles Muhairwe, Forests New South Wales, pers. comm., 2006) to determine a site index (indexed at age = 20 y) for all stands surveyed. Site index (*SI*) was determined using:

$$SI = \frac{B_0}{1 - (1 - B_0/H_1)(A_1/20)^{B1}}, \tag{1}$$

where B_0 and B_1 are established coefficients for MDH, H_1 is current MDH (m) and A_1 is current age (y).

The established coefficients for MDH in *E. pilularis* were also applied to *E. cloeziana* to determine site indices in the absence of established MDH coefficients for this species (due to the young age of plantations). This assumption is reasonable given the similar relative performance of these species across sites of differing quality. The site index range for both species was used to separate the sites surveyed into the following three quality classes: low (22–27), medium (28–33) and high (34–39) (Fig. 1).

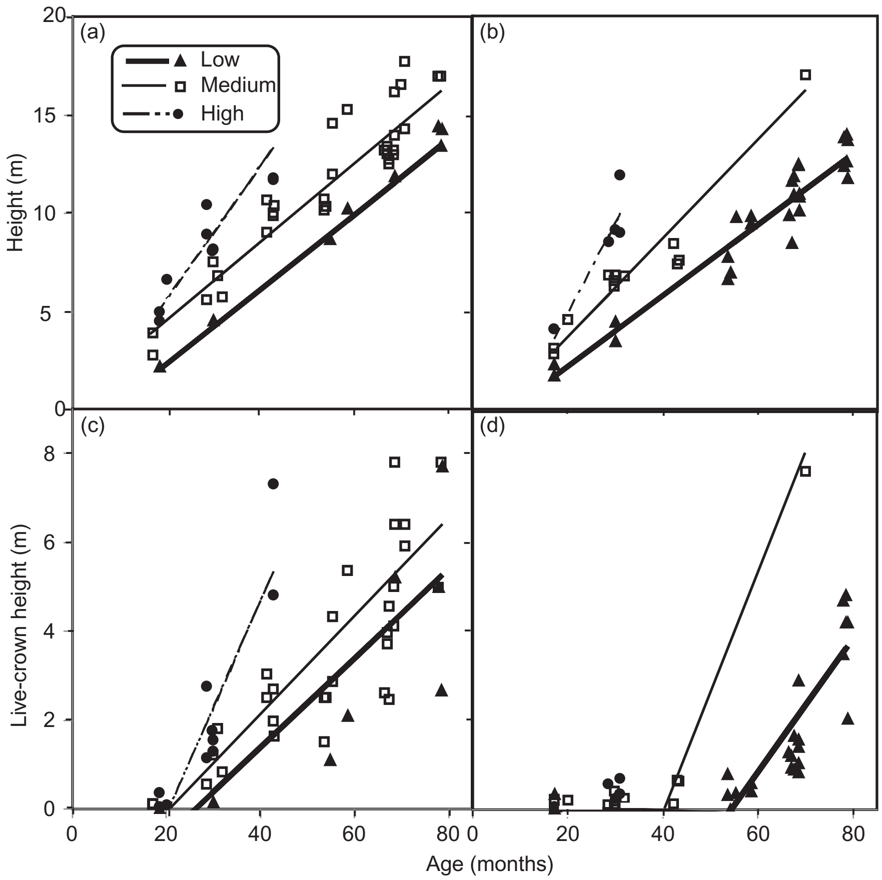

Figure 1. The relationship between tree height and age for (a) *E. pilularis* and (b) *E. cloeziana* or between live-crown height for (c) *E. pilularis* and (d) *E. cloeziana* plantation sites surveyed on three different site qualities (high, medium and low) in north-eastern NSW, Australia. Fit statistics for lines are presented in Tables 4–5. For (d), lines are fitted to data from when the live-crowns began to lift; there were too few trees to permit this analysis for high-quality sites

For the development of suitable pruning regimes, three different scenarios were considered: a low single-lift pruning regime (0–2.9 m), a high single-lift pruning regime (0–5.5 m) and a high-pruning regime comprising two lifts (0–2.9 m, 2.9–5.5 m). These scenarios were assessed on the basis of the minimum or maximum threshold of seven decision criteria—stem, branch and crown variables critical in influencing the timing of pruning (Table 3). Threshold values were set (a) to achieve a maximum knotty core at breast height of 15 cm or less over bark, (b) to avoid pruning of dead branches following a rise of the live crown and the development of a dead-branch zone, (c) to avoid pruning large live branches, (d) to avoid pruning more than 50% of the live crown, (e) to avoid pruning large dead branches and (f) to avoid pruning branches prior to canopy closure.

To estimate the size of the stem at which pruning should occur to achieve a maximum knotty core diameter at breast height of 15 cm, an average thickness of the occlusion layer until clearwood is produced was assumed to be 2.5 cm over a given branch stub. (This assumption is based on a report that an occlusion layer 2.5 cm thick was required for branches of 2.0–2.5 cm diameter in *E. nitens* (Gerrand *et al.* 1997b), as this information was not available for either *E. pilularis* or *E. cloeziana*.) Consequently, for a 15-cm knotty core, these two species would have to be pruned before attaining stem diameters of 10 cm (i.e. 15 – 2.5 × 2 cm) at 1.3 m height ($d_{1.3m}$).

To estimate the maximum knotty core size over bark at stump height, regression relationships between $d_{1.3m}$ and diameter (cm) at stump height (0.3 m above ground, $d_{0.3m}$) were developed for *E. pilularis* ($d_{0.3m} = 1.84 + 1.05\ d_{1.3m}$, $F = 2477$, $P < 0.001$, $r^2 = 0.98$) and *E. cloeziana* ($d_{0.3m} = 2.08 + 1.05\ d_{1.3m}$, $F = 758$, $P < 0.001$, $r^2 = 0.95$). The inclusion of site class (low, medium and high) did not significantly improve these relationships. Based on these relationships and assuming a knotty core size of 15 cm at 1.3 m, a maximum knotty core size at stump height would be 17.6 cm for *E. pilularis* and 17.8 cm for *E. cloeziana*.

For a low single-lift pruning regime, thresholds influencing the time to prune included:

- maximum stem $d_{1.3m}$ of 10 cm
- maximum height of the lowest live-crown branch of 1 m
- maximum live-branch diameter of 25 mm or 30 mm
- maximum dead-branch diameter of 10 or 15 mm
- minimum height of 5.8 m (to avoid more than 50% crown removal with a total pruned height of 2.9 m)
- pruning at or after canopy closure.

For a high two-lift pruning regime, thresholds influencing the time to prune for the first-lift pruning were the same as for the low-lift pruning described above. The threshold for the second lift was the same as for the low lift, except that there is no requirement to prune the second lift before canopy closure and the minimum tree height was set at 8.1 m to ensure pruning does not remove more than 50% of the live crown remaining from the first lift. In addition, to ensure that the knotty-core diameter at the commencement of the second-lift height of 2.9 m above the ground does not exceed the knotty-core diameter at stump height, it was determined that pruning must occur before the stem diameter at 2.9 m reaches 12.6 cm (17.6 cm stem diameter over bark less an assumed occlusion thickness of 5 cm of the stem diameter) for *E. pilularis* and 12.8 cm (17.8 cm less 5 cm occlusion thickness diameter) for *E. cloeziana*.

For a high single-lift pruning regime, thresholds influencing the time to prune were the same as for the low-pruning regime above, except a minimum tree height of 8.1 m was set in order to compare results with the high two-lift regime. To ensure that no more than 50% of the live crown is removed at pruning, it is also necessary to ensure that the live-crown height has not risen above the ground by more than 2.9 m at the time of pruning.

Pruning heights of 2.9 m for a low-lift pruning and 5.5 m for a high-pruning lift were determined from the standard of 2.5-m log length specifications for plywood manufacture in Australia (James 2001). (A stump height of 0.3 m, one standard log length of 2.5 m and 0.1 m waste, produced the low lift of 2.9 m; similarly, for a high lift, 0.3 m stump height, 2 × 2.5-m log standard lengths and 0.2-m trim allowance resulted in 5.5 m.)

Statistics and calculations

Regression analysis was used to examine the response of stem diameter, crown height, branch diameter and tree height to age and site quality. Site quality was included as a dummy variable

Table 3. Range of tree variables on high-, medium- and low-quality sites for *E. pilularis* and *E. cloeziana*

Variable	Range for *E. pilularis*			Range for *E. cloeziana*		
	High	Medium	Low	High	Medium	Low
Age (months)	18–43	17–79	18–79	17–31	17–70	17–79
Site quality index	34–38	28–33	24–27	34–39	28–33	22–27
Height (m)	3.8–14.5	2.2–17.3	2.2–14.4	3.9–11.8	3.5–18.1	2.2–14.8
Diameter at 1.3 m height (cm)	4.1–14.8	1.3–20.7	0.9–18.9	4.0–13.3	3.2–18.8	1.1–19.0
Diameter at 0.3 m height (cm)	6.6–17.9	3.2–21.7	3.3–23.2	6.2–15.0	4.7–16.4	3.3–23.5
Height lowest live branch (m)	0.1–6.4	0.1–9.2	0.0–5.0	0.1–0.7	0.0–7.6	0.0–4.8
Height lowest live-crown branch (m)	0.1–7.3	0.1–9.3	0.0–7.7	0.0–0.7	0.0–7.6	0.0–4.8
Maximum live-branch diameter (mm)	16–43	13–55	12–57	23–36	12–33	9–42
Maximum dead-branch diameter (mm)	2–18	2–33	0–30	0–16	1–17	0–32

and its effect was examined by testing for significant differences in intercepts and slopes. The threshold values established for each variable in Table 3 were used to construct a pruning decision matrix based on maximum or minimum pruning age on sites of different quality for each species. Age of canopy closure was set as the earliest age at which canopy closure was observed in stands of each species in the different site quality classes.

In order to examine the effect of site quality on the height of the lowest live-crown branch in *E. cloeziana*, data only for trees greater than 40 months of age were used. Up to 40 months, there was no increase in crown lift with an increase in age (Fig. 1d). In addition, there were insufficient numbers of trees greater than 40 months of age in the high site-quality class of this species to permit reliable statistical analysis. All analyses were completed using Genstat (VSN International 2004, Hemel Hempstead, Herts, UK).

Results

Effect of age and site quality on branch and stem size characteristics

For each species, diameters (at 0.3 m and 1.3 m), heights (total and live-crown; Fig. 1) and maximum branch diameters (live or dead) were positively correlated with age (Table 4 and 5). Diameter (at 1.3 m) and heights increased faster with increasing site quality (steeper slopes). Maximum branch diameters also increased with increasing site quality, but only for *E. cloeziana*.

Assessment of a low single-lift pruning regime (to 2.9 m)

To examine the influence of stem diameter, branch or crown criteria on the timing of pruning in each species under different regimes, the regression equations presented in Table 5 and the threshold values for each variable (Table 6) were used. For a low-lift pruning regime, the timing of pruning in *E. pilularis* trees on high-quality sites will be determined by the rise of the live crown and the height growth of the trees. Accordingly, pruning should be done by age 25 months otherwise the h_L will be above 1 m, but it should not be done earlier than 21 months because trees will not have reached 5.8 m height (Table 6). On medium-quality sites, pruning should be delayed until at least 26 months to avoid removing more than 50% of live-crown length but be carried out before 29 months to restrict dead branches to less than 10 mm in size. Pruning before 29 months would also restrict live branches to less than 25 mm and the canopy should be approaching closure. On low-quality sites it is not possible to achieve all objectives. Pruning could be delayed until 40 months to avoid removing more than 50% of the live-crown length. This, however, may lead to a maximum dead-branch size greater than 10 mm in diameter (but less than 15 mm) and maximum live-branch size greater than 25 mm diameter (but less than 30 mm diameter) and the bases of live crowns may already be above 1 m above ground. It is also likely that that pruning will not be done before canopy closure. However, the results for live-branch size need to be interpreted cautiously, given the weak relationship between maximum live-branch diameter and age for *E. pilularis* (Table 5).

Pruning of *E. cloeziana* on high-quality sites should be considered when trees are at least 22 months of age to avoid removing more than 50% of the live-crown length (Table 6). This delay, however, means that the maximum live-branch diameter can be greater than 25 mm (but less than 30 mm) (Table 6). On medium- and low-quality sites, pruning should not be carried out before 28 and 40 months of age, respectively, to avoid removing more than 50% of the live-crown length (Table 6). For these sites, the risk that branches become too large is much lower and this criterion does not conflict with maintaining a minimum live-crown length. Pruning at 30 months of age on sites of moderate quality will occur around the time of canopy closure, and on

Table 4. Summary of linear regression analyses fitted sequentially with age as explanatory variable and site quality as the group variable for *E. pilularis* and *E. cloeziana* tree data

Species and response variable	Single line		Separate lines (parallel lines, different intercepts)		Separate lines (different slopes)	
	F	*P*	*F*	*P*	*F*	*P*
E. pilularis						
Height (m)	346.40	< 0.001	23.90	< 0.001	3.77	0.031
Height lowest live-crown branch (m)	67.44	< 0.001	28.97	< 0.001	20.43	< 0.001
Diameter at 1.3 m height (cm)	147.52	< 0.001	70.96	< 0.001	46.70	< 0.001
Stem diameter 2.9 m (cm)	236.71	< 0.001	11.41	< 0.001	2.65	0.083
Max. live-branch diameter (mm)	11.95	0.001	0.69	0.507	0.41	0.667
Max. dead-branch diameter (mm)	121.35	< 0.001	0.63	0.537	1.37	0.264
E. cloeziana						
Height (m)	332.35	< 0.001	34.52	< 0.001	7.01	0.003
Height lowest live-crown branch (m)*	19.35	< 0.001	40.22	< 0.001	38.64	< 0.001
Diameter at 1.3 m height (cm)	120.71	< 0.001	103.06	< 0.001	74.27	< 0.001
Stem diameter 2.9 m (cm)	337.17	< 0.001	23.47	< 0.001	4.70	0.015
Max. live-branch diameter (mm)	61.02	< 0.001	8.73	< 0.001	0.25	0.778
Max. dead-branch diameter (mm)	204.93	< 0.001	7.77	0.002	1.49	0.240

*Data for 40^+ months only and two site qualities (low and medium)

Table 5. Linear regression equations for *E. pilularis* and *E. cloeziana* trees growing on three sites of different quality. The age (months) range for which the regressions were developed are shown in Table 3. Site quality was included as a dummy variable

Species	Response variable	R^2	Site quality	Equation
E. pilularis	Height (m)	0.89	High	Height = –1.18 + 0.34 × age
			Medium	Height = 0.51 + 0.20 × age
			Low	Height = –1.47 + 0.19 × age
	Height lowest live-crown branch (m)	0.67	High	Height = –4.91 + 0.24 × age
			Medium	Height = –2.26 + 0.11 × age
			Low	Height = –2.61 + 0.10 × age
	Diameter at 1.3 m height (cm)	0.83	High	DBH = –0.36 + 0.33 × age
			Medium	DBH = 1.36 + 0.20 × age
			Low	DBH = –3.23 + 0.25 × age
	Diameter at 2.9 m height (cm)	0.83	High	Diameter = 0.56 + 0.22 × age
			Medium	Diameter = –1.90 + 0.22 × age
			Low	Diameter = –3.77 + 0.22 × age
	Max. live-branch diameter (mm)	0.19	High	Diameter = 18.03 + 0.22 × age
			Medium	Diameter = 18.03 + 0.22 × age
			Low	Diameter = 18.03 + 0.22 × age
	Max. dead-branch diameter (mm)	0.72	High	Diameter = –0.51 + 0.36 × age
			Medium	Diameter = –0.51 + 0.36 × age
			Low	Diameter = –0.51 + 0.36 × age
E. cloeziana	Height (m)	0.91	High	Height = –4.28 + 0.46 × age
			Medium	Height = –1.27 + 0.25 × age
			Low	Height = –1.33 + 0.18 × age
	Height to lowest live branch (m)	0.82	High	Excluded from analysis
			Medium	Height = –6.57 + 0.18 × age
			Low	Height = –10.15 + 0.18 × age
	Height lowest live-crown branch (m)*	0.82	High	Excluded from analysis
			Medium	Height = –10.87 + 0.27 × age
			Low	Height = –8.15 + 0.15 × age
	Diameter at 1.3 m height (cm)	0.90	High	Diameter = –5.83 + 0.55 × age
			Medium	Diameter = –1.51 + 0.28 × age
			Low	Diameter = –2.65 + 0.23 × age
	Diameter at 2.9 m height (cm)	0.90	High	Diameter = –8.85+ 0.57 × age
			Medium	Diameter = –2.07 + 0.22 × age
			Low	Diameter = –4.36 + 0.22 × age
	Max. live-branch diameter (mm)	0.65	High	Diameter = 18.63 + 0.39 × age
			Medium	Diameter = 9.42 + 0.39 × age
			Low	Diameter = 6.07 + 0.39 × age
	Max. dead-branch diameter (mm)	0.84	High	Diameter = –3.43 + 0.48 × age
			Medium	Diameter = –5.59 + 0.48 × age
			Low	Diameter = –11.18 + 0.48 × age

*Fitted to data from when the live crowns began to lift

low-quality sites pruning before 44 months will avoid maximum dead-branch diameters greater than 10 mm (Table 6). However, at 44 months pruning may occur prior to canopy closure (Table 6).

Assessment of a high-pruning regime in two lifts (to 5.5 m)

The decision for the timing of the first 2.9-m pruning lift for both species will follow the same criteria as described above for the low single-lift pruning regime. The second pruning lift from 2.9 to 5.5 m in *E. pilularis* on high-quality sites can be undertaken as early as 27 months as the critical height for 50% live-crown length removal has been reached, but it should be completed before 29 months to avoid dead branches greater than 10 mm in diameter (Table 6). On sites of medium quality, pruning should be delayed until 38 months to reach the critical height threshold to avoid the removal of more than 50% of the live-crown length (Table 6). This is likely to result in dead branches greater than 10 mm in diameter (but less than 15 mm) and potentially large live branches more than 25 mm (but less than 30 mm). Delaying pruning on low-quality sites until less than 50% live-crown length is removed, at 52 months, would result in dead branches greater than 15 mm and live branches greater than 25 mm (Table 6).

For *E. cloeziana*, the second-lift pruning on high-quality sites can be conducted as early as 27 months (so long as height criteria are met, although live branches will be greater than 25 mm but still less than 30 mm at this time (Table 6). On medium-quality sites, pruning should be delayed until 37 months to reach the critical height. However, this will result in dead branches greater than 10 mm in diameter. On low-

Table 6. Pruning decision matrix for *E. pilularis* and *E. cloeziana* trees pruned in a single lift to 2.9 m or in two lifts to a stem height of 5.5 m (0–2.9 m first lift and 2.9–5.5 m second lift) based on stem, branch and crown criteria as determined by the regression equations in Table 5. The lowest maximum and the earliest age at which pruning should be carried out are in bold figures

Pruning lift and pruning criteria	Earliest (>) or latest (<) age at which pruning should be carriedout in *E. pilularis* at sites of different quality (months)			Earliest (>) or latest (<) age at which pruning should be carriedout in *E. cloeziana* at sites of different quality (months)		
	High	Medium	Low	High	Medium	Low
First lift (0–2.9 m)						
Stem diameter (1.3 m) 10 cm over bark	< 32	< 43	< 53	< 29	< 41	< 55
Live-crown height = 1 m	**< 25**	< 33	< 36	N/A	< 44	< 61
Live branch = 25 mm	< 32	< 32	< 32	**< 16**	< 40	< 49
Live branch = 30 mm	< 54	< 54	< 54	< 29	< 53	< 61
Dead branch = 10 mm	< 29	**< 29**	**< 29**	< 28	< 32	**< 44**
Dead branch = 15 mm	< 43	< 43	< 43	< 38	< 43	< 55
Height = 5.8 m	**> 21**	**> 26**	**> 40**	**> 22**	**> 28**	**> 40**
Complete canopy closure	< 29	< 30	< 55	< 29	< **30**	< 54
Second lift (2.9–5.5 m)						
Stem diameter over bark at 2.9 m—12.6 cm for *E. pilularis* and 12.8 cm for *E. cloeziana*	< 55	< 66	< 74	< 38	< 68	< 78
Live-crown height = 2.9 m	< 33	< 47	< 55	N/A	< 51	< 74
Live branch = 25 mm	< 32	< 32	< 32	**< 16**	< 40	< 49
Live branch = 30 mm	< 54	< 54	< 54	< 29	< 53	< 61
Dead branch = 10 mm	**< 29**	**< 29**	**< 29**	< 28	**< 32**	**< 44**
Dead branch = 15 mm	< 43	< 43	< 43	< 38	< 43	< 55
Height = 8.1 m	**> 27**	**> 38**	**> 52**	**> 27**	**> 37**	**> 52**

quality sites, pruning should be delayed until 52 months, where maximum live-branch diameter is greater than 25 mm but less than 30 mm and dead-branch size over 10 mm in diameter (Table 6).

Assessment of a high single-lift pruning regime (to 5.5 m)

For *E. pilularis*, a single high-lift pruning would have to wait until 36, 52 or 69 months to reach the minimum height required to remove less than 50% of the live-crown length on high-, medium- and low-quality sites, respectively (Table 7). This carries the risk of the need to prune dead branches above 1 m on the lower stem, of live branches being greater than 25 mm and dead branches greater than 10 mm, and a closed canopy at pruning. Similarly for *E. cloeziana*, delaying pruning until 33, 49 and 69 months on high-, medium- and low-quality sites to achieve the minimum height required for pruning less than 50% of live-crown length will result in large live branches (> 25 mm), dead branches greater than 10 mm and potentially pruning after canopy closure (Table 7). Delaying pruning to meet minimum height requirements will also result in mortality of branches above 1 m and, on low-quality sites, stem diameter above 15 cm over bark.

Table 7. Pruning decision matrix for a high (5.5 m) single-lift pruning in *E. pilularis* and *E. cloeziana* trees growing at high-, medium-, and low-quality sites based on stem, branch and crown criteria as determined by the regression equations in Table 5. The lowest maximum and the earliest age at which pruning should be carried out are in bold figures

Pruning criteria	Earliest (>) or latest (<) age at which pruning should be carried out in *E. pilularis* at sites of different quality (months)			Earliest (>) or latest (<) age at which pruning should be carried out in *E. cloeziana* at sites of different quality (months)		
	High	Medium	Low	High	Medium	Low
Stem diameter (1.3 m) 10 cm over bark	< 32	< 43	< 53	< 29	< 41	< 55
Live-crown height = 1 m	**< 25**	< 33	< 36	N/A	< 44	< 61
Live-crown height = 2.9 m	< 33	< 47	< 55	N/A	< 51	< 74
Live branch = 25 mm	< 32	< 32	< 32	**< 16**	< 40	< 49
Live branch = 30 mm	< 54	< 54	< 54	< 29	< 53	< 61
Dead branch = 10 mm	< 29	**< 29**	**< 29**	< 28	**< 32**	**< 44**
Dead branch = 15 mm	< 43	< 43	< 43	< 38	< 43	< 55
Height = 8.1 m	**> 36**	**> 52**	**> 69**	**> 33**	**> 49**	**> 69**
Complete canopy closure	< 29	< 30	< 55	< 29	< 30	< 54

Discussion

Increased resource availability in relation to site quality or fertiliser application can significantly increase diameter growth and the rate of canopy closure (Cromer and Jarvis 1990; Florence 1996), as was the case in this study. This supports the concept that the optimal time for pruning is strongly influenced by site quality. *E. cloeziana* and *E. pilularis* differed in stem, crown and branch development such that the trade-offs between the criteria in Table 6 varied between the two species. For *E. cloeziana* the maximum size of live and dead branches in the lower crown (0–5.5 m) increased with site quality. Similarly, increases in leaf areas of *E. nitens* trees in response to fertiliser application resulted from reduced branch senescence and faster branch growth in the lower crown (Wiseman *et al.* 2006; Forrester *et al.* 2012a) more than in the upper crown, as found for *Pseudotsuga menziesii* (Brix 1981). This site effect on branch sizes means that pruning will need to be done at an earlier age on higher-quality sites than on sites of lower quality for *E. cloeziana*. More specifically, for *E. cloeziana*, timing of pruning has to be balanced between removing less than 50% of the live-crown length and the development of large live branches on high-quality sites and large dead branches on low-quality sites. In contrast, site quality did not influence the maximum branch sizes of *E. pilularis* trees, even though stem diameters increased. This is consistent with results from other *E. pilularis* plantations in the region, where maximum branch diameters of *E. pilularis* trees were not correlated with stem diameter (Alcorn *et al.* 2007). So for *E. pilularis,* the timing of pruning has to be balanced between removing less than 50% of the live-crown length and the aim to remove branches before the rapid rise of the lower live crown and pruning large dead branches on all site qualities.

Low single-lift pruning to 2.9 m

For a low single-lift pruning to 2.9 m all criteria could be met for *E. pilularis* on high-quality sites, if pruning is done about 21 months after planting. But as site quality decreases, there is a divergence of maximum and minimum ages for pruning according to the individual criteria and therefore trade-offs will need to be made. Either more than 50% of the live-crown length need to be removed to minimise the risk that branches become too large or vice versa.

In contrast, for *E. cloeziana* trees on all site qualities, there is little difference between the earliest and latest age at which pruning should be carried out according to the different criteria, indicating that trade-offs for pruning are small. On high-quality sites, the timing for a low-lift pruning to 2.9 m will be determined by the development of large live branches. If a live-branch size up to 30 mm diameter on the lower stem is tolerable, then pruning could be conducted at about 22 months without compromising other critical variables.

High two-lift pruning to 5.5 m

Timing of the second lift for *E. pilularis* trees on all site qualities will be a compromise between dead-branch size and ensuring sufficient height growth to avoid removing more than 50% of the live-crown length to reach the pruned height of 5.5 m. High-quality stands should be considered for pruning about 6 months after the first-lift pruning (21 months). Similarly, timing of second-lift pruning in *E. cloeziana* should also be considered 6 months after first-lift pruning (22 months) to avoid development of live branches greater than 30 mm and dead branches greater than 10 mm in diameter.

For medium- and low-quality sites, second-lift pruning in both species represents a compromise between the development of large dead branches and ensuring sufficient height growth to avoid removing more than 50% of the crown. However, as this study has not examined whether the time taken to reach critical branch size on the upper 2.9–5.5 m bole is different to the lower 2.9 m bole, there may be greater flexibility in timing before large live and dead branches form in the 2.9–5.5 m section of stems. This may mean that pruning *E. cloeziana* and *E. pilularis,* respectively, at age 37 and 38 months on medium-quality sites, and 52 months on low-quality sites for both species, may not be compromised by unfavourable branch development. It is also important to note that the effects on tree growth of removing 50% of the live-crown length twice within a six-month period, as suggested by these results in Table 7 (for high-quality sites), is unknown. A single-lift prune to remove 50% of the live-crown length was found to have no long-term effect on *E. cloeziana* or *E. pilularis* diameter (Alcorn *et al.* 2008). The effect of a second pruning lift on growth will depend on how well the crowns have recovered and the trees have replenished carbohydrate reserves that were used to recover from the first lift. For *E. nitens,* pruning 50% of the live-crown length at age 3.2 y reduced tree diameters by 5% at age 8.1 y (Forrester *et al.* 2012a). A second–lift prune that also removed 50% of the live-crown length at age 4.7 y (1.5 y after the first lift) reduced diameters by a further 8% (Forrester *et al.* 2012a). Increasing reductions in growth were also found for *E. globulus* with repeated artificial defoliations (Pinkard *et al.* 2007). Further work is required to investigate the effect on tree growth and recovery of multiple pruning events that are only 6 months apart.

High single-lift pruning to 5.5 m

The advantage of a single pruning to 5.5 m is the cost savings obtained by carrying out just one operation. However, this study showed that a single pruning lift to 5.5 m is unsuitable to achieve the silvicultural objectives in either species. Given the time required to reach sufficient height to avoid removing more than 50% of the live-crown length, large live and dead branches are likely to be present on the stem. The trade-offs between tree growth and branch or crown development attributes critical to preventing stem defects were least compatible with a high single-lift scenario. This is consistent with other high-pruning regimes in eucalypts, which advocate pruning in two or more lifts for similar reasons (Gerrand *et al.* 1997b; Dickinson *et al.* 2000; SGS Qualifor 2005a, b).

Age of pruning

The process of determining the timing of pruning operations for eucalypt species is quite different from that used for conifers, where the emphasis can be on matching the timing of pruning to stem diameter alone. This study also shows that, although similar in principle, the prescription for pruning will differ between eucalypt species. Based on our criteria, high-quality sites may require pruning as early as 22 and 27 months in *E. pilularis* and 22 and 28 months in *E. cloeziana* to achieve a height of 5.5 m in two lifts. These schedules are comparable to pruning regimes used elsewhere. Prescriptions for *E. grandis* in Argentina have included three lifts to 3, 6 and 9 m at ages 1.5, 2.5 and 3 y, respectively (SGS Qualifor 2005b), and in Uruguay have included five lifts to 2.3, 4.5, 6.5, 8.5 and 10.5 m at ages 1.5–2, 2–2.5, 2.5–3, 3–4 and 4.5–5 y, respectively to achieve a diameter over branch stubs of 12, 12, 13, 15 and 16 cm, respectively (SGS Qualifor 2005a). Prescriptions for *E. nitens* in Tasmania, Australia, specify three lifts to 2.4, 4.5 and 6.4 m at ages 3–4, 4–5 and 5–6 y, respectively (Neilsen 1991), and in Chile, 2–4 lifts starting at 2–3 y old and reaching up to between 7 and 12 m by age 5.5 y (Valencia 2008). The variability between these regions and species results from differences in growth rates, crown development and various financial criteria. Few comparisons are available for *E. pilularis* and *E. cloeziana*. Dickinson *et al.* (2000) described a two-lift pruning regime with a first lift to 2.4 m at age 1.5–2.5 y and a second lift to 5.4 m at age 3.5–4.5 y, such that each pruning lift removes about 30% of the live-crown length. This was to be applied to *E. pilularis*, *E. cloeziana*, *E. argophloia* and *Corymbia variegata* without any variation due to site quality or species. Our results and the prescriptions for *E. nitens* and *E. grandis* described above suggest that timing of pruning should vary depending on species and site qualities.

Wood quality considerations

Pruning of dead branches may result in wood quality issues, where the removal of dead branches has the potential to lead to development of kino traces in the clear-wood zone (Gerrand *et al.* 1997a). This phenomenon has not been reported for the two species in this study. Further work is required to confirm that pruning of dead branches should be avoided as assumed in our set of criteria for determining the timing of pruning.

Season of pruning

The season in which pruning is conducted may also be an important consideration. Gadgil and Bawden (1981) reported a lower risk of fungal decay in *E. delegatensis* when pruning was conducted in winter due to the lower activity of wood-decaying fungi in that season. In contrast, examination of the level of decay associated with pruning in *E. nitens* showed limited influence of season, although higher levels of infection were observed with spring and summer pruning (Mohammed 1999). Timing of other plantation operations may also influence the most convenient times of the year to prune. In the sub-tropics, pruning before or after the planting season (from November to March) may improve the availability of labour as planting crews can become involved in pruning work.

Pruning decision

The information presented in this study to facilitate decisions surrounding the time to prune *E. pilularis* and *E. cloeziana* focussed on biological processes and tree properties. The ultimate decision to begin pruning stands or not depends largely on economic and market factors. A comparison of the revenue that could be obtained from the production of veneer-quality logs in plantations where crop trees have been pruned, versus plantations without these silvicultural interventions, will be important in the assessment of the economics of pruning for both species. In addition, in the absence of relevant data our analysis could not consider the economic importance of each criterion used to determine the timing of pruning. Of all our criteria, the restriction to prune just the lower 50% of the live crown was the only criterion important for each species and site quality. It is possible that some reduction in growth could be accepted if the value of the improvement in wood quality outweighs the reduction in wood volume. Also, the investment of pruning is less likely to be lost if there is a small reduction in growth, whereas if (i) dead branches are pruned resulting in kino trails or other defects or (ii) large live branches are pruned, increasing the risk of stem infection and wood decay, then the whole investment in pruning may be lost. The suggested regimes could then be modified accordingly to focus more on the other criteria. It is also important to note that this study used unthinned stands. Pruning is often carried out in conjunction with thinning, and such changes in stand density are likely to influence live-crown heights and branch sizes, and can also interact with pruning to influence growth (Forrester and Baker 2012; Forrester *et al.* 2012a). Assuming thinning is done at around the same time as a first-lift pruning, the pruning matrices for second-lift pruning presented in this study may be further developed to incorporate possible thinning effects on crown development.

This study highlights the extent to which site quality and differences in stem, branch and crown development may influence the timing of pruning in young *E. pilularis* and *E. cloeziana* plantations in north-eastern New South Wales, Australia. Pruning is more likely in plantations on sites of higher productivity owing to the faster growth rates and return on investment of this silvicultural operation on such sites. At these sites, the determination of the time of first pruning *E. pilularis* trees will be largely a balance between live crown rise and retaining 50% live-crown length, while in *E. cloeziana* it will be a balance between large-branch development and retaining 50% live-crown length.

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