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Solid-wood production from temperate eucalypt plantations: a Tasmanian case study

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Since 1988, there has been a major focus in Tasmania on research for the management of temperate eucalypt plantations for solid wood. This coincided with the formal transfer of large areas of native forest that had previously been part of the production forest estate into reserves, a decision that triggered the establishment of eucalypt plantations for solid wood. This review summarises research on several key areas: silvicultural requirements for solid-wood production; wood properties of plantation-grown eucalypts and the influence of silviculture and genetics on these properties; factors influencing stem defect and decay; balancing silvicultural requirements with maintenance of tree vigour; and issues concerning wood processing and products. We conclude that there are still operational challenges to be confronted in the production of solid wood from plantations. If these can be overcome in the medium term, temperate plantation eucalypts have the potential to provide wood products that meet the requirements for appearance-grade material and that can compete in the same markets as wood from native forests. The bigger challenge at the national level will be to provide the log volumes of suitable material to meet the anticipated demand 25 to 30 years from now.

Keywords: *Eucalyptus*, plantations, solid wood

Introduction

The development of plantations in Australia can be viewed as having four phases (Bureau of Rural Sciences, 2002). The first, between 1900 and 1960, was for the replacement of imported softwood. The second, between 1960 and 1980, was part of a drive towards self-sufficiency and the first attempt to try and deal with the negative trade balance in wood and wood products. The period 1980–1990 marked a third phase with a shift from softwoods planted using government funds to hardwoods planted using private investments. During the fourth phase from 1990 to the present day, plantation establishment, primarily with hardwoods, was dominated by the private sector. Managed investment schemes (MIS) became major initiators of plantation establishment, with small-scale investors accessing favourable up-front tax deductions for primary industry.

Since 1990, most hardwood plantations on mainland Australia and in parts of Tasmania have been established on ex-agricultural sites and managed over short rotations for pulpwood production. In Tasmania, there has been a policy to establish plantations also for solid wood to replace the resource made unavailable because of the transfer of large areas of native forest into national parks and world heritage areas. This expansion of reserves in Tasmania has reduced the harvest of sawlogs from almost 800 000 m^3 a^{-1} in the mid-1970s to the current legislated supply figure of 300 000 m^3 a^{-1} from crown forests. Almost half the current sawlog yield is from regrowth forests (≤120 years old). After 2020, plantations are expected to provide at least 75 000 m^3 a^{-1}, or one-quarter of the total sawlog supply. While volume production can be maintained at 300 000 m^3 a^{-1} through the use of plantation sawlogs, there are questions over their potential quality.

There are currently about 35 000 ha of publicly- and jointly-owned hardwood plantations in Tasmania that can potentially supply high-value sawlogs. In addition, there are about 140 000 ha of hardwood plantations in the private sector (Bureau of Rural Sciences, 2007). However, most of the latter are bound under MIS arrangements for harvest over a short rotation for pulpwood.

There are many uncertainties associated with producing high-value solid-wood products from eucalypt plantations. Unpruned plantation eucalypts do not deliver high-quality appearance-grade sawlogs (Nolan *et al.*, 2005). Because hardwoods compete in the same markets as softwoods, issues such as growth strain and tension wood that are often a feature of young eucalypt wood must be, and are being, addressed through new sawing and drying technologies. For example, hew-saw technology that relieves growth stresses during processing can produce structural hardwood timber from unpruned plantations that matches pine for strength in expansion, greater leaf development in the upper crown, greater leaf area to branch basal area ratio and reduced leaf senescence (Pinkard and Beadle, 1998b). Significant increases in light-saturated rates of single-leaf net photosynthesis (A_{max}) that can be up to 190% of those in an unpruned tree occur throughout the crown, the magnitude of the response decreasing with canopy depth (Pinkard *et al.*, 1998). These findings suggest that pruning severity should be linked to the capacity of these responses to result in no significant change in the growth of pruned, compared to unpruned, trees in the stand. However, while this can be achieved for first-lift pruning, the physiological responses to second- and third-lift pruning have been investigated less intensively to link pruning strategies to outcomes with certainty.

Thinning

It is recommended that eucalypt plantations managed for solid wood be established at around 1000 stems ha^{-1}. This is done to ensure sufficient potential final-crop trees in the stand that meet the criteria for pruning and also to impose some control on branch size. Large branches are more difficult to prune and are also more susceptible to decay entry (see below). Therefore thinning becomes essential to reduce intraspecific competition and to extend the characteristically fast early growth rates of *E. globulus* and *E. nitens*. Thinning may also be associated with higher recoveries, less drying degrade and lower growth stresses (Nutto and Touza, 2005; Washusen, 2002b).

Thinning intensity affects stand growth. In an *E. nitens* plantation, cumulative basal area growth seven years after thinning at age six years was unaffected by thinning intensity down to 300 stems ha^{-1}; removal of >66% of standing basal area at thinning that resulted in a stand density of 100 stems ha^{-1} was associated with a significant reduction in basal area growth (Medhurst *et al.*, 2001). Individual tree growth increased with thinning intensity and, in general, it was the dominant and co-dominant trees that produced a significant basal area response. The lower the quality of the site, the less the ability of the stand to respond to thinning (Medhurst *et al.*, 2001).

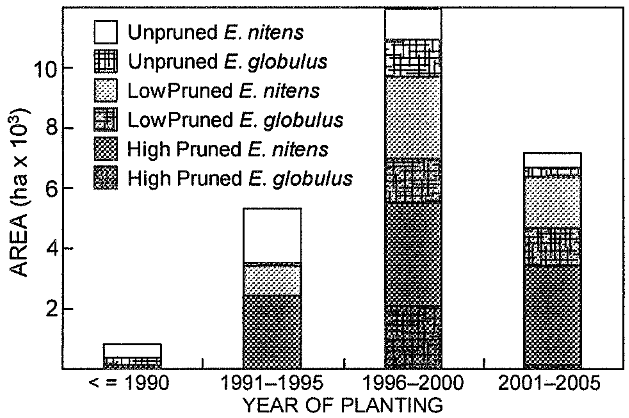

Figure 1: The distribution of the hardwood solid-wood plantation resource in Tasmania by species and pruning intensity

Thinning modifies the distribution of light and canopy photosynthesis (Medhurst and Beadle, 2005). Significantly higher fractions of incident light are found in the middle and lower crowns, and significantly greater A_{max} is observed in the lower crown, compared to unthinned stands (Figure 2). This is expressed through changes in the distribution of nitrogen (N) in the canopy that result in positive relationships between foliar N content and the fraction of incident light or A_{max}. Increases in foliar N content are related to a significant decrease in specific leaf area (Medhurst and Beadle, 2005). Changes in leaf area per tree are associated with an increase in crown length in thinned stands (Medhurst, 2000).

These observations suggest that thinning at or soon after canopy closure will maximise the growth response; conversely, delaying thinning until after there has been appreciable crown lift will decrease the magnitude of the response. Thinning intensity should be commensurate with the maximisation of light interception and therefore growth of individual trees. However, as thinning regimes should maximise stand productivity as well as optimise tree size at harvest, the ideal residual stand density after thinning should maximise leaf area index towards the end of the rotation. In general, thinning intensity needs to increase with increasing site quality. As trees have a capacity to develop longer tree crowns on high-quality sites, delaying thinning will not, up to a point, preclude a growth response from thinning. This provides a greater opportunity to thin commercially for pulpwood on such sites.

Stem defect

Stem-defect agents such as insects (borers), canker, decay and stain fungi are potential sources of loss of value and downgrade in plantations managed for solid wood. Defect may also arise from excess kino production in response to damage. Research in regrowth forests on decay originating from stem wounds inflicted during thinning operations highlighted the importance of minimising this potential source of defect (White and Kile, 1991). However, thinning can also reduce the incidence of defect in the final crop as trees showing signs of decay can be removed. In plantations, potential sources of decay include pruning as well as thinning

Table 1: The percentage of crown length removed that affects growth in a range of species pruned in plantations

Species	Crown length removed (%)
Acacia melanoxylon[1]	25
Acacia mangium[2]	40
Eucalyptus grandis[3]	40
Eucalyptus nitens[4]	50
Pinus patula[5]	25
Pinus radiata[6]	35
Pinus sylvestris[7]	40
Cryptomeria japonica[8]	30

[1] Medhurst *et al.* (2003); [2] Majid and Paudyal (1992); [3] Bredenkamp *et al.* (1980); [4] Pinkard and Beadle (1998a); [5] Karani (1978); [6] Sutton and Crowe (1975); [7] Långström and Hellqvist (1991); [8] Fujimori and Waseda (1972)

Utilisation of genetic variation is a possible management tool to reduce decay incidence and spread. In *E. nitens*, family and progeny trials have shown that the incidence of heart and wound rot is under moderately strong genetic control (heritabilities 0.27 to 0.4 and 0.6, respectively; Kube, 2004; D Wiseman, unpubl. data) and easily assessed during routine sampling for wood properties. Susceptibility to sapwood decay appears not to be under widespread genetic control, although southern races of *E. nitens* are more susceptible to sapwood decay (D Wiseman, unpubl. data).

In eucalypts, kino veins are often considered to be barrier zones, a traumatic response to damage to the vascular cambium. *Eucalyptus nitens* does not actually form kino veins, which sets it apart from many eucalypt species (Eyles and Mohammed, 2002a, 2002b), including *E. globulus*. Wound tissue of *E. nitens* that is formed after wounding but is not induced by biotic damaging agents was investigated by Eyles *et al.* (2003a), who suggested its importance in defence had been overlooked. The detection of traumatic oil glands in wound tissue was a new finding for eucalypts (Eyles *et al.*, 2004). A cocktail of chemicals was extracted and identified from such wound tissue (Eyles *et al.*, 2003b, 2003c). These chemicals may have a multifunctional role as antioxidants and may make the wound tissue inhibitory to both fungi and pests. The same class of compounds has been found in wound tissue formed in response to infection by decay and canker fungi (Eyles *et al.*, 2003c).

There are clear opportunities to refine selection strategies in breeding programs to target chemical traits that confer greater resistance to damaging agents. Novel science and investigative techniques must be applied to develop a bio-assay indicative of eucalypt susceptibility to stem defect.

Combating biotic stress

The condition and characteristics of the crown and of the branches that support the crown can be used as a basis for exploring ways of dealing with biotic stress. Live branches are the key to good outcomes from pruning eucalypts; dead branches are associated with kino production and stem degrade (Mohammed *et al.*, 2000). A corollary to this requirement is that crown lift must be avoided prior to pruning. Initial spacing is one variable that affects retention of live branches. In a five-year-old *E. nitens* spacing trial, the height to green crown varied from 1 to 6 m as stocking increased from 500 to 2500 stems ha^{-1} (Gerrand and Neilsen, 2000). Crown lift is also a function of site quality, poorer sites being associated with earlier crown lift. Application of N fertiliser is one option for slowing crown lift and significantly increased the proportion of living branches in two *E. nitens* plantations four years after pruning (Wiseman *et al.*, 2006). Another factor promoting branch senescence is leaf disease. *Mycosphaerella* leaf disease is the major leaf disease of eucalypts worldwide that affects foliage throughout the crown and in severe cases is associated with branch death.

As indicated above, a higher proportion of decay is associated with large branches and mostly large living branches. Large branches are strongly associated with spacing; the largest changed in size from about 2 to 5 cm as spacing decreased from 2500 to 500 stems ha^{-1} (Gerrand and Neilsen, 2000). The proportion of branches in the larger size classes also increased with the application of N fertiliser (Figure 4; Wiseman *et al.*, 2006), potentially leading to more decay. Pruning can also significantly increase branch diameter immediately above the pruned zone (Pinkard and Beadle, 1998b).

A rapid rate of occlusion or closure of the wound created by pruning is required to maximise the production of clear wood. Occlusion and the factors affecting it have not received much attention to date in eucalypt plantations. The number of occluded branches in pruned *E. nitens* was low (46%), occlusion increased with stem height and fertiliser led to a lower percentage of occluded branches (D Wiseman, unpubl. data). The average distance to occlude from the end of the cut surface is a function of cut-face diameter, bark width and the presence of excess kino (positive relationship), and stub length and decay in the stub (a negative relationship). As these relationships were unaffected by fertiliser application (D Wiseman, unpubl. data), they suggest that later applications around the time of pruning can be made to enhance growth rates and clear-wood production.

Ideally, every tree planted would remain single-stemmed and of good form. This does not happen, and because fertiliser (Beadle *et al.*, 1994) and wider spacing increase the number of trees with multi-leaders, selective pruning systems are a necessary way of managing eucalypt plantations for solid wood. As growth since pruning has by far the largest effect on clear-wood production, the logic is to manage pruned stands to maximise growth rates once a pruned stem has been established. *Eucalyptus globulus* and *E. nitens* both have potentially very high early growth rates and in plantations have been demonstrated to respond to both N and P fertilisers (Cromer *et al.*, 2002).

Fertiliser application can also help to maintain growth following insect foliar attack. An artificial spring defoliation of a 13-month-old *E. globulus* plantation that removed all foliage from 50% of the crown length significantly reduced height growth six months later compared to an undefoliated control. The addition of 100 kg N ha^{-1} significantly increased height growth of the defoliated treatment compared to a defoliated control not receiving fertiliser; the height growth of the defoliated fertilised treatment was at least as great as that of the undefoliated control (Pinkard *et al.*, 2006a). In a

Table 2: The effects of pruning or not pruning *Eucalyptus nitens* at three sites on the number of decay columns one and 5.5 years after treatment. Values are the mean ± SE. The effects of time ($p < 0.001$) and site ($p = 0.0022$) were significant (adapted from Barry *et al.*, 2005)

Time since pruning (years)	Flowerdale		Evercreech		Hastings	
	Pruned	Control	Pruned	Control	Pruned	Control
1	2.3 ± 0.6	0.8 ± 0.3	1.1 ± 0.7	0.6 ± 0.3	1.7 ± 0.6	0.2 ± 0.1
5.5	4.6 ± 0.9	4.1 ± 0.8	3.4 ± 0.9	1.4 ± 0.5	0.8 ± 0.6	0.6 ± 0.3

plantations. Young and fast-grown wood may have very different wood properties to that from native forest (Hillis, 1984) and smaller logs mean lower recovery of select-grade material (Figure 5; Washusen and Clark, 2005). A feature of research has therefore been the application of emerging as well as conventional processing technologies, partly to improve recovery but also to reduce processing costs. Development of resources to meet the wood quality, log quality and size requirements of prospective processing systems must therefore be the future aim.

The research to date has appeared *ad hoc*, in that it has involved numerous, quite separate, processing trials. However, together these trials have emerged as a 'systematic resource evaluation' that has assessed factors limiting product quality, recovery and processing efficiencies in several eucalypt species. More detailed research has led to a better understanding of how plantation wood behaves during processing. In particular, defects associated with branches and tension wood have received much attention.

The presence of knots, decay and kino associated with branches is most important in terms of production of conventional appearance products. In unpruned stands, yields of high-quality logs are low and pruning appears to improve the recovery of appearance-grade timber (Washusen and Clark, 2005). Tension wood is a major issue limiting the recovery of wood. It affects most trees, even those with form considered likely to produce high-quality sawlogs (Washusen and Ilic, 2001; Washusen, 2002a; Washusen *et al.*, 2002). Much of the investigation of tension wood has been undertaken in *E. globulus*. However, tension wood has been found also in *E. nitens* (Washusen, unpubl. data). When located at or near the stem periphery, tension wood is associated with very high growth stresses that result in board distortion (Washusen, 2005) and poor accuracy during sizing. When located anywhere within the log/board, tension wood results in high transverse and longitudinal shrinkage (drying defect) during drying (Figure 6; Wardrop and Dadswell, 1948, 1955; Pillow, 1950; Kauman, 1964; Boyd, 1977; Washusen, 2000).

Research suggests that silvicultural practices affect tension-wood formation in *E. globulus*. In unthinned stands and in straight vertical stems, tension wood forms in many dominant or codominant trees below 30% tree height. As the severity of its formation increases, tension wood extends further up the stem. The distribution of tension wood is significantly correlated to form factor (taper) and as basal area increases, so does the severity of tension-wood formation (Washusen, 2002a).

In thinned stands the occurrence of tension wood appears less predictable. In stands of *E. globulus* thinned at age 2–4 years, tension wood was difficult to locate when the trees were aged 10 and 22 years (Washusen, 2002b; Washusen *et al.*, 2004). Conversely, heavy thinning in a stand aged eight years promoted tension-wood formation in the clear-wood zone (Washusen *et al.*, 2005). When fertiliser was applied in this stand at thinning, the growth response was associated with a reduced formation of tension wood. Thus there may be a strong link between wind and tension-wood formation that can be ameliorated by stimulating a growth response. Effectively, increased stem bulk substitutes for tension wood as a mechanism for resisting mechanical stresses.

In processing trials in thinned and pruned *E. globulus* where tension-wood volumes are low, good recoveries have been recorded, even with back-sawing (Washusen *et al.*, 2004). Application of modern linear-type sawing systems has indicated that small-diameter logs can be processed efficiently in lengths up to 4.8 m without producing adverse effects from board distortion due to stress release (Washusen, 2006). This has been attributed partly to the lack of tension wood and partly to the log profiling in which chippers operate in front of saws to remove the highest-stressed outer wood. This is significant because these systems may produce good recoveries at higher feed rates and produce similar product quality and dimensions to conventional processing equipment. It remains unclear whether linear sawing systems can be applied to thinned and pruned *E. nitens* to produce appearance products because of the difficulties of drying low-density back-sawn wood. Future research should clarify this and examine also the effect of product thickness on drying performance of back-sawn wood and the potential of highly efficient quarter-sawing systems.

Rotational-scale strategies

In Tasmania, the current resource is in its first rotation and the oldest plantations are at least 10 years from harvest. The intensive management adopted should have included the best operational practices for plantation establishment, including weed control and protection from browsing. Pruning and thinning will have followed well-defined regimes. Supplementary fertiliser will have been applied if necessary and the foliage protected from defoliating insects. To what extent can these inputs minimise the risk of failure and ensure sustainable yields?

The main objective was to create Category 3 sawlog of 6.2 m lengths with a small-end diameter >30 cm, no tension wood, defect-free clear wood and an acceptable Internal Rate of Return. In broad terms stands are established at around 1000 stems ha^{-1}, 250–350 stems ha^{-1} are pruned to 6.4 m height by age six years and, after thinning, a final crop of

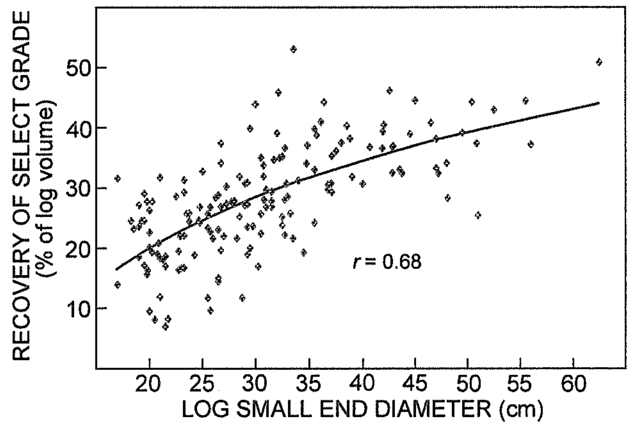

Figure 5: Recovery of select-grade material from pruned eucalypts and its decline with decreasing small-end diameter (adapted from Washusen and Clark, 2005)

for the full range of products and have the potential for the greatest value recovery (Figure 9).

To be sustainable, each section of the value chain, i.e. grower, processor, wood user and the wider community, must receive a suitable return from hardwood plantations. The wider community must be satisfied that environmental costs are minimised and balanced by economic and social returns. Wood users require fit-for-purpose and preferably renewable products for appearance and structural applications at competitive prices. Timber processors must be able to recover and market sufficient quality products efficiently from an available resource while growers must provide this resource; both need to generate a sufficient return to remain in business. In determining the economics of growing and processing, the ability to sell the full range of solid and fibre products is critical. If the whole tree cannot be used, it may not be viable to grow the tree at all. Threshold volume and quality levels exist. Recovery of appearance material from large pruned logs can be high and structural material relatively low. This ensures a relatively high average product value. However, as log quality and size fall, the proportion of non-appearance product increases, overall recovery and average value of production fall, and average cost of production can rise. As shown in Figure 9, the average value of production can fall much faster than the average cost of production until it becomes unviable to economically mill logs.

While the logs from hardwood plantations are of different species and character to those from a native forest, they are not so different that they offer producers potentially new and different markets. Plantation hardwood products must largely compete in the same market and address the same requirements of performance and economy as native-forest hardwood products. To date, processors of plantation-grown eucalypt logs have limited experience with this developing resource. Currently, it is being processed into boards and veneer as structural and industrial products. As discussed above, there are significant operational challenges that revolve around shrinkage and collapse, tension wood and growth stress, checking and drying. If these can be overcome, a ready supply of plantation logs grown for solid-wood products will change the structure of the hardwood production industry. It will allow the sorting and streaming of logs and boards, optimisation of sawing handling and drying, and improved integration among product streams. Grown well, plantation eucalypts are a potentially excellent source for sustainable wood products that deliver the key wood properties of hardness, stability, workability and durability that support the feature, colour and grain characteristics required for appearance-grade material.

Can plantation hardwoods provide a resource for technically feasible and commercially viable processing of this type of material and is there going to be enough of it to support an industry? Of the current hardwood plantation estate in Australia, less than 20% is managed for sawlog production. Most of this estate has been planted since 1995 and it is estimated that the annual sawlog yield from this resource will increase to about 376 000 m^3 by 2035 (Nolan *et al.*, 2005). This is likely to be only about 18% of total estimated log availability in 2035 and less than half of the estimated log availability lost from public native forest between 2000 and 2035. So, looking out from now, the biggest problem for establishing a sustainable hardwood process industry is a lack of suitably managed hardwood plantations.

Summary and conclusions

Establishment of hardwood plantations managed for solid wood means longer rotations, higher costs and therefore greater risks than for short-rotation pulpwood for which the majority of eucalypts are planted in Australia. These risks are uncertainties about markets for plantation-grown wood that has not previously been part of the traditional market for hardwood and those related to growing and processing. These factors have contributed to the low

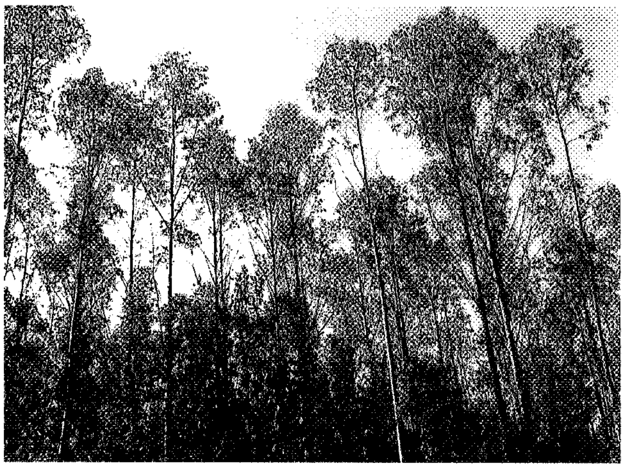

Figure 7: Loss of crown vigour in a eucalypt plantation being managed for solid-wood products. The cause is usually an inadequate nutrient supply and/or defoliation by a biotic agent. A potential solution is the application of supplementary fertiliser

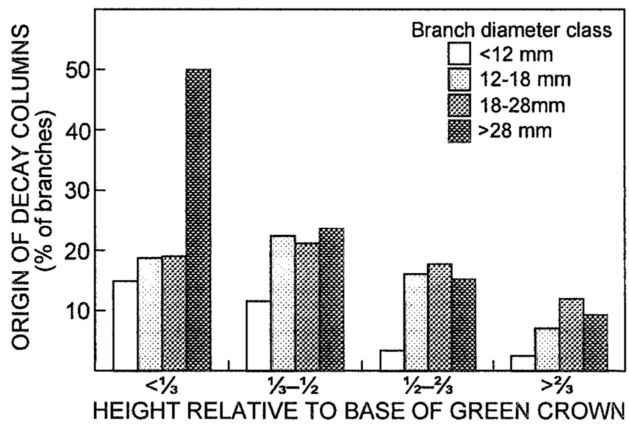

Figure 8: The proportion of dead branches in each of four diameter classes that were the origin of decay columns in an unpruned stem of *Eucalyptus nitens*, relative to the height of the green crown. Note that the branches at the bottom of the stem (<1/3) were long dead and those just below the green crown (>2/3) were recently dead

While tension remains an issue in wood, there are also tensions between the silvicultural systems imposed on trees and the sawlogs they are anticipated to deliver. It would be easier if the trees were the same size and produced small branches but these possibilities are some time away for the species used. Thus final-crop trees must be managed to ensure criteria for their selection, branch management, pruning, thinning, and pest and disease control are strictly adhered to. The industry needs sophisticated contractors who fully understand the demands of a complex silvicultural operation. Good site selection and good silviculture are the most secure way forward to ensure a successful solid-wood industry based on plantation hardwoods.

The focused nature of plantation forestry assists in giving us a chance of getting it right, but how do we make it sustainable? For any industry to be sustainable in the broad sense it must provide economic returns to all parts of its value chain, including the services on which it relies, whilst providing a clear environmental and social dimension to the wider community. Management for landscape, recreation, ecological and hydrological values already forms a crucial dimension of plantation forestry; its role in bioenergy and carbon sequestration is becoming of increasing importance. As plantations managed for solid wood have the potential to deliver a wide range of products, the development and maintenance of markets for them is critical to the success of the industries based on them. This review has shown that there are still operational challenges to be confronted but if these can be overcome in the medium term, there is no reason why temperate plantation eucalypts cannot deliver wood products that provide the key wood properties for appearance-grade material and that can compete in the same markets as native forest hardwoods. The bigger challenge at a national level will be to provide the volumes of suitable material to meet the anticipated demand for hardwood logs 25–30 years from now.

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