Growing eucalypt plantation sawlogs on the Gippsland Plains in southern Victoria: A case study

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Revised manuscript received 25 June 2007

Summary

This case study is based on the growth of a 10-y-old plantation at Bairnsdale in Victoria's East Gippsland. The site is owned by the local water management authority, East Gippsland Water, and contains both a dryland blue gum (*Eucalyptus globulus*) plantation and an irrigated agroforestry trial using municipal wastewater.

The irrigated agroforestry trial consists of three eucalypt species watered by two different sprinkler systems. The set-up costs and the relatively poor recorded growth suggest that this is a very expensive way to grow sawlogs. Observations and growth measurements indicate that spotted gum (*Corymbia maculata*) is a far better agroforestry species than either Sydney blue gum (*E. saligna*) or southern mahogany (*E. botryoides*). From an agricultural viewpoint, this agroforestry trial has provided good shelter and feed for a successful beef cattle venture. Without data to quantify its effect on agricultural productivity, it is difficult to evaluate the trial's overall success.

The dryland blue gum plantation has recorded moderate to poor growth. This result, however, must be viewed in the context of the area receiving 17% less than the long-term average annual rainfall since the plantation was established in 1996. Any continuation of this trend, as forecast by CSIRO predictions of global warming, has potential to further reduce the long-term suitability of what was already a marginal site for this species. The results suggest that it may be wise to limit future blue gum sawlog plantations in this area to sites with long-term rainfall averages of at least 800 mm y^{-1}, and to plant more drought-tolerant species such as sugar gum (*E. cladocalyx*) or spotted gum in the 600–800 mm rainfall zone.

Keywords: plantations; agroforestry; rain; irrigation; waste water; productivity; stem form; log grade; economics; *Eucalyptus globulus*; *Eucalyptus saligna*; *Eucalyptus botryoides*; *Corymbia maculata*; Gippsland

Introduction

The viability of producing eucalypt hardwood sawlogs from plantations is currently receiving considerable attention due to the timber industry's reduced access to public native forests. Most research, however, appears to be focused on wood quality issues rather than on the economic viability of sawlog production.

There are essentially two streams of hardwood sawlog plantation establishment — small-scale farm forestry plantings by individual landowners, and corporate plantation development on a much larger scale involving considerable expenditure to acquire suitable land.

On appropriate sites, farm forestry has greater potential to be economically viable, as land is freely available and landowners can use their own labour to reduce expenses. Conversely, the high external cost of land and labour over long sawlog rotations creates an inherent viability gap for corporate plantation development. Whilst this may eventually be helped by developing markets for environmental services and carbon sequestration, other financial impediments continue to make eucalypt sawlog plantation ventures unattractive (Kelly 2005).

The case study outlined in this paper is closer to the farm forestry model although the land is owned by a regional water authority, East Gippsland Water (EGW). It differs from traditional farm forestry, however, because the landowner has contributed little time and effort to plantation establishment and management, preferring instead to pay external contractors to undertake these roles. As such, the plantations featured here are arguably similar to those on an increasing number of 'hobby' farms whose owners have high disposable incomes and who are electing to pay for management expertise and services rather than devote significant amounts of their own time and labour.

East Gippsland Water and the Bairnsdale plantation

In the past decade, East Gippsland Water has established eucalypt plantations at a number of its wastewater treatment properties to facilitate treated wastewater re-use in accordance with a policy that at that time favoured discharge onto land. The 1996 establishment of a plantation adjacent to the Bairnsdale Treatment Plant was essentially aimed at testing wastewater irrigation methods, tree species and two sawlog management regimes — wide-spaced agroforestry and fully stocked dryland plantations.

It was hoped that the trial would encourage adjacent and nearby landowners to develop their own plantations, thereby increasing the opportunities for re-use of treated wastewater. However, as changes to the treatment process have improved wastewater quality, discharge into adjacent wetlands has since become the preferred means of disposal. While this has not affected the watering of the Bairnsdale plantation, it has effectively removed the option of further wastewater disposal onto land. New irrigated plantations are now unlikely to be established on adjacent properties.

More than half of the Bairnsdale plantation site is unsuited to irrigation due to soil type and slope, and so was used for unwatered dryland plantations. The application of wastewater for irrigation was restricted to flat ground where a widely-spaced agroforestry configuration was tested (see Fig. 1). Whilst irrigated wastewater can dramatically increase plantation productivity, the Bairnsdale site is considered to be marginal for dryland sawlog production due to a number of factors:

- **Rainfall** — close to 700 mm y^{-1} prior to planting in 1996. This is based on the 74-y record of the weather station at the nearby Bairnsdale Post Office (about 3 km from the plantation) which recorded annual rainfall averaging 699 mm from 1896 to 1970.
- **Soils** — two distinct land systems are represented on the plantation site. The Red Gum Plains soil type on the flat upper ground is characterised by a thin layer of sandy loam overlying hard alluvial gravel with consequent poor drainage and difficult conditions for root penetration. The natural woodland of forest red gum (*Eucalyptus tereticornis*) that formerly populated these plains is indicative of these difficult conditions. On the slopes falling from the upper flat ground toward the Macleod Morass, the soils change to a deep, well-drained sandy loam that provides much better conditions for root development but has low fertility and reduced water-holding capacity.
- **Wind** — the upper flats that form part of the Gippsland plains, and the adjacent southern slopes, are subject to very strong winds that have proven to be an important consideration for species selection and plantation management.

Whilst soil structure and fertility problems can be addressed to some extent by appropriate plantation establishment techniques, problems with wind and drought are more difficult to manage. Since the plantation was established in 1996, rainfall recorded at the adjacent treatment plant has averaged just 580 mm y^{-1} (17% below average). This highlights the risks inherent to the planting of marginal sites.

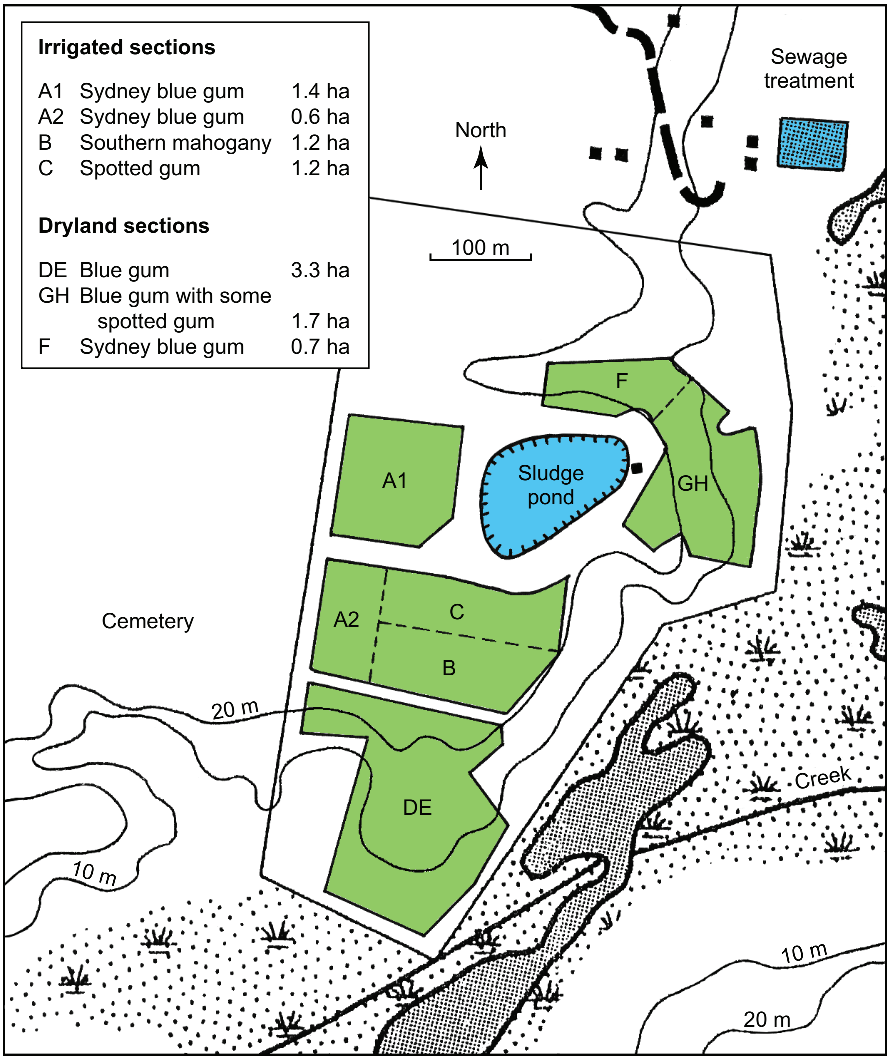

Figure 1. Map of the Bairnsdale plantation owned by East Gippsland Water Corporation

Irrigated agroforestry trial

The irrigated agroforestry trial initially consisted of four species that have grown well under irrigation in other places and appeared to be suited to the East Gippsland climate — Sydney blue gum (*E. saligna*), southern blue gum (*E. globulus*), southern mahogany (*E. botryoides*) and spotted gum (*Corymbia maculata*).

Initially, three irrigation techniques were tested to evaluate their efficiency — fixed micro-sprinklers, larger laterally-moveable sprinklers (of the type often used on sports fields), and a drip-feed system using black poly-tubing. The sprinkler systems were established on the flat upper ground in conjunction with an evenly spaced agroforestry planting configuration at 600 trees ha^{-1}, using three species — Sydney blue gum, spotted gum and southern mahogany (i.e. sections A1, A2, B and C in Fig. 1).

The drip-feed system was established on the most gentle of the southern slopes to water a section of fully stocked (1000 trees ha^{-1}) southern blue gum (part of section DE). It was abandoned within 2 y, however, because of repeated blockages that made consequent demands on the time of EGW staff, and because of physical damage to the poly-piping by sheep that were introduced to graze the site 12 months after planting. The sheep had minimal effect on sprinkler infrastructure in adjacent agroforestry sections.

As a result of the abandonment of the drip-feed system, irrigation with wastewater has been restricted since 2 y after planting to the 4.4 ha of wide-spaced agroforestry plantings of three species on the flat upper ground (sections A1, A2, B and C in Fig. 1).

Only the 1.4 ha area of Sydney blue gum (section A1), irrigated with fixed under-tree sprinklers, has been watered consistently due to the ease of operation of a system that requires activating just one lever to deliver water evenly across the site. Detailed records kept in the first 5 y after planting show that this section was supplied with an extra 500 mm of rainfall equivalent per annum. As natural rainfall during this period was down by an average of 125 mm y^{-1}, section A1 received water (rainfall + wastewater) equivalent to 1075 mm y^{-1} during its first 5 y.

The remaining 3 ha (sections A2, B and C) have been watered in a more ad hoc and uneven manner consistent with a system that required time and considerable effort to move sprinklers periodically within the plantation to ensure an even application of water. Detailed records kept in the first 5 y after planting show that these sections were supplied with about an extra 300 mm of rainfall equivalent per annum. Taking account of the deficit in natural rainfall during this period, these sections received water (rainfall + wastewater) equivalent to 875 mm y^{-1} during their first 5 y.

Recognising their far greater effectiveness, EGW installed additional fixed under-tree sprinklers about 6 y after planting. These water parts of sections B and C and have greatly improved the growth of spotted gum in particular.

The costs of installing sprinkler and drip irrigation systems are considerable. Initial estimates from the irrigation supplier and consultant indicated that the materials required for this site would cost \$6500 ha^{-1} for fixed under-tree sprinklers, \$2600 ha^{-1} for moveable lateral sprinklers and \$7150 ha^{-1} for the drip-feed system. In addition the costs of trenching and burying supply mains was estimated at \$12 300, and a further \$2800 was spent on installing an automatic control mechanism to operate the fixed under-tree sprinkler system.

The costs of managing agroforestry plantings are also high regardless of whether or not they are irrigated. At Bairnsdale, despite obtaining seed of reputable wood production provenances, the three agroforestry species have all grown with relatively poor form, which, particularly in the case of southern mahogany and Sydney blue gum, has manifested itself in a general lack of apical dominance and associated heavy side branching. Whether this is totally attributable to a poor choice of provenances is difficult to determine due to the likely effects of site factors such as strong prevailing winds and heavy soils, combined with a wide plant spacing. However, as an unwatered Sydney blue gum section (F) also grew with similar poor form despite closer spacing under conventional stocking (i.e. 1000 ha^{-1}), site conditions may well be the most important factor.

The major implication of this has been the need for considerable expenditure on form and stem pruning so as to give trees the opportunity to develop straight bole lengths for potential sawlog production (Table 1). The need to maintain apical dominance limited pruning to frequent light treatments that, in many trees, allowed large branches to develop higher up the stem. The later removal of these in order to provide logs of adequate length has created large pruning wounds (up to 10 cm wide) that cast considerable doubt on the quality of future sawlogs. In addition, a high proportion of trees exhibited such bad form as to be beyond correction, and this has limited the number of pruned trees and reduced the average length of pruned bole in each section.

Despite the high management expenditure and the benefits of added water, the productivity of trees growing in the irrigated agroforestry sections has been poor in the 10 y since planting. The best performer has been spotted gum, which has grown to a larger average size with better form despite receiving less water than other sections, as well as being injured by severe frost within a year of planting and suffering periodic insect attack.

Southern mahogany has been extremely disappointing. It has grown very slowly with heavy branching and an apparent brittleness that predisposes it to wind damage. It has also suffered badly from insect attacks that have substantially defoliated it on a number of occasions whilst leaving the adjacent spotted gum and southern blue gum relatively untouched.

Whilst Sydney blue gum has generally grown better than southern mahogany, it also has exhibited heavy branching that has limited the number of trees that could be pruned to yield potential sawlogs. Large branches have also predisposed many trees to wind-induced stem splitting.

The nature of agroforestry is that it compromises both wood and agricultural productivity to enable both to co-exist. As such, the planted trees occupy only a portion of the site, thereby considerably limiting wood volume growth per hectare compared with fully stocked plantations. Nevertheless the productivity of these plantings, shown in Table 2, is disappointing, particularly given the high costs incurred in supplying additional water. With

Table 1. Irrigated agroforestry management regime and costs[a]

Year	Operation		Cost ($ ha^{-1})
0	Plantation establishment @ 600 trees ha^{-1}		
	Broadcast spray pasture		43
	Disc pasture		34
	Rip and mound planting lines		172
	Additional broadcast weed control		39
	Pre-plant mound weed control		136
	Plants and planting (including seed costs)		478
	Fertilising		124
		Sub-total	**1026**
0	Irrigation infrastructure installation		**5365**
0	Planning and supervision		**105**
	Pruning and non-commercial thinning		
1	Form pruning		225
2	Stem pruning		350
3	Thinning		100
4	Stem pruning		275
6	Stem pruning		500
8	Stem pruning		100
8	Thinning[b]		1600
		Sub-total	**3150**
	Sundry costs		
1 and 2	Early monitoring		200
Various	Travel and mileage		265
		Sub-total	**465**
		Total	**10 111**

[a]Not all costs have been included. For example, insecticide spraying undertaken in early years, and the later installation of additional fixed under-tree sprinklers in year 6, have been omitted. Many of the costs are estimates as work invoices were not sufficiently detailed to allow an accurate allocation of work to different plantation sections[1].
[b]Thinning in year 8 was undertaken using a fall, chip, mulch and remove method that cost $1600 ha^{-1}. Although cheaper means could have been used, EGW preferred the advantage of removing all material from the site that could otherwise have contributed to soil nutrient build-up (an important consideration in wastewater irrigation) and impeded the access of cattle to grass for grazing.

the benefit of hindsight, overall productivity could have been significantly improved if the whole area had been planted with the most successful species, spotted gum, and fully watered using the most efficient fixed under-tree sprinklers.

It is difficult to evaluate the economic viability of agroforestry systems because it requires valuing both their wood production and agricultural outputs. Presuming a 25-y rotation, the best growth so far measured in this trial (i.e. spotted gum) would produce at best 115 m^3 ha^{-1} of pruned sawlog at final harvest. Unless pruned hardwood plantation sawlogs become very valuable in the future, this level of productivity will not go very far towards recovering the substantial costs of growing them under sprinkler irrigation. It is uncertain whether this substantial shortfall in economic viability can be offset by the co-existing cattle enterprise, but the EGW farm manager has noted that the shelter and shade provided by the trees (Fig. 2) has had a positive effect on stock health and productivity.

Dryland blue gum plantations

The dryland blue gum plantations at Bairnsdale have generally performed better than the adjacent irrigated plantings, despite receiving no additional water and requiring much less management expenditure. This is likely to be because:

- they have been planted at a high stocking (i.e. 1000 stems ha^{-1}) that fully occupies the site, thereby maximising productivity and encouraging better form and self-pruning
- they are growing on soils with better structure for tree root development, that is deep, well drained, sandy loams.

Since their establishment, these plantations have received 17% less-than-expected rainfall, averaging only 580 mm y^{-1}. With the threat of climate change foreshadowing a permanent continuation of lower-than-average rainfall (Pearman 2004), the long-term survival and growth of high-water-use species such as blue gum on already marginal sites becomes questionable.

Table 2. Productivity of irrigated agroforestry plantings at age 10 y

Section and species	All trees				Pruned trees[a]			
	Dbhob[b] (cm)	Height (m)	Merchantable volume[c] (m^3 ha^{-1})	MAI (m^3 ha^{-1})	Number of pruned trees[d] (ha^{-1})	Average pruned log length (m)	Pruned stand volume (m^3 ha^{-1})	Pruned MAI (m^3 ha^{-1})
A1. Sydney blue gum	21.8	15.1	53	5.3	210	3.7	25	2.5
B. Southern mahogany	17.8	12.0	29	2.9	120	3.4	9	0.9
C. Spotted gum	25.0	16.9	88	8.8	230	5.0	46	4.6

[a]Pruned trees have been stem pruned to a height of at least 2 m and up to 6 m. Poor form limited pruning height.
[b]Dbhob = diameter at breast height over bark; MAI = mean annual increment (wood volume)
[c]Merchantable volume = stem volume from stump height at 10 cm above ground to point where log SED = 10 cm
[d]More trees than just the pruned trees are present on the agroforestry sections so as to facilitate wastewater disposal — average total stockings are 280–350 trees ha^{-1}. However, the pruned target trees have been given space to maximise their growth by the removal of neighbouring trees.

[1] Cost estimates for plantation establishment and management, including the installation of irrigation infrastructure, were determined from cost records supplied in 2004 by East Gippsland Water Corporation, PO Box 52, Bairnsdale, Victoria 3875, Australia.

On this site, a program of gradual non-commercial thinning to reduce stocking has given potential final-crop trees greater access to the available soil moisture. This has also provided growing space to enable them to reach sawlog size as soon as possible. This approach fits with recent plantation wood quality research indicating that short, fat sawlogs grown at low stockings are preferable to those from taller, slender trees produced under higher stockings (Washusen *et al.* 2004).

In other parts of Victoria, blue gum sawlog plantations are being heavily pruned and non-commercially thinned down to low final stockings of 150 stems ha^{-1} by year 4 or 5, but here there has been a more gradual stocking reduction. This has:

- reduced costs by taking advantage of the natural self-pruning capability of the species if higher stocking is maintained for longer (some limited pruning has been done along plantation fringes where greater light exposure hampers self-pruning)
- reduced the potential for wind damage which increases when stands are suddenly opened up, particularly on exposed sites such as the southern slopes of this plantation (i.e. section DE)
- staggered the build-up of potential wildfire fuel that results from concentrated non-commercial thinning and pruning.

This strategy also retains the opportunity to conduct later commercial thinnings for firewood or pulp. In this case, however, the 5 ha of dryland blue gum is likely to be too small and too distant from processors for pulpwood thinning, whilst occupational health and safety concerns have thus far prevented EGW from allowing firewood thinning.

Non-commercial thinning has so far been undertaken in two stages (at ages 5 and 8 y) using stem injection with RoundUp in accordance with specifications developed for thinning dense natural regrowth (Sebire 1997). Compared to mechanical thinning, herbicide stem injection is safer, quicker and less expensive, and results in a more gradual opening up of the stand as trees take several months to die, and may then stand for a number of years before falling over. However, its use carries a risk of 'flashback' onto non-target trees unless injected herbicide doses are carefully regulated. Some retained trees in this plantation have been adversely affected by flashback, particularly in section GH. Although relatively few have been killed outright, many affected trees have been substantially weakened and may eventually succumb in the future. The experience here suggests that the risk of flashback increases with the age of the trees, presumably because higher doses of herbicide are required.

Whereas the more intensive early pruning and thinning regimes being used in north-eastern Victorian blue gum sawlog plantations are costing around \$2000 ha^{-1}, the regime used in these dryland plantations cost \$290 ha^{-1} to year 8 (Table 3), with a subsequent further light thinning required in the near future. This significant cost advantage is offset to some degree by the untidy state of the plantation for a considerable period (Fig. 3), plus the possibility that reliance on natural stem pruning will translate into sawlogs of lower quality. This will not be confirmed until harvesting and processing some 25–30 y into the future.

The growth rate of these plantations is significantly less than the 16–20 m^3 ha^{-1} y^{-1} predicted for unthinned short-rotation (10–15 y) blue gum plantations in this area (Borschmann *et al.* 2000). However, as regional productivity estimates were based on long-term average rainfall that has not been realised since the site was planted, a return to average seasons would presumably close the gap between actual and estimated productivity. In addition, the adoption of a non-commercial thinning regime has lowered productivity by reducing the level of site occupancy compared to that of an unthinned plantation.

Discussion

There is little to be gained from comparing the growth of the irrigated agroforestry and dryland sections of the plantation

Figure 2. Spotted gum agroforestry planting at age 8 y

Table 3. Blue gum dryland plantation management regime and costs[a]

Year	Operation	Cost ($ ha^{-1})
0 and 1	Plantation establishment @ 1000 trees ha^{-1}	
	Broadcast spray pasture	43
	Disc pasture	112
	Rip and mound planting lines	287
	Pre- and post-planting mound weed control	246
	Plants, planting, replanting (including seed costs)	700
	Fertilising	186
	Sub-total	**1574**
0	Planning and supervision	**105**
	Pruning and non-commercial thinning	
5	Thinning by stem injection	100
8	Light stem pruning of edge trees	90
8	Thinning by stem injection	100
	Sub-total	**290**
	Sundry costs	
1 and 2	Early monitoring	200
Various	Travel and mileage	265
	Sub-total	**465**
	Total	**2434**

[a]Not all costs have been included. Omitted costs include insecticide spraying undertaken in early years, sprinkler irrigation of section GH during the very dry summer of 1997–1998, and the costs of annually monitoring plantation growth. Many of the costs are estimates as work invoices were not sufficiently detailed to allow an accurate allocation of work to different plantation sections[1].

Figure 3. Blue gum at age 8 y (section GH) —the stand has an untidy appearance whilst natural self-pruning slowly occurs and dead poisoned trees remain standing

because they consist of different species growing on very different soil types under different water availability and management regimes.

Irrigated agroforestry sections

Agroforestry is by definition a compromise between agriculture and forestry, so very high timber productivity is not to be expected. Nevertheless, with the amount of water provided, these sections have underperformed — presumably for the following reasons:

- the sub-optimal soil structure of the planting site — a shallow sandy loam underlain by hard gravelly sub-soil not ideal for either tree growth or irrigation
- the use of sub-optimal species — most notably southern mahogany, but also Sydney blue gum which has displayed very poor form and heavy branching. The far better performance of spotted gum highlights the shortcomings of the other two species. The irrigated section would be far more productive if its whole area had been planted to spotted gum.
- differing irrigation techniques — the areas watered with lateral hand-shift sprinklers have received less water than those watered with fixed under-tree sprinklers which are more convenient to operate
- higher-than-necessary retained stocking including many unproductive trees that are to an extent competing with good quality pruned trees. The former have been retained to fill gaps and optimise waste-water re-use, which is a competing aim of the planting.

As this was a trial planting it is hardly surprising that sub-optimal practices have been identified. The project does provide some valuable lessons for future agroforestry plantings.

Many eucalypt species are unsuited to wide-spaced agroforestry as it is inconsistent with natural regeneration featuring dense initial stocking that promotes height growth and limits side branch development. In this trial, Sydney blue gum and southern mahogany have had problems of form and heavy branching that suggest they are unsuitable for agroforestry. Further to this, southern mahogany has shown a brittleness and susceptibility to wind damage that make it risky for commercial plantings, except perhaps on very sheltered sites.

Spotted gum, on the other hand, has grown with much finer branching even when widely spaced, and although there is often a need to correct poor stem form it seems better suited to agroforestry provided there is sufficient rainfall.

The trial has shown that wide-spaced planting, such as the 5 m × 7 m grid used here, does not foster good tree form. A better option may be to plant trees very densely in widely spaced corridors to promote good form and reduce branch size, before eventually thinning out the poorer trees to create a low stocking of good trees. This would entail higher initial establishment costs due to a greater number of trees being planted, but that could well be offset by lower pruning costs and far better individual tree productivity.

Agroforestry establishment could be considerably cheaper if conventional plantation establishment techniques were replaced by cheaper alternatives such

Table 4. Productivity of dryland blue gum plantations at age 10 y

Section / species	Average tree growth		Stocking (trees ha^{-1})	Merchantable volume[a] (m^3 ha^{-1})	MAI at age 10 (m^3 ha^{-1})
	Dbhob (cm)	Height (m)			
DE Blue gum	21.3	16.6	300	79	7.9
GH Blue gum	19.7	15.3	400	67	6.7
Year 10 — weighted average[b]	20.8	16.0	335	75	7.5

[a]Merchantable volume = stem volume from stump height at 10 cm above ground to point where log SED = 10 cm
[b]Weighted average takes account of the greater area of section DE (3.3 ha) compared to section GH (1.7 ha)

as direct seeding, whilst management costs could be minimised by using only proven species and provenances that naturally grow with good form and small branching.

Dryland commercial forestry sections

It is easier to benchmark the growth of dryland plantations because predictions of regional blue gum growth have been available for some years. For the locality of this plantation, the Bureau of Rural Sciences' 1996 predictive plantation productivity map forecast a growth rate of 16–20 m^3 ha^{-1} y^{-1} based on average rainfall and a fully stocked pulpwood regime over 10–15 y.

That the actual growth rate of this plantation averages just 7.5 m^3 ha^{-1} y^{-1} after 10 y (Table 4) suggests that it has substantially underperformed. The following factors go some way to explaining what has occurred:

- since planting, the plantation has received significantly less rainfall than the long-term average of around 700 mm y^{-1}; the 580 mm y^{-1} received is 17% less than expected and significantly less than what is generally considered the minimum for blue gum
- in view of this, the plantation's continuing health may be attributable to the progressive reduction of stocking that has minimised between-tree competition for moisture
- progressive thinning has undoubtedly also reduced growth rates by reducing site occupancy for substantial periods — this is a departure from the stand conditions envisaged in the growth predictions, which were based on maintaining full stocking for at least 10 y
- the relatively poor form and vigour of the blue gum provenance initially planted has also been a factor — this is starkly apparent because different planting stock used to fill gaps caused by early mortality has grown with substantially better form.

The Bureau of Rural Sciences' predictions are now widely regarded as overly optimistic and may be revised downwards in the future, particularly given the now greater certainty about climate change.

Efforts have been made to reduce the very high cost of non-commercial thinning and pruning that is associated with conventional management of eucalypt sawlog plantations. Typically this results in plantations, initially established at 1000 stems ha^{-1}, being thinned down to 150 stems ha^{-1} and pruned to 6 m by about age 5 y. This often costs around \$2000 ha^{-1}, which exceeds the initial establishment cost.

When planted at 1000 stems ha^{-1}, blue gum is a good natural self-pruner. If left long enough at a high stocking, this characteristic can be capitalised upon to significantly reduce the cost of pruning. When this trial was planned, it was expected that gently and progressively reducing plantation stocking over an extended period would maintain high growth rates and encourage height growth (i.e. longer sawlogs), while herbicide stem injection would be safer and cheaper than conventional mechanised non-commercial thinning.

The management of these dryland sections has indeed been considerably cheaper than conventional methods because only limited pruning has been required around plantation edges.

The effectiveness of this strategy has been constrained somewhat because the blue gum provenance used here has often grown with poor form and failed to shed its branches as well as would be expected. In addition, chemical thinning has not always been effective. Many treated trees remain alive, albeit mostly in a sickly state, and flash-back onto adjacent non-target trees has been significant in some places. There remains a need to reduce the stocking of dryland sections down to about 200 stems ha^{-1} in order to limit between-tree competition for moisture and further concentrate growth onto the best stems.

Chemical thinning was also undertaken in a small area of Sydney blue gum (section F) which proved to be more resistant and harder to kill than blue gum (*E. globulus*).

Conclusions

It is unwise to draw strong conclusions from any one case study. Nevertheless, the Bairnsdale plantation experience adds to the body of information accumulating from other cases and more formal studies, particularly with regard to agroforestry and the use of irrigated wastewater.

Irrigated agroforestry

The experience at Bairnsdale suggests that irrigated agroforestry is a very expensive way of producing wood. At this plantation, wood production is only one of three aims — the others being to beneficially reuse treated wastewater and to enhance on-going agricultural production. Both of these are being achieved but are difficult to quantify in economic terms.

The costs of installing, maintaining and operating sprinkler irrigation systems are very high. It is unlikely that the delivery of extra water to eucalypts in this manner could ever be economically justifiable in its own right unless the value of pruned hardwood sawlogs rises dramatically, or if growers become timber processors so as to maximise the value-added benefit of potentially high sawn timber recoveries.

Of the three watering methods tried here, fixed under-tree sprinklers have worked best because they are far more convenient to operate than lateral hand-shift sprinklers, and they have fewer maintenance issues than drip-feed systems.

The likelihood of low timber productivity from wide-spaced agroforestry stands highlights the importance of minimising costs which seem otherwise unlikely to be recovered by even the combined value of wood and agricultural production.

Dryland plantations

The dryland blue gum plantings at Bairnsdale are representative of many small farm forestry plantings established on sub-optimal sites in the 650–750 mm y^{-1} rainfall zone under Victorian government subsidy schemes during the past decade.

The trial has provided some valuable lessons about chemical thinning, such as that blue gum (*E. globulus*) is more sensitive to herbicide treatments than Sydney blue gum (*E. saligna*). The greater sensitivity of blue gum translates to a much higher risk of flash-back on adjacent non-target trees and dictates that substantial care needs to be exercised, particularly as the trees age. In this trial, flash-back was far more evident from the year 8 treatment than from the year 5 treatment. This could be due to poor stem injecting technique such as over-dosing, or to greater prevalence of inter-locking root systems — in any event, it suggests greater caution is needed when using this technique beyond year 5.

The measured dryland plantation growth at Bairnsdale must be considered in the context of the 17% decline in annual rainfall since planting compared to the long-term rainfall average. Most Victorian farm forestry plantings will have suffered similarly. The CSIRO has predicted that reduced precipitation will continue due to global warming, with annual rainfall averages in southern Victoria in 2030 expected to be 15% lower than 1990 long-term averages (CSIRO 2001). If this eventuates, sites that are currently marginal for high-water-using species such as blue gum are likely to become unsuitable over the long 25–30 y rotations required to produce sawlogs.

At least in East Gippsland, it may be prudent to limit future blue gum sawlog plantations to areas with current long-term annual rainfall averaging at least 800 mm, whilst using more drought-tolerant species in lower-rainfall areas. Species such as sugar gum (*E. cladocalyx*) and spotted gum planted on sites with long-term average rainfalls of 600–800 mm y^{-1} will be capable of continued survival and reasonable growth if the prediction of prolonged lower rainfall materialises. However, it is likely that the sawlog productivity of plantations of these species will be much lower than previous expectations based on using blue gum.

Current growth rates suggest that if the Bairnsdale dryland plantations survive the anticipated drier conditions, they are likely to produce, at best, around 115 m^3 of sawlog ha^{-1} over a 25–30 y rotation. There is considerable uncertainty as to whether this will be sufficient to ensure recovery of the costs of establishment and management discounted over the rotation, plus a worthwhile grower profit. Economic analyses of growing hardwood sawlogs have shown that long-term returns are very sensitive to log price, rotation length, land acquisition costs and site productivity — all of which carry a high degree of uncertainty. A mean annual increment (MAI) at age 10 y of at least 20–25 m^3 ha^{-1} is thought necessary to ensure profitable corporate investment (Nolan *et al.* 2005).

Lower dryland plantation productivities are more likely to be economically viable under farm forestry systems where landowners reduce external costs by self-planting their own land.

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