Thinning and pruning eucalypt plantations for sawlog production in Tasmania

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Abstract

Seven research trials have been established to investigate initial spacing, thinning and pruning in eucalypt plantations grown for sawlog production. Preliminary results indicate that Eucalyptus nitens *is the most promising species for Tasmania and that it should be possible to grow sawlog-sized trees in plantations within 30 to 40 years. Good diameter growth responses to thinning have been obtained in research plots. Results indicate problems of decay entering pruning wounds, and pruning methods have been adopted to reduce the likelihood of decay entry.*

A provisional management regime has been developed for E. nitens *plantations. An initial stocking of 1000 stems/ha is recommended to ensure sufficient trees of good form for selection of 250 stems/ha final-crop trees. Pruning to either 2.7 m or 6.4 m height is advocated in two regimes that are discussed. The regimes include an early, light, non-commercial thinning to release final-crop trees, and a later commercial thinning to improve the financial viability of the regime. Problems of growing eucalypt sawlogs in plantations are discussed.*

Introduction

Tasmania has approximately 47 700 ha of eucalypt plantations, with most of this area planted within the last 15 years (Forestry Commission 1993). The majority of this area has been established by private companies for pulpwood production. Current government-owned plantations are planned to be primarily for sawlog and veneer log production but there has been little information available on which to base the development of sawlog regimes for eucalypts (Neilsen and Wilkinson 1990). Caution has been advocated while necessary research is undertaken to determine suitable methods of growing eucalypt sawlogs in plantations (Shepherd *et al.* 1990).

A programme to develop industry initiatives included the establishment of over 6000 ha of eucalypt plantations aimed at producing saw-logs and veneer logs, and this establishment was funded under the Intensive Forest Management (IFM) Program. At the same time, a five-year research project commenced to develop the silvicultural regimes and techniques for the production of sawlogs and veneer logs from these plantations.

In Tasmania, intensive management of eucalypt plantations will be required to produce logs of suitable sawlog quality at economically acceptable rotation lengths. Treatment will involve pruning to improve veneer and sawn wood quality, combined with thinning to encourage rapid diameter growth and to assist financial viability. This project aimed to collect information on the effects of initial spacing, thinning and pruning treatments on the wood quality and productivity for a range of sites and species.

The main objectives were to:

- Research a range of possible regimes for thinning and pruning eucalypts;
- Evaluate the economic feasibility of producing sawlogs and veneer from plantation eucalypts;
- Recommend initial spacing for growing stands of eucalypt sawlogs;
- Quantify any thinning response;
- Develop and recommend methods of pruning eucalypts; and
- Evaluate the effectiveness of pruning and thinning, and determine operational costs.

Research programmes closely allied to this project were established to evaluate wood quality characteristics of plantation-grown eucalypts (Waugh and Yang 1994) and problems of wood decay from pruning (Wardlaw 1995).

Methods

Trials were established in several locations (Table 1, Figure 1). Commercial eucalypt sawlog plantations are limited to sites capable of producing high growth rates (Neilsen and Wilkinson 1990; Gerrand *et al.* 1993). In Tasmania, this requires deep, fertile soils and an annual rainfall over 1000 mm but preferably over 1200 mm (Neilsen 1990; Laffan 1993). Trials were restricted to sites with these characteristics.

Spacing

A trial to investigate the effects of initial spacing on the growth and form of *Eucalyptus nitens* (Dean & Maiden) Maiden and *E. regnans* F. Muell. was established in northern Tasmania (Table 1, site 8). The trial was initially planted in 1992 but, due to poor survival, the *E. regnans* was replanted the following year. The trial included stockings ranging from 500 to 1667 stems/ha in 30 m x 30 m plots for both *E. nitens* and *E. regnans,* in a randomised complete block design with four replications of six stocking treatments. The area with *E. nitens* also had a modified Nelder trial design called a 'Scotch Plaid' trial to investigate extremes of stockings and rectangularity (Zavitovski *et al.* 1983). This sub-trial covered stockings from 278 stems/ha up to 2500 stems/ha.

Thinning and pruning

Three thinning and pruning research trials were established to form the main body of the eucalypt plantation sawlog/veneer research project. These were the Hastings trial with young *E. nitens* (Table 1, site 2), the Goulds Country trial with older *E. nitens* (site 1) and the Westfield trial with young *E. regnans* (site 3). This research aimed to determine the response of *E. nitens* and *E. regnans* plantations to pruning and early thinning in terms of volume production, stem form and stem quality. The research trials were based on a direct clearwood regime with pruning to a height of 6.4 m and a heavy, early, non-commercial or waste thinning to accelerate diameter growth. Four thinning levels (100, 200, 300 and 400 stems/ha) plus an unthinned control treatment were tested to gain an indication of the effects of early thinning on growth of the final-crop trees.

For the three trials, a randomised complete block design was used for pruning and thinning. There were two replicates and the plots were 0.1 ha in area.

For *E. regnans,* an additional trial established in 1987 at Mount Helen (Table 1, site 4) was assessed. This research trial covered a number of thinning and pruning regimes in young *E. regnans.* It was laid out as a randomised complete block design, with two replications of eight treatments. The plots were 30 m x 50 m laid along the rows. In 1991, a plot was established in adjacent areas of *E. globulus* Labill. of the same age, to enable comparisons of relative growth rates between the species, and this was re-measured in 1994. The *E. globulus* trees were unthinned and unpruned.

Table 1. Location, species, age, and type of research for project trial sites.

Site	Location	Research	Species	Year planted	Year trial established	Altitude (m)	Rainfall (mm)
1	Goulds Country 1 St Helens	Thinning and pruning	*E. nitens*	1984	1990	120	1000
2	Hastings 19 Geeveston	Thinning and pruning	*E. nitens*	1988	1991	160	1400
3	Westfield 100 Maydena	Thinning and pruning	*E. regnans*	1988	1991	400	1300
4	Mount Helen Scottsdale	Thinning and pruning	*E. regnans* *E. globulus*	1982 1982	1987 1991	180	1250
6	Creekton Dover	Pruning methods and costs	*E. nitens*	1989	1992	120	1400
7	Sideling Scottsdale	Commercial thinning	*E. globulus*	1981	1992	420	1300
8	Upper Castra 14a Devonport	Spacing	*E. nitens* *E. regnans*	1992 1993	1992 1993	310	1250

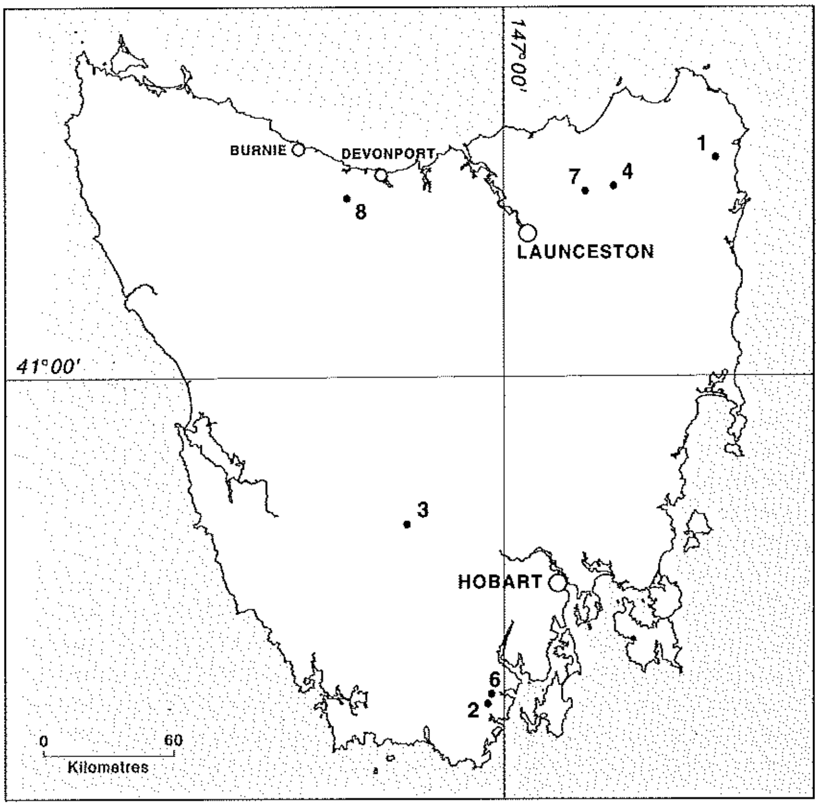

Figure 1. Map of Tasmania showing location of project trials. (Numbers refer to locations in Table 1.)

For these research trials, the diameter at breast height (DBH) of all the trees was measured. Heights of all trees selected for pruning were measured, along with approximately 10% of remaining trees across a wide range of diameters. The volume of trees measured for height was calculated using a suitable tree volume equation (Opie 1976). Volumes of other trees were estimated using a volume to basal-area regression relationship established from the trees measured for height (Wilkinson and Neilsen 1995). Volumes of the selected best 100, 200, 300 and 400 stems/ha were determined and compared for each thinning treatment.

A system used by Forestry Tasmania (van Schie 1969) for describing tree form was modified and used to allocate trees into classes for form, branching, damage, dominance and merchantability. Average proportions of the plots with various branch sizes, form defect and merchantability classes were determined for each thinning and pruning treatment.

Selection for final-crop trees during thinning operations in the trials was based on a combination of form, size, damage, branching habit and spacing.

Pruning methods

A pruning trial was established in an *E. nitens* plantation at Creekton Road to evaluate pruning methods and costs for a two-lift pruning regime (Table 1, site 6). The trial was established as a randomised complete block design, with four replicates of two low-pruning methods plus unpruned controls. The pruned plots were laid out at 40 m x 40 m (0.16 ha). The unpruned plots were smaller: nominally 12 m x 16 m to include 30 trees. The trial evaluated the operational costs of pruning 400 stems/ha of *E. nitens* to 2.7 m in one lift and high pruning 250 stems/ha of these to 6.4 m in a second lift. Two pruning methods were employed in the timed low-pruning trial to 2.7 m. Half of the pruned plots were pruned using double-action shears and the remainder pruned with small pruning saws. For the high pruning to 6.4 m, all eight of the plots were pruned using saws, safety harnesses and 4.5 m, modified ladders.

A detailed damage assessment after low pruning was carried out to determine levels of damage caused by each tool. The proportions of branch stubs, bark tears, branch collar damage, gum flows and saw teeth marks were determined separately for each pruning tool.

Commercial thinning

A research trial was established to test the feasibility of commercial thinning operations in a previously unthinned stand, to quantify the thinning response of the retained stems and to test the susceptibility of eucalypt plantations to wind and thinning damage (Table 1, site 7). Eight plots, two control plots and six thinned plots were laid out in an 8 ha plantation of *E. globulus* being thinned from 900 stems/ha to 300 stems/ha, using a third row outrow system. One control plot was accidentally thinned. Thinning and wind damage were quantified by determining the percentage of trees damaged in the plots.

Results and discussion

Species and growth rates

Six eucalypt species were considered for study, but trials concentrated on *E. nitens* and *E. regnans* because areas of suitable quality of the other species, *E. globulus*, *E. sieberi* L. Johnson, *E. delegatensis* R.T. Baker and *E. obliqua* L'Hérit., were not found in plantations.

Eucalyptus nitens was found to be the most promising eucalypt species for high quality timber production from plantations in Tasmania. It had good growth rates on a wide variety of sites and was frost tolerant. It produced good wood quality for pulp, sawn timber and veneer, and generally had good form and stem straightness even at an early age (Pederick 1979; Neilsen 1990). Persistent branches causing knots in wood were a problem and there was a risk of decay entering through pruning wounds (Waugh and Yang 1994; Wardlaw 1995).

Eucalyptus regnans could also produce a fine-grained timber and good pulp. However, it was prone to regular severe insect attack and had poor growth and extremely poor form. The two trials at Westfield and Mount Helen showed levels of growth and stem quality unsuitable for sawlog production. Volume mean annual increments (MAI) were in the order of 2–2.5 m^3/ha/year to age six years in the Westfield trial, and to age 12 years in the Mount Helen trial (Figure 2). This was well below the benchmark of 15 m^3/ha/year required for financially viable production of sawlogs in plantations (Neilsen and Wilkinson 1990; Gerrand *et al.* 1993). Both the Mount Helen and Westfield trials were severely affected by insect attack. Insect defoliation has been shown to have highly significant effects on growth of young *E. regnans* (Leon 1989; Elliott *et al.* 1990; Candy *et al.* 1992; Elliott *et al.* 1992).

Volume growth of the selected 250 stems/ha at Mount Helen was not significantly greater following thinning when compared with the selected 250 stems/ha in the unthinned plots. Mean diameter of the selected 250 stems/ha ranged from 15.1 to 17.1 cm at age 12 years. In the seven years of the trial, the best diameter growth was less than 6 cm. Mean dominant height (MDH) of the stand ranged from 12.8 m to 15.5 m at age 12 years. The site was capable of producing very good growth as indicated by the MAIs for *E. globulus* of 20 m^3/ha/yr in an adjacent plot. Stocking rates for the unthinned *E. regnans* in the Mount Helen trial have progressively declined to very low levels of around 500 stems/ha. The levels of mortality are continuing to rise although the stands had very low crown cover. The stands were also of poor potential merchantability and a high proportion of the thinned and pruned trees were still only of pulpwood quality. By age 12 years, 49% of trees on the control plots had branches greater than 35 mm in diameter.

At Westfield, the volume of the top 200 stems/ha at age six years was only 7 m^3/ha for the treated plots and 4 m^3/ha for the control. Significant differences between some of the thinning treatments and the controls may have been due to treatment but variable frost damage may have been involved. Mean

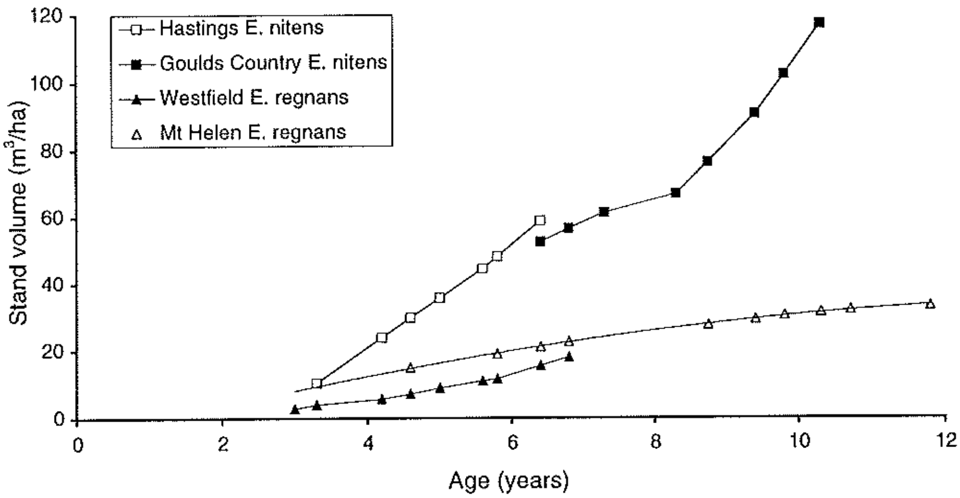

Figure 2. Total stand volumes for the unthinned plots of E. nitens *and* E. regnans *over the period of measurement from four project trials.*

diameter of the total stems in each thinning treatment ranged from 6.5 cm to 11.8 cm at age six years. In the best 100 stems/ha, the 300 stems/ha treatment had a mean diameter of 12 cm which was significantly different from that of the control treatment at 9.8 cm. Mean height was not significantly affected by either thinning or pruning treatments,

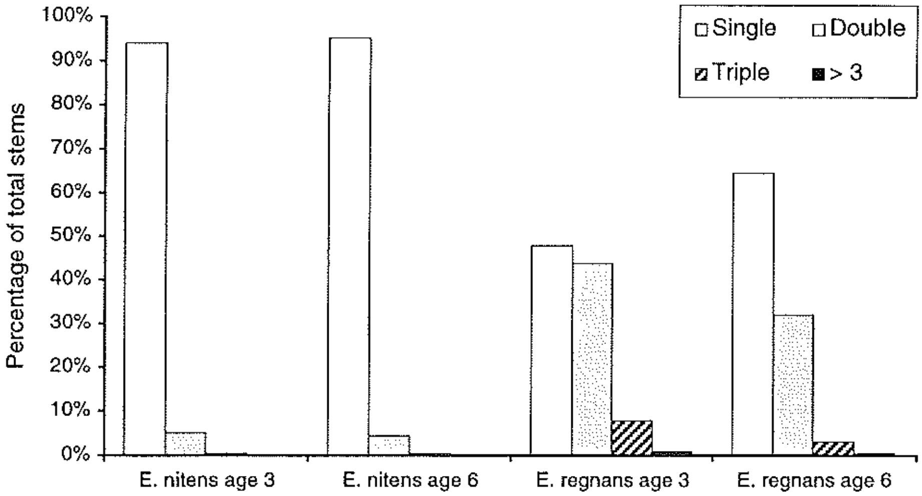

Figure 3. Percentage of single, double, triple, and multiple stems in studies of E. nitens *and* E. regnans *aged three and six years.*

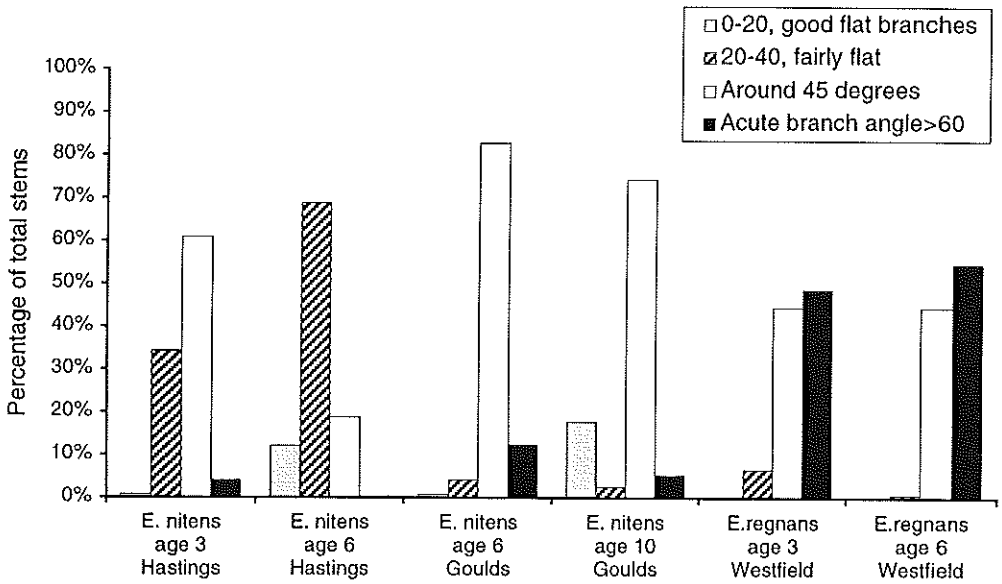

Figure 4. Comparison of branch angle classes for E. nitens *for two sites for ages three and six years and ages six and ten years and* E. regnans *for one site, ages three and six years.*

with the mean height around 7 m at age six years. Pruning had no significant effect on the growth of the pruned plots. Importantly, although the pruning was effective at removing existing branches, epicormic shoots developed along the pruned section of the stem on a number of trees.

The form of *E. regnans* at Westfield was particularly poor. Virtually none of the trees in any of the thinning treatments was considered to have potential as a high quality sawlog. Little more than half of the retained trees were considered potential sawlogs of any grade. Virtually all stems displayed some degree of lean, sweep or kink, and these form defects accounted for the major downgrading to pulpwood quality.

In contrast, *E. nitens* has been found to have better growth rates (Figure 2), good form and wood qualities. Even so, heavy weed competition would have resulted in growth rates below the potential for the sites. Although potential growth rate was good, *E. nitens* adult foliage was also browsed by defoliating beetles (Leon 1989; Elliott *et al.* 1990; Bashford 1992). Significant annual variability in current annual increment (CAI) growth occurred in the Goulds Country and Hastings trials. In the Goulds Country trial, this was associated with observed variations in the density of foliage on the trees and was partly attributed to the amount of defoliation by chrysomelid beetles (R. Bashford, pers. comm.).

In addition to poor stem straightness, young plantation-grown *E. regnans* had a strong tendency to produce multiple leaders, with only 65% of trees at the Westfield site having single main stems at age six years. Differences in form and branching habit between *E. nitens* and *E. regnans* were evident in comparisons, with *E. regnans* having a substantial proportion of multi-stem trees (Figure 3). Plantation-grown *E. regnans* had a significantly steeper branch angle at a young age (Figure 4).

Because of poor growth and form, *E. regnans* is not currently being considered for operational plantations. The majority of plantations established for sawlog in Tasmania contain *E. nitens*.

Volume growth of the control plots at Goulds Country at age 10 years averaged only 11.7 m^3/ha/yr. At age six years at Hastings, MAI was 9.9 m^3/ha/yr. Growth rates at Goulds Country varied annually, with CAIs from 10 m^3/ha/yr to almost 30 m^3/ha/yr (Figure 5). Variations in growth due to uncontrolled agents, such as insects and variable climate, made it very difficult to obtain clear growth trends for *E. nitens*. The Goulds Country trial was the most advanced, with measurements to age 10 years, but the nature of the growth data to date for this trial made it difficult to determine a rotation length needed to obtain a log of 50–60 cm DBH. However, with diameters of about 25 cm at age 10 years, a rotation of around 30–40 years should be feasible.

Spacing

The initial stocking rate chosen for a plantation is a crucial decision. It affects the financial viability and many of the subsequent operations, and the overall ability of the plantation to produce the desired product volume or quality. Pulpwood plantations, which comprise the vast majority of eucalypt plantations, have been planted at initial stockings of 1300–1700 stems/ha while the few sawlog plantations, mainly in South Africa, have been planted at around 1000–1100 stems/ha (Jenkin 1992).

The initial stocking required to provide competition to produce suitable form and branching in the planted crop needs to be refined. The spacing trial, covering a wide range of initial stockings and rectangular as well as regular spacing, should provide useful information. Sufficient trees need to be planted to allow selection of suitable final-crop stems. In unthinned and unpruned stands at Goulds Country, by age 10 years, 44% of stems assessed (337 stems/ha) were of veneer quality and 81% (614 stems/ha) were sawlog quality or better. At Hastings, at age

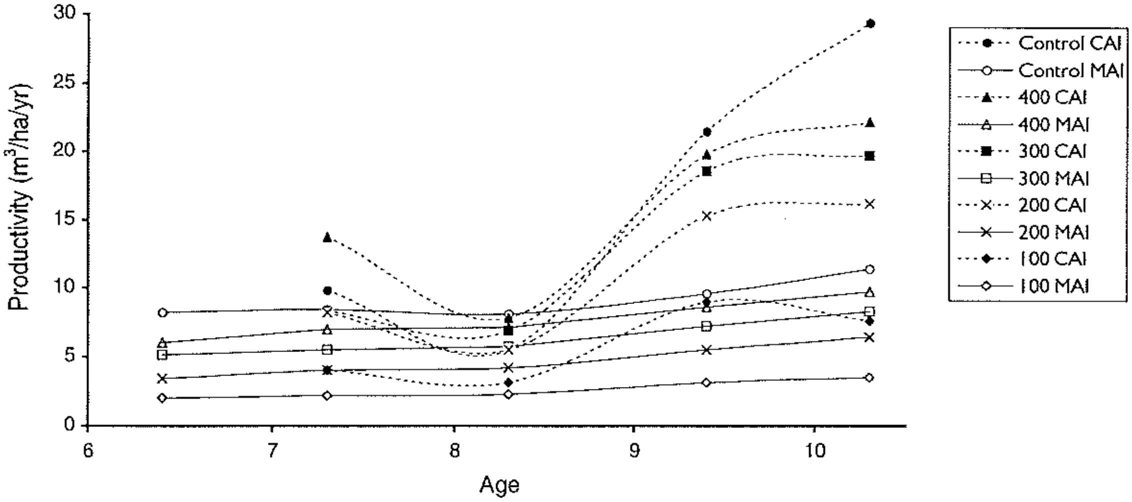

Figure 5. Volume productivity (MAI and CAI) to age 10 years for thinning treatments applied to E. nitens *at age six years at Goulds Country. (Numbers in the legend are stems/ha.)*

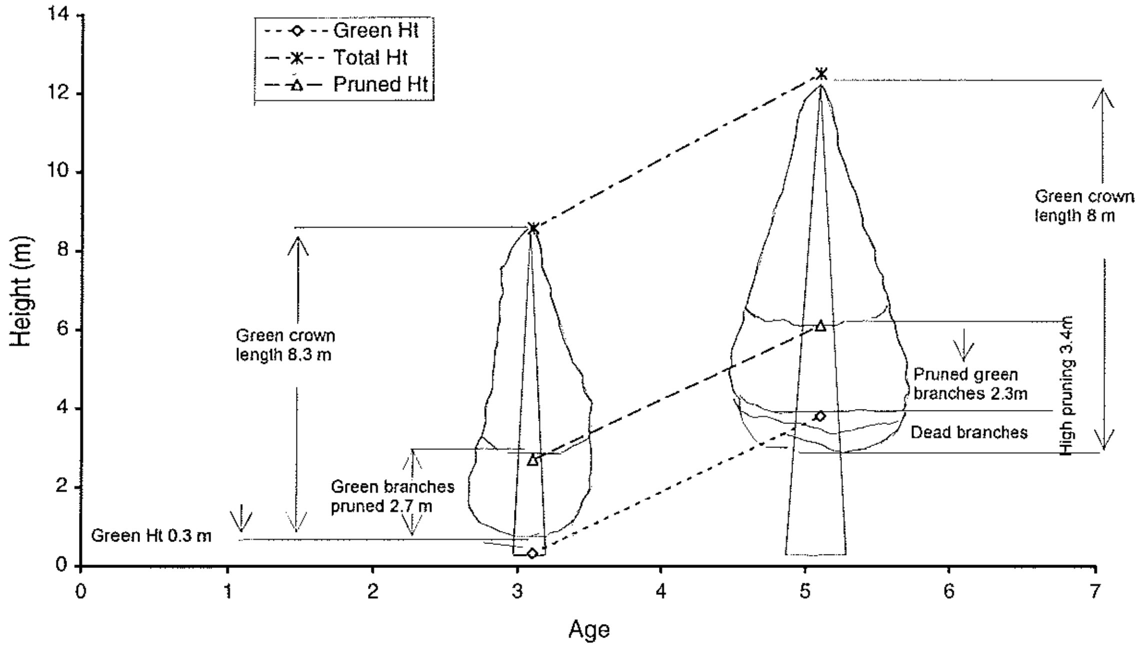

Figure 6. Average green crown, pruned and total height for E. nitens *at Creekton, for ages three and five years.*

Table 2. Stocking and mean diameter in potential merchantability classes for unthinned stands of E. nitens *at age ten years at Goulds Country and at age six years at Hastings.*

	Potential merchantability class			
Thinning treatment	High quality veneer	Sawlog	Pulp	Unmerchantable or dead
Goulds Country				
Stems/ha (all trees)	337	277	120	27
% of trees	44.3	36.4	15.8	3.5
DBH (cm)	17.8	17.3	15.4	16.0
Hastings				
Stems/ha (all trees)	357	657	142	30
% of trees	30.1	55.4	12.0	2.5
DBH (cm)	11.7	11.5	10.2	7.2

six years, 30% of stems assessed (357 stems/ha) were of veneer quality and 84% (879 stems/ha) were sawlog quality or better (Table 2). In these stands, planted at 1000–1300 stems/ha, it was relatively straightforward to select 300 stems/ha of *E. nitens* suitable for retention at age three years. However, attempting to select 400 stems/ha did start to include stems of poorer form or vigour. Beadle *et al.* (1994) found about 400 stems/ha suitable for pruning at ages 3–10 years out of 1430 stems/ha planted, in various *E. nitens* stands in southern Tasmania. The percentage of prunable stems was less at higher altitude.

An initial stocking of 1000 stems/ha (4 m x 2.5 m) was accepted as suitable for sawlog plantations using current genetic stock. Machine access between rows was important to allow for mechanical operations such as fertilising, spraying, and other maintenance. Row widths greater than 3.5 m generally allow sufficient access for machines for the first few years when tending operations are most likely.

Pruning of E. nitens

Eucalyptus nitens has poor branch suppression and shedding under routine plantation stockings (Gerrand 1992). Sawing trials have indicated that knots from dead branches are the biggest reason for downgrading of sawn timber from unpruned *E. nitens* and *E. regnans* plantation logs (McKimm *et al.* 1988; Waugh and Yang 1994).

Pruning is considered necessary to produce high quality, knot-free timber. Research studies have recommended early pruning, starting around age three years, to avoid pruning dead branches and causing degrade (Gerrand *et al.* 1997). At Creekton Road, the green crown started to rise rapidly from age three years when the trees were 7 m tall (Figure 6).

The Creekton Road trial determined the costs of a two-lift pruning regime (Tables 3, 4). The low pruning time-trial using saws and shears showed that there was no significant difference between tools in the time taken to prune a plot. There was no significant difference in the volume increment of pruned and unpruned plots in the two years following pruning, with less than 40% of green crown pruned at age three years. Other studies have also indicated that pruning of 50% of the green crown in young co-dominant *E. nitens* causes no significant reduction in growth (Beadle and Pinkard 1997; Pinkard and Beadle, in press).

A significant relationship was established between the largest branch diameter and tree DBH for *E. nitens* at age three years ($R^2 = 0.40$).

During pruning, the aim should be to prune all branches flush to the stem without damaging the surrounding bark. Even slight bark damage slowed recovery and increased the possibility of decay entry. Pruning should occur in the autumn or winter to reduce risk of decay and development of kino defect.

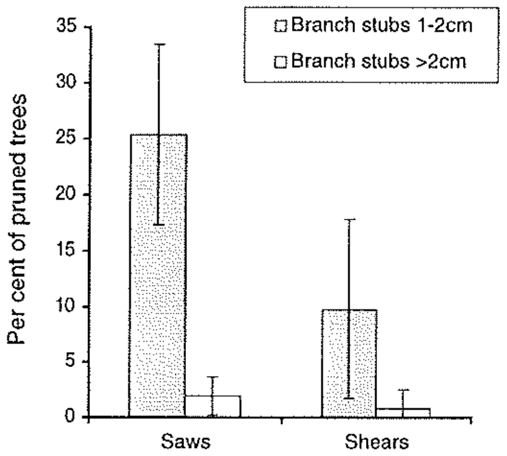

Figure 7. Percentage of branch stubs 1–2 cm and greater than 2 cm produced from low pruning with saws and shears at Creekton.

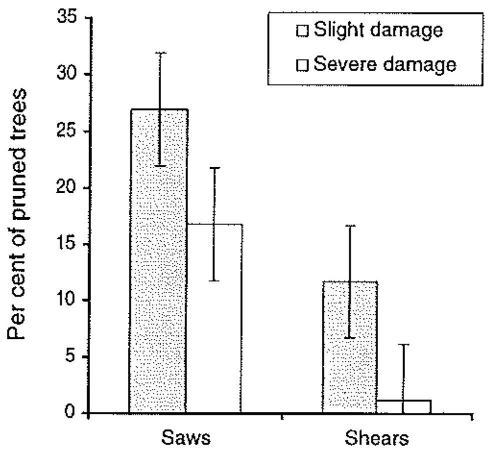

Figure 8. Slight and severe damage levels to the main stem produced by low pruning with saws and shears at Creekton.

The risk of decay establishing after pruning increases with increasing branch diameter. Branches between 2 cm and 3 cm diameter were almost three times as likely to develop decay as branches less than 2 cm, while branches greater than 4 cm diameter were four to six times more likely to develop decay (Wardlaw 1995). Therefore, where practicable, branches should be pruned while they are below 2.5 cm diameter in *E. nitens*. This means first-lift pruning needed to be done when mean DBH of the trees was near 10 or 11 cm. This would generally contain the defect core diameter to below 15 cm. The actual first pruning at Creekton Road was carried out later than ideal, at age five years, when average DBH was 16.1 cm (Table 3).

Pruning damage to *E. nitens* bark and branch collars is serious and should be kept to an absolute minimum. In particular, damage to the 'eyelid' of bark above the branch must be avoided because this part needs to grow and close over the branch stub.

Analysis of the branch stub and damage assessment data collected after the low-pruning operation showed the levels of damage varied significantly between the saws and the shears. On average, one-quarter of the trees pruned with saws had branch stubs between 1 cm and 2 cm in length. In comparison, only one-tenth of the trees pruned with shears exhibited this problem (Figure 7). There was no significant difference in the level of branch stubs greater than 2 cm, with both tools averaging levels less than 5% of pruned trees. Damage was assessed as either slight or severe. Minor injuries such as small bark tears, saw-teeth marks, and minor gum flows were classed as slight damage. Excessive gum flows and branch collar damage which would impede recovery and occlusion were classed as severe damage. The difference between tools in severe damage level was highly significant (Figure 8).

Measuring the time taken to prune plots of known area and number of trees enabled cost estimates to be placed on low pruning in three-year-old *E. nitens* plantations and high pruning in five-year-old plantations (Table 4).

Table 3. Times of treatment application in the Creekton Road pruning costs and methods trial.

Age pruned (years)	Stand mean DBH (cm)	Pruned trees mean DBH (cm)	Stand MDH (m)	Mean height of pruned trees (m)	Mean pruned height (m)
3	9.4	11.3	10.0	8.6	2.7
5	13.4	16.1	14.1	12.5	6.1

Table 4. Calculation of pruning costs from the Creekton Road trial.

	Low pruning	High pruning
Time per tree	2.94 minutes	4.9 minutes
Cost per tree	approximately $0.92/tree	approximately $1.46/tree

Selection of trees for pruning should be based on the criteria of form, branch size and angle, and tree size and spacing in that order of priority. Trees selected for pruning should have branches which are no more than 3 cm (preferably < 2.5 cm) in diameter at their junction with the stem and which do not make an acute angle with the stem (< 60°). If larger branches must be cut, then undercutting before sawing is essential to avoid the branch tearing a strip of bark down the tree as it falls.

The risk of decay entry increases with increasing height up the stem. This is probably due to the increase in branch diameter with increasing height. To minimise this risk, it is important not to delay the second and third pruning lifts. Delayed lifts will result in a larger, knotty core and greater decay risk.

A multiple-lift pruning regime allows greater containment of the knotty core, with an earlier low pruning followed by later high pruning to the full log length. Because of the requirement of extreme care in pruning and the need to prune small, live branches, three-lift pruning is recommended to reach 6.4 m in height in routine operations.

In the Goulds Country trial, pruning at age six years had no significant effect on volume growth over the following three years. At the time of pruning, the stand had a MDH of approximately 13.7 m, and trees were pruned to 6.4 m in one lift. Height growth, as measured by MDH, was not significantly affected by thinning or pruning treatments over the four years the trial was measured, averaging 17.6 m at age 10 years. Lack of height response was in keeping with results from other studies (Hamilton and Christie 1974).

Beadle and Pinkard (1997) showed that for co-dominant *E. nitens*, removal of up to 50% of the canopy did not reduce growth. In the Hastings trial, growth of the selected best 100 stems/ha was not significantly affected by pruning. These trees had large green canopies, and pruning had relatively little impact on their growth. However, pruning did significantly reduce growth on the selected best 200, 300 and 400 stems/ha. Trees in these groupings were progressively smaller, with more sub-dominant trees selected, and thus also had their growth progressively reduced by pruning, which removed proportionally more green crown. The best 200 stems/ha pruned trees had 31% less volume than those unpruned at age six years. The Hastings trial was the only trial where pruning was carried out at currently recommended ages and the effects on growth measured in this trial indicate that growth losses might be expected on pruned stems relative to unpruned stems.

Growth losses due to pruning are of minor consequence in fully pruned stands, but a temporary growth setback becomes important when pruned trees are kept within a stand that contains larger unpruned trees. If pruned trees are slightly reduced in growth, this would change their relative dominance within the stand and lead to suppression. If thinning is not done in the stand for a number of years, then the growth of pruned trees may fall

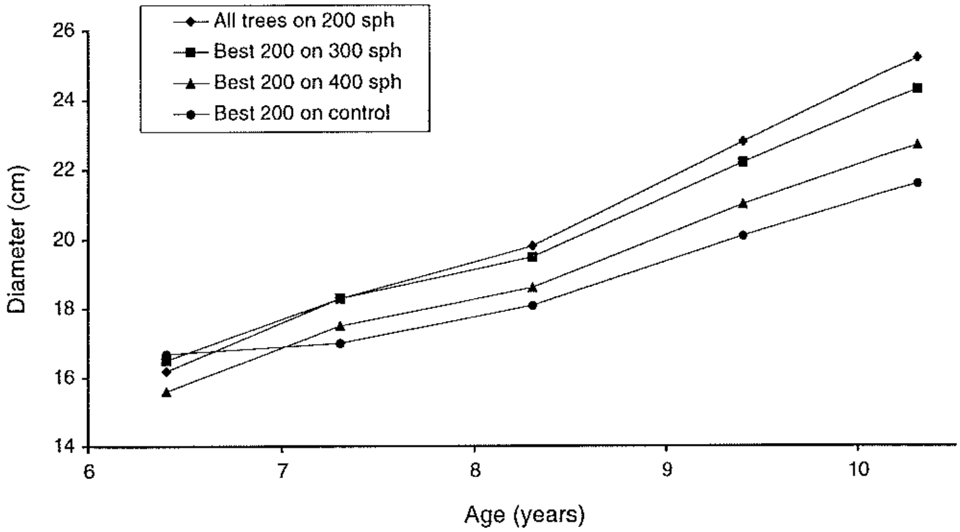

Figure 9. Diameter growth for E. nitens *from age six to ten years for the selected best 200 stems/ha in plots thinned to various final stockings at Goulds Country.*

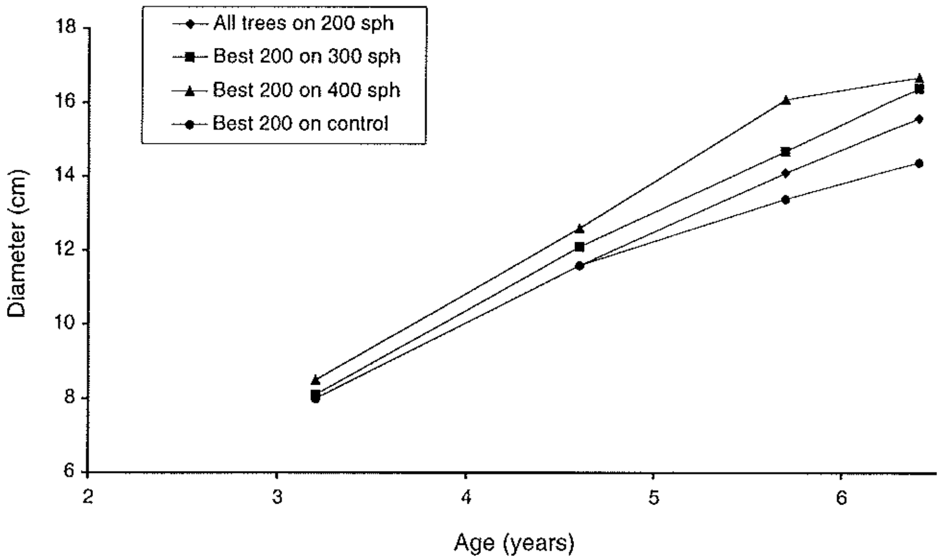

Figure 10. Diameter growth for E. nitens *from age three to six years of selected best 200 stems/ha in plots thinned to various final stockings at Hastings.*

well behind. Such stands will need thinning, possibly non-commercially, at the same time as pruning, to avoid suppression and maintain good diameter growth of pruned stems.

Thinning of E. nitens

The Goulds Country trial demonstrated a significant response to thinning at age six years for *E. nitens* for both diameter and volume increment at all thinning intensities. At age 10 years, the trees in the plots thinned to 200 stems/ha had a volume 20% greater than the best 200 stems/ha in the control plots. It is expected that the thinning response will continue, resulting in a substantial reduction in rotation length. By age 10 years, the DBHs of trees in the stand thinned to 200 stems/ha were on average 3.6 cm larger than those of the select 200 stems/ha in the control plots (Figure 9). At age 10 years, the mean DBH of the best 200 stems/ha for each thinning treatment was significantly greater than that of the control. Over the four years of the trial, the selected best 200 stems/ha on the unthinned control plots had diameter increments of only 4.9 cm compared with the 9.0 cm increment on the plot thinned to 200 stems/ha. This diameter difference already represented a three-year advantage over the unthinned plots.

At Hastings, total volume production on the control was 58.9 m^3/ha at age six years while plots thinned to 300 stems/ha carried 32.6 m^3/ha. Thinning at age three produced significant positive responses in diameter and volume by age six years in the selected best 300 and 400 stems/ha but not in the best 100 or 200 stems/ha trees (Figure 10). The two heaviest thinning treatments, to 100 and 200 stems/ha, showed no significant thinning response. As more trees were included in the selected best groupings, from 200 to 300 and 400 stems/ha in this trial, the size and relative dominance of the selected trees decreases with some subdominants being retained. These responded when competing trees were removed. Earlier studies by Webb (1966) and Goodwin (1990) have indicated that subdominant trees respond to thinning at lower thinning intensities than dominant trees. Mean diameters of the top 300 stems/ha range from 14 cm to 16 cm at age six years. There was considerable variation in the MDH across the trial site at Hastings, but no thinning response.

Goodwin (1990) found lasting tree growth responses to thinning of 50-year-old *E. obliqua* regeneration stands. The long duration of response in regrowth eucalypts provided evidence that the time required to produce sawlog-sized trees could be considerably reduced by thinning. The intensity of thinning was an important factor in determining the length of response time, with heavily thinned stands having a longer duration of response (Brown 1996). In native forests, co-dominants have been found to respond, rather than dominants or others canopy classes (Forestry Tasmania, in press).

Wind damage

The commercial thinning *E. globulus* trial at the Sideling had been established on a high quality site, with initial stockings of 1333 stems/ha yielding an MAI of 30 m^3/ha/yr. To achieve a commercially attractive average tree size of around 0.2 m^3 and thinning volume of around 100 m^3/ha, the thinning was not done until age 11 years. The relatively high stocking restricted diameter growth but did not affect the good height growth. This resulted in tall but slender trees with a large height to diameter ratio.

Approximately 15% of trees were damaged during and following commercial thinning of the stand, 8% from logging and 7% from wind through stem breakage (Photo 1). At the time of thinning, MDH was 28–30 m with diameters of the largest 200 stems/ha ranging from 24 cm to 30 cm. The height/diameter ratio of the top 200 stems/ha ranged from 0.90 to 1.13. Volume harvested was 107 m^3/ha of 311 m^3/ha.

The wind damage was mainly near the edge of the stand adjacent to an open paddock. Damage occurred despite attempts to minimise opening up the edge by avoiding thinning edge trees except on outrows. The results showed that there was a risk of

Photo 1. Wind damage after commercial thinning in an 11-year-old stand of E. globulus *at the Sideling.*

wind damage in plantation stands that were established at high stockings (> 1300 stems/ha) if thinning was not done early.

Cremer *et al.* (1982) found that the height/diameter ratio of the 200 largest diameter stems per hectare was a useful indicator of the risk of wind damage for *Pinus radiata* D. Don. When this ratio was calculated for the 11-year-old stand of *E. globulus* at the Sideling commercial-thinning trial, it was found to be over 100, which is within the range considered as high-risk category for *P. radiata*. Eucalypts may be more stable than pines due to stronger stem wood and a less dense crown, but the difference appears to be marginal.

The remaining half of the damage was attributed to the thinning operation itself. Damage was generally in the form of open scars and bark damage.

Merchantability

Analysis at age 10 years at Goulds Country showed that the general stem form of *E. nitens* was good, with 81% of the trees even in the unthinned and unpruned stand having sawlog potential. At age six years at Hastings, 85% of *E. nitens* trees in the unpruned and unthinned control plots were of form suitable for potential sawlog production. Notably, the best form trees were not necessarily the largest, as can be seen by comparing the high quality veneer average diameters with those for sawlogs where diameters of both groups are similar (Table 2).

The large number of pulp or unmerchantable quality trees in the unthinned stands indicated that, without thinning, the stand would be putting volume increment onto trees of poorer form. Also noticeable was the large size of some of these trees, sometimes larger than the better formed trees. These trees could be expected to suppress the better formed trees if no thinning were done.

Wood quality

It was anticipated that a final log for eucalypt sawlog production from plantations would

Table 5. Recovery of sawn timber and timber of select or better quality from various sawing trials of young unpruned eucalypt logs (after various authors).

Species, age or size	Recovery (%)	Select or better (%)	Reference
50–60 cm *E. regnans* and *E. globulus* plantations	22	10	Walker (1984)
30-year-old *E. nitens, E. regnans* and *E. globulus* plantations	30	2	Waugh and Yang (1994)
50-year-old *E. regnans* regrowth	44	11	Waugh and Rozsa (1991)
Simulation of eucalypt regrowth	45	14	Waugh *et al.* (1990)

need to be between 50 and 60 cm DBH (Neilsen and Wilkinson 1990). Problems of growth stresses on sawing should be overcome with sawlog diameters of this size (Walker 1984; Waugh and Rozsa 1991). To accommodate growth stresses in eucalypts, a final log size of 50–75 cm DBH has been recommended in New Zealand (Fry 1983; Deadman and Hay 1987; Haslett 1988). A previous study of the sawing of plantation-grown *E. globulus* and *E. regnans* logs (Walker 1984) showed little downgrade due to growth stresses. These trees were from 34-year-old plantations in Tasmania and were 50–60 cm DBH.

Sawing studies of regrowth eucalypt sawlogs of sizes to be expected from plantations resulted in a recovery of 37%, of which only 14% was joinery or select quality when quarter sawn (Waugh and Rozsa 1991). A sawing study of plantation-grown *E. globulus, E. nitens* and *E. regnans* achieved only 2% select grade and about 30% recovery overall from 30-year-old plantations (Waugh and Yang 1994) (Table 5). Their work found that knots were the major defect causing degrade in *E. nitens.* The elimination of knots through pruning may substantially increase select grade recovery and will be necessary if sawlog plantations of *E. nitens* are to achieve their objectives. No utilisation studies of pruned material have been carried out but select grade recovery could be more than 60% of the out-turn of the pruned log and perhaps 20–25% of the tree.

Occlusion

Investigations into occlusion of pruned branch stubs in *E. nitens* showed that the rate of occlusion varied with site, stem diameter, diameter of the pruned branch and with relative suppression of the branch at time of pruning. Occlusion of many pruned branch stubs was very good, with wood closing rapidly over the pruned stub, sometimes completely and cleanly or with only a small amount of kino.

However, large high-angle branches were sometimes snapped off and pushed horizontally as the tree grew, producing a major defect and a large knotty core. A large pocket of kino may form around the stub. A proportion of stubs from branches which had died before pruning were broken off by growth pressures and pulled out with the bark, preventing healing of the cambium and leaving behind a hole filled with kino (Photo 2). This was also noted by Waugh and Yang (1994) and it constituted a significant defect in *E. nitens* logs.

To avoid the defect of kino-filled holes, it appeared that branches should be pruned while small and alive and when kino production is less in winter (Jacobs 1955). Trees with large, steep-angled branches should not be selected for pruning.

Decay

A sawing study revealed little decay associated with dead branch stubs in unpruned plantation-grown *E. nitens* (Waugh and Yang 1994). Infection of pruning wounds by fungal pathogens may be more serious than infection through branch stubs of unpruned stems (Gadgil and Bawden 1981).

Preliminary results from examination of pruned *E. nitens* stems indicated that substantially increased levels of decay existed as a result of pathogens entering through pruning wounds compared with unpruned branch stubs. Chances of infection with decay-forming fungi in *E. nitens* through pruned branch stubs were greater with pruning of live branches, and increase with increasing branch size. Infection varied with site factors (Wardlaw 1995). Damage to surrounding cambium during pruning of branches effectively increased the size of the wound and the chances of infection. Importantly, this was also outside the branch's own barrier zone set up internally within the tree.

A certain amount of decay and other defect will occur in any stand of eucalypts (Wardlaw 1995). However, there are some factors in plantations that may increase the amount of defect. Regimes incorporating production thinning and inevitable damage to a proportion of retained trees may lead to serious losses due to wood decay, particularly over long sawlog regimes (White and Kile 1991). While the defect core at first pruning may be 10–12 cm DBH, decay can move quickly up and down the tree. If the decay is contained within the wood laid down before pruning, then later pruning lifts will expose wood outside the original pruned core to the risk of decay. There is a risk that this may result in a defect core of 18–20 cm following high pruning. Although high pruning potentially doubles the volume of high quality, knot-free timber, decay studies are needed to evaluate the effects of high-pruning wounds that may allow decay entry.

Photo 2. Pruned branch stub being pushed out by subsequent growth, leaving a kino trace as a defect.

Regimes

To produce high quality timber in the shortest time possible, thinning and pruning will be necessary. Two regimes differing in pruning height are examined. Whether to low prune or high prune depends on the risk of decay movement within the tree. If the pruning decay problem can be overcome, high-pruning options will produce more recoverable quality timber.

High pruning.—This regime aims to produce a high proportion of high quality products in the final crop by pruning 300 stems/ha to 6.4 m, and prescribes two thinnings, one non-commercial and one later commercial thinning to maintain fast growth of the selected trees. The three-lift pruning regime consists of one pruning from the ground to approximately 2.7 m using shears, and a second pruning to 4.5 m and a third pruning to 6.4 m using ladders and saws.

First pruning should be done when the trees are around 7 m tall: usually around age three years. Final high pruning should be completed by age five or six years, to keep the defect core to around 15 cm and remove branches before they become too large. Later commercial thinning is expected around ages

Table 6. An outline of the operations to be undertaken and indicative ages and stand conditions for E. nitens *sawlog plantations for a high pruning regime.*

Age	Stand conditions	Operation
0	Initial stocking.	1000 stems/ha (4 m x 2.5 m).
3 or 4	> 300 prunable trees/ha, DBH of prunable trees 8–10 cm, height of dominants > 7 m.	Select and low prune best 300 stems/ha to at least 2.5 m; selectively waste thin trees competing with the final-crop trees.
4 or 5	DBH of pruned trees 10–12 cm, height of dominants > 9.5 m.	Prune 300 stems/ha to 4.5 m.
5 or 6	DBH of pruned trees 11–13 cm, height of dominants > 12 m.	High prune to 6.4 m.
10 to 12	Volumes to be thinned 70–100 m^3/ha, average tree size to be removed 0.2 m^3.	Commercial thin to 250 trees/ha; essential to minimise damage to final-crop trees.
30 to 40	Average DBH from 50 to 60 cm for sawlogs.	Clearfell.

10–12 years and clearfelling between 30 and 40 years (Table 6).

Pruning needs to be done early, aiming to prune small live branches only. This may result in some loss of vigour relative to adjacent competing trees. Release thinning would be needed to prevent selected pruned stems being suppressed by adjacent unpruned stems. An early release thinning is needed for maximising the growth of selected final-crop trees. A commercial thinning is considered vital for financial viability.

The release thinning is considered beneficial as the selected best trees in the stand, based on form, are not always the largest, and the final-crop trees may become suppressed by adjacent dominant trees having poorer form. Release thinning should only remove dominants or co-dominants competing, or likely to compete within five or six years, with the pruned trees. Results from trials in this project indicate that competition is significant from around age six years. This is well before the unpruned dominants are likely to be removed in a commercial thinning.

The commercial thinning should be carried out as early as possible to release final-crop stems from competition and to minimise damage from thinning and outrows, or tracking will be needed to further minimise damage.

Low pruning only.—The second regime involves low pruning only for the selected best 300 stems/ha when they have reached approximately 7 m tall. Otherwise the recommended regime is identical to the high-pruning regime.

The advantage of pruning only the bottom 2.7 m of the tree is that the regime minimises the risk of decay entry and spread. Any decay that does enter as a result of low pruning is likely to be contained within an unavoidable central defect core that is mainly juvenile wood. In addition, pruning when branches are small reduces the risk of decay entry. Other benefits from pruning from the ground include lower cost of pruning and improved safety. All pruning can be done with shears, resulting in low levels of damage.

Conclusions

A great deal of information on responses to thinning and pruning of eucalypts has been obtained. However, there are still areas of poor knowledge which constrain our ability to make sound operational decisions or to predict the long-term outcome of investment in growing eucalypt veneer/sawlog stands.

A provisional management regime has been developed for *E. nitens* plantations. Initial stocking is recommended at 1000 stems/ha (4 m x 2.5 m) to ensure sufficient trees of good form for selection of 250 stems/ha final-crop trees. In high quality stands, the selected best 300 stems/ha should be low pruned, using shears, to a height of 2.7 m when the trees are about 7 m tall. If decay studies indicate high pruning is an acceptable risk, the output of high quality clearwood can be doubled by pruning to 6.4 m. This should be done in three operations. High-pruned stands should have a light release thinning.

A commercial thinning for pulpwood should follow at around age 10 to 12 years. This should provide revenue and improve the financial viability of the plantation. The final 250 stems/ha could then be left to grow on to achieve the required size of between 50 cm and 60 cm diameter. This should occur when the trees are between 30 and 40 years old. At these relatively young ages, the proportion of sawlog quality material is expected to be only 15% of the total stand volume for low-pruned stands and 30% for high-pruned stands. Alternatively, stands could be felled earlier for veneer-based products.

An initial spacing of 1200 stems/ha, with progressive thinning to 100 stems/ha final stocking, has been recommended in New Zealand (Deadman and Hay 1987). Williamson (1979) found that, with a variety of thinning regimes in an *E. saligna* Sm. plantation, the best diameter response to age 10 years was with heavy thinning from 760 stems/ha to 100 stems/ha at age seven years. Messina (1992) found that a diameter growth benefit was obtained from thinning a seven-year-old *E. regnans* plantation. However, radical thinning from 1200 stems/ha to 150 stems/ha provided no growth advantages over a less extreme thinning to 350 stems/ha.

South African work has indicated that there may be no long-term benefits of artificially pruning eucalypts such as *E. grandis* (Hill) Maiden, a species which sheds its branches well (Luckhoff 1967; Schönau 1974; Maree 1979; Bredenkamp *et al.* 1980; Schönau and Stubbings 1987). Schönau (1974) found that pruning 30% of the live crown reduced growth in *E. grandis*. However, loss of growth measured in the year after pruning of up to 50% of the live crown of *E. grandis* on good sites (Luckhoff 1967) was insignificant at time of harvest at age 25 years (Bredenkamp *et al.* 1980). Pruning also had little benefit at harvest, with no increased recovery of knot-free timber. These findings may be attributed to the high degree of self-pruning which occurs naturally in *E. grandis* (Jacobs 1979).

A financial analysis based on current costs and returns indicated that eucalypt plantation sawlog production was only likely to be financially viable on very high quality sites managed under a commercial thinning regime (Gerrand *et al.* 1993). The Nett Present Value was very sensitive to both site quality (productivity) and distance to pulp mill. A study of various regimes based on the growth models of Candy (1997) indicated relative values of management strategies (Candy and Gerrand 1997).

Many issues remain unresolved. Continued long-term growth at current rates is uncertain, with a threat of serious insect attack. The degree of decay infection and its development in the pruned stems is also uncertain. Further research is proceeding to resolve these issues.

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