First thinning in sub-tropical eucalypt plantations grown for high-value solid-wood products: a review

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Summary

The decision to first thin a eucalypt plantation grown for high-value products must be based on the growth, wood quality and financial consequences of the decision. These factors are inter-related and at present some are difficult to quantify. This review summarises available knowledge on a range of factors influencing the decision to first thin in eucalypt plantations, with specific reference to sub-tropical eastern Australia.

The most compelling reason for early thinning is to remove defective stems before they become dominant within the stand. In plantations of unimproved genetic stock, a high proportion of stems can be of inferior quality, and in these circumstances stand quality and value recovery can be greatly increased by early, possibly non-commercial, thinning. Stands of 'intolerant' species, such as *Eucalyptus grandis,* segregate into dominance classes earlier than do stands of more 'tolerant' species. Delaying thinning may allow defective stems to become dominant, suppressing some of the higher-quality stems which are then less able to respond to later thinning. In this regard, management options for eucalypts are generally much less flexible than for tolerant genera such as pines. This may be less important for stands of improved genetic material, which are more uniform, or for stands with a small proportion of defective stems.

To maximise growth on final-crop trees, thinning should be undertaken as early as possible to take advantage of early rapid growth rates that cannot be attained later. Thinning too early, however, may reduce wood quality. The most common reason for downgrade in eucalypt plantation timber is knots. If pruning is not undertaken, delaying thinning until the lower branches die takes advantage of the excellent self-pruning behaviour of some sub-tropical species.

Optimum thinning regimes are a trade-off between maximising growth on the smallest possible number of stems while fully utilising the site and minimising risk from biological and climatic factors. Maximising growth on the smallest number of stems allows critical threshold log sizes to be attained rapidly, thereby maximising the advantages from minimising time to financial returns. If thinning is too severe the site will not be fully occupied, resulting in lost production and problems such as weed growth, epicormic flushing and wind damage.

The benefit or cost of early thinning depends on harvest costs, its effect on wood quality, product assortment, average piece sizes and available volumes per hectare. There are significant risks and opportunity costs associated with delaying thinning that may be greater than the perceived financial benefits — e.g. the immediate saving from not conducting a non-commercial thinning may be negated by a reduced total (net present) value recovery and lower internal rate of return over the rotation.

Keywords: forest management; silviculture; silvicultural characters; plantations; stand characteristics; wood properties; thinning; pruning; crown; growth; returns; optimization; subtropics; *Eucalyptus*

Introduction

The area planted to sub-tropical eucalypts for the purpose of producing high value solid-wood products has expanded rapidly. The question of whether to thin, and if so when and how intensely, then arises. Many factors influence the decision about when and how to conduct a first thinning in a plantation. When the aim is to produce high-value solid-wood products, a common view is to thin eucalypts 'hard and early' (Opie *et al.* 1978; Schonau and Coetzee 1989; Florence 1996; Reid 1998; Donnelly *et al.* 2003; Bevege 2005; Nolan *et al.* 2005). This is largely because the aim of thinning is almost always to ensure that stem diameters attain a desired threshold as early as possible in the life of a stand; the earlier thinning is undertaken, the earlier the threshold will be achieved. However, as eucalypts have not commonly been grown in plantations for solid-wood products, previously-held views about the best approach to thinning may be based on assumptions about products and markets that may no longer be valid. Regimes appropriate for regrowth in native forests are not necessarily optimum in plantations. The products, ages and time frames of thinning in even-aged regrowth may not be relevant in plantations, where narrower management objectives usually apply — notably maximising production and return on investment. For example, trees 80 cm diameter at breast height at age 65 y, suggested as a goal by Horne (1994), are much larger and older than would now be considered optimum in eucalypt plantations. Moreover, the stand conditions and behaviour of trees within plantations are not necessarily the same as in native regrowth forests (Zeide 1985; West 2001).

The decision whether to thin, and if so when and how heavily, must ultimately be guided by the intended final products and the market opportunities for those products. This decision should be made before stand establishment, as it affects the choice of sites, species, and establishment and tending regimes. Any thinning decision has trade-offs in terms of stand growth and wood quality. These attributes determine the log product assortment, product grades and recoveries and thus the financial outcome, encompassed here by the term 'value recovery'. The first thinning will largely determine what log sizes and qualities are possible in a given rotation (Evans and Turnbull 2004).

This paper focuses on the management of longer-rotation plantations of sub-tropical eucalypts intended to produce high-value logs for processing into solid-wood products. Rotation lengths are envisaged to be 15–40 y depending on a variety of factors, and will inevitably produce some lower-value products such as pulp logs. To date, the greatest area of eucalypt plantation established primarily for this purpose has been in eastern Australia, east of the Great Dividing Range in south-eastern Queensland and northern New South Wales, using sub-tropical species (Nolan *et al.* 2005).

The aim of this review is to identify and discuss issues that are important in evaluating the merits and demerits of first thinning at various ages — from very early to mid-rotation. The nature of this operation forms a continuum from non-commercial thinning to waste, through harvests with a negative return, to a cost neutral or profitable, but perhaps delayed, thinning.

Approaches to thinning decisions

Traditional approaches to analysis of thinning response are based on stand growth dynamics. The timing of thinnings and final harvest in relation to patterns of current and mean annual volume increment can be used both to maximise volume production over the rotation and to underpin financial analyses (Bevege 2005). Nolan *et al.* (2005) used current and mean annual increment in value, rather than growth, to analyse several scenarios involving growth rates, wood quality, differential product pricing, discounting and market factors. Such an approach is necessary when different products, with different values, are grown within the one stand. An early example of this approach was described by Smith (1962) for hardwoods grown for solid wood; the final-crop trees were the main focus of decision-making due to the much higher value of products from these trees. The effect of silvicultural decisions on other trees and on lower-value products assumed a secondary role. In such a setting, thinning is not undertaken to capture potential mortality (Jack and Long 1996) but to release potential crop trees, thereby increasing stand value rather than overall stand volume production (Long *et al.* 2004).

This situation is similar to that for sub-tropical eucalypts grown for high-value products (Donnelly *et al.* 2003; Montagu *et al.* 2003), and for this reason much of this review focuses on the final-crop trees rather than stand volume or basal area. Where plantations are grown for high-value products (generally on high-quality sites), there is a consensus that the optimum density of final-crop trees will be in the range 200–400 stem ha^{-1} (Florence 1996; Donnelly *et al.* 2003; Montagu *et al.* 2003; Nolan *et al.* 2005), and therefore many of the examples refer to stocking densities within this range.

In their financial analyses, Nolan *et al.* (2005) considered only one temperate eucalypt species for which considerable data were available. Several species are used in sub-tropical eucalypt plantations but there are few data for them, a situation that is common throughout the tropics (Evans and Turnbull 2004). Because a number of interacting factors — species, site quality, stocking and intended products — affect decisions on thinning, the financial consequences of a large number of alternatives could be evaluated. Even with sophisticated analytical techniques this can be difficult (Kemmerer 2005).

The problem can be addressed in part, however, by restricting the options analysed to those which are likely to satisfy overriding considerations of wood quality, stand growth and market opportunities. All approaches make assumptions about a range of factors that underpin the analysis, and the validity of these assumptions must be assessed by individual growers for their own circumstances.

We discuss issues under the broad areas of stand and wood quality, growth response and stand dynamics, the biological and climatic risks associated with thinning (or not), and the financial evaluation of alternatives.

Stand and wood quality

Crop tree selection

One of the most important reasons for thinning early is to remove poor quality trees, thereby retaining and maximising the growth of the best trees within the stand for future harvest. Selection criteria typically include dominance (a proxy for vigour), stem form and evidence of bole defect. There is not necessarily any relationship between dominance and form or defect, and therefore not all dominants are the best trees to retain. If thinning is delayed too long, a significant proportion of the largest trees can have major (or minor) defects. Later thinning to release subdominant trees of superior form may not be successful as the growth response will be compromised (see section on growth response and stand dynamics). It follows that the early selection of final-crop trees is a critical consideration in plantation stand management.

Data from genetically unimproved *E. pilularis* and *E. dunnii* planted at three initial stockings on an ex-pasture site, where high levels of early damage occurred (Southgate plantation, near Nana Glen, NSW) (Fig. 1), show no relationship between tree form and size. Among the largest 300 trees ha^{-1} in each stand, the proportion of trees without defect was essentially constant, and trees with major and minor defects constituted a large part of the stand. If thinning was delayed, one-third of the dominant trees would have major defects while less than one-third would be high-quality stems. An early thinning to retain selected, high-quality trees would greatly reduce the proportion of crop trees with major defect.

The independence of dominance and form is further illustrated by data from *E. dunnii* stands that had contrasting levels of defective trees (Table 1). The data represent the incidence of trees in quality classes before and after early thinning of unimproved *E. dunnii* at two sites: Moonmerri plantation near Dorrigo, NSW, and the Southgate plantation. Of the two sites,

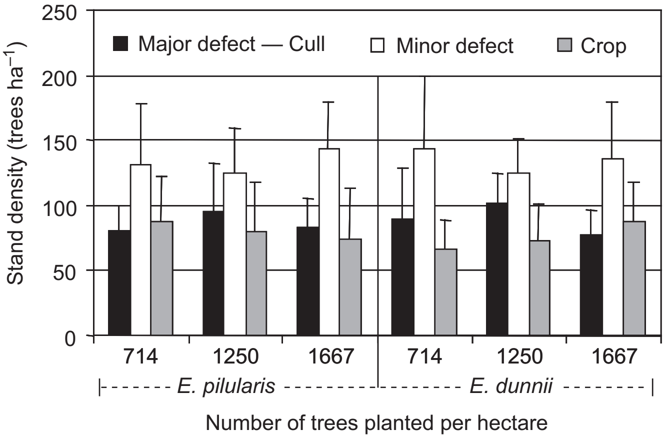

Figure 1. Stem quality of the largest 300 trees ha^{-1} of unimproved *E. pilularis* and *E. dunnii* at three initial stockings at age 3.5 y at Southgate plantation, near Nana Glen, NSW. The bars indicate standard deviations.

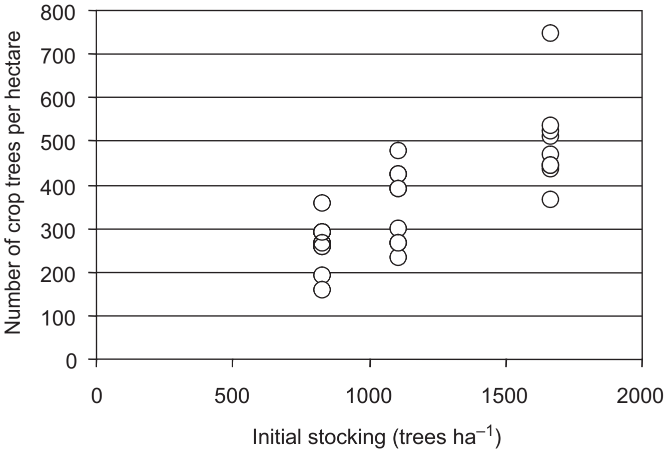

Figure 2. The numbers of crop trees in plots of *E. grandis* at Hardacres property spacing experiment, Coffs Harbour, NSW

Southgate had been subject to greater levels of wallaby, frost and hail damage than Moonmerri, resulting in a higher incidence of trees with defect. The thinning at the Moonmerri site significantly improved stand quality by removing defective stems, although in order to maintain uniform spacing some trees with major defect remained after thinning. In the Southgate stands, the main effect at both stockings was to reduce the proportion of trees with major defect. At Southgate, the stems retained in the stand with higher initial stocking included a high proportion without defect (see below).

Most regimes developed for eucalypts include an early (usually non-commercial) thinning to remove poor stems (Schonau and Coetzee 1989; Jenkin 1990; Gerrand *et al.* 1997; Keenan 1998; Black and Simpson 2001; G. Dickinson, Queensland Department of Primary Industries and Fisheries, *pers. comm.* 2005; R. Moore, WA Forest Products Commission, *pers. comm.* 2006). Where defects are the result of early damage to stands, thinning can be used as a risk management strategy (this is discussed further under biological and climatic risks, below).

If early thinning is to be used to remove defective trees, the question arises of how many trees to plant to achieve the desired number of final-crop trees at first and subsequent thinnings. A greater initial stocking increases the number of high-quality stems available for selection, but early thinning is required to favour these trees before the expression of dominance within the stand begins (see the section on growth and stand dynamics). Figure 2 shows the number of final-crop trees within unimproved *E. grandis* plots of various initial stockings. To obtain more than 300 final-crop trees ha^{-1} in all plots, initial stockings >1250 stems ha^{-1} are often necessary (Gerrand *et al.* 1997 recommend 1000–1100 as being barely sufficient; see also Neilsen and Gerrand 1999). This number may be inadequate if preference for even spacing means that not all high-quality trees can be retained. In the Southgate stand (Table 1) with high levels of defect, even planting 1667 trees ha^{-1} resulted in some trees with minor defect being retained after thinning to maintain even spacing.

Removal of defective stems may be less important in stands of genetically-improved trees due to better form, greater stand uniformity and delayed differentiation of the stand into dominance classes (Binkley *et al.* 2002). We have observed that the extent of variation in form within stands of unimproved trees differs among species. *Eucalyptus pilularis* and *Corymbia variegata* exhibit greater variation than *E. grandis, E. dunnii* and *E. cloeziana*. Variation is also affected by site factors. Trees on ex-pasture and more fertile sites often have poor form and large branches. The linear increase in the number of final-crop trees within the range of stockings examined (Fig. 2) does not support the view that greater initial stocking density will improve form, but higher stocking density does affect branch size and therefore wood quality (Montagu *et al.* 2003).

Table 1. The number of *E. dunnii* trees per hectare with three levels of stem defect before and after thinning at Moonmerri plantation near Dorrigo, NSW, and a pre-thinning selection at Southgate plantation near Nana Glen, NSW. Moonmerri was established at 833 trees ha^{-1}; Southgate at both 714 and 1667 trees ha^{-1}.

Defect class	Moonmerri 833		Southgate 714		Southgate 1667	
	Pre-thin	Post-thin	Pre-thin	Post-thin	Pre-thin	Post-thin
Crop (no defect)	363	250	97	95	182	132
Minor defects	113	56	280	194	583	171
Major defects	274	40	296	31	764	9
Total	750	346	673	320	1529	312

Branch shedding and knots

Several studies have shown knots to be the major cause of downgrade in timber from plantation-grown eucalypts. This is a major issue because the main market opportunities for hardwood plantations are predicted to be for visual-grade material with minimal knots and other visual defects (Donnelly *et al.* 2003; Nolan *et al.* 2005). Two strategies exist to minimise knot formation. Some species (including several sub-tropical eucalypt plantation species) self-prune efficiently, shedding dead branches (Smith *et al.* 2006), while species that retain dead branches may need to be pruned to ensure branches are not retained to become dead knots (Montagu *et al.* 2003).

When pruning is required, thinning to maximise growth of pruned trees usually follows immediately after the first or second pruning lift. Thinning after the first lift can encourage greater branch growth above the pruned height and create problems for the second lift of pruning. On the other hand, delaying thinning carries a risk of loss of dominance by pruned trees if pruning is severe enough to reduce growth. If pruning removes >50% of the depth of the live crown, growth may be retarded (Pinkard and Beadle 1998; Montagu *et al.* 2003).

Unlike some temperate species (Nolan *et al.* 2005), many sub-tropical eucalypt species self-prune efficiently and may not require operational pruning, which is expensive and may not be justifiable financially (Smith 1962; Montagu *et al.* 2003; Evans and Turnbull 2004). Rates of occlusion of dead branches vary with species; the process is very efficient in *E. grandis* and *E. dunnii*, intermediate in *E. pilularis* and less rapid in *E. cloeziana* (Smith *et al.* 2006). If plantations are not pruned, stocking density must be used to manipulate crown dynamics (and therefore branch growth) to ensure early death of low branches and to increase the height to the base of green crown. There is a greater incidence of persistent large branches at lower stockings (Florence 1996; Kearney 1999).

Early thinning will act in the same way as low initial stocking by increasing light to the lower limbs and reducing competition within the stand, resulting in larger branches in the lower part of the crown (Medhurst and Beadle 2001). While this is desirable to maintain rapid growth of individual trees, the increased volume will be of low-quality wood due to the increased number of larger knots (if trees do not self-prune efficiently or pruning is not carried out). Conversely, maintaining higher initial stockings until crowns rise will control the development of large branches (Florence 1996; Kearney 1999; Montagu *et al.* 2003). It is not clear whether risks of pathogen and insect attack and other defects are associated with pruning large branches, as has been observed in temperate species (Wardlaw and Neilsen 1999), because little research has been undertaken on sub-tropical species.

The timing of thinning after maintaining higher stockings will depend on the crown dynamics of the species. In *E. grandis* up to 5 y old, crown rise has been found to be predictable across a range of sites. Klootwijk (2001) found that the height to the base of the live crown had reached 6 m when stand height reached 12 m. The timing of thinning is a compromise between increasing growth and decreasing wood quality due to knots. Maximum value recovery will occur when both the growth rate of the lower bole and wood quality are optimised.

Stocking and growth stress

Thinning can affect product recovery through its effect on the development of wood within the tree, which in turn affects the ease of conversion and drying. The two most important wood properties, after knots, are juvenile wood and tension wood/growth stresses. The formation of juvenile wood at any point in the stem is related to proximity to the crown (Evans *et al.* 2000). As the crown base rises, a transition from juvenile to mature wood occurs. The rise of the crown is related to age, site quality and stocking. Silvicultural treatments that accelerate radial growth at an early age, without a corresponding increase in the height to the base of the live crown, may therefore result in a greater proportion of wood with juvenile characteristics, especially in younger and smaller trees grown in plantations.

The production of wood of lower strength and stiffness in younger trees has been recorded in sawing studies of plantation-grown *E. dunnii* (Dickson *et al.* 2003) and *E. grandis* (Armstrong and Heathcote 2003). However, all the *E. dunnii* logs processed had sufficient strength, hardness and stiffness to make structural-grade products suitable for common applications such as flooring, and the properties of *E. dunnii* were comparable to those of young plantation-grown *E. pilularis*, *C. variegata* and *E. cloeziana* reported in other studies (Dickson *et al.* 2003). The problem of variation in wood properties associated with the presence of juvenile wood may be negated to some extent by an effective strategy to manage branches. If stands are maintained at high stockings until after crown rise or are pruned, the properties of wood formed in the stem below the crown should be more comparable with those of mature wood.

A number of other wood quality traits in eucalypts vary from pith to bark (Hillis 1978; Opie *et al.* 1978; Malan and Hoon 1992). There is evidence that larger trees that have grown more rapidly through thinning (or fertiliser application) have more uniform pith-to-bark densities (Maree and Malan 2000; De Bell *et al.* 2001; Nolan *et al.* 2005). The effect of thinning on the development of tension wood is not clear, although where stands have been thinned early, difficulties associated with tension wood are reduced (Washusen 2002; Washusen and Clark 2005). Nolan *et al.* (2005) suggest reducing tension wood should be a major aim in plantations managed for solid-wood products. Early work found no relationship between growth stress and age or growth rate (Hillis 1978; Boyd 1980; Ferrand 1982), but there is more recent evidence that silvicultural treatments, including thinning, that increase stem diameter and maintain more constant growth rates are associated with reduced growth stress (Wilkins and Kitahara 1991; Washusen 2002; Waugh 2004), lower stress gradients (Washusen and Waugh 2000; Nolan *et al.* 2005), and less log end-splitting (Garcia and de Lima 2000; Leggate *et al.* 2000).

Growth response and stand dynamics

The growth of a stand is largely constrained by physical limitations of the resources of the site. Thinning seeks to reallocate site resources to concentrate the growth within a stand on the retained stems. If thinning is too severe, however, the resources will not be fully used by the retained trees and total stand growth will be reduced (Shepherd 1986; Medhurst *et al.* 2001). Therefore, thinning should maintain the stand within a range of basal area (or leaf area, or number of stems per unit area for a given age), that will be optimal for maximising growth of individual stems while also maximising growth of stand volume (or value). Where the aim is to achieve a particular tree diameter threshold for the production of solid-wood products, then the earlier and heavier the thinning, the quicker the threshold will be attained. This is the basis for thinning 'hard and early'. In an unthinned stand, growth of the dominant stems is restricted due to competition from less dominant trees. The competitive processes within a stand as it ages will decrease overall stand growth due to lower efficiency of resource use by the increasing number of sub-dominant trees (Smith and Long 2001; Binkley *et al.* 2002; Ryan *et al.* 2004).

The effect of species tolerance

The expression of dominance within stands, and self-thinning, are caused by competitive processes and occur at different rates for species of different tolerance (Oliver and Larson 1990). At one extreme, tolerant species such as cypress pine experience 'stand lock up', reducing the growth of all trees (Baur 1985). Although there are exceptions, eucalypts tend to be at the other extreme, where the larger trees within a stand become dominant and smaller trees rapidly become suppressed and die. Compared to other taxa, eucalypts are intolerant of competition from larger trees. The major sub-tropical plantation species in eastern Australia are considered to be intolerant, but there is a range in their behaviour: for example *E. pilularis* is less intolerant than *E. grandis* (Opie *et al.* 1978; Florence 1996).

The different tolerances of sub-tropical eucalypt species have implications for thinning. In a thinning trial in 6-y-old plantations, Horne (1978) found that *E. grandis* self-thins very rapidly and therefore the effect of thinning may be short lived. Despite a significant response in volume in the largest 370 stems ha^{-1}, the basal area of thinned plots converged in time to the basal area of unthinned plots. While Horne concluded that thinning offered little benefit, he did not however take into account wood quality or consider value recovery. Florence (1996) argues that to gain a more sustained response, thinning in intolerant species should be more intense. Thinning in intolerant species may also be undertaken early for other reasons, such as the release of trees of good form that would otherwise become suppressed (see stand and wood quality section above). This is more important for intolerant species as trees become suppressed more quickly and lose the capacity to respond to any later release (Medhurst *et al.* 2001).

Timing of thinning

The question of when to thin is important, as poor timing of thinning can have serious consequences for the stand. Stand growth begins to decline shortly after canopy closure, which usually coincides with the development of maximum leaf area (Smith and Long 2001). Florence (1996) recommends thinning intolerant species such as *E. grandis* within 2–4 y of canopy closure. The live crown ratio (ratio of height to the base of the live crown to the height of the tree) can be an indicator of when to thin (Daniel *et al*. 1979; Ang and Weinland 1990; Florence 1996; Evans and Turnbull 2004). As stands mature, competition forces crowns to rise and the live crown ratio (and leaf area) decreases. Live crown ratios of 30–40% have been recommended as limits after which response to thinning will be compromised. However, we are not aware of published data on the relationship between live crown ratio and growth or thinning response of sub-tropical eucalypts. The crown ratio (the ratio of crown diameter to stem diameter) has also been used to calculate levels of site occupancy as an aid to stand management of eucalypts and other tropical species (Samarasinghe *et al.* 1995; Kumar *et al.* 1997; Seling *et al.* 2001).

There will be differences in stand dynamics, and hence timing of thinning, within stands of the same species derived from different genetic material. Competition within stands of clonal material is highly symmetric compared to that within stands of seedling origin, delaying the expression of dominance and self thinning — as happens in tolerant species (Binkley *et al.* 2002). This has the advantage that thinning can be delayed without the same consequences for dominance within the stand, because trees retain greater capacity to respond after a period of stagnation or suppression. But it has the disadvantage that growth of the final-crop trees is slowed due to competition and consequently more time is taken to achieve a nominated log size. Tolerance provides greater flexibility for management.

It is often recommended that thinning be carried out before the peak of current annual increment. In *E. pilularis* this occurs at age 12–20 y (Florence 1996), but because of the gradual decline in stand growth that begins at an early age, the growth benefit of thinning also declines as thinning is delayed. This is due to the competitive effect of smaller trees restricting the growth of the larger trees from an early age, rather than to the decline in overall stand growth with age, which is due to inefficient resource use by sub-dominant trees (Binkley *et al*. 2002). This effect will be greater in less intolerant species such as *E. pilularis*. In more intolerant species such as *E. grandis*, the peak in current annual growth can occur much earlier (Florence 1996). In this case a very early thinning may be impractical for reasons such as its effects on wood quality (see section on stand and wood quality).

Thinning intensity

The optimum thinning intensity will depend on the condition of the stand and the market value of products that might be gained from an intermediate thinning. As mentioned previously, there seems good agreement on the optimum final stockings in solid-wood product regimes. The range of stocking considered to achieve an optimum response for plantations of *E. pilularis* is 200–400 trees ha^{-1} over a wide range of ages (Florence 1996), and for *E. globulus* plantations about 200–300 trees ha^{-1} (Medhurst *et al.* 2001). Stand basal area increment in both native forest and plantations of eucalypts and other species is generally not reduced until more than 50% of basal area is removed (Webb and Incoll 1969; Medhurst *et al.* 2001).

Biological and climatic risks

Early thinning may be used as a strategy to manage biological and climatic risk in plantations. Damage from wallabies, cockatoos, stem borers, storms, hail or frosts (such as double leadering) can affect a significant proportion of a stand (Table 1).

Thinning can remove these trees before they become dominant. Where damage or mortality due to biological and climatic factors is likely to be great, higher initial stockings in combination with thinning can be used to ensure a viable stand. For example, species susceptible to attack by stem borers (*E. grandis* and *E. dunnii*) could be planted at higher stockings and not thinned until after affected trees become obvious, although it is not yet clear at what age this occurs (A. Carnegie, Forests NSW, *pers. comm.* 2006).

Thinning also carries certain risks, such as wind damage and associated greater tension wood development (see sub-section on stocking and growth stress), epicormic flushing, coppicing and weed invasion, all of which can affect wood quality and growth. For wind damage, epicormic growth and weed invasion, the risk increases as the intensity of the thinning increases. Regimes optimum for stand growth and reduced windthrow risk entail frequent light thinning, but economic and environmental considerations restrict the number of thinnings. Early thinning may reduce risk of wind damage compared to later commercial thinnings (Gerrand *et al*. 1997), because delaying thinning results in trees having greater ratios of height to diameter at breast height (West 2001). Cremer *et al.* (1982) suggested that their index of wind damage risk, developed largely from data from conifer plantations, would probably be adequate for eucalypt plantations in the sub-tropics, although there is as yet no confirmation of this.

Drought is also a significant risk that can be managed using spacing and thinning regimes, such as is practised in south-western Australia and in south-eastern Queensland where mean annual rainfall is 600–900 mm (Dickinson *et al.* 2005). It is less likely to be a significant risk in higher-rainfall areas (>900 mm), although even in these areas there can be lengthy episodes of well-below-average rainfall, such as occurred in north-eastern NSW during 2001–2004. Such episodes can present real risks to stands fully occupying their site, particularly on soils with low available water storage capacity. Although drought may not be the direct cause of tree mortality, the resulting stress can increase susceptibility to pests and diseases, which can result in unacceptable damage or mortality.

Financial evaluation

The major problem for financial analysis of regimes for sub-tropical eucalypt plantations in Australia is the lack of data on plantation yields and thinning responses. In Brazil, solid-wood regimes based on early thinning appear to be more profitable than pulpwood regimes (Seling *et al.* 2001). Thinning 'hard and early' has been shown to be profitable in other species due to the decrease in time taken to produce a crop of acceptable value (Hiley 1956), and early thinning combined with pruning appears to be the chosen strategy of leading international eucalypt growers (Donnelly *et al.* 2003; Nolan *et al.* 2005). More intensive management of plantations through capital investment in silviculture becomes more feasible or justifiable where land becomes scarce and expensive (Binkley 1999), such as has occurred on the northern coast of NSW and in south-eastern Queensland.

Environmental considerations and costs of harvesting typically restrict operationally-feasible regimes to one or two thinning events. Harvesting costs include planning overheads and provision of infrastructure such as roads. Environmental considerations include measures for habitat, soil and waterway protection. In addition, there are economies of scale associated with piece size, piece numbers and volume per hectare, and these factors dictate whether or not a thinning can be done commercially. Where a forest estate is characterised by many planted blocks of relatively small size (as is common for longer-rotation eucalypt plantations established in more recent times), the financial viability of an early thinning will be reduced by low available volumes and diseconomies of small-scale operations. There are also market timing considerations.

Plantation managers will often find that the optimum time for first thinning, in terms of stand growth and value recovery, is not necessarily compatible with the desire for a first thinning to be commercial. The focus then becomes the trade-off between total stand volume and value increment, and the decision of whether or not to thin to waste.

There will often be circumstances when there will be commercial advantage in sacrificing volume production to achieve a threshold stem diameter sooner (Hiley 1956; Florence 1996). This occurs when the increased value of large logs being produced sooner (due to a non-commercial thinning) is greater than the value of small logs realised from a first commercial thinning plus the cost of non-commercial thinning (Gerrand *et al.* 1997; Keenan 1998). Prices likely to be achieved for various end products will have an effect on the outcome — the wood quality of logs will be crucial to determining what end-uses, and thus log prices, can be obtained.

Another significant problem for growers of longer-rotation plantations is market uncertainty. In this regard, thinned and pruned (or self-pruned) plantations confer flexibility and will produce logs that can be converted to a wide variety of high-value uses (Donnelly *et al.* 2003; Nolan *et al.* 2005). Thinning has other financial benefits in that it promotes greater uniformity in log dimensions, meaning reduced unit harvest costs and greater efficiencies in processing (Nolan *et al.* 2005; Washusen and Clark 2005). In addition, conversion losses are greater with logs of smaller average diameter (Florence 1996), and certain larger products cannot currently be produced from small logs without costly reconstitution.

Conclusions

Early non-commercial thinning can greatly reduce the time to first commercial and final harvest, and improve the wood quality of logs from eucalypt plantations by removing defective stems. Thinning, however, can result in larger branches in the lower crown, adversely affecting wood quality and product value due to knots, unless pruning is also carried out or the trees effectively shed dead branches. Delaying thinning sacrifices opportunities for diameter growth of the better stems, and may result in other problems such as more tension wood and possibly wind damage. The timing and intensity of first thinning represents a trade-off between growth, wood quality and biological, climatic and market risks. The timing and intensity of thinning will depend largely on species and site characteristics, market opportunities and financial considerations, such as discount rate. Evaluation of different early thinning options in sub-tropical eucalypt plantations is imprecise at present, as much of the required data, such as thinning response, and effects of thinning and pruning on wood quality and end uses, and hence realisable log value, are currently lacking. Research is needed to provide these data so that maximum value can be recovered.

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