Management of eucalypt plantations for profitable sawlog production in Tasmania, Australia

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Abstract

Forestry Tasmania is required to make available annually 300,000 m³ of eucalypt sawlogs for the veneer and sawmilling industries as part of its multiple-use management of State forests. A substantial proportion of this timber volume is planned to come from Eucalyptus globulus *and* E. nitens *plantations on State forest. Management of eucalypt plantations for sawlogs typically requires an intensive approach, with timely application of value-adding operations such as pruning and thinning to ensure the quality and size, respectively, of selected stems within 20-25 year rotations.*

This paper describes the broad strategic and operational challenges faced in managing eucalypt plantations across Tasmania for sawlogs. These include ensuring that wood-supply obligations are met whilst maximising profitability, and that key value-adding operations are applied to specification whilst limiting associated risks such as pests and disease, fire and windthrow. The economic and silvicultural outcomes of several variants of a base (unpruned and unthinned) regime are then modelled and considered. Overall, profitability increased with increasing site quality (peak mean annual increment, pMAI over the range examined (pMAI 20 to 35 m^3 ha^{-1} yr^{-1}), whilst the optimum rotation length, as measured by maximum profitability, decreased with increasing site quality. High-pruning (to 6.4 m) became more profitable as site quality increased. Moreover, at each site quality, regimes incorporating a commercial thinning were more profitable than those where thinning was either excluded or carried out 'to waste'.

The current Forestry Tasmania estate model indicates that legislated sawlog production targets will require some 40% of the 48,860 ha of eucalypt plantation anticipated to be owned by Forestry Tasmania to be managed under a high-prune, commercial thinning regime. We show here that this represents a compromise between profitability and total production, with a greater profit being returned if a no- or low-prune, commercial thinning regime were applied to some of this area. The use of Decision Support Systems that incorporate detailed information relating to site characteristics and stand performance will be critical in deciding the most appropriate management regime for each site.

Introduction

Section 22AA of Tasmania's Forestry Act 1920 reads: "*Each year, from multiple use forest land* [i.e. land managed for landscape values, such as biodiversity and amenity, as well as timber production], *the corporation must make available for the veneer and sawmilling industries a minimum aggregate quantity of eucalypt veneer logs and eucalypt sawlogs that meet the prescribed specifications*." The minimum aggregate quantity is currently 300,000 m³, while the minimum dimensions prescribed for sawlogs are 30 cm small-end diameter and 3.6 m length (Forestry Regulations 1999). The most recent Five Yearly Wood Review (Forestry Tasmania

2007) demonstrates how Tasmanian State Forest, managed by Forestry Tasmania, is expected to meet this legal requirement (Figure 1).

The strategy presented in Figure 1 has been designed to produce a sustainable annual yield of eucalypt sawlogs at or above 300,000 m^3 over the 90 years from 2006. Mature native forests are critical in maintaining the yield in the short- to medium-term, but will cease to make any significant contribution from 2030 onwards. The contribution of regrowth native forest changes from those of unspecified age (usually associated with pre-1960 wildfires) to those of specified age (usually associated with clearfell, burn and sow silviculture applied after the 1950s). Thinned eucalypt native forest will add significantly to sawlog yield in the medium term, and potentially in the longer term as well if a substantial thinning program is initiated. Notably, plantation-grown sawlogs, principally *Eucalyptus globulus* and *E. nitens*, are expected to contribute to more than half of the total sawlog volume, that is, some 160,000 m^3 yr^{-1} by the year 2023.

The current area of hardwood plantation on State forest, owned wholly or in part by Forestry Tasmania as of July 2007, is 35,646 ha. This is summarised by species and management regime in Table 1. In addition to this current estate, a further 13,214 ha are presently leased to other companies and may become available to Forestry Tasmania over the next 5-10 years, bringing the possible future estate to 48,860 ha.

In order to deliver legislated wood flows, Forestry Tasmania employs a forest estate model, built with Remsoft's Spatial Planning System, Woodstock (Remsoft Inc. 2006). This allows managers to determine how (in terms of management regime), and to what extent (as area under a given management regime), the current and future plantation estate should be managed to successfully deliver the planned 160,000 m^3 ha^{-1} yr^{-1} of pruned sawlogs. The most recent model (Figure 1) indicated that, in order to deliver this target, the following approach should be adopted:

- Over the first rotation, maintain current management objectives and pruning and thinning regimes as prescribed (Table 1), and
- Over the second and subsequent rotations, apply high-pruning and commercial thinning to that proportion of the estate with a site quality is defined by peak mean annual increment (pMAI) of 25 m^3 ha^{-1} yr^{-1} and greater, which represents some 19,544 ha (40%) of the anticipated 48,860 ha of hardwood plantation.

Management of plantations to produce pruned sawlogs, notably the application of these high-pruning and commercial thinning operations, is far from straightforward, given the range of strategic and operational challenges. As a result, the effective allocation of limited resources, in terms of both the productive area and the application of prescribed silviculture, must be carefully judged to ensure volume production goals and maximise profitability. To explore this concept further, we asked the following questions:

- Which management regime offers the best return in terms of profitability for a given site quality, based on current operational costs and market expectations, and given the production goal of high-quality sawlogs? and
- What factors, other than profit, are likely to influence management to this end?

Silvicultural considerations and challenges for sawlog production

Silviculture for sawlogs

Management of plantations for sawlogs typically requires a more intensive approach than management for pulp logs. This includes the timely application of pruning and thinning operations to ensure the

Table 1. Area (ha) of eucalypt plantation species by management regime on Tasmanian State forest (July 2007).

	Eucalypt species			
Regime	*E. globulus*	*E. nitens*	Other	Total
Sawlog - high-prune and commercial thin	2690	13,041	41	15,772
Sawlog - other*	2772	6614	4290	13,676
Pulp	2429	3305	464	6198
Total (ha)	7891	22,960	4795	35,646

*Historical regimes typically including some combination of both thinning and pruning.

quality and size, respectively, of selected stems. Currently in Tasmania, sites with favourable soil and climatic conditions are chosen for establishment of eucalypt plantations, where a pMAI of 20 m^3 ha^{-1} yr^{-1} or greater can be expected at some point within a 20-25 year rotation (Neilsen 1990; Gerrand *et al*. 1993). In practice, however, not all sites achieve this productivity.

Each site is established at 1100 stems ha^{-1}, providing adequate control of branch size and stem form, then 300-350 stems ha^{-1} are high-pruned to 6.4 m over a series of three 'lifts', typically between ages 3-5 years (Neilsen 1990). The upper pruning height limit of 6.4 m is dictated largely by Occupational Health and Safety considerations, but also by limits on the size of logs that can be transported by road. Pruning is undertaken to promote the development of 'clearwood', wood free of knots and other defects, along the length of the pruned stem. This is critical given the poor natural branch-shedding ability of plantation-grown *E. globulus* and *E. nitens* (Gerrand *et al.* 1997). Under current specifications, no more than 40% of the

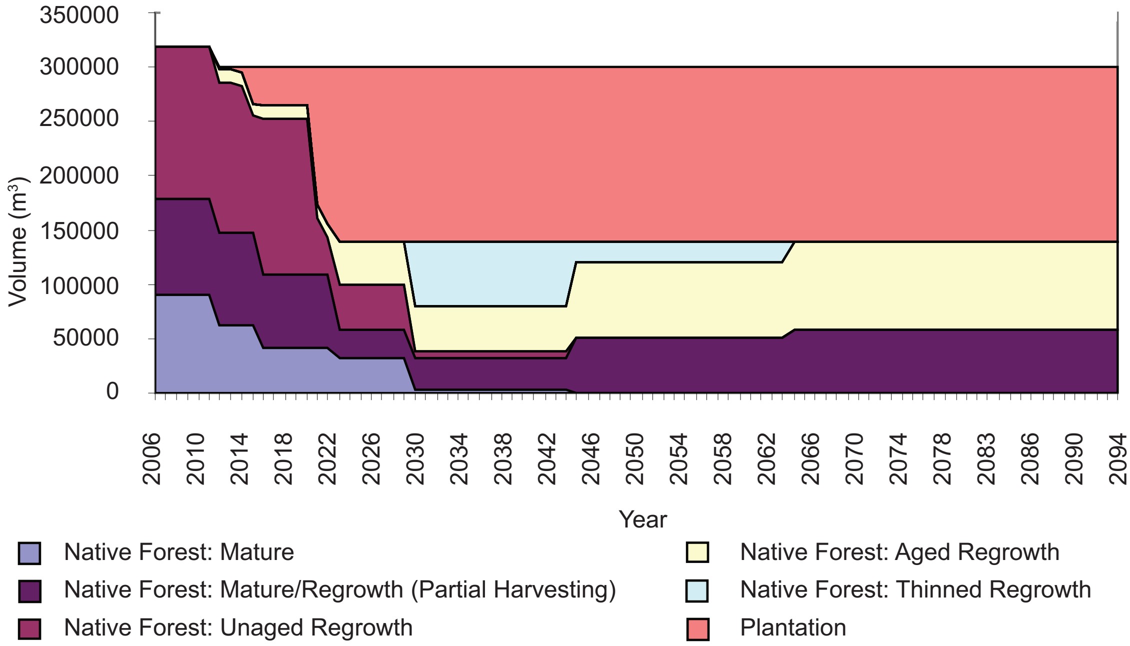

Figure 1. Planned sustainable yield of high-quality eucalypt sawlog from State forest in Tasmania.

live crown is removed during any single lift, thereby limiting adverse impacts on growth rates (Pinkard and Beadle 1998). Furthermore, trees with large, dead or acutely angled branches are left unpruned to limit the occurrence of large knots and/or decay entry via the pruned stub (Wardlaw and Neilsen 1999).

Thinning is later carried out to reduce stand density, serving to lessen competition for essential growing resources and promote rapid diameter growth on the retained stems (Savill and Evans 1986; Smith *et al.* 1997; Cameron 2002). This is critical given the relatively short rotation lengths associated with plantation sawlog regimes in Tasmania. Economic analysis (Gerrand *et al*. 1993) demonstrated that, in order for plantations to achieve maximal financial returns, thinning should be delayed wherever possible until ages 8 to 12 years, by which time sufficient volumes of thinnings are available for sale, typically as pulp, thus providing an early return on the investment in plantation management for sawlogs.

Strategic challenges

Forestry Tasmania is the only enterprise in Tasmania that continues to pursue a significant production goal of pruned sawlogs from eucalypt plantations. This position is derived largely from the limited area of native forests available for timber production, and a growing awareness of non-timber outcomes of native forest management (carbon storage, biodiversity and amenity), some of which may not be compatible with intensive harvesting regimes. Consequently, as the proportion of the potential native forest wood resource now protected in reserves has increased, Forestry Tasmania has found itself subject to a reduced sawlog resource base.

The pursuit of pruned sawlogs occurs at the expense of other log product markets ordinarily serviced by plantations (e.g. unpruned sawlogs and pulpwood). To maximise profitability, material removed during plantation thinning operations has traditionally been sold as pulpwood. Whilst a useful outlet, thinning volumes are variable both in quantity and quality. Furthermore, due to a tendency to delay thinning until sufficient 'commercial' volumes exist, the timing and/or intensity of thinning may not produce the optimum silvicultural response in the retained stems destined for sawlogs (in terms of diameter growth) and may leave the stand at risk from windthrow.

Finally, efforts to meet the legislated timber production goals described above must be set against the broader management objectives identified within the Sustainability Charter (Forestry Tasmania 2008). These include the promotion and maintenance of biodiversity and habitat, employment and livelihood, environmental services (carbon storage, clean air and water), community access and heritage, and science-based stewardship.

Operational challenges

Tasmania has a diverse and complex pattern of soils resulting from its wide range of landforms, geology, climate and vegetation (Laffan 2000). Subsequently, plantation growth rates and/or stand uniformity vary spatially and temporally, both between and often within stands. Other features such as wildfire, competition, pests and disease, though not considered to be inherent site attributes, can further impact upon growth rates and stand uniformity. Given the dynamic nature of the resource, scheduling critical events such as pruning and thinning according to the silvicultural requirements and economic objectives described above is a complex task.

Eucalypt plantations for sawlog production were first established by Forestry Tasmania in the mid-1980s, with the majority of plantings made throughout the 1990s under the Intensive Forest Management Program (Farmer and Smith 1997). Much of the current estate is thus less than 10 years old, and both contractor experience and availability is limited. Pruning is a highly skilled and physically demanding activity with a number of Occupational Health and Safety issues, notably where high-pruning is prescribed (Figure 2). Thinning operations typically employ machinery more suited to native forest operations, and there are currently few contractors with the appropriate tools for handing the smaller piece sizes associated with plantation forests (Figure 3). Furthermore, intensive thinning operations promote tree instability and the risk of windthrow, notably where the retained trees have a height:diameter ratio of 1.0 m cm^{-1}or have exceeded a mean dominant height of 20 m (Cremer *et al.* 1982; Savill 1983; Quine *et al*. 1995; Ruel 1995). In Tasmania, this has been especially problematic, and costly, on exposed sites where thinning has been delayed until the stand has been close to, or in excess of, this critical height threshold (Figure 4) (Wood *et al.* 2008; Wood 2008).

Methods

Farm Forestry Toolbox v.4 (Private Forests Tasmania 2003) was used to model the silvicultural outcomes (timber products, m^3 ha^{-1}) and financial outcomes (\$AU ha^{-1}) of a number of alternative regimes applied over a range of site qualities. A total of 60 different management scenarios were modelled, each designed to reflect the current operational practices of Forestry Tasmania and its contracted staff.

Site quality and silvicultural inputs

For each scenario, site quality was based on peak mean annual increment (pMAI, m^3 ha^{-1} yr^{-1}). The pMAI parameter is defined simply as the maximum MAI for an unthinned stand with an initial stocking of 1100 stems ha^{-1} without specifying when this occurs in the rotation. Four site qualities where chosen (pMAI values of 20, 25, 30 and 35 m^3 ha^{-1} yr^{-1}), with these pMAIs typically occurring after 25, 18, 19 and 16 years respectively, and representing the range in site qualities over which Forestry Tasmania currently seeks to produce sawlog crops.

Basic management up to age 5 years for each scenario included clearing and wind-rowing, ripping and ploughing, pre-plant spraying, planting (*E. nitens*, assuming 95% survival after the first year) and primary fertiliser application (actual fertiliser responses were not included).

Three pruning regimes were considered:
1. No pruning,
2. Low-pruning: prune 350 stems ha^{-1} to 2.7 m at age 3 years,
3. High-pruning: prune 350 stems ha^{-1} to 2.7 m at age 3 years, 325 stems ha^{-1} to 4.5 m at age 4 years, and 300 stems ha^{-1} to 6.4 m at age 5 years. This assumed a reduction in the number of stems ha^{-1} suitable for pruning at each successive lift of approximately 5% (i.e. that some of the stems that had received their first lift were no longer suitable for a second or third lift due to poor form and/or mortality).

In applying the pruning regimes, it was acknowledged that selected stems may reach an appropriate size for pruning sooner or later (± 6 months), given variation in growth rates and/or stand uniformity both within and between stands. This, however, could not be satisfactorily included in the analysis given that Farm Forestry Toolbox operates in time-steps of 12 months.

Five thinning regimes were considered:
1. No thinning,
2. Non-commercial thinning: thinning 'to waste' from 1100 stems ha^{-1} to a final pruned stocking of 300 stems ha^{-1} (no out-row) at age 6 years using stem injection,
3. Two-stage thinning: thinning 'to waste' from 1100 stems ha^{-1} to 725 stems ha^{-1} at age 6 years using stem injection, followed by a 'commercial' thinning' (see below) to a final pruned stocking of 300 stems ha^{-1} (no out-row),
4. Commercial thinning: thinning from 1100 stems ha^{-1}, or previously reduced

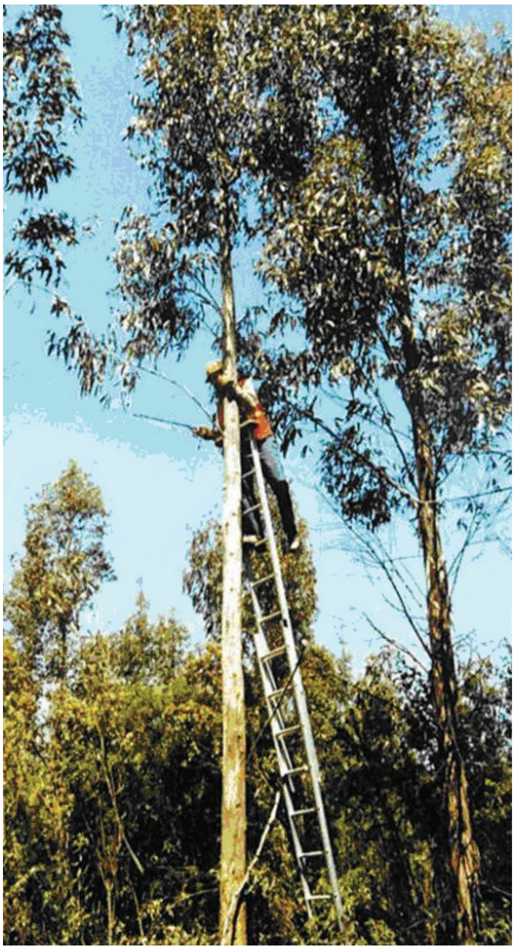

Figure 2. High-pruning a eucalypt plantation in Tasmania.

stocking, to a final pruned stocking of 240 stems ha^{-1} (including a 5th-row out-row) and scheduled so as to return a minimum merchantable thinning volume of 70 m^3 ha^{-1} (Colin Leary, pers. comm. 2008),

5. Double commercial thinning: thinning from 1100 stems ha^{-1} to 450 stems ha^{-1} (including a 5th-row out-row) followed by a second thinning to a final pruned stocking of 240 stems ha^{-1} (no out-row), each scheduled so as to return a minimum merchantable thinning volume of 70 m^3 ha^{-1}.

Economic inputs

Costs ($AU ha^{-1}) for each of the operations described above were based on State averages (Forestry Tasmania 2005, unpublished data). Commercial thinning and all harvesting operations were assigned net revenue only (start-up costs were not included). The log-grade set (product specifications) and market prices (stumpage) applied were each based on current expectations (Forestry Tasmania 2007, unpublished data). The log grades were ranked in order of value (pruned sawlog > unpruned sawlog > pulp) to inform Farm Forestry Toolbox on how to prioritise the

Figure 3. Thinning a eucalypt plantation in Tasmania using modern equipment; such machines ensure minimum damage to both the harvested and the retained stems.

break-down of each stem at thinning and clearfall, based on a stump height equal to half the tree diameter at 1.3 m from the ground.

To allow a comparison of the effects of site quality, pruning and thinning on profitability over time without disclosing sensitive commercial information, the net present value (NPV, \$AU ha^{-1}), in time increments of 1 year, was first calculated for each scenario using:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

where n is the total time (years) of the project, t is the time (year) of the cash flow, C_t is the net cash flow at time t and r is the discount rate of 9.25%, the latter considered appropriate for an investment of this nature (Penny Egan, pers. comm. 2008). For each scenario, harvesting (clearfall age, years) was then scheduled to maximise the net present value ($NPV_{max,}$ \$AU ha^{-1}). The profitability of each management scenario over infinite rotations ($NPV_{total,}$ \$AU ha^{-1}) was then calculated using:

$$NPV_{total} = NPV_{max} + NPV_{total}\left[\frac{1}{(1+i)^n - 1}\right]$$

where n is the length of a rotation in years at the interest rate i of 9.25%. Finally, the values of NPV_{total} for each management scenario were expressed relative to a base scenario by subtracting from each the NPV_{total} of the untended or 'base' regime

Figure 4. Windthrow in a eucalypt plantation in Tasmania following thinning when the mean dominant height of the stand exceeded 20 m.

Table 2. Optimum clearfall age (years) based on maximum profitability (NPV, \$AU ha^{-1}).

	Site pMAI (m^3 ha^{-1} yr^{-1})											
	20			25			30			35		
	Pruning			Pruning			Pruning			Pruning		
Regime	No	Low	High	No	Low	High	No	Low	High	No	Low	High
No thinning	17	17	17	16	16	17	16	16	18	15	16	18
Non-commercial thinning	19	22	25	18	19	21	17	17	18	17	15	17
Two-stage thinning	20	23	27	19	22	22	18	18	19	18	16	18
Commercial thinning	20	23	25	19	19	21	18	16	19	17	14	17
Double-commercial thinning	22	25	28	21	22	23	20	18	21	19	16	19

(pMAI 20 m^3 ha^{-1} yr^{-1}, no pruning, no thinning), to give a relative NPV, $NPV_{total\text{-}base}$ (\$AU ha^{-1}). These relative NPV values were then used for comparisons of regime profitability.

Results

The optimum clearfall age (years), based on maximising NPV, is presented in Table 2 for each management scenario. For each management scenario, the optimum clearfall age typically occurred earlier with increasing site quality. For example, and subject to the pruning regime, the optimum clearfall age following commercial thinning fell from 20-25 years at a site quality of pMAI 20 m^3 ha^{-1} yr^{-1} to 14-17 years at a site quality of pMAI 35 m^3 ha^{-1} yr^{-1}. Similarly, and again subject to the pruning regime, the optimum clearfall age following double-commercial thinning fell from 22-28 years at a site quality of pMAI 20 m^3 ha^{-1} yr^{-1} to 16-19 years at a site quality of pMAI 35 m^3 ha^{-1} yr^{-1}.

At site qualities of pMAI 20-30 m^3 ha^{-1} yr^{-1}, NPV_{max} and thus clearfall generally occurred later with each successive pruning lift, that is, NPV_{max} occurred soonest under the no-prune scenario and latest under the high-prune scenario for each site quality. However, at the highest site quality, pMAI 35 m^3 ha^{-1} yr^{-1}, NPV_{max} and thus clearfall generally occurred sooner under the low-prune scenario and slightly later under both the no-prune and high-prune scenarios.

Where thinning was applied, the optimum clearfall age generally occurred on average 3 years later compared to the equivalent unthinned regime. However, differences became less pronounced at higher site qualities. For example, at a site quality of pMAI 20 m^3 ha^{-1} yr^{-1}, and where high-pruning was applied, double-commercial thinning resulted in an increase in the optimum rotation length of 11 years over the equivalent unthinned regime. In contrast, at a site quality of pMAI 35 m^3 ha^{-1} yr^{-1}, and where low-pruning was applied, commercial thinning resulted in an decrease in the optimum rotation length of 2 years over the equivalent unthinned regime

Total productivity (total merchantable grades arising from thinning and clearfall excluding waste) for each management scenario are summarised in Table 3. The total volume of merchantable grades (m^3 ha^{-1}) generally increased with increasing site quality. At clearfall, scheduled to coincide with NPV_{max}, the lowest total volume (225 m^3 ha^{-1}) occurred under the pMAI 20 m^3 ha^{-1} yr^{-1}, no prune,

Table 3. Total productivity (m³ ha⁻¹) of merchantable grades of timber.

		Site pMAI (m³ ha⁻¹ yr⁻¹)											
		20			25			30			35		
		Pruning			Pruning			Pruning			Pruning		
Regime		No	Low	High	No	Low	High	No	Low	High	No	Low	High
No thinning	Pruned sawlog	0	0	0	0	1	2	0	6	18	0	15	42
	Unpruned sawlog	83	83	83	83	129	147	201	195	232	237	254	285
	Pulp	182	182	181	181	188	176	198	186	146	201	178	146
	Total	265	265	264	264	318	325	399	387	396	438	447	473
Non-commercial thinning	Pruned sawlog	0	36	113	113	51	135	0	58	153	0	55	181
	Unpruned sawlog	172	190	166	166	202	164	291	233	167	378	250	196
	Pulp	53	54	54	54	51	36	50	41	2	49	28	0
	Total	225	279	333	333	304	335	341	332	322	427	333	377
Two-stage thinning	Pruned sawlog	0	21	94	94	62	123	0	58	155	0	55	182
	Unpruned sawlog	156	187	183	183	231	170	301	243	176	389	261	207
	Pulp	136	136	136	136	134	118	124	114	74	138	116	87
	Total	292	344	413	413	427	411	425	415	405	527	433	476
Commercial thinning	Pruned sawlog	0	37	107	107	44	124	0	44	150	0	40	162
	Unpruned sawlog	160	173	137	137	183	142	295	193	168	356	203	189
	Pulp	114	114	113	113	108	106	110	101	81	105	103	79
	Total	273	323	357	357	335	372	405	338	400	461	346	430
Double-commercial thinning	Pruned sawlog	0	25	91	0	41	113	0	42	143	0	42	157
	Unpruned sawlog	172	196	179	248	228	178	333	235	208	407	261	239
	Pulp	165	165	163	162	160	144	154	144	112	152	131	108
	Total	337	385	433	410	430	436	487	422	463	559	433	503

Clearfall scheduled to maximise profitability. Volumes shown include both thinning and clearfall outcomes.

non-commercial thinning scenario, while the highest total volume (559 m³ ha⁻¹) occurred under the pMAI 35 m³ ha⁻¹ yr⁻¹, no-pruning, double-commercial thinning scenario.

Similarly, the total volume of pruned sawlogs increased with increasing site quality, with high-pruning consistently returning the highest volume of pruned sawlogs. Pruning unthinned stands on low-quality sites (pMAI 20 m³ ha⁻¹ yr⁻¹) did not produce any pruned sawlogs at clearfall, and the lowest non-zero volume of pruned logs (1 m³ ha⁻¹) occurred under the pMAI 25 m³ ha⁻¹ yr⁻¹, low-pruning, no thinning scenario. The highest volume of pruned sawlogs (182 m³ ha⁻¹) occurred under the pMAI 35 m³ ha⁻¹ yr⁻¹, high-prune, two-stage thinning scenario.

For each management scenario, the remainder of the total volume (m³ ha⁻¹) was made up of unpruned sawlogs and pulpwood. In general, and in the absence of thinning, the volume of pulpwood changed little with increasing site quality, ranging between 146 and 201 m³ ha⁻¹. In contrast, the volume of unpruned sawlogs increased with increasing site quality from 83 m³ ha⁻¹ (pMAI 20 m³ ha⁻¹ yr⁻¹) to 285 m³ ha⁻¹ (pMAI 35 m³ ha⁻¹ yr⁻¹). A similar pattern was observed for each of the scenarios where

Table 4. Economic outcomes measured as profitability relative to the base regime ($NPV_{total\text{-}base}$, $AU ha^{-1}).

	Site pMAI (m^3 ha^{-1} yr^{-1})											
	20			25			30			35		
	Pruning			Pruning			Pruning			Pruning		
Regime	No	Low	High	No	Low	High	No	Low..	High	No	. Low	High
No thinning	0	-443	-1268	815	361	-582	1729	1261	133	2659	2113	1142
Non-commercial thinning	-640	-766	-1187	34	126	-145	879	1093	1026	1786	1976	2423
Two-stage thinning	87	-176	-686	954	927	558	1944	2097	1953	3012	3205	3455
Commercial thinning	268	107	-309	1085	1093	864	2078	2134	2129	3077	3157	3638
Double-commercial thinning	271	13	-497	1181	1061	669	2253	2241	1848	3383	3318	3255

thinning was applied; however, any further increment in unpruned sawlog production was limited by the increase in the volume of pruned sawlogs.

Increased profitability, as NPV compared to the base regime over infinite rotations ($AU ha^{-1}), is summarised in Table 4 for each management scenario. For each scenario, profitability increased with increasing site quality. In the absence of thinning, pruning operations reduced profitability with each successive lift (no-pruning > low-pruning > high-pruning). Where thinning was applied, profit was consistently highest under the no-pruning scenario at the lowest site quality (pMAI 20 m^3 ha^{-1} yr^{-1}), but at site qualities of pMAI 25 and 30 m^3 ha^{-1}

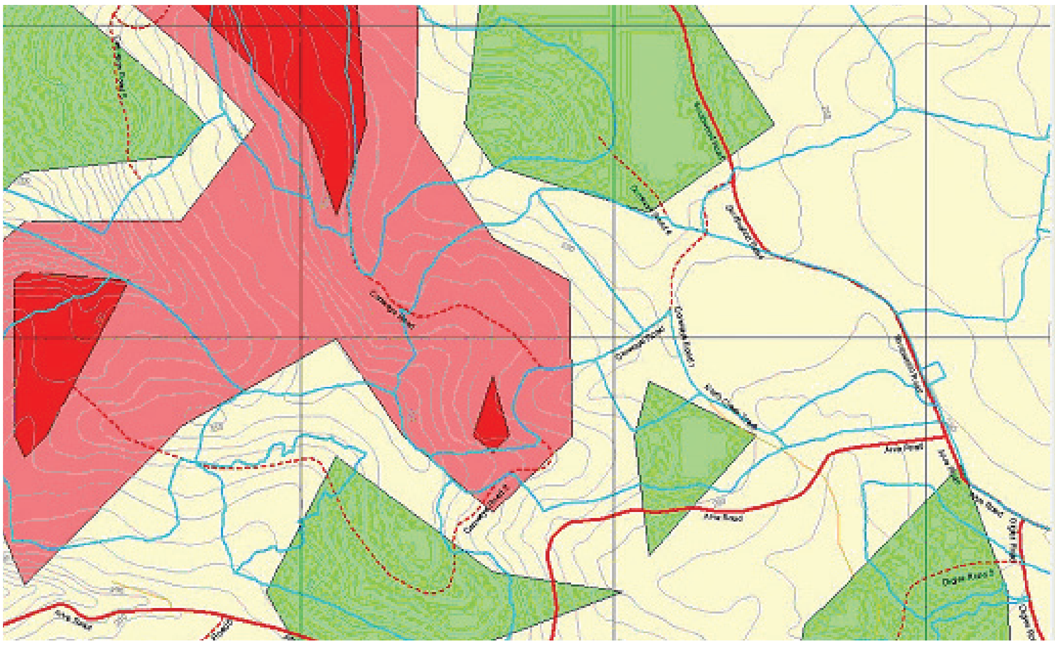

Figure 5. Topographical exposure mapped using WindRISK; areas sheltered from the wind are shown in green, and more exposed areas in red, coupe boundaries are shown in blue and contours in purple.

yr^{-1} profit was generally highest following either no- or low-pruning. At the highest site quality (pMAI 35 m^3 ha^{-1} yr^{-1}), profit increased with each successive pruning lift (no-pruning < low-pruning < high-pruning) where followed by either non-commercial, two-stage or commercial thinning; this was not the case where pruning was followed by double-commercial thinning, although the difference in profit under each of the three pruning regimes (no-, low- or high-pruning) was only \$128 ha^{-1}.

For the range of site qualities examined, regimes incorporating a commercial thinning were always more profitable than the base regime of no thinning. Only at the highest site qualities, however, was high-pruning, commercial thinning the most profitable regime, with lesser pruning regimes coupled with other thinning regimes becoming relatively more profitable as site quality decreased.

Only at these higher quality sites, therefore, was management for sawlogs the most profitable option.

Discussion

Management of hardwood plantations for sawlog production in Tasmania currently involves, wherever practical, high-pruning to 6.4 m between ages 3 to 5 years followed by commercial thinning typically applied between ages 8 to 12 years. Pruning maximises the quality of the lower log, whilst thinning promotes growth of final crop trees and the sale of thinning material ensures cash flow. The analysis presented here demonstrates that high-pruning to a height of 6.4 m becomes less profitable with decreasing site quality. Regimes incorporating a commercial thinning were always more profitable than the base regime.

Overall, these results show that management of Tasmanian State forests to produce the wood-flow illustrated in Figure 1 represents a necessary compromise between profitability and production. Scheduling clearfall operations to provide sawlog requirements may therefore result in individual coupes being harvested at some point after their peak mean annual increment has been achieved, and at a time that may not coincide with their NPV_{max}. In order to deliver 160,000 m^3 ha^{-1} yr^{-1} of pruned sawlogs, the Forestry Tasmania wood-flow model required that the area currently managed under a high-pruning, commercial thinning regime (15,772 ha, Table 1) be extended to at least 19,544 ha during second and subsequent rotations. Overall, this equates to that part area of the predicted estate with a site quality (pMAI) of 25 m^3 ha^{-1} yr^{-1} or greater, including some sites on which high-pruning and commercial thinning is not the most profitable regime.

Moreover, the analysis indicated that, to maximise profit on the proportion of the estate with a site quality (pMAI) of 20 m^3 ha^{-1} yr^{-1} or less, such sites should be left unpruned, though management should include a commercial thinning. Thinning operations, even in the absence of pruning, can produce a range of increasingly sought-after products, notably small sawlogs suitable for a range of both veneer and sawn timber products. With management of hardwood plantations for high-value sawn timber and veneer in Tasmania a relatively new endeavour, it is thus critical that managers keep a keen eye on market opportunities and new value-adding processing technologies. For example, in Tasmania, the recently established Ta Ann rotary veneer mills in the Huon Valley and at Smithton, and the multi-saw operation at Bell Bay operated by Forest Enterprises Australia, present to an opportunity to utilise small diameter logs for products other than pulp and potentially increase profitability of these thinning regimes. Given that experience with processing the plantation resource remains limited, forest growers will need to work with contractors to ensure investment in the appropriate machinery and training in order to take advantage of these opportunities.

Limitations

The analysis described here included a number of assumptions regarding input costs, growth rates, product yield and profit, all of which may change over time, and hence modelled outputs were considered indicative and relative rather than absolute.

The analysis assumed no change in pMAI over subsequent rotations. Whilst this may be reasonable for ex-native forest sites, those previously occupied by pasture will almost certainly experience a drop in productivity between the first and second rotations. Moreover, the analysis assumed optimum stand management, that is, the appropriate specification and timely application of prescribed silviculture in relation to individual stand performance. Operational realities and risk management will in fact mandate that the actual area required for sawlog production will likely be greater than the 19,544 ha identified in the wood-flow model. Further sensitivity analyses are required to explore this issue. Factors likely to create a requirement for more area managed for sawlog production include poorer than expected growth rates and/or variation in stand uniformity both within and between stands, the ever-present threat of wildfire, competition, pests and disease, and windthrow, lack of availability of skilled contractors and appropriate machinery, and changing markets and processing technologies. Furthermore, while this study identified the optimum clearfall age in terms of maximising profit (NPV_{max}), these other factors will ultimately have a bearing on exactly when clearfall takes place.

Finally, and despite growing evidence that plantation-grown material will provide an adequate substitute for material previously sourced from native forests, several issues remain which may impact on silvicultural management and profitability. Preliminary studies in Tasmania have indicated that conventional processing strategies, that is, sawing and drying regimes applied to logs taken from native forests, will not be suitable for plantation-grown logs, notably given the shorter rotations and smaller piece sizes associated with the latter where the adverse impacts of internal stresses and/or density gradients on product recovery may become more pronounced. Moreover, the effects of rapid growth rates on internal wood properties such as density and stiffness are not yet fully understood. Wood properties are not accounted for by the Farm Forestry Toolbox, hence longer rotation lengths may be required over those dictated by economics or volume productivity alone. Whilst silvicultural responses, such as the removal of competition, reduce the development of internal stresses in *E. globulus* (Washusen *et al.* 2004), tree breeding and/or alternative sawing strategies will be required to reduce the occurrence of surface and/or internal checking, a major cause of downgrade in *E. nitens* (Washusen *et al.* 2007). Opportunities to gain further understanding of the factors affecting wood quality and product recovery are emerging as the first plantings reach clearfall age.

Decision Support Systems and risk

To ensure that social, economic and environmental outcomes are optimised in the above context, and any associated risks are limited, forest managers have at their disposal a growing arsenal of planning or decision support systems (DSS). These range from simple decision trees to more complex computer-based systems that facilitate the integration of data stores with analytical and operational models to provide expert systems for selecting appropriate courses of action. These tools can be applied at all stages of forest management, that is, from site selection right through to harvesting and processing, and at all scales, that is at coupe, District or estate levels.

To get the most from these tools, detailed information relating to site characteristics and stand performance is required. One recent innovation in this regard by Forestry Tasmania includes the Pruning Assessment Tool, which combines post-pruning quality assessment with collection of pre-thinning inventory. This information can then be used by managers, in combination with other tools such as the Farm Forestry Toolbox (Private Forests Tasmania 2003), to effectively predict coupe-level silvicultural and economic outcomes over time relative to the original management goals.

As noted above, intensive thinning operations increase the risk of windthrow, notably during the few years immediately after thinning. In Tasmania, this has been most evident where the stand has reached a mean dominant height of 20 m or greater at the time of thinning. For each thinning regime applied in the exercise described here, the mean dominant height at the time of thinning increased with increasing site quality: under the commercial thinning regime, mean dominant height at the time of thinning ranged between 18 to 20 m (not shown), which suggests little margin for error when determining the exact timing and/or intensity of thinning under this regime in the field.

To manage the threat of plantation windthrow associated with intensive thinning operations, WindRISK (Wood *et al.* 2008) is used to identify the level of risk (Figure 5), and where appropriate inform alternative management strategies such that the threat of windthrow is reduced. These alternative strategies may include the application of an early and/or two-stage thinning that reduces stocking well before the stand reaches 20 m, or that reduces stocking in stages such that retained stems have an opportunity to stabilise between thinning events.

Conclusion

Forestry Tasmania's goal of producing about 160,000 m^3 yr^{-1} of pruned sawlogs from hardwood plantations on State forest, in partial fulfilment of the broader legislative requirement to produce sawlogs, presents forest managers with a series of strategic and operational challenges, many of which have taken on increasing significance as the plantation estate has matured.

Wood-flow modelling has shown that a minimum of 40% (19,544 ha) of the anticipated 48,860 ha hardwood plantation estate on State forest will need to be managed under a high-prune, commercial thinning regime to produce the required sawlog volumes. Sawlog production under this regime is the most profitable option on high-quality sites (pMAI of 35 m^3 ha^{-1} yr^{-1}). However, the sawlog production goal also involves an economic compromise given that, at low and intermediate site qualities (pMAI 20 to 30 m^3 ha^{-1} yr^{-1}), a no- or low-prune, commercial thinning regime would be more profitable. Further compromises, notably in terms of the timing and intensity of both pruning and thinning operations, will be likely where stand performance and/or risk deviate from the ideal.

Many questions remain regarding the relationships between the management regimes described above and wood quality, as well as the compounding effects of site, climate and genetics. Importantly, however, the plantation resource in Tasmania managed for sawlogs is reaching clearfall age, and we can now begin to understand the properties of the harvested timber, and how both wood quality and total recovery might be improved through alternative silvicultural and/or processing strategies.

In the face of the challenges described above, the effective allocation of limited resources to managing plantations for sawlog production will rely heavily on the timely application of innovative Decision Support Systems that integrate wood quality with our growing understanding of the relationships between silvicultural management and associated risks.

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