



Pruning Eucalypts

**The biology and silviculture
of clear wood production in
planted eucalypts**

**A report for the RIRDC/Land & Water
Australia/FWPRDC
Joint Venture Agroforestry Program**

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Foreword

This report was prepared as part of a nationwide cooperative project, which aimed to summarise the national knowledge base on clear wood production in eucalypts. This report collates literature, both from Australia and internationally, and recent information on eucalypt plantation silviculture from unpublished research and field experience.

Silvicultural techniques such as pruning, are used by growers to produce logs with a high proportion of clear wood suitable for high value end uses. However, there is little information available to growers on how best to apply such techniques to eucalypts. This report summarises the research results to date thereby providing a basis for the development of species and regional specific pruning regimes by growers and advisers and helping to direct future silvicultural research in planted eucalypts.

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Abbreviations

DBHOB	Diameter at Breast Height Over Bark
DOB	Diameter Over Bark
DOO	Diameter Over Occlusion
DOS	Diameter Over Stubs
LAI	Leaf Area Index
FLP	Fixed Lift Pruning
VLP	Variable Lift Pruning
MAI	Mean Annual Increment
AFG	Australian Forest Growers Association
NFI	National Forest Inventory

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Executive Summary

The last decade has seen a rapid expansion in the planting of eucalypts across Australia. By 2000 more than 500,000 ha of hardwood plantings had been established, much of which to produce pulpwood. Plantings to produce high-value, solid wood products have also increased. These plantings aim to produce logs with a high proportion of high value clear wood. Early indications from sawing studies indicate that knots substantially decrease the amount of high value wood that can be recovered from planted eucalypts. To increase the production of clear wood, pruning may be necessary. This report summarises the biological and silvicultural literature on clear wood production from planted eucalypts and examine how the biology of eucalypts will interact with the markets to determine the economics of clear wood production.

The canopy dynamics of eucalypts and there management, impact on both the growth of the tree and, via the process of branch shedding, wood quality. To maximise the production of clear wood a balance is required between canopy size, to sustain growth, and early branch removal to restrict the size of the knotty core. Failure to restrict the knotty core in planted eucalypts may result in the down grading of timber due to branch related defects. Pruning is the main means by which branch related defects can be minimised in eucalypts.

The limited evidence suggests that eucalypt branches should be pruned when green to contain the knotty core. Pruned dead branches may occlude no faster than those shed via self-pruning. Thus, if pruning is to be undertaken pruning green branches will produce more clear wood than if pruning was delayed and the branches were pruned when dead. In many eucalypt species the green crown rises rapidly, requiring pruning to be done early if green branches are to be removed (at 1 to 4-years old depending on species and site). The amount of green canopy that can be removed without decreasing tree growth varies between 30 – 50%. If stand growth rates are to be maintained a leaf area index above 4 m² of leaf per m² of ground area should be maintained. Timing pruning to coincide with canopy closure can reduce the impact of green pruning on tree growth. Information on the effect of pruning on tree growth and wood quality in low rainfall areas and in wide spaced plantings is limited.

Pruning eucalypts may increase the risk of decay. When branches are pruned no protective layer is present and decay organisms can enter the stem. The risk of decay associated with pruning appears higher in wetter (Tasmania, Northern NSW) than drier (WA and Victoria) climates. The risk of decay entry can be reduced by ensuring branches are small when pruned and growth is rapid so that the wounds are rapidly occluded.

A number of pruning regimes are available which aim to restrict the size of the knotty core and hence maximise clear wood production. The most appropriate regime will depend on the species, growth rates, level of input (reflecting the size of plantings), objectives of grower and the market the trees are being grown for. The importance of pruning only a select number of the best trees and then thinning to ensure the remaining pruned trees grow rapidly can not be stressed enough.

Growers need to make silvicultural decisions with reference to the economics of pruning, notwithstanding the difficult of predicting markets 15 to 30 years ahead. Questions of concern include a consideration of what markets will be available for pruned eucalypts, what will be the value of the logs in the market and how can the economic benefit of pruning be evaluated? Importantly, when the trees are harvested standardisation and certification of pruning may assist the grower in realising the added value of pruning.

Clearly, further research is required to ensure pruning regimes are developed which produce high quality clear wood. Because of the wide range of species, growth environments and management options we recommend that a ‘trait’ based approach be considered. This would require experimental work to include general tree and stand characteristics as well as measuring the specific species performance at a particular site. For example, pruning trials should include measurements of branching and canopy characteristics to allow generalisations beyond the specific species and site. Finally, wood studies to develop sawing and drying techniques to maximise the recovery rates from planted eucalypts is required.

1. Introduction

In the last decade there has been a rapid expansion in the area of eucalypts planted across Australia (Table 1). In Western Australia, Tasmania and the “Green triangle” region of South Australia and Victoria industrial plantings for pulpwood have largely driven this expansion. Smaller, but significant areas of eucalypt plantings are also being established with the intention of producing high value solid wood, particularly by state agencies in Tasmania, NSW and Queensland. These plantings aim to augment the projected shortfall in high quality hardwood logs resulting from the declining supply from native forests and to supply new and developing export markets (Commonwealth of Australia, 1997). To date only small areas have been established in Victoria and Western Australia for such markets, mainly by small-scale growers. However, there are large areas of pulpwood plantations that may have potential for conversion to solid wood production.

Table 1. Total area of planted eucalypts and recent rates of new plantings in Australia. (Accounts only for estates greater than 1,000 ha).

State	Recent rates of new plantings (ha year ⁻¹)				Total area (ha)
	1995	1996	1997	1998	
WA ¹	9,677	20,182	22,250	21,000	120,110
Tasmania ¹	6,177	8,126	7,546	8,367	78,024
Victoria ¹	440	1,480	2,955	8,399	40,870
New South Wales	1,630	3,234	3,502	7,460	39,623
Queensland	1,003	1,202	2,089	1,989	8,414
South Australia	194	500	1,040	1,897	3,469
Northern Territory	1	3	200	8	501
A.C.T	0	0	0	0	0
TOTAL	19,122	34,727	39,582	49,120	291,011

Source: (National Forest Inventory, March 2000)

¹The majority of these plantings would be for pulpwood.

The rate of eucalypt planting in smaller farm woodlots (< 1,000 ha total area) has also increased rapidly during the 1990's. By 2000 more than 30,000 ha of planted eucalypts were reported as farm forestry plantings, representing 7% of the hardwood plantation estate across Australia (Wood *et al* 2001). Plantings on farms are often undertaken to address environmental issues, such as dryland salinity mitigation, soil protection, wildlife habitat and landscape aesthetics. If revegetation is to occur on a scale required to address land degradation issues commercial returns from tree crops will be required to offset the establishment and opportunity costs of this land-use-change. Thus, while commercial returns may not be the main driver of farm forestry plantings, commercial returns from farm forestry plantings will greatly encourage the integration of trees into farming systems. Management options, such as pruning and thinning, can be important in determining the returns obtained from such plantings.

1.1 Major Species

The eucalypt species currently being planted throughout Australia have been chosen to suit regional growing environments and the wood quality requirements of current markets. *Eucalyptus globulus* is by far the dominant species planted throughout Western Australia, Victoria, and Tasmania. This reflects its general versatility in terms of suitability to various growing conditions, as well as its desirability as a pulp species and utility for other solid wood products (Yang & Waugh, 1996a). In northern New South Wales and southern Queensland a range of other species are being planted including *E. pilularis*, *E. grandis*, *E. cloeziana*, *E. dunnii* and *Corymbia variegata* (formerly *E.*

maculata). In Tasmania, Victoria and the cool temperate regions of New South Wales, *E. nitens* and *E. regnans* are also widely planted (National Forest Inventory, 1997). Internationally *E. grandis*, *E. saligna* and *E. globulus* are also common plantation species for production of both pulp fibre and solid wood (Jenkin, 1992). Other species less commonly planted in Australia, such as *E. tereticornis* and *E. urophylla* are planted in countries such as China and India (Jiang *et al*, 2000; Pandey, 2000). Furthermore, eucalypt hybrids, *E. sideroxylon*, *E. crebra*, *E. occidentalis*, *E. camaldulensis* and *E. benthamii* are currently being investigated, particularly for lower rainfall areas.

1.2 A New Silvicultural Challenge

The management of planted eucalypts for solid wood markets will require a range of silvicultural options to cover the increasing diversity of eucalypt plantings. Eucalypt plantings for solid wood markets are occurring in traditional large-scale plantation estates in high rainfall areas through to small farm forestry plantings in lower rainfall areas. In order to meet the requirements of solid wood markets, planted eucalypts will require silvicultural management which reflect the differing environments and objectives of the diverse range of planted eucalypts. Designing such regimes will require a greater understanding of factors that influence wood quality and silvicultural methods that maximise the production of defect free (clear) wood. Clearly, such silvicultural regimes will differ from those used for pulpwood production. Over the coming years there is a need to define the links between silviculture and wood quality if planted eucalypts are to supply the solid wood market. Already such work is under way (e.g. Washusen *et al* 2000).

The planting of eucalypts in lower rainfall area (<700mm pa) presents a particular silvicultural challenge. Lack of water will limit growth. Under these conditions heavier and earlier thinning at the time of pruning may be required to achieve reasonable growth rates. Currently there is little information on management options for low rainfall plantings.

Given the wide range of species, sites, desired products and/or reasons for planting, it is not possible to prescribe regimes that are applicable to all eucalypts. As the industry is still very young and diverse there are many areas where information is not yet available. This is particularly so for farm forestry plantings. This report gathers together literature and current research to identify some general principles of eucalypt silviculture that need to be adapted to the circumstances of individual growers. It should be noted that the available information is from a limited range of species growing in higher rainfall areas under plantation conditions. Consequently, care is required in applying such results to different species, environments and management objectives. Summary sections are presented on the biology of wood production and wood quality assessment as background for the management regimes and options that are described in later sections. We also touch on the economics of different management options. The report concludes with a summary of research needs.

2. The biology of wood production

In this section we outline the biology of the dynamic processes of canopy development, branch senescence and shedding, and their impact on eucalypt wood production. This section provides the background to the silvicultural management options discussed in Section 3. While the information here is from commonly planted species, some generalisations are possible and the applicability to other species can be assessed based on the similarity of traits exhibited by commonly planted species.

2.1 Canopy Dynamics

Canopy dynamics impacts on wood production in two separate ways. Firstly, the canopy is the “powerhouse” of the tree providing the carbon, via photosynthesis, for growth and wood production. Hence the response of the canopy to the environment will determine the wood volume produced. Secondly, as trees grow in height the canopy rises and dead branches are left behind. The process of branch senescence, ejection and occlusion has an important impact on wood quality, and is outlined in Sections 2.2 and 2.3.

The early growth of planted forests is directly related to the size of the tree canopy. Differences in growth rates between species and sites can be simply a function of a more rapid development of canopy size in the early years. Larger canopies are able to intercept more light and convert this to carbon for tree growth (Beadle, 1997). Under favourable growing conditions canopies develop both faster and to a greater size (Figure 1).

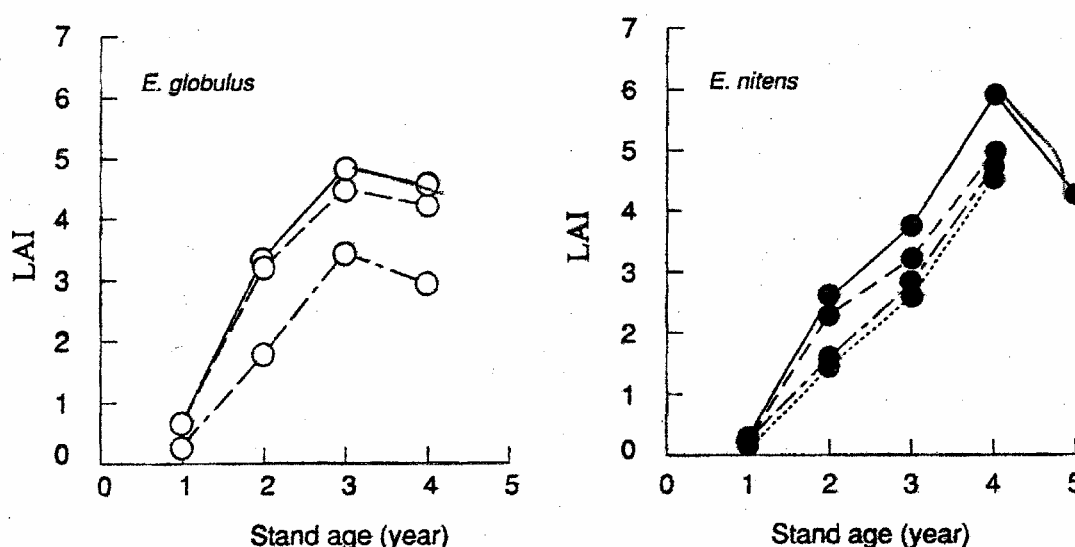


Figure 1. Differing leaf area index (LAI) development rates of *Eucalyptus globulus* and *E. nitens* at four contrasting sites in Tasmania (From Beadle, 1997).

Leaf area index, LAI (foliage area per land area) is the most common variable used to define canopy size. Values of LAI for planted eucalypts in higher rainfall areas range from 2 – 9 (Beadle, 1997); i.e. trees will have 2 – 9 m² of foliage for each square meter of land. For planted eucalypts a maximum LAI at canopy closure is typically 6. The development of LAI and its maximum value is dependent on species and growing environment. For example, *E. nitens* can reach its maximum LAI in four years (Beadle *et al.*, 1995), while *E. grandis* may take as little as 12 months (Cromer *et al.*, 1993). The measurement of LAI requires specialist equipment (Cherry *et al.*, 1998). However, the length of the green crown (the distance from the top of the tree to lowest branch that is part of the canopy) is linearly related to LAI (Pinkard & Beadle, 2000). Once established, this relationship can be used in management situations, for example to set limits on the amount of foliage to be removed by pruning which does not reduce growth.

Canopy closure, where the crowns of neighbouring trees meet, represents an important change in the development of a planted forest. After canopy closure stand leaf area stabilises and can decrease in eucalypts (Figure 2). At the individual tree level this results in the rise of the green crown as the tree grows. Light, or lack of it, is the driver of these processes. Prior to canopy closure all parts of the crown are exposed to some direct sunlight and the assimilation of carbon by leaves is not light limited. After canopy closure, leaves in the lower parts of the crown are shaded and the amount of carbon assimilated by these leaves is reduced. When the leaf is unable to intercept enough light to maintain a positive carbon balance the leaf and ultimately its branch senesces. The level of light at which this occurs (light compensation point) varies between tree species. Species, growing conditions and stocking rates (Figure 2) will affect this process and determine the rate of green crown rise.

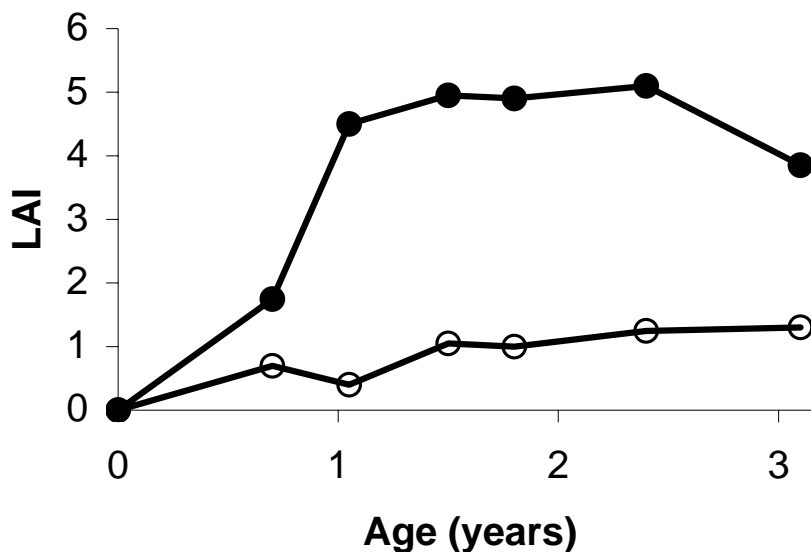


Figure 2. Development of leaf area index over time in *Eucalyptus grandis* with (●) or without (○) fertiliser (from Cromer 1999).

Compared to exotic forestry tree species, such as *Pinus radiata*, eucalypts are not shade tolerant. As a result, senescence of the lower branches of eucalypts can occur rapidly following canopy closure. Within the eucalypts there is considerable species variation in shade tolerance and this affects the response of the species and their management. For example, *E. grandis* foliage appears quite shade intolerant resulting in the early senescence of lower branches and rapid rising of the green crown after canopy closure. In contrast the rise of the green crown of *E. nitens* is considerably slower, due to the retention of the lower branches for longer, indicating a greater shade tolerance.

Conditions that promote canopy closure and shading of the lower branches will also promote the rise of the green crown. Tree stocking levels and growth rates are the major factors that determine when canopy closure occurs. There is less growing space for each tree at high stocking rates. As a result canopy closure occurs sooner and the green crown rises earlier and more rapidly (Merriam *et al*, 1995; Jack & Long, 1996). Reducing the stocking rate allows the trees more space and light, delaying the rise of the green crown. This is clearly shown for five year-old *E. grandis*, *E. pilularis* (Kearney, 1999) and *E. nitens* (Nielsen & Gerrand, 1999) (Figure 3). The pattern of increased height to the green crown with increased stocking rates (closer spacing) is similar for the three species. The rise of the green crown will also be delayed in trees on edges of blocks or in narrow shelterbelts where lower branches continue to be exposed to full sunlight.

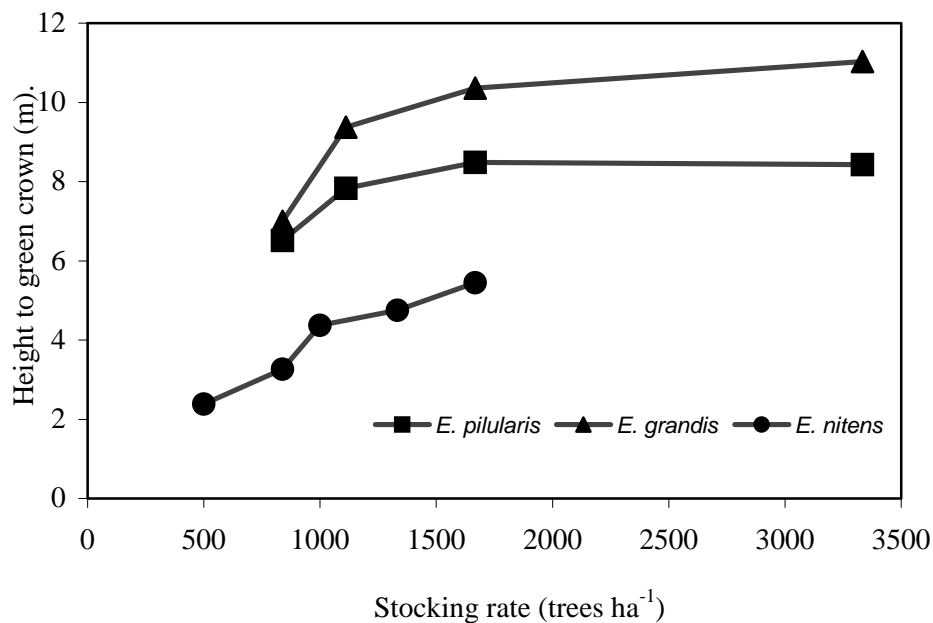


Figure 3. Effect of tree stocking rate on height to the bottom of the green crown of *Eucalyptus pilularis*, *E. grandis* (from Kearney, 1999) and *E. nitens* (from Neilsen & Gerrand, 1999) crown at age 5.

Finally, nutrient and water availability will also affect the dynamics of the canopy (e.g. Figure 2). When nutrients are limiting growth, trees may extract nutrients from shaded leaves and translocate them to new, well-lit foliage (Field and Mooney, 1983). By internally cycling nutrients the tree optimises the nutrient use for carbon gain by the canopy (Hirose & Werger, 1987). A consequence of the increased nutrient cycling on poor sites is the earlier senescence of lower branches and subsequent rise of the green crown. When nutrients are limiting the rise of the green crown may occur before canopy closure. Water stress can have a similar effect on the canopy dynamics.

2.2 Self-pruning

Eucalypts are commonly referred to as self-pruning. Jacobs (1955) noted “.. the shedding of the branches and the occlusion of the resulting wounds has become so efficient as to be a noteworthy feature”. This observation was based on eucalypts growing in native forests with large branch-free trunks. The natural regeneration of native eucalypts forests results in very high initial tree stocking rates. Following disturbance tens of thousands of seedlings per hectare may compete for site resources (Florence, 1996). This combination of high stocking rates and rapid early growth results in early canopy closure. Thus height growth is rapid and the reduced light levels in the lower canopy inhibit branch growth and induce early senescence. It is by this process that self-pruning of many fast growing eucalypts is promoted in native eucalypt forest (Shepherd, 1986). However, trees are grown to a larger size in native forest allowing additional time for the production of clear wood. Planted eucalypts are grown under different conditions. Economic constraints force short rotation lengths and relatively low stocking rates in planted forests (Johnston *et al*, 1967). Planted forest stocking rates generally range from 700-1,500 trees ha⁻¹ compared with tens of thousands in native forests. In agroforestry or low rainfall areas tree stocking rates may be even lower. The lower initial stocking rates delay canopy closure and the rise of the green crown (see Section 2.1). The short rotation length and unfavourable self-pruning conditions in plantations work against the production of clear wood.

The rise of the green crown and senescence of lower branches (Section 2.1) is the first step in self-pruning. Three additional steps are required for self-pruning to occur successfully and for clear wood to be produced; a branch abscission layer must form, the branch and stub must be ejected and occlusion of the wound must occur.

The formation of a branch abscission layer is similar to the formation of leaf abscission layers and has been noted in many tree species (Kramer and Kozlowski 1979). The abscission layer creates a zone of weakened tissue where the branch can separate from the trunk. In eucalypts a brittle zone may also form externally at the junction of the branch and the stem (Jacobs, 1955). This allows the branch to break away from the trunk leaving behind a stub within the trunk. Finally the dead stub is broken at the abscission layer by a build up of pressure due to radial growth of the trunk. The broken stub is then ejected by continuing pressure exerted by the expanding stem and occlusion occurs when cambial tissue grows over the wound. Subsequent radial growth is free of knots. The rate of occlusion will be largely determined by the size of the wound (i.e. branch size) and the radial growth rate of the tree. Occlusion will be most rapid on fast growing trees with small branches.

2.3 Defect Formation due to Unsuccessful Branch Shedding

Inefficient ejection and occlusion of branches can lead to the formation of defects within the growing stem. Defects in timber associated with unsuccessful branch shedding have been reported for *E. regnans* (Marks *et al*, 1986), *E. nitens* (Gerrand *et al*, 1997; Yang & Waugh, 1996b), *E. grandis* (Poynton, 1980; Maree, 1979; Stackpole *et al*, 1999) and *E. globulus* (Stackpole *et al*, 1999; Yang & Waugh, 1996a). It seems likely that such defects will be common to all eucalypt species.

Problems during the ejection of the dead branch stub are the major cause of defects. These can be caused by: 1) large and high angle branches delaying the ejection process, 2) inclusion (i.e. failure to eject branches) of the dead branch or stub producing loose knots, 3) kino deposits produced when the stub is not cleanly ejected (Jacobs, 1955; Yang & Waugh, 1996a and b; Gerrand *et al*, 1997). These problems are discussed in detail below. Decay entry can also occur during branch shedding (Section 3.2.3).

Large branches are problematic because the time to senescence is increased, and the occurrence of branch shed and ejection may be delayed or not occur at all. The size at which a branch becomes a problem has not been quantified for most eucalypt species. Jacobs (1955) suggested that branches greater than 25 – 30 mm will not be efficiently shed. Larger branches are more likely at low stocking rates. However, small branch sizes do not guarantee clean stub ejection. In one of the few studies of these processes, only 35% of branches greater than 10 mm were successfully ejected in *E. regnans* (Marks *et al*, 1986). High branch angles associated with large, vigorous branches (Gerrand *et al*, 1997; Kearney, 1999) also contributed to delays in ejection and occlusion.

Loose knots occur when the branch or its stub is included into the clear wood. Loose knots cause the downgrading of sawn timber as structural grade timber is weakened (Bourough & Humphreys, 1996; Bootle, 1983) and the visual blemish down grades appearance grade timber.

Pockets of kino (a polyphenol exudate produced in response to injury) (Tippett, 1986) are another common cause of degradation found in eucalypt timber (Haslett, 1988). The process of branch stub ejection can result in kino pockets or traces forming (Jacobs, 1955) and have been reported in *E. regnans* (Marks *et al*, 1986), *E. nitens* (Yang & Waugh, 1996b), *E. grandis* and *E. globulus* (Stackpole *et al*, 1999). Kino traces occur when a dead stub remains in the cambial layer and is dragged along by the radial growth of the stem before it is fully ejected. The resultant hole formed behind the stub is filled with kino. These kino traces cause a defect in sawn timber or veneer.

For most species, specific information regarding the size and type of branches that cause these defects is lacking. However, anecdotal observations suggest differences between species. Some species, such as *E. grandis*, *C. maculata* and *E. dunnii*, appear able to cleanly and efficiently shed lower limbs. Other species, such as *E. globulus* and *E. nitens*, display poor self-pruning. Despite the rise of the green crown, lower dead branches are not shed in these species at normal plantation stocking rates (Gerrand *et al*, 1997; Yang & Waugh, 1996a; Yang & Waugh, 1996b).

The amount of silvicultural management required to maximise clear wood production will depend on the ability of a species to self-prune, susceptibility to disease and decay and the relationship of these factors to site quality. It may be possible by manipulating stand conditions to promote self-pruning, particularly if high stocking rates are used on high quality sites. However, even with the most efficient self-pruning species, a reliance on natural branch shedding may require uneconomically high stocking rates with subsequent loss of growth of individual trees. For most species and sites it is likely some form of stand tending or pruning will be necessary.

Case Study 1. Occlusion rates of pruned and unpruned branches in four subtropical Eucalypt species

Branch occlusion processes were compared in pruned and unpruned trees of *E. cloeziana*, *E. pilularis*, *E. dunnii* and *E. grandis* in subtropical northeast NSW (Smith *et al.*, 2000). Trees were pruned at age 3.5 years and the fate of live and dead branches of both pruned and unpruned trees was reassessed 2 years later.

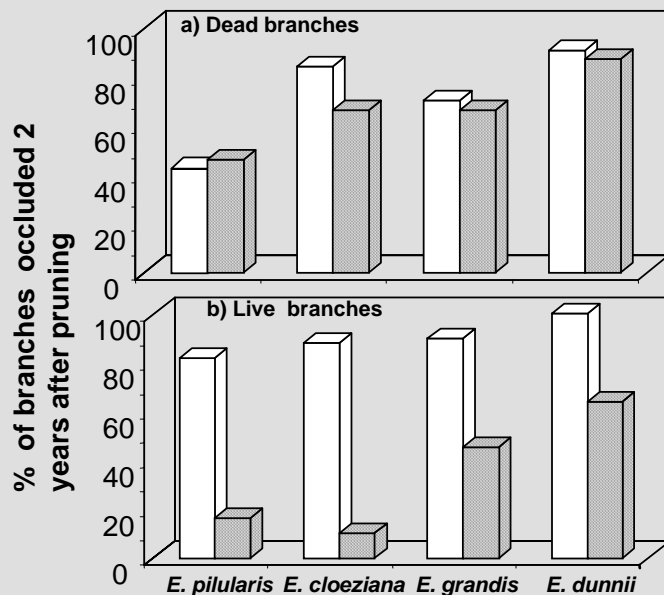


Figure A & B. The percentage of pruned ☐ or unpruned ☐ branches which had occluded two years after pruning for a) dead branches or b) live branches.

In all four species pruning of dead branches only slightly improved the percentage of branches occluded (Fig. A). This occurred because the stubs of the pruned dead branches were slow to occlude and a high percentage remained 2 years after pruning.

When branches were pruned green, occlusion rates were greatly increased (Fig. B). For example, in *E. pilularis* close to 80% of pruned green branches had occluded 2 years after pruning. Only 15% of unpruned green branches had occluded after the same time period. Species differences in response to green pruning are evident. *E. pilularis* and *E. cloeziana* (poor self pruners) benefited most from green pruning while *E. grandis* and *E. dunnii* benefited less from green pruning due to the good self pruning nature of these species. For implications on the economics of pruning see section 5.3. Green pruning is required to increase occlusion rates and thus the proportion of clear wood produced by these species. See sections 3.2 and 4.2.2. for implications with regard to canopy dynamics and tree growth.

Results from this study suggest that pruning of green branches is more effective in producing clear wood than the pruning of dead branches.

3. Silvicultural management

3.1 Assessment of Wood Quality

Planted eucalypts have traditionally been grown on short-rotations to produce wood fibre for pulp. Wood quality issues for this market are concerned primarily with intrinsic properties associated with tree species such as fibre properties (Downes *et al*, 1997). There is only limited information on the wood quality from planted eucalypts because the industry is so young. In general, studies to date have given positive signals with a number of eucalypt species producing encouraging results. In this section we consider general wood quality characteristics such as appearance and density, and how planted eucalypts have performed in grading studies.

General Wood Quality Parameters

The wood quality parameters that are most important for solid wood products are density (hardness, strength, workability) durability, colour, shrinkage, stability, processing properties and the absence of defects (Leggate *et al*, 2000).

The basic density of wood is an important quality parameter (Bamber, 1983). Plantation grown eucalypts typically have lower density than that of mature native forest trees, but higher than that of plantation grown Radiata Pine (Washusen *et al*, 1998; Haslett, 1988). Low wood density can be a problem with some species if trees are harvested young. For example, young *E. regnans* and *E. delegatensis* both produce a comparatively large volume of low density wood (Waugh, 1996). However, for a range of plantation eucalypts including *E. grandis*, *E. saligna*, *E. nitens*, *E. denticulata*, *E. camaldulensis* and *E. globulus*, wood density is generally within the range that is suitable for structural and appearance products when grown to suitable dimensions (Washusen *et al*, 1998; Yang & Waugh, 1996a; Yang & Waugh, 1996b).

Growth stresses in young logs, which can cause spring during sawing, can cause problems in the utilisation of young eucalypts. The timber of some species can collapse and shrink during drying resulting in substantial losses. The development of new sawing and drying technologies are expected to overcome these problems by the time substantial volumes of planted eucalypts become available for harvesting (Waugh, 1996; Leggate *et al*, 2000).

Eucalypt species produce wood of various colours and textures, many of which are suitable for appearance grade products (Haslett, 1988). However, the economics of growing these species will depend on the processing properties and their desirability in the market.

Grading Performance of Young Eucalypts

Grading studies are used to measure the quantity and quality of wood obtained from logs. Because quality is subjective, the criteria applied to grade timber will depend on the end use. There are three main product types for solid wood;

- Structural sawn products in which visual stress grading rules are used - AS2082-1979 (SAA, 1979).
- Appearance grade products that are also assessed visually.
- Veneer products

Each of these product types have specific requirements by which wood is graded and in all cases products derived from clear wood will achieve the highest grading.

In interpreting grading studies it is important to note how the results are expressed so that valid comparisons can be made. Graded recovery can either be reported as a percentage of the total timber volume recovered from a log, or as a percentage of the total log volume. For example, a 3 m log with a 40 cm mid-point diameter has a total log volume of 0.38 m³. When this is sawn, the *recovered* timber may account for 60% of this volume, or 0.23 m³. When this timber is *graded* then perhaps only 30% will be of appearance grade, or 0.07 m³. Thus, the appearance grade recovery is either 30% (when expressed as a percentage of timber recovered) or 18% (when expressed as a percentage of the total log volume). In this report we have expressed grading studies on the basis of the volume of timber recovered from a log.

Early indications of graded recovery from planted eucalypts in Australia have been obtained from sawing studies of largely untended stands. The volume of high grade timber recovered in these studies has been variable, though generally lower than graded recovery rates of logs from native forests (Leggate *et al*, 2000; Waugh, 1996) or from well managed plantation grown *Pinus radiata* (MacLaren, 1993). Considerable care is required in interpreting species differences as results may be confounded by different log sizes (e.g. Washusen *et al*, 2000).

In all studies, knots have been the major grade limiting factor, whether recovery was evaluated using a structural or appearance criteria (Yang & Waugh, 1996a; Yang & Waugh, 1996b; Washusen *et al*, 1998; Waugh & Yang, 1994; Waugh, 1996; Leggate *et al*, 2000, Washusen *et al*, 2000). Consequently, unless silvicultural techniques are used to control branching and hence the occurrence of knots, the quality of wood from eucalypt plantations may be reduced to the point where economic returns are not achieved (Leggate *et al*, 2000).

By applying specific silvicultural treatments there is potential to substantially increase the recovery rates in planted eucalypts (Waugh, 1996). For example, a recovery rate of 60% appearance grade was achieved in high pruned 13 year-old *E. globulus* (Moore *et al*, 1996) (see Section 3.3 Case Study 4). By comparison graded recovery rates of less than 20% appearance grade have been reported in unpruned *E. globulus* (Washusen *et al*, 1998).

Graded recovery is largely determined by the amount of clear wood contained within a log. In the remainder of this report we outline how management can increase the production of clear wood by restricting defects to a central core.

3.2 Pruning

The decision to prune requires consideration of species, stand and site characteristics and economic considerations. Furthermore, pruning can not be considered in isolation from other silvicultural operations. Thinning operations should be an integral part of planning any pruning operation and are discussed in Section 3.3.1. For pruning to be successful and economically viable it must produce sufficient additional volume and quality of clear wood to justify the additional expense. Economic factors that need to be taken into consideration are discussed in Section 4. In this section we discuss the biological issues influencing the decision to prune and how pruning can affect tree growth and decay entry.

The Objective of Pruning

Pruning is undertaken to maximise the amount of clear wood produced by a tree. Pruning achieves this by removing branches early, containing branch related defects to a central knotty core (Shepherd, 1986), and allowing subsequent growth to be defect free. Pruning also assists in producing a more uniform crop of logs. Log uniformity can help reduce the processing costs and result in higher prices being paid to the grower. Before commencing pruning a growers need to design a management

regime that aims to produce logs of certain specifications for a particular market. If this planning is not attempted then increased returns from pruning may not be realised

Only a percentage of trees should be pruned. Not all trees in a stand will be of sufficient form and vigour to produce logs to specification and therefore selection of the crop trees is required (Section 4.3.1). The targeted specifications for logs should be based on a maximum allowable knotty core diameter (Stackpole *et al*, 1999; Koehler, 1984). For example, to produce 90 % clear wood volume from a six meter log would require a centre diameter at harvest of 50 cm and a knotty core diameter of 15 cm (Gerrand *et al*, 1997). Pruning above the first two logs (6-7 m) has been found to be uneconomic in pines, due to logistical difficulties, causing increased expense for a relatively small return due to the smaller size of upper logs (James, 1990). It is envisaged that this would also apply to eucalypts. To date, studies on green pruning have concentrated on the first lift (i.e. to 2.5 m). There is no explicit information on the growth or physiological response of eucalypts to repeated pruning (Pinkard & Beadle, 2000).

Containing the knotty core of eucalypts

The diameter of the stem at the time of pruning establishes the ‘diameter over stubs’ (DOS). However, this does not define the ultimate diameter of the knotty core. Clear wood is not produced until the occlusion process is completed. Hence, the size of the knotty core will be equivalent to the DOS, plus the additional radial growth (the X factor in Figure 4a) required to fully occlude stubs and defects (Section 4.2.3). This is termed the ‘diameter over occlusion’ (DOO) (Gosnell, 1987; Petruncio *et al*, 1997). The profile of the defect core will be a function of the maximum DOO combined with the form and taper of the tree (Figure 4b). Therefore, only good form trees should be pruned in order to ensure minimal defect core proportions (Reid, 1997).

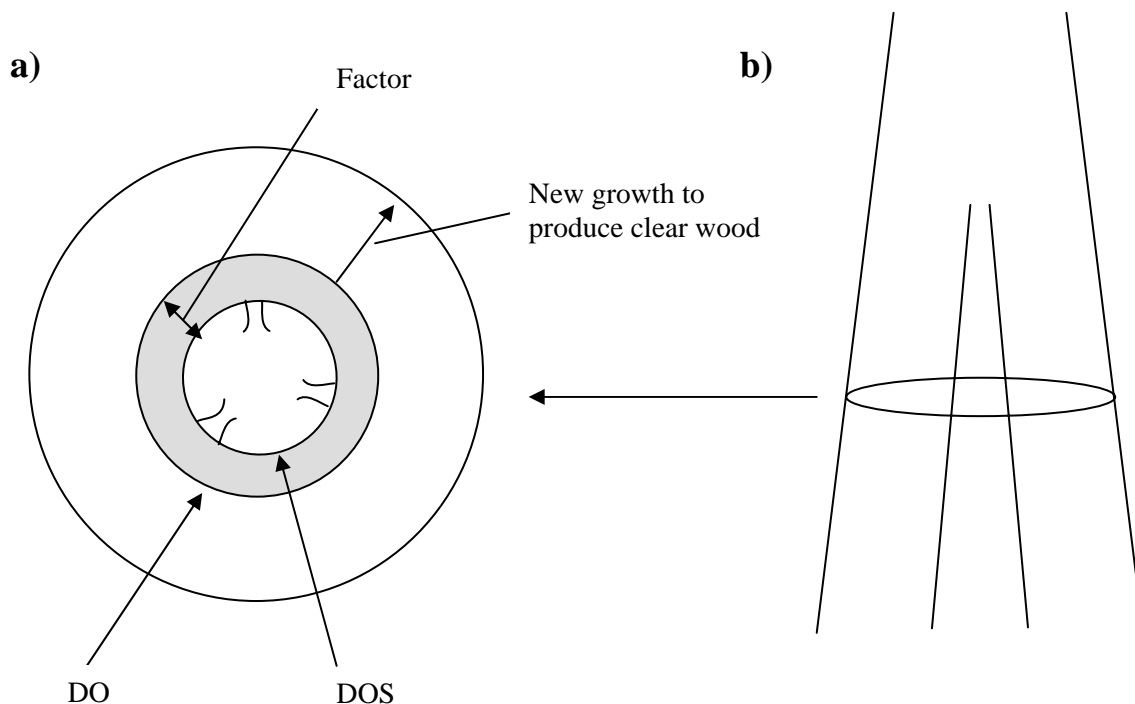


Figure 4. a) The stem cross-section highlighting the defect knotty core. The knotty core is a product of the diameter over pruned branch stubs (DOS) plus the additional growth before clear wood is produced (the x factor) to give the diameter over occlusion (DOO), and b) the tapering characteristic of the knotty core within the tree

For radiata pine DOO can be predicted from DOS measurements as all branches occlude at the same rate (Gosnell, 1987). This allows the clear wood volume to be accurately predicted using measurements of DOS immediately following pruning. Unfortunately not all tree species behave as predictably as radiata pine. The time taken for pruned Douglas-fir branches to occlude is a function of stem and branch size, stub length, stem growth rate, live or dead branch condition, and whether pruning produced a rough or a smooth cut surface (Petruncio *et al*, 1997). The limited studies to date indicate that similar factors affect occlusion rates in eucalypts after pruning. However, there is little information on which to predict the x factor (Figure 4) and hence the clear wood volume produced by pruning. This is a reflection of the young age of most eucalypt plantings.

Live and dead branches

The different responses of live and dead branches to pruning suggest that only pruning of live branches (“green pruning”) will be beneficial in containing the knotty core. Studies of *E. nitens* have revealed that pruning of dead branches leads to the same defects forming as when the branches are left to shed naturally (Gerrand *et al*, 1997). Preliminary results from pruning trials in *E. grandis*, *E. dunnii*, *E. pilularis* and *E. cloeziana* indicate that pruned dead branches occlude no faster than those shed via self-pruning (Smith *et al*, 2000). This suggests that the pruning of dead branches would not reduce the size of the knotty core. By contrast, branches pruned while green tended to occlude effectively. If this is common to all eucalypt species then pruning may have to be scheduled to ensure all branches are pruned while they are alive. This has the potential to impact on tree growth by removing foliage that is actively participating in light capture and photosynthesis.

Pruning and tree growth

The limited studies of eucalypt pruning suggest branches should be pruned when alive for maximum benefit. Green pruning, and thus removal of leaf area, has the potential to decrease tree growth rates. Consequently, the green pruning of eucalypts must balance the need to prune live branches with that of maximising early canopy size to maximise tree growth (Section 2.1). In this section we ask how much foliage can be removed without affecting growth, and when is the best time to do this? Furthermore, by outlining the principles of pruning physiology we provide a framework which can be used to come up with “best guesses” for new species or silvicultural regimes until specific information becomes available.

How much foliage can be removed without reducing growth?

The amount of foliage that can be removed without reducing growth will be determined by; 1) the amount of foliage prior to pruning (a product of tree spacing and stand growth rates) and 2) the ability of the remaining foliage to respond following pruning. There is an optimum LAI for maximum production based on light interception (Jarvis and Leverenz, 1983). As LAI increases, more light is intercepted by the canopy (Figure 5). The optimum LAI is that when the canopy intercepts 95% of the available light. This is typically at a LAI of 6, but is affected by leaf angle and canopy structure (Figure 5). However, it is clear from Figure 5 that a LAI of roughly 4 is capable of intercepting 80% or more of the available light and only marginal increases in light interception occur at higher LAI. The reason for this is that shading occurs in the lower canopy. At high values of LAI the lower canopy contributes little to light interception and subsequently carbon supply of the tree (Section 2.1). Therefore, removal of foliage from the bottom of the canopy by pruning will have little effect on tree growth. For example, the LAI of *E. nitens* growing in Tasmania may exceed 6 (Figure 1, Section 2.1). Pruning of 50% of the green crown, which reduced the LAI to 3.9, had no effect on growth of *E. nitens* (Pinkard & Beadle, 1998) or *E. grandis* (Bredenkamp *et al*, 1980). Pruning 30% of the green crown had no effect on growth of *E. pilularis*, although significantly reduced growth in *E. dunnii* two years after pruning (Smith *et al*, 2000). There have been conflicting results for *E. cloeziana*. In Queensland, pruning 30% of the canopy had no effect on growth (Dickinson, unpublished), however in New South Wales there was a small decrease in diameter growth two years after pruning (Smith *et al*, 2000).

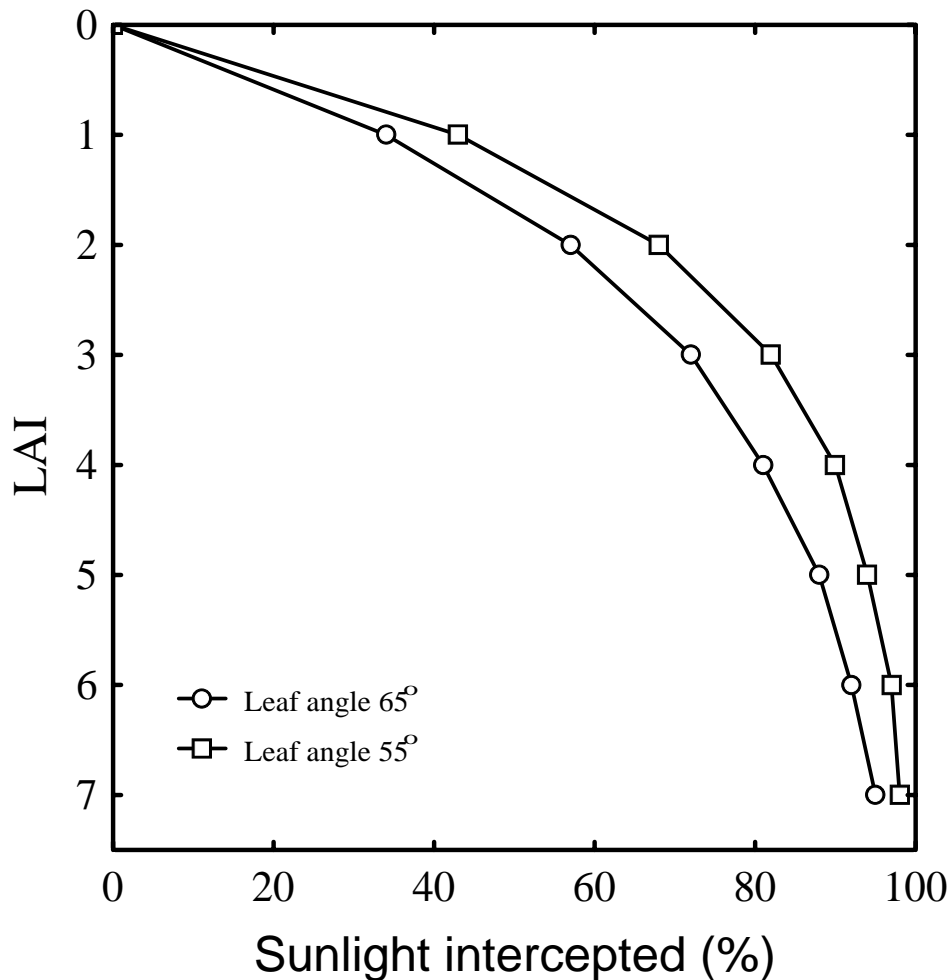


Figure 5. Relationship between leaf area index (LAI) and percentage of sunlight intercepted by the stand.

Green pruning can induce changes in the remaining canopy that compensate for the reduction in LAI. Within weeks of removing 50% of a *E. nitens* green crown, a 35% increase in the photosynthetic rates of the remaining foliage was observed (Pinkard & Beadle, 1998). An increase in photosynthetic capacity was also observed in leaves produced after pruning and was sustained for 17 months. This response helps to maintain the carbon supply to the tree in the short to medium term. Canopy growth responses were also observed in the same study and the pruned trees were able to restore their canopy size to that of the unpruned trees within 13 months (Pinkard & Beadle, 1998). This was possible due to the production of larger leaves and a greater allocation of carbon to foliage at the expense of the branches (Pinkard & Beadle, 1998). Removal of 70% of the green crown reduced tree growth in *E. nitens* (Pinkard & Beadle, 1998). Subsequent sensitivity analysis indicated that changes to the leaf area and foliage distribution accounted for the majority of the observed increases in productivity of trees where 50% of the green crown had been removed (Pinkard *et al*, 1999).

When is the best time to green prune?

Timing of pruning to coincide with canopy closure is likely to reduce the impact of pruning on tree growth. After canopy closure the lower branches become shaded and will contribute little carbon to the tree (Section 2.1). Pruning before canopy closure will remove branches that are still contributing carbon to the tree and will be more likely to reduce tree growth rates.

Wide spacing is often used in farm forestry plantings leading to low stocking rates (<200-300 stems ha⁻¹). Under such conditions the timing of pruning should be related to individual tree factors as opposed to stand factors discussed above. The branch sizes and target DOO of the individual trees will be important factors in determine the timing of pruning. In low stocked plantings failure to prune before branches become too large can be detrimental to wood quality. Large branches will not only take a longer timer to occlude but also increase the risk of decay (Sections 2.3 and 3.2.3).

Thinning

Thinning can affect the growth response to green pruning. Thinning of the stand will increase the light reaching the lower canopy and hence the supply of carbon to the tree to support growth (Medhurst & Beadle, 2000). Thus if a stand is thinned and pruned, green pruning may have a greater effect on subsequent tree growth rates.

Given the considerable investment pruning represents, thinning should aim to maximise growth of the pruned trees within the stand. This will generally mean thinning early to low stockings (see Section 3.3.1).

Decay Associated with Pruning

The incidence of decay caused by fungi in standing trees is common in natural regrowth stands (Wardlaw *et al*, 1997). Decay fungi are able to readily gain access to the woody tissue of eucalypts through wounds to a trees surface and infections can spread from a range of wound types (White & Kile, 1991). Eucalypts in the natural forest are particularly vulnerable to rot causing pathogens during branch shed, where wounds from ejected branches can expose the inner woody tissue of the stem. However, if branch shed is efficient, eucalypts have a natural defence against the entry of decay fungi (Jacobs, 1955). During branch shedding an abscission layer develops. This protective layer forms by the secretion of substances such as tannins, resins and kino near the base of the branch (Jacobs, 1955). Thus, when branches are shed efficiently, decay causing fungi cannot readily gain entry to the inner woody tissue of the stem. When branches are removed by pruning no protective layer is present and the inner woody tissue is exposed providing a possible entry point for decay organisms.

Pruning planted eucalypts may increase the risk of decay. Decay associated with pruning in *E. nitens* plantations in Tasmania was found to be quite widespread and has since become a major research priority for Forestry Tasmania and the CRC for Sustainable Production Forestry (Gerrand *et al*, 1997). The incidence and severity of decay in *E. nitens* was correlated to site factors, where wetter more fertile sites showed higher incidence and greater spread of decay in pruned stems (Mohammed *et al*, 2000). In contrast, no decay was associated with pruned *E. globulus* in Western Australia (Bob Hingston, Western Australian Department of Conservation and Land Management, pers. comm.). Likewise in Victoria no decay was observed in the 3 years following pruning of three eucalypt species (Des Stackpole, Center for Forest Tree Technology, Victoria, pers.comm.). These examples are both associated with pruning in low rainfall, high evapotranspiration areas.

Studies of *E. regnans* and *E. delegatensis* from New Zealand, showed widespread decay in eucalypt plantations associated with pruned branches (Gadgil & Bawden, 1981; Glass & McKenzie, 1989). In some instances infection through pruning wounds may lead to tree mortality. Wounds associated with pruning of *E. delegatensis* in New Zealand were found to be frequently colonised by the decay fungus, *Stereum purpureum* (*Chondrostereum purpureum*), which can cause progressive dieback in a number of host species (Gadgil & Bawden, 1981).

The examples above indicate that the incidence of decay varies with species and site. In the following section we examine the potential damage caused by decay and identify management of risk factors.

Potential Extent of Damage

Decay pathogens can spread readily both in a vertical direction and inwards towards the pith of the tree from a wound infection site (Wardlaw & Neilsen, 1999; White & Kile, 1991; Glass & McKenzie, 1989; Gadgil & Bawden, 1981; Wilkes, 1985a; Wilkes, 1985b). This results in internal columns of decay within the woody stem. Unresolved questions include whether decay organisms can attack new clear wood, having gained entry to the stem, and what is the potential extent of decay following pruning?

Growth of new wood following wounding (causing occlusion) and the development of chemical reaction zones (or 'barrier' zones) in the wood surrounding the wound, may confine the damage caused by decay to an internal column (Glass & McKenzie, 1989; Wilkes, 1985a and b; Wardlaw & Neilsen, 1999). The nature of such barrier zones is not well understood for most eucalypt species. Recent work has indicated that the reaction zone in pruned *E.nitens* was characterised by increased phenol and tyloses concentrations (Barry *et al*, 2000). Accumulation of such chemicals may be important in the defence of the tree in inhibiting the spread of decay organisms. Unless the decay organisms can function in the anaerobic environment of the stem and breach these barrier zones, they may cause no further damage following occlusion (White & Kile, 1991). Where wounds are small it is usually the case that the wound will be rapidly occluded and an effective barrier zone will form. However, where wounds are large and occlusion does not readily take place, cracking of scar tissue around the wound may cause a physical breach of the barrier zone.

It is likely that some species of decay fungi will be more adept at spreading and causing damage ranging from discolouration to destruction of cell walls (and hence wood structure). Decay fungi may also affect tree health and even cause mortality. The time frame for the development of decays and the damage they cause will be critical. Planted eucalypts that are grown to produce clear wood logs are expected to be harvested on rotations of around 30 years. There is no evidence to suggest whether decay fungi can cause significant damage in this period.

Risk Factors and their Minimisation

Live and dead branches

There may be some variation in the risk of infection depending on whether a branch has been pruned while it is live or dead. When branches are pruned, no protective layer is present, and there is a risk of pathogen entry through the exposed woody tissue of the branch stub. This stub will remain susceptible to pathogens until it is fully occluded. If a stub is colonised by decay fungi prior to occluding then decay can spread into surrounding wood of the stem (Marks *et al*, 1986; Yang & Waugh, 1996a; Yang & Waugh, 1996b). Wardlaw and Neilsen (1999) hypothesised that branches pruned while they were alive were more likely to be a point of decay entry in *E. nitens* in Tasmania. However, recent results from a study involving a number of eucalypt species on the north coast of NSW showed dead pruned branches to have a higher level of infection than live pruned branches (Jack Simpson, State Forests of NSW, pers. comm.) Speed of occlusion is suggested as the factor controlling decay entry. Dead branches may take years to eject if abscission is not effective, while live branch wounds are more likely to occlude quickly.

Wound Size

Several studies have found that the incidence of infection is correlated with the size (diameter) of pruned branches. Large branches are associated with greater incidence of decay (Gadgil & Bawden, 1981; Glass & McKenzie, 1989; Gerrand *et al*, 1997; Wardlaw & Neilsen, 1999). This suggests that it may be possible to mitigate the risk of decay infection if branches are pruned while small. Once again a plausible explanation is that smaller branches occlude faster minimising the time of exposure

to infection. It is commonly recommended that branches be pruned while they are less than 30mm in diameter (Gadgil & Bawden, 1981; Glass & McKenzie, 1989; Wardlaw & Neilsen, 1999). If this is to be achieved it will be necessary to prune eucalypts when they are very young.

Season

Pruning in winter is often prescribed as a measure to mitigate the decay risk (Gadgil & Bawden, 1981; Glass & McKenzie, 1989). However, Mohammed *et al* (2000) found that, in Tasmania, season of pruning has little effect on the incidence of infection in *E. nitens*, and recommended that *E. nitens* could be pruned at any time of year. Season of pruning may be important in determining the incidence of decay in other areas due to the changes in temperature, rainfall and humidity. Although, if a wound is not occluded and remains exposed to decay infection through a number of seasons, these variations will not affect the risk of infection.

Tools and Techniques

Pruning tools and techniques should aim to minimise the damage to the collar of bark surrounding the branch at the junction with the trunk. It is the growth of this collar that covers the pruned area and protects the tree from decay. Damaging the collar not only increases the surface area exposed through which decay causing organisms may enter, but also slows the rate of occlusion. Pruning damage to the collar has been reported to increase in the extent of decay in *E. nitens* (Wardlaw & Neilsen, 1999). The most commonly used pruning tools are loppers, secateurs, saws and ladders. Practical guidance on the safe use of these tools for pruning eucalypts is provided in video form (Noble 2001) and on the World Wide Web (Australian Master TreeGrower).

Other

It is not known to what extent the susceptibility to decay fungi is genetically controlled. Some species are clearly less susceptible to decay entry and spread, e.g. *E. sideroxylon* (Wilkes, 1985a). There may be some scope for breeding decay resistant clones or hybrids, however such solutions are only available in the long term.

The use of paints or wound sealant has been suggested and tried. However, where these measures have been experimentally successful, it is usually the case that they are not economically viable for commercial purposes, due to the cost of labour required to treat the large number of branch wounds created by pruning (Mohammed *et al*, 2000).

Management Considerations

Pruning is a labour intensive operation. Scheduling of pruning activities will thus vary depending on the scale of operation and the labour management regimes in place. Large scale industrial plantations will require more sophisticated scheduling, which will typically involve predictions of stand development, to optimise both time of pruning and labour use (e.g. Pinkard and Beadle 2000). This would be aided by the development of silvicultural decision support tools similar to those used in large-scale softwood plantations.

By contrast, small-scale growers are able to undertake pruning as a continuous process rather than a distinct operation. Stands can be monitored regularly and pruning undertaken in response to the development of the stand (see Variable Lift Pruning Section 4.3.2.). However, if multistage, continuous pruning is undertaken the need for quality control remains (Section 5.5). Failure to undertake such programs may result in the grower not being able to obtain a premium for the carefully tended stands when these are sold.

3.3 Management Regimes

The production of high quality clear wood from planted eucalypts involves more than just pruning. Judicious timing of operations, such as weed control, fertilising, pruning and thinning, will be required to production of high quality logs. In this section we highlight the importance of tree stocking rates, tree selection and thinning before considering different pruning regimes.

Tree Stocking Rates, Final Crop Selection and Thinning

The ultimate aim, when choosing an initial tree stocking rate is to produce a sufficient number of good form, vigorous trees which can be grown through to harvest (Neilsen & Gerrand, 1999; Beadle *et al*, 1994). In eucalypt plantings some individuals will not be suitable for final crop selection due to poor form or growth (Shepherd, 1986). Poor form and growth can result from insect attack (Stone *et al*, 1998), poor planting, variable planting stock or micro-site variations. To compensate for these factors the normal range of stockings rates used range from 800-1700 trees per hectare from which 100-350 trees per hectare are typically grown through to harvest.

Initial stocking rates will be influenced by quality of the planting stock, expected survival rates, establishment techniques while final stocking rates will be influenced by target log size and desired length of the rotation. For example, in Tasmania *E. nitens* is planted at rates of 1000–1100 (4x2.5 m) stems per hectare, from which at least 300 trees can be selected for pruning and retention for the final crop (Neilsen & Gerrand, 1999). In South Africa stocking rates between 1111 (3x3 m) and 1667 (3x2 m) stems per hectare for *E. grandis* are used in conjunction with various thinning and tending regimes (Jenkin, 1992).

Both initial and final stocking rates will also be influenced by the environment and the objectives of the grower. As more eucalypts are planted in drier environments and on farms stocking rates will depart from typical plantation stocking rates. In deciding on the final stocking rates to conflicting objectives need to be considered; is total wood volume or large individual tree-size (in shorter time) more important. Typically, lower value products such as pulpwood are dependent on high volume for profitability. For smaller growers Reid (1998) has argued that producing large sized individual tree quickly is more important to achieve good returns. But to achieve the rapid growth of the individual trees the stand growth rate is reduced. For example, then total volume of wood produced per hectare per year, by *E. globulus* growing in Western Australia, was halved when the stand was thinned down to 135 stem per hectare at age 8 and subsequently harvested at 13 years old for sawlogs (Moore *et al*, 1996) (see Case study 4).

One of the most common and costly mistakes is pruning and retaining too many crop trees. Only crop trees of good form and vigour should be pruned. Once pruning has been undertaken it is essential to concentrate subsequent growth on these crop trees as premium prices are paid for large log sizes with a higher proportion of clear wood (Waugh, 1996). This is achieved by thinning of the stand to remove non-crop trees. This provides more resources (water, light, and nutrients) for the pruned trees to grow rapidly and obtain the target size quickly. By thinning and concentrating growth on fewer pruned trees a greater volume of clear wood can be produced. For example, if we assume that trees were 10cm DBH when pruned and allow a further 2cm of growth for occlusion (section 4.2.1), then trees thinned to 190, 301 and 412 trees ha⁻¹ would produce 23, 20 and 17 cm of clear wood, respectively, compared with 12 cm of clear wood if left unthinned (Figure 6). Furthermore, the thinned stand will reach a harvestable size considerably quicker than the unthinned stand.

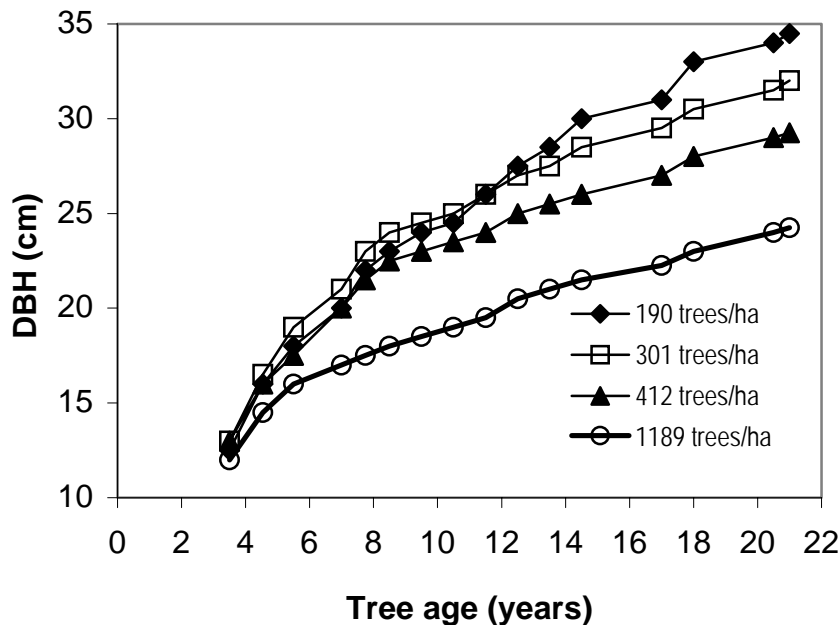


Figure 6. The tree growth response of 3-year-old *E. cloeziana* to four levels of thinning (From Dickson *et al* 2000).

A wide range of thinning management regimes is applied to planted forests. Direct regimes, where stands are pruned and thinned to final crop trees at an early age, are often applied to radiata pine grown specifically for clear wood production (James, 1990). Such regimes sacrifice cash flow from thinning during the rotation for greater returns at harvest. The market for thinnings (e.g. pulp, poles) and the expected value of the crop trees will determine the most suitable regime for each grower. However, thinning prescriptions typically change in response to market conditions. As a result the most efficient regime for producing clear wood logs may need to be compromised in order to generate cash flow income prior to final harvest.

Initial stocking/spacing also has a direct influence on the rise of the green crown, branching habit, tree form and vigour, and hence the future management of a stand (Section 2). Therefore it is necessary to determine the optimal combination of spacing and tending prior to planting. It is important to know how the green crown will develop and rise, so that appropriate regimes can be designed to accommodate stand development. Below we outline how pruning schedules can then be incorporated into silvicultural regimes.

Fixed and Variable Lift Pruning regimes

Fixed and variable lift pruning regimes assume that a pruning operation is scheduled and occurs as a once only activity. Such occurrence is typical in plantations or larger blocks where contractors may be used. In smaller farm forestry plantings pruning is more a continuous process undertaken by the landowner. Consequently, greater control over branch size and DOS at pruning can be achieved with the potential to produce a higher value log. No matter what the pruning regime used growers are advised to measure the stand at pruning and consider obtaining certification of the pruning operation (see Section 4.5). Failure to do so may make it difficult for the grower to realise the full value of the logs at the time of sale.

Fixed Lift Pruning Regimes

Fixed lift pruning (FLP) is the simplest form of pruning. It involves pruning to a fixed height (typically 2.0 - 2.5m in the first lift), with operations scheduled by age or the mean dominant height (MDH) of a stand. In FLP regimes all trees are pruned to the same height, regardless of variations in individual tree size (Figure 7). The resulting DOS, and proportion of crown removed, will vary across the stand depending on tree size. For example, a large tree will have a larger DOS and a smaller proportion of the crown removed than a small tree. For FLP regimes to be successful, a strong relationship between tree age or height and DOS must exist together with consistent form, to ensure that the knotty core is contained to the desired diameter.

Case Study 2: Fixed Lift Pruning of *E. nitens* in Tasmania

Pruning regimes typically aim to produce a butt log around 6 m long. To achieve this three FLP regimes were trialed for *E. nitens* in Tasmania (Gerrand *et al*, 1997) involving a single FLP, a two lift FLP, and a three lift FLP (each pruning to 6.4 meters).

The single lift pruning was the least expensive regime requiring only one operation to remove branches to 6.4 m. However, there was poor control of the knotty core. The single lift occurred at age 6 and involved the removal of mostly dead branches and some large live branches. Pruning such branches is not likely to increase the production of clear wood (See Sections 3.2.1 and 3.2.3).

Three-lift pruning provides the greatest control over the knotty core. Predominantly small live branches were removed resulting in rapid occlusion and the production of clear wood. The use of three lifts to achieve a butt log of 6.4 m was more expensive than the single lift regime and required stand monitoring in the first 5 years to ensure that pruning kept up with the rise of the green crown. Double lift pruning was intermediate between the single and three lift pruning treatments, with the draw back of increased cost, while still removing dead and large branches.

A three-lift regime is now recommended for *E. nitens* in Tasmania, as it is the only means by which the production of high value clear wood logs can be guaranteed. The cost of this regime restricts it to stands where growth rates are high ($MAI > 15 \text{ m}^3 \text{ yr}^{-1}$) (Battaglia & Pinkard, 2000).

Variable Lift Pruning

Variable Lift Pruning (VLP) involves adjusting the pruning to match the tree. A number of size criteria can be used. Trees may be pruned to a minimum stem diameter (pruning directly to knotty core objectives e.g. Case study 3), or to a set proportion of tree height or crown length, e.g. Case study 4, (Figure 7) (Koehler, 1984). The main benefit of VLP over FLP is that it allows growers to exercise more control over DOS of individual trees (and therefore DOO; see Section 4.2). Larger trees will receive the same treatment, in terms of DOS, as smaller trees, which are less likely to be over-pruned (Koehler, 1984). However, VLP requires greater monitoring of the stand to ensure that the desired tree size is not exceeded before pruning is undertaken. For this reason VLP regimes suit small-scale farm forestry who can more readily undertake more frequent pruning.

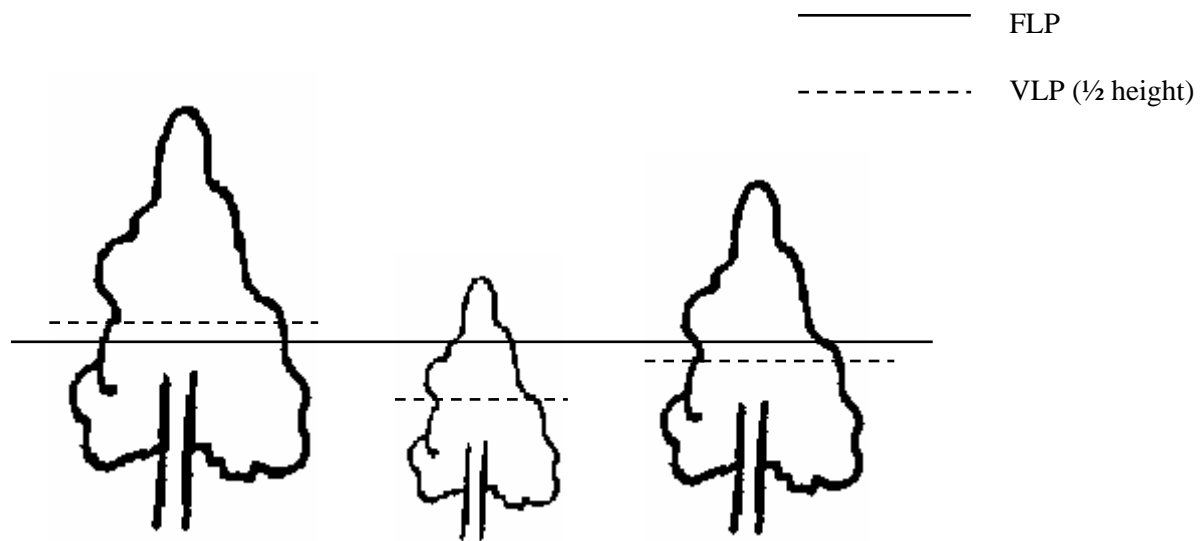


Figure 7. Example of the impact of Fixed Lift Pruning (FLP; to a height of 2.0 m) or Variable Lift Pruning (VLP; to half tree height) regimes on the diameter over stubs and amount of crown removed following pruning.

**Case study 3: Variable Lift Pruning based on stem diameter in *E. globulus*,
E. grandis and *E. nitens***

A trial of VLP was undertaken in northern Victoria involving *E. globulus*, *E. grandis* and *E. nitens* (Stackpole *et al*, 1999). All branches were pruned until the stem diameter was 7, 12 or 17 cm to try and limit the knotty core to approximately 10, 15 and 20 cm, respectively. 200 or 400 stems per hectare (sph) were pruned annually until a pruned height of 6.5 meters. Three thinning intensities were also applied; unthinned (1200 sph), and 400 or 200 sph residual densities.

The most severe pruning regime, where branches were removed up to a stem diameter of 7 cm, reduced growth in all three species. This was due to the large amount of canopy being removed and its effect on subsequent growth (see Section 4.2). Differences were most pronounced in *E. globulus*. Total stem volume across the three thinning regimes was reduced by about 35% in the 7 cm treatment compared to the 17 cm pruning treatment, 3 years after pruning commenced. Thinning to either 200 or 400 sph increased total stem volume by 40% 3 years after thinning.

The most suitable pruning regime was when branches were removed up to a stem diameter of 12 cm. This treatment maintained growth, allowed branches to be pruned green and took four visits to reach a pruned height of 6.5 m. However, the most appropriate regime was strongly influenced by the growth rate of the stand.

Pruning branches up to a large stem diameter (17 cm), failed to keep up with the rise of the green crown and dead branches were pruned. Because of the defects associated with dead branch ejection the treatment failed to produce a knotty core of the targeted dimension (see Sections 2.2 and 4.1.1)

Case study 4: Variable Lift Pruning based on tree height in *E. globulus*

A three lift VLP regime was applied to *E. globulus* in Western Australia (Moore *et al*, 1996). The regime involved pruning to half the tree height at ages 3, 5 and 8 when trees were 5, 12 and 16 m, respectively. At the first and second pruning the stand was also thinned to 540 and then 135 stems per hectare.

After 13 years, logs of millable size (46 cm dbh) were produced. The downside of achieving millable size individual trees rapidly is the reduction in the total stand growth rate. In this example, total stand growth rate ($\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$) was about halved to achieve the rapid growth of the remaining trees. This highlights the need for growers to decide what markets they are growing for: the high volume lower value market or the high value market (see Section 3.3.1).

The pruning regime produced a high proportion of appearance grade timber in 13 years. The total recovery of green sawn timber was 35% sawn recovery and importantly a high percentage was of appearance grade (21%) (see Section 3.1). This is a marked improvement on unpruned material which when unpruned produced only 6% of appearance grade timber (Washusen *et al*, 2000).

Self Pruning Regimes (Brashing)

In this section we look at the alternatives to pruning which may be used to restrict the size of the knotty core. Essentially these attempt to take advantage of the natural branch shed by some eucalypts species (Section 2.2). In South Africa, where *E. grandis* is widely grown for solid wood products, FLP regimes were abandoned as scheduling pruning to keep up with the rise of the green crown was not practical. Thus, in order to rationalise management and reduce costs, a pruning regime termed “brashing” was adopted (Schonau, 1984; Maree, 1979; Poynton, 1980). Brashing involves a single operation where all branches are removed from ground level to a height of 7 meters or more at age 3-4 years (stocking rates of 1,111-1,667 stems ha^{-1}). In stands of this age branches to a height of 7 meters are typically dead and can easily be brushed from the stem with the weight of a saw alone (Poynton, 1980).

Brashing is an appealing option for species that have suitable rates of branch mortality and shedding, as it is comparatively fast and low cost, requiring less infrastructure, and is applied later in rotation than FLP or VLP. However, brashing provides less direct control over knotty core, which will be determined by the rate of branch mortality. The knotty core, being confined to a single cone equivalent to the trees dimensions at the time of brashing plus the distance to occlusion.

If self-pruning is to be used as a silvicultural measure branch shedding will need to occur early and efficiently. Similarly, if a brashing regime is to be applied, it will be essential that all branches within the section to be brashed are dead at the age scheduled for treatment (usually 3-4 years) (Poynton, 1980). As mentioned previously, self-pruning is a trait that appears to be strong in some species and weak in others. Consequently, brashing can only be considered where branch suppression and mortality can be induced. To induce early branch shedding will require higher stocking rates than those typically used in eucalypt plantations, even in species with a strong tendency for self pruning (Kearney, 1999). The increased cost associated with high initial planting density may jeopardise the economic viability of such regimes.

It should also be stressed that brashing has not been tested in Australia, and its practicality for removing branch stubs and subsequently its effect on wood quality are unknown. Doubts have been

raised over the effectiveness of brashing in removing dead branch stubs, and its propensity to cause stem damage.

Conversion from Pulpwood to Sawlog Regimes

The majority of eucalypt plantations established to date (both in Australia and internationally) have been grown on short rotations for pulpwood (see section 1.1). Pulpwood is produced as a commodity and there are no value adding opportunities. Pulpwood plantations are typically managed under simple, low intensity regimes and harvested at age 10–15 (Jenkin, 1992).

Current forecasts of wood markets show the emergence of strong competition in the pulp wood sector and an increased demand for solid wood products at a national and global scale. As a result there is increasing interest in the conversion of pulpwood plantations to sawlog regimes.

Applying principles that have already been discussed in this paper, the feasibility of conversion will depend on the species, site and stocking of a plantation as well as the age at which the decision to “convert” is made. To produce an optimum clear wood log requires an early containment of the knotty core, and if self pruning has produced a sufficient length of clear stem then “conversion” may simply involve thinning of non-crop trees to allow remaining stems to grow-on. However, if self pruning is poor, and the decision to “convert” is made at a late age this may not be possible. For example, in the most widely grown pulpwood species, *E. globulus*, green and a very low recovery of high quality products was possible from 15 year-old untended trees (Washusen *et al*, 2000). The authors conclude that “without mechanical pruning there is little prospect for this species”. If the knotty core is large, a higher proportion of clear wood could be gained by extending rotations to increase the log diameter. However, increasing rotation lengths greatly reduces the net present value of returns and can jeopardise the profitability of a plantation.

The role of pruning will also depend on the state of the plantation at the age of conversion. If all branches are dead and there are a number of stubs on the stem, then pruning may provide no benefit. This reinforces the point that, where pruning is to be used, it is essential that regimes are well planned and growers have a clear idea of what they want to achieve from the time a plantation is established.

There may also be genetic impediments to conversion, as described in Lima *et al* (2000), where generations of genetic selection for pulpwood traits have bred against traits that are desirable for solid wood products.

4. Economics of Clear Wood Production

The economics of planted forests are principally determined by the time taken to produce a return (i.e. the tree growth rate and target log size), the size of the return (i.e. the market when the crop is sold) and the capital on which a return is required. Pruning is but one factor that will influence the economic performance of planted forests. It is beyond the scope of this report to examine the economics of planted forests in their entirety. Instead we have examined how the biology of eucalypts will interact with markets to determine the economics of clear wood production. We have addressed this area by attempting to answer three questions; what markets will be available for eucalypts? How will logs be valued in the market? And how can pruning be economically evaluated?

4.1 What markets will be available for Eucalypts?

There are clearly defined sectors in log markets. There is a 'pulpwood' sector, which is characterised by short rotation, high volume, low value harvests, typically exported for processing. The pulp market is a commodity one, and is subject to strong international price competition (Clark, 1995). Low-grade logs are also utilised by composite wood processors. In the solid wood market there are three main sectors; the low grade case/pallet grade sector, the structural sector, and the high value appearance grade sector, across which log price may vary by 100 fold.

The case/pallet sector requires only low grade logs (e.g. thinnings) and will not award premiums for clear wood. Output is low value and quality requirements of timber are not high. The 'structural' sector requires high quality logs with fewer knots and other defects so that strength grades can be met. While eucalypts have traditionally supplied the 'structural' sector in recent decades softwoods have dominated this sector. Softwood plantations produce suitable logs cheaply and efficiently (Clark, 1995). It is unlikely that eucalypts will be able to compete with pine in this market, as industry has come to accept pine as a standard for uses such as framing. However, there will be opportunities to supply structural timber where strength and size are important, a market currently being supplied by native forest eucalypts.

The highest value sector supplies appearance grade timbers for uses such as furniture, flooring, decorative timbers and veneers. This appears to offer the best opportunity for eucalypt plantations to gain a strong market and high returns. Traditionally native forest timbers, and imported old growth and rainforest hardwoods have supplied this sector. It is projected that supply from these sources will become increasingly scarce (MacLaren, 1993). Eucalypt plantations could potentially move into this market provided suitable logs can be produced through appropriate silviculture.

4.2 How will logs be valued in the market?

The prices received by growers will depend on a number of factors, and it is not possible to predict accurately or precisely future prices. However, if the pine plantation log market (Figure 8) is used to illustrate the nature of log markets, it is apparent that prices received for logs are derived from two key factors: log quality (knotty core size) and log size.

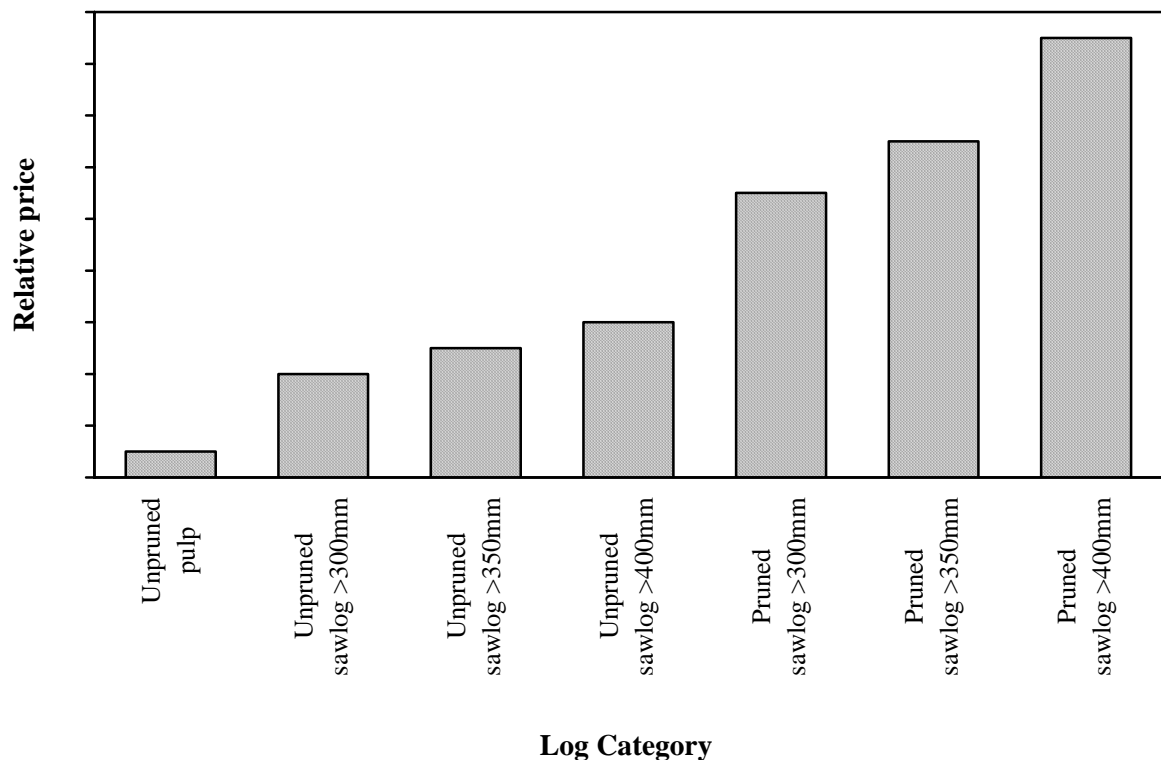


Figure 8. The relationship between log size and clear wood and relative price for softwoods.

Figure 8 shows that log markets have a ‘step’ nature, and hence value is added by moving logs up these steps. The two factors controlling price are pruning and log size as these control the proportion of higher value products that can be recovered from a log. Pruning as a value adding activity must therefore move logs into higher price brackets, creating a margin for the grower.

It is not clear what eucalypt log markets will look like, however there is a strong possibility that, unlike the pine log market, demand for structural grade eucalypt logs will be small. For this reason low quality (unpruned) logs may find no market other than pulpwood, or case/pallet market, although there will be pole markets for more durable species. This would then result in a distinct high/low value market structure for eucalypt logs. If pruning is undertaken then it must move the logs up to the high value end of the market.

The volume of planted eucalypt logs entering the market in the next 20 to 30 years will increase rapidly as plantings mature. New postharvest technologies could change the utilisation of small piece size timber (e.g. finger jointing). Such technologies would create a greater demand for poorer quality logs. However, such technologies are typically dependent on purchasing wood cheaply as the processing costs are high.

4.3 How can pruning be economically evaluated?

The gain from pruning is the difference in value of pruned, compared with unpruned logs, of similar dimensions at harvest. This difference must offset the extra discounted cost of pruning. Thus to determine the value of pruning some assumptions regarding the amount of clear wood produced and the value the market will place on this is required. As discussed in Sections 4.2 and 5.2 both of these

areas are subject to uncertainty. If it is assumed that, similar to pines, eucalypts are to be priced according to the proportion of clear wood within a log then the value added by pruning can be expressed as the reduction in knotty core diameter achieved through mechanical pruning as opposed to self-pruning. The marginal return from pruning can then be evaluated using discounted economic analysis. Such analysis will again highlight the importance of selecting vigorous trees that can produce marketable sized logs within a shorter period (Section 4.3.1).

There are likely to be species differences in the economic returns achieved from pruning. For example, some species (those which display high levels of self pruning), may produce an acceptable proportion of clear wood without pruning. Pruning such species may increase the proportion of clear wood but only by a smaller margin (e.g. Figure 10c & d). In species that retain their branches, pruning will be required to achieve a clear wood volume to attract a premium (Figure 10a & b). Such species consideration should be taken into account when targeting pruning programs across a range of eucalypt species. For example, product recovery studies indicate that pruning of *C. maculata* and *E. cladocalyx* would only see a modest improvement in quality due to the good natural branch shedding characteristic (Washusen *et al*, 2000).

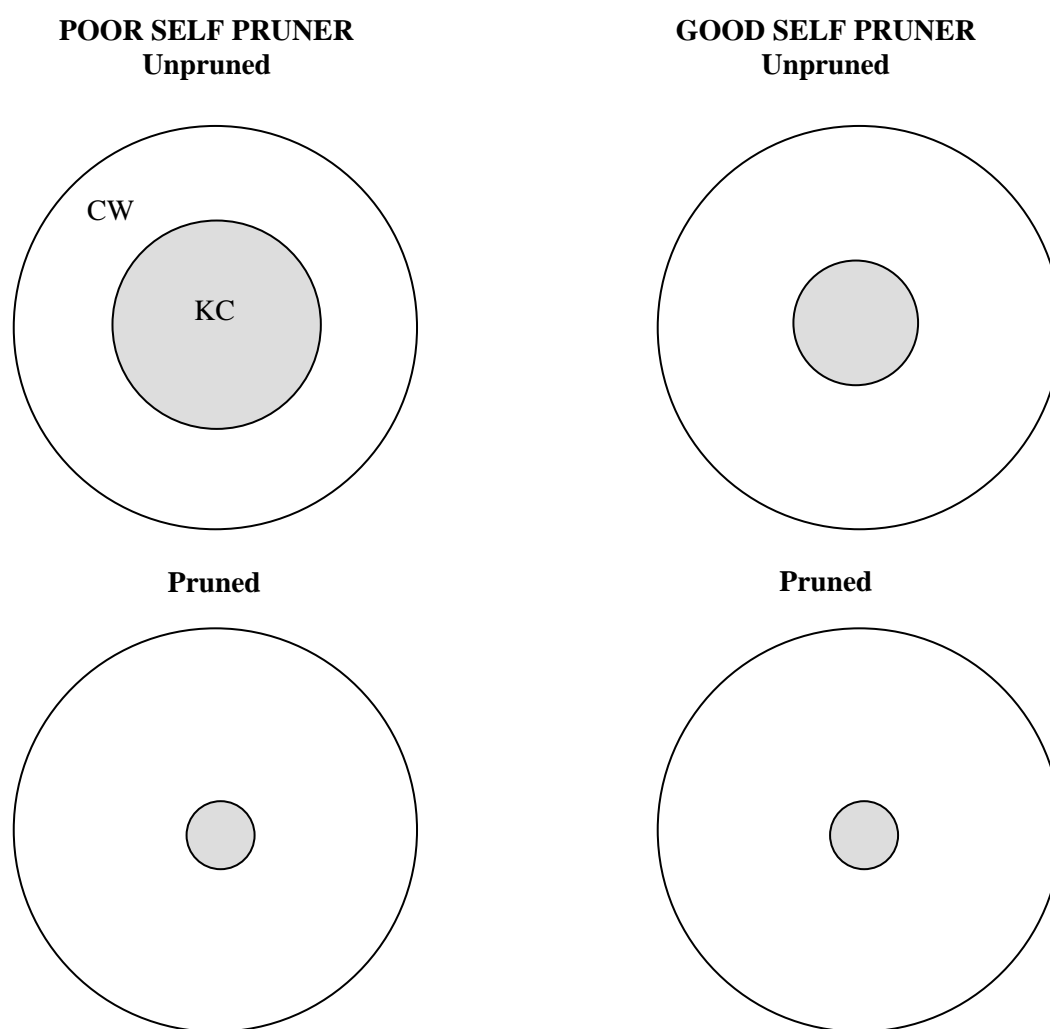


Figure 10. The effect of pruning on the size of the knotty core (KC) and clear wood (CW) in species with contrasting natural branch shedding characteristics.

4.4 Further Considerations

The comparison of presented here is simplistic, and is used only to illustrate the nature of value adding through pruning. There are many further considerations in determining the economic viability of a silvicultural regime. All operations from site establishment through to harvesting costs must be discounted and included into final economic appraisal. The marginal gain from pruning is sensitive to a number of factors, such as growing costs, rotation length and most importantly log price, which demonstrates the importance of growing for a specific market.

Pruning to produce a quality log may also play an important role in market capture. It also has been observed that higher quality logs are more able to hold their value through market down turns, while low quality logs quickly lose their value. Planted eucalypts are expected to follow a similar pattern.

4.5 Quality Control: Standardisation and Certification of pruning

Pruning is a value adding activity. For growers to realise this added value, processors must be able to produce a higher proportion of high grade product and hence pay a premium for pruned logs. This requires that a critical mass of pruned logs can be supplied to the processor and that continuity of supply can be maintained. Without both of these the processor will be unable to optimise the processing to produce a high proportion of high grade product. Standardisation and certification of pruning will play an important role in ensuring processors are able to realise the greater value of the pruned crop. This is particularly important to smaller growers who will be selling small wood volumes onto the market. *Failure to supply audited quality standards of the crop being sold will make it difficult to achieve the best return to the grower.*

The importance of standardisation and certification is highlighted by the problems which occurred in the radiata pine industry in New Zealand (Park, 1994). When pruning was adopted on a wide scale by growers, without an industry standard, the resulting pruned logs showed up to 100% variation in clear wood potential between sources. Logs with sound external appearance could contain any amount of clear or knotty wood, depending on the silviculture applied (Park, 1994). This led to a situation where saw-millers had to undertake expensive sawing trials to determine the quality of logs from different growers. The cost of such an approach could potentially become a real barrier to industry development. Unless producers can trust the quality standards of the resource offered, an effective chain of production may not develop. To overcome this problem, a system of pruned stand certification was designed. The assessment, on which this certification is based, is usually conducted immediately following pruning operations, although retrospective audits can be undertaken. The procedure involves comprehensive mapping and description of the stand and simple measurements of DOS. This gives buyers an indication of the value of logs based on the proportion of clear wood and, importantly, helps growers realise the added value achieved through pruning.

The Australian Forest Growers Association (AFG) offers a certification scheme via a nationwide network of auditors who are able to visit stands soon after pruning. The process of certification will add a further cost to the price of producing pruned logs, but without certification the grower may not be able to realise the value added through pruning. This is particularly so for small growers. For larger growers, in-house quality control assessments will normally be undertaken and can be used to negotiate directly with processors. Pruned stand certification offers dual benefits to growers. Firstly, it creates the climate necessary for open trade between growers and millers and thus helps growers realise the value added through pruning. Secondly, it helps growers to focus on the over-riding objective of pruning; the containment of the knotty core to known, minimal dimensions.

5. Future Research Needs

The future research needs identified in this report reflect the concentration on the biology and silviculture of clear wood production in this report. But, there is a need to link the biological and silvicultural research to wood utilisation studies. A particular research challenge is the diverse range of eucalypt species and growing environments. Clearly, given the resources available empirical research trials can only tackle a small number of eucalypt species and environments. Consequently, the authors recommend that future research should adopt a ‘trait’ or process based approach. This would require experimental work to include general tree characteristics as well as measuring the specific species performance at a particular site. For example, pruning trials should include measurements of branching and canopy characteristics to allow generalisations beyond the specific species and site. As information builds it may be possible to define related groups of traits that control response to silvicultural techniques. This approach would allow more immediate transfer of information to independent growers and reduce obsolescence as new breeds and/or silvicultural systems evolve.

The planting of eucalypts in lower rainfall area (<700mm pa) presents a particular silvicultural challenges. Currently there is little information to base management decisions on for low rainfall plantings.

The main traits that are important in determining the most appropriate silviculture for producing clear wood are canopy dynamics, tree and stand growth and development, and decay susceptibility. The data generated from such studies will also make an important contribution to the development of tree and stand growth models. Such growth models, which incorporate the responses to thinning and pruning, are required to undertake the economic evaluation of pruning. Assessing how these factors impact on clear wood production requires integration with wood quality studies. In addition there are some specific wood quality issues which need to be addressed and these are also outline below.

5.1 Canopy dynamics

- The development of the canopy (green crown models), and the leaf area distribution/dynamics of a species, and how these are changed by initial stocking/spacing and environment.
- Branch shedding habits, the efficiency of abscission and ejection mechanisms (ability to ‘self-prune’), branching characteristics (size of branches and growth dynamics, how this will change with variations in initial spacing /stocking).
- Canopy growth and leaf area responses to pruning, particularly the effect of repeated pruning and its timing.

5.2 Stand growth and development

- Interactions between pruning and the individual and stand tree growth rates and response to thinning and how this will change with variation in initial spacing. Such information is required for the development of silvicultural regimes.
- Development of stand growth models. Such models, which incorporate thinning and pruning responses, are required to undertake the economic evaluation of pruning.

5.3 Decay susceptibility

- Wood characteristics determining susceptibility to the ingress and spread of decay organisms
- Occlusion rates and response to wounding (differential occlusion rates between live and dead

- branches, large and small branches and the effect of collar damage)
- Intrinsic response of stem woody tissue to wounding (barrier zone formation and effectiveness)

5.4 Wood quality

- How pruning and thinning regimes affect growth stress in eucalypts
- Sawing and drying techniques to maximise recovery rates from planted eucalypts.

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