Effects of thinning and coppice control on stand productivity and structure in a silvertop ash (*Eucalyptus sieberi* L.Johnson) forest

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Summary

The effects of commercial thinning on stand structure and productivity were investigated in a 28-y-old stand of silvertop ash (*Eucalyptus sieberi*) near Orbost, Victoria. Thinning reduced basal area by 40–50% in treated areas and stocking from about 1400 to 250 merchantable stems ha^{-1}.

Replicated experimental plots were established in unthinned, thinned-only, and thinned and coppice-treated forest to measure the effects of thinning and coppice competition on the growth of retained trees. Stand basal area increments averaged 1.76 m^2 ha^{-1} y^{-1} and thinning did not significantly reduce stand basal area increment even in the first year after treatment. Over the 6 y of measurement, the relative basal area growth in thinned-only forest was 47–67% higher than in unthinned forest, and in thinned and coppice-treated forest basal area increases were 60–89% greater than in unthinned (a further 15–23% over thinned-only).

Basal area increment for the potential sawlog trees (the largest 150 stems ha^{-1}) in thinned-only forest exceeded basal area increment of potential sawlogs in unthinned forest by 40–60%. In forest where coppice competition was removed, growth rates were increased by a further 15–20% in all years. Smaller trees retained in thinned forest (potential pulpwood for a second thinning) grew 69% faster than similarly-sized trees in unthinned forest, and removal of coppice competition increased this response by a further 38%. Competition from coppice regeneration developing on cut stumps reduced potential basal area growth of retained trees by about 20% in all years following thinning. Coppice contributed extra basal area to the stand (from 0.7 m^2 ha^{-1} y^{-1} in the first year after thinning to 1.3 m^2 ha^{-1} y^{-1} in the sixth year). After 6 y, coppice regeneration from cut stumps persisted in thinned-only forest (but declined from 1100 to 500 coppice stems ha^{-1}) and contributed about 16% of total basal area, but less than 1% in volume.

Keywords: thinning; coppice; responses; growth increment; yields; silviculture; *Eucalyptus sieberi*

Introduction

Most of the eucalypt species comprising Australia's wood production forests are inherently productive (mean annual increments (MAIs) range from 10 to 20 m^3 ha^{-1} over a rotation of about 60 y) when growing in well stocked stands on sites of reasonable fertility (West and Mattay 1993). The commercial productivity of regrowth eucalypt stands, however, is usually restricted by over- or under-stocking, nutrient limitations, or soil water deficit. In regrowth forests dedicated primarily to wood production most of these constraints can be ameliorated by silvicultural treatment (Connell *et al*. 2001).

Stand density can be manipulated at the time of natural regeneration by control of seeding rates (Raison *et al*. 1995), by non-commercial thinning of young regrowth, or by commercial thinning at a later age. Commercial thinning provides a financial return and is also beneficial in accelerating growth of high quality or high value sawlogs (Horne and Robinson 1990; Flinn and Mamers 1991; Brown 1995; Connell *et al*. 1997). Fertiliser application provides the potential to further increase production of both pulpwood and sawlogs (Connell and Raison 1996). A review of literature (Connell and Kellas 2001) showed that growth of dominant trees in regrowth stands is generally accelerated by spacing and thinning.

The factors affecting the variability and longevity of stand responses to silvicultural treatment are not well understood. This uncertainty relates primarily to the extent to which nutrition and water availability to retained trees are increased, and to stand dynamics including the development of competing coppice or understorey vegetation (Henry 1960; Goodwin 1990; West 1991). Coppice response is quite variable, depending on the tree species and on the age and season of harvesting (Hoare 1993). The vigour of competing coppice stems will be linked to their access to soil resources through their parent stump. The competitive effect of coppice (and other vegetation) in stands may be increased by fertiliser application.

There are relatively few studies that have quantified the long-term responses to thinning in regrowth forests, and no studies investigated the magnitude or longevity of competition from coppice regeneration following thinning. This information, however, is critical to the economic assessment of the benefits of thinning operations. The study reported here was established to provide data on long-term thinning responses and effects of coppice competition on the growth of the retained sawlog trees in regrowth stands of silvertop ash (*Eucalyptus sieberi* L.Johnson) forest, in East Gippsland. Early growth responses (6 y post thinning) to treatments are reported.

Methods

Study area

The study is located at Towser Creek in East Gippsland, Victoria, in a stand of almost pure, pole-sized *E. sieberi* growing in the coastal foothills about 40 km east of Orbost. The stand was naturally regenerated following harvesting and burning in 1963 and was 28 y old at the commencement of the experiment. The original overstorey supplied the seed source and created the typically very dense 'wheatfield' regeneration found in ash eucalypt forests. Residual overstorey trees were killed during the early growth of the new stand using Tordon® herbicide.

The site is located on fertile gradational soils in a high rainfall area (>1000 mm y^{-1}). Rainfall in this area of East Gippsland is distributed evenly throughout the year (Connell and Raison 1996), allowing year-round growth of trees in most years. However, periods of reduced summer rainfall combined with higher temperatures can result in periods of little or no growth.

Experimental design

Areas of uniform stand structure, size class distribution and basal area were chosen for the experiment. Within the selected areas, four replicates of three treatments were established using a randomised block design. Treatments were unthinned, thinned without control of coppice, and thinned with control of coppice. Blocking was based on initial basal area which also reflected tree size class distribution and slope position. Plots (0.16 ha, usually 40 m x 40 m) were established containing 400–500 stems 5–65 cm diameter at breast height over bark (dbhob). In each experimental plot about 45 of the largest potential sawlog trees (about 250 stems ha^{-1}) were selected and marked for retention on the basis of dominance, form, crown vigour, bole length, and spacing relative to other potential sawlog trees. Tree marking and identification was also carried out in unthinned plots identifying a subset of trees (selected trees) the growth of which could be compared with that of retained trees (retained trees) in thinned plots. Prior to commercial thinning the basal area (BA) in each plot was calculated and selections were adjusted if necessary to provide a BA reduction of a nominal 50%.

Thinning

Eight randomly selected plots were commercially thinned with a Waratah grapple harvester following operational guidelines (Dept of Conservation and Environment 1992) in late April (autumn) 1992. Outrows (4–5 m wide) were used to facilitate felling and extraction using a rubber-tyred forwarder. Trees were topped and debarked in the forest, and crowns, branches and bark were redistributed over the soil and litter surface. In thinned plots all non-merchantable stems (<15 cm dbhob) were culled to waste.

Coppice control

Four of the thinned plots were randomly selected for thinning and culling of coppice regeneration. Coppice control was not required for the first few months. In late spring 1992, when most coppice shoots had become established on the cut stump, the shoots were broken or cut off at the point of attachment. Following this initial treatment, large plastic bags were fitted tightly over the cut and treated stumps and secured with strong twine to restrict the development of new coppice shoots. Chemical treatment was not applied as it could have affected the growth of surrounding trees if they were connected through root grafts.

Tree measurements

Stand BA was estimated using steel tape measurements of dbhob of all trees within the plots. Average tree height and average crown length were estimated for each plot, from five of the larger-diameter co-dominant trees per plot, using a clinometer.

Following treatment allocation, merchantable-sized trees (>15 cm dbhob) on all plots were numbered and had loose outer bark at breast height removed to create a smooth surface to facilitate accurate measurement of diameter change over time. Dendrometer bands were fitted to a representative sample of trees across treatments to monitor the seasonal and temporal pattern of bole growth. Within treatments, 3–4 trees of each of the pre-thinning dominance strata (suppressed, co-dominant and dominant trees) were banded. These classes represented the range of potential sawlog and pulpwood trees for future harvest. Dendrometer bands were read at times corresponding to the end of summer and winter periods, and following short-term dry and wet periods, for 5 y. Heights of selected trees and dbhob were measured annually in the winter months. Data sets for each plot were analysed either as the contribution of all merchantable trees in unthinned plots (unthinned stand), or as subsets (see Table 1) based on about 250 retained trees ha^{-1} in thinned plots (retained trees), the about 250 marked trees in unthinned plots (selected trees), or the largest 150 potential sawlog trees ha^{-1} (potential sawlogs) in thinned or unthinned plots.

Very few smaller trees (less than 15 cm dbhob) in unthinned plots grew sufficiently to be included in merchantable size classes during the study period; they made almost no contribution to stand increment and were therefore not included in calculations of basal area and volume increment. During annual measurements, unlabelled suppressed trees around 13–14 cm in diameter were measured to see if they had attained merchantable size during the growth period. In unthinned forest some 500 small-diameter suppressed trees ha^{-1} contributed less than 4% to initial total BA,

Table 1. Stand elements used in analysis of growth at Towser Creek

Stand elements	Description
Merchantable trees	All trees >15 cm dbhob and utilisable for conversion to woodchips during thinning
Non-merchantable trees	All trees <15 cm dbhob
Unthinned stand	All merchantable trees in unthinned plots
Selected trees	Marked trees in unthinned plots which would have been retained if the plot had been thinned (about 250 trees ha^{-1})
Retained trees	All trees retained in a thinned plot (about 250 trees ha^{-1})
Potential sawlog trees	Largest 150 trees ha^{-1} of Selected trees (unthinned plots) or Retained trees (thinned plots)

and during the 6-y measurement period trees that did eventually grow into the >15 cm diameter class contributed less than 1 m^3 ha^{-1} in total to merchantable production (<0.25%).

Coppice stems in thinned-only plots were measured during the winter months in 1994, 1996, 1997 and 1998. Diameters (dbhob) were recorded for each coppice stem measured but stems were not individually identified.

Estimation of merchantable volume

The volume equations for *E. sieberi* developed by Bi and Hamilton (1998) which calculate underbark volume from dbhob, tree height and a stem quotient reflecting diameter over bark at 4.5 m, were used to estimate total volume of individual trees using measurements of individual dbhob and average plot tree height for each plot. As average tree height (and therefore height increment) was estimated from larger-diameter trees there was no usable relationship ($r^2 < 0.15$) to estimate height of each individual tree in a plot. Merchantable volume was estimated by subtracting estimated woody crown volume calculated from average crown length. The woody stem component of the crown of these pole-shaped trees was assumed to be conical and to be the major woody component of the crown. The stem diameter at the base of the crown was found to be variable, both between trees of similar diameter class and between trees of similar height, and ranged from 10 to 15 cm over bark in this forest. For calculation purposes the diameter overbark at the assumed 'base' of the crown was taken as 13 cm as this corresponds to the small-end diameter of pieces (billets for pulpwood) that are processed by machinery during thinning operations. Processing heads can remove small branches at the base of the crown to facilitate stem processing down to a diameter of 13 cm even on larger trees. The resultant estimate of merchantable volume was regarded as a sufficient approximation for comparison of plot volume responses, assuming little change in crown volume and extension due to treatment which would affect crown calculations. For all plots total merchantable volume (expressed in m^3) was calculated as the sum of estimated merchantable volume for all individual trees:

$$\text{tree merchantable volume} = a(d^2h) - b(d^2h^2) + c(h) - e(h-g)\ ,$$

where $a = 0.2178 \times 10^{-4}$; $b = 0.2000 \times 10^{-7}$;
$c = 0.4000 \times 10^{-3}$; d = dbhob in cm;
$e = 0.2619 \times 10^{-2}$ (a factor for volume in the upper crown);
g = average crown depth in m; h = average tree height in m.

Prior to thinning, average height of each plot was determined from five healthy dominant or co-dominant trees within the plot; plot averages were 29–35 m. Very few trees were dominants; co-domination was a feature of this evenly structured regrowth, trees of the mid- to upper size classes (>20 cm) having similar heights. Standing merchantable volume in unthinned forest was estimated at 221–255 m^3 ha^{-1}, and about 85–100 m^3 ha^{-1} of merchantable pulpwood was harvested during thinning operations.

Effects of fertiliser addition in a demonstration plot

Fertiliser (nitrogen at 100 kg N ha^{-1} as ammonium sulphate and phosphorus at 100 kg P ha^{-1} as single superphosphate) was broadcast by hand on an area (792 m^2) of the operationally thinned forest at Towser Creek to examine responses of coppice regeneration and retained trees to enhanced nutrition. All trees and coppice stems were measured in the same manner as in the main experiment.

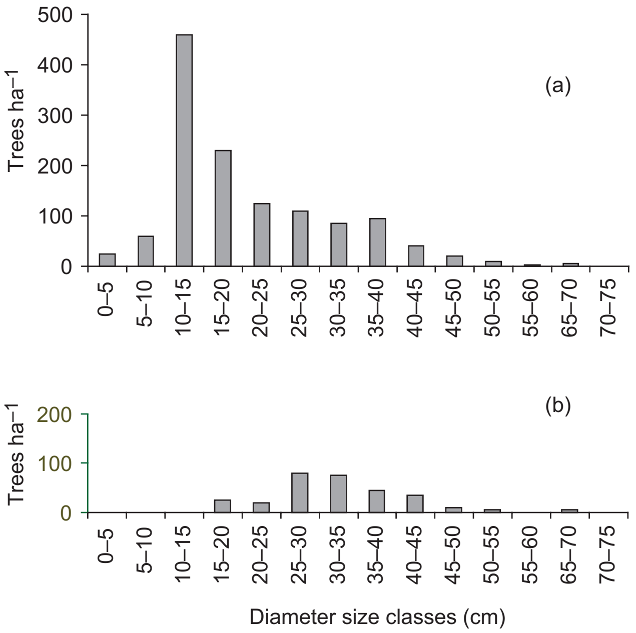

Figure 1. Distributions of stems of 28-y-old *E. sieberi* regrowth, (a) unthinned, and (b) thinned, in diameter classes

Results

Initial stand characteristics for unthinned and thinned forest

Although plots were dominated by *E. sieberi*, most plots had a small component of brown stringybark (*Eucalyptus baxteri* (Benth.) Maiden and Blakely) and/or white stringybark (*Eucalyptus globoidea* Blakely) as associate overstorey species. Prior to thinning, the natural forest contained about 3000 stems ha^{-1}, ranging in diameter from 5 to 65 cm dbhob (Fig. 1a). About 1400 stems ha^{-1} were of merchantable size, giving a mean merchantable basal area of 37.5 m^2 ha^{-1} (SE = 1.2, n = 12) with a mean tree diameter of about 24 cm. Individual plots contained about 110 merchantable stems. Total BA (merchantable and non-merchantable trees) ranged from 32.6 to 45.7 m^2 ha^{-1}.

Thinning reduced stand BA by around 40–50% and the number of stems to about 250 ha^{-1}. After thinning, experimental plots contained about 45 trees each with a diameter range of 20–50 cm, and a mean diameter of about 28 cm. Thinned forest had a mean BA for retained trees of 21.1 m^2 ha^{-1} (SE = 0.2, n = 8). Thinning markedly affected size class distribution, and resulted in most stems being within size classes 25 cm and above (Fig. 1b).

Merchantable basal area response to thinning and coppice treatment

Six years after thinning, unthinned, thinned-only, and thinned and coppice-treated forest had basal areas of 44.9 (SE = 1.5), 28.8 (0.5) and 29.3 (0.5) m^2 ha^{-1}, respectively. Tree size class distribution in

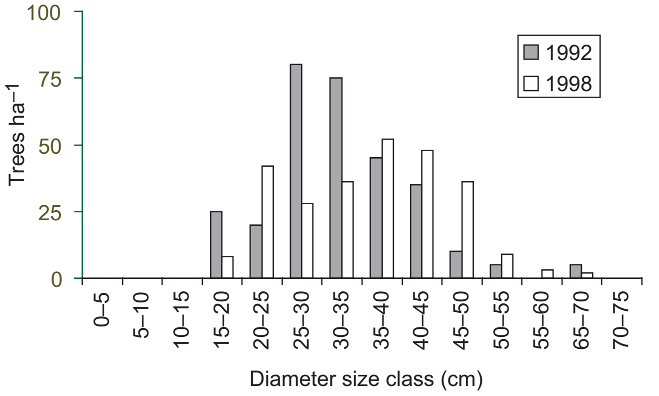

Figure 2. Distributions of stems of *E.sieberi* in diameter classes immediately after thinning and 6 y later (thinned-only treatment)

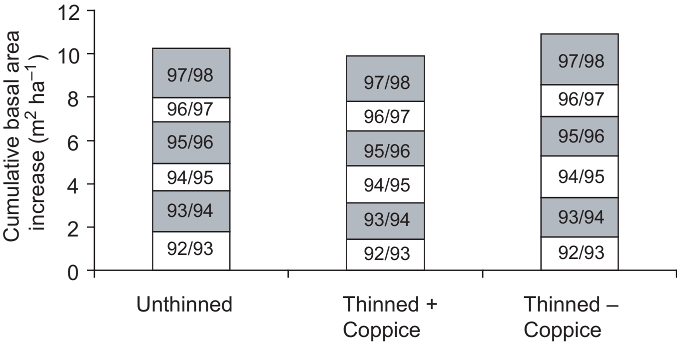

Figure 3. Stand basal area increments of *E. sieberi* — all trees in the unthinned treatment, and for retained stems in the two thinned treatments (with and without coppice), over 6 y following treatment (each annual band is a mean of 4 plots and all SEs are less than 0.13 m^2 ha^{-1})

all thinned plots (Fig. 2) changed over this period, with many more stems now in the 35–40 and 40–45 cm size classes and about 20% of all retained stems in the small sawlog size class (> 44 cm dbhob). Small merchantable trees that were retained in thinned plots to fill large gaps exhibited accelerated diameter growth.

There was no mortality of merchantable or non-merchantable stems in unthinned plots. However, growth of stems in smaller merchantable size classes was very small in unthinned forest due to suppression by dominant and co-dominant trees. Very few non-merchantable trees grew sufficiently to enter merchantable size classes. Small trees (<15 cm dbhob) generally contributed < 1% of total stand basal area and < 0.1% of basal area increment.

Responses in basal area growth to thinning treatments were variable in the first 2 y following treatment. The BA increment of thinned plots ranged from 40% less, to 2% more, than that of the unthinned plots in the same replication. Mean total BA increment of thinned forest was less than that of unthinned forest in the first, second and fourth years following treatment. Averaged over the 6 y of the study, mean total BA growth was similar in all treatments (Fig. 3), with indications that coppice competition lowered total BA growth in thinned untreated areas (1.82 ± 0.22, 1.65 ± 0.10 and 1.82 ± 0.13 m^2 ha^{-1} y^{-1} for unthinned, thinned-only, and thinned and coppice-treated, respectively).

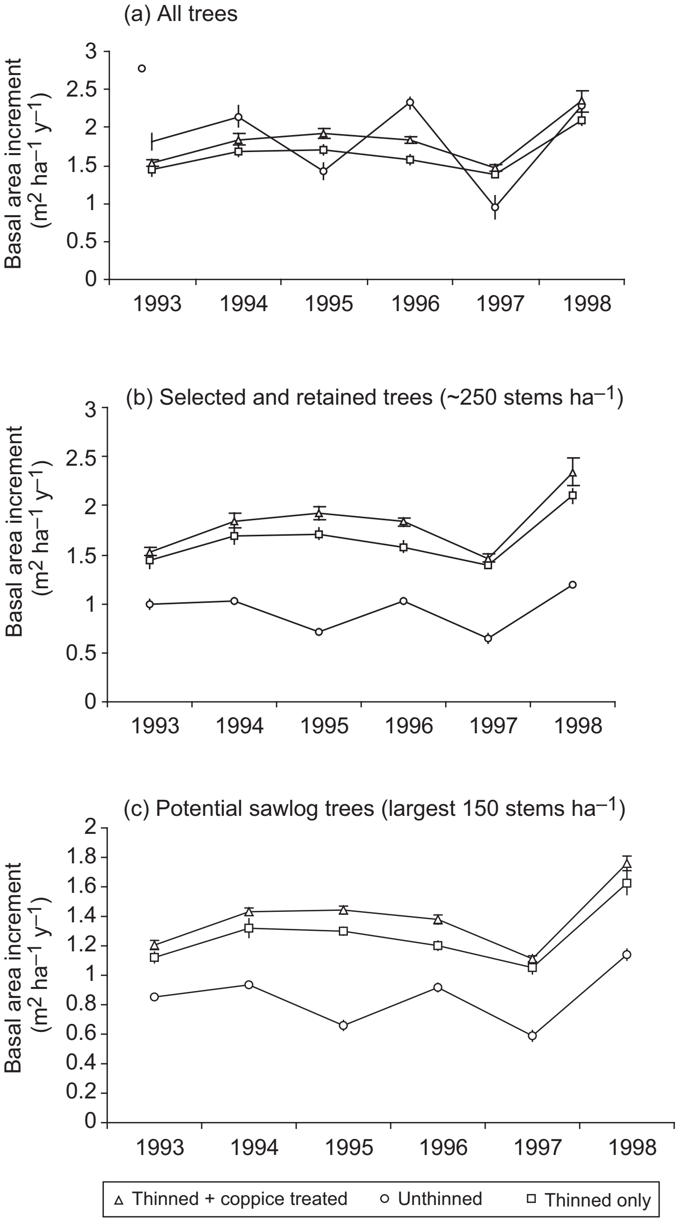

Figure 4. Annual (May–April) basal area increments for (a) all trees, (b) selected (unthinned) and retained trees, and (c) potential sawlog trees, for 6 y after thinning and coppice treatment (the SEs are often too small to appear)

When only the 250 selected trees in unthinned forest were compared to retained trees in the thinned-only forest, BA growth in the latter exceeded ($P < 0.01$) that in unthinned forest by more than 44% in all years (Fig. 4). Basal area growth of potential sawlog trees in thinned-only and thinned coppice-treated forest exceeded ($P < 0.01$) that of potential sawlogs in unthinned forest by 40–60% and 60–80% in all years, respectively. After 6 y, trees in thinned forest continued to show significantly higher BA growth when compared with similar-sized trees in unthinned plots, even in the presence of significant coppice regeneration (Figs 4 and 5).

Assuming that all trees other than the largest 150 will be available for pulpwood harvest (or possibly small sawlogs during a subsequent thinning), it is important to look at the growth of this component of the stand (potential pulpwood). In unthinned forest,

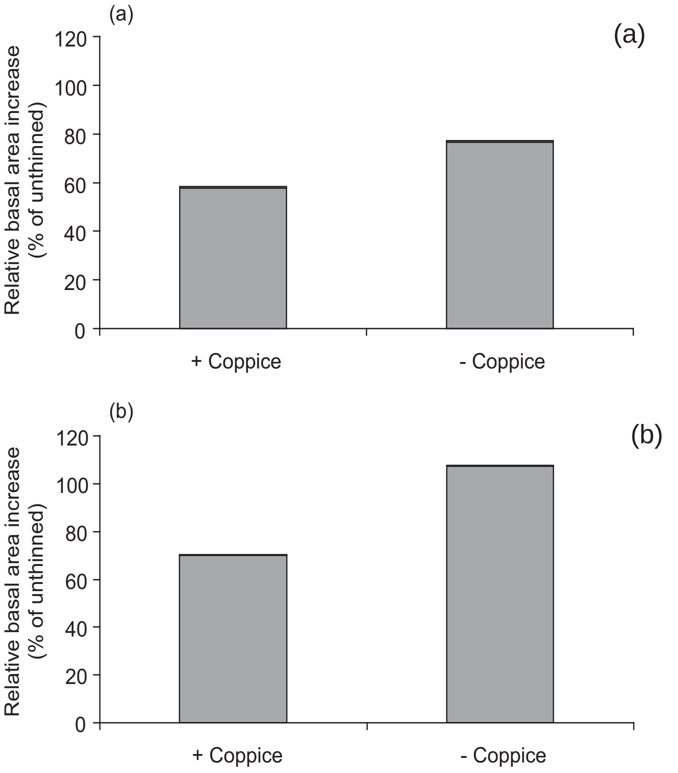

Figure 5. Effect of coppice removal on growth of (a) potential sawlogs and (b) potential pulpwood in thinned *E. sieberi* forest 6 y after thinning (SEs of the ratio approximated using Yates (1960) are too small to be visible)

growth of the smaller trees is limited by competition and very few trees of 15–20 cm diameter exhibited anything but minimal diameter growth. Potential pulpwood in thinned forest (all trees other than the largest 150 ha^{-1}) grew 70% faster than similarly-sized trees in unthinned forest (Fig. 5). With removal of the competition from coppice, a further 37% growth response is achieved — a total of 107% over similar trees in unthinned forest.

Over 6 y, heights have increased by 4–7 m in unthinned and 3–10 m in thinned forest. There were no significant differences in height increment between treatments.

Merchantable volume growth in response to thinning and coppice treatment

Merchantable volume increments (estimated using mean height and crown depth) in all plots were 20–34, 14–25 and 25–36 m^3 ha^{-1} y^{-1} in unthinned , thinned-only and thinned coppice-treated forest, respectively during the 6 y following thinning. Coppice competition reduced ($P < 0.01$) potential volume increment of thinned forest in all years following thinning. Volume increments in thinned-only forest were reduced (compared to unthinned forest) in the first 2 y following thinning, whilst coppice was developing. Merchantable volume increments in thinned forest without coppice competition were always similar to, or in drier years, greater than, increments in unthinned forest. After 6 y, total volume increment in unthinned, thinned-only, and thinned coppice-treated forest was 159, 114 and 172 m^3 ha^{-1}, respectively.

Table 2. Basal area in treatments, and contribution of coppice regeneration to the stand for thinned-only plots, of *E. sieberi* forest at Towser Creek ($n = 4$) for the 1992–1998 measurements (standard errors in brackets)

Treatment and	Year of measurement				
stand components	1992	1994	1996	1997	1998
1. Unthinned overstorey, no coppice					
Overstorey basal area	34.7	38.6	42.4	43.3	45.6
(m^2 ha^{-1})	(1.18)	(1.31)	(1.35)	(1.46)	(1.51)
2. Thinned overstorey, coppice present					
Overstorey basal area	18.8	21.9	25.2	26.6	28.7
(m^2 ha^{-1})	(0.29)	(0.36)	(0.45)	(0.45)	(0.48)
Coppice basal area	0	1.6	3.2	4.2	5.6
(m^2 ha^{-1})	(0)	(0.14)	(0.28)	(0.31)	(0.35)
Overstorey + coppice basal area (m^2 ha^{-1})	18.85	23.56	28.50	30.90	34.34
Coppice contribution					
No. of coppice stems	0	174	129	114	79
plot^{-1} (about 0.16 ha)	(0)	(28)	(18)	(10)	(6)
No. of coppice stems ha^{-1}	0	1087	806	713	494
Basal area increment of coppice (m^2 ha^{-1} period^{-1})		1.58	1.65	1.02	1.34
Coppice as a fraction of total stand BA (%)	0.0	6.7	11.3	13.7	16.3
Coppice as a fraction of total stand volume (%)	0.00	0.00	0.01	0.02	0.04
3. Thinned overstorey, coppice removed					
Overstorey basal area	8.3	21.6	25.4	26.9	29.2
(m^2 ha^{-1})	(0.27)	(0.33)	(0.40)	(0.39)	(0.48)

Volume increment of potential sawlog trees (largest 150 stems ha^{-1}) was almost doubled (relative to unthinned forest) in forest where coppice regeneration was controlled following thinning. Volume of sawlog trees increased by 77, 90 and 130 m^3 ha^{-1} in unthinned, thinned-only and thinned and coppice-treated forest, respectively, in the 6 y following treatment.

Growth of coppice regeneration

In thinned and coppice-treated forest the physical removal of early coppice sprouts and the subsequent covering of the stumps with the plastic bags effectively removed all coppice competition. Even as the plastic bags degraded, few stumps produced further coppice shoots. It was observed that stumps cut cleanly during machine harvesting with no damage to the bark/sapwood attachment at the cut face coppiced more readily than damaged stumps. Stumps that had the bark/sapwood interface damaged during harvesting operations (either by breaking away at the cut surface or by vehicle tyres or tracks), or that had been manually damaged by axe or machete, generally produced less coppice — often with weaker attachment to the stump. This effect was not quantified during this study.

In plots where coppice was not controlled, coppice shoots had reached maximum numbers within 2 y (Table 2), with little mortality or detachment from the stump. More than 1000 stems

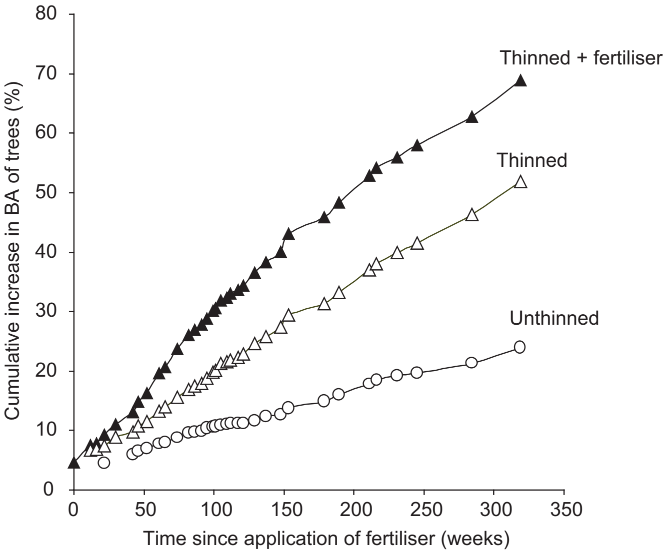

Figure 6. Periodic growth of trees fitted with dendrometers following application of fertiliser (summation of all banded trees in each treatment)

ha^{-1} were attached to the cut stumps or damaged small trees, although not all stumps or trees produced coppice shoots. After 6 y, only about 500 coppice stems ha^{-1} remained. Basal area of coppice material had increased from 0 to 5.6 m^2 ha^{-1}, with some coppice stems achieving diameters greater than 12 cm dbhob, but its contribution to stand volume was still less than 0.5% after 6 y. On thinned-only plots, coppice reached a top height of 5–7 m in 6 y and coppice basal area was equivalent to about 16% of the total basal area of the stand (Table 2).

Removal of coppice competition increased the basal area growth of potential sawlogs in thinned forest by 19% over that of those trees in thinned-only forest, and the estimated volume increment is significantly greater. Mean annual increments (MAIs) of merchantable trees calculated for the 6 y of growth after treatment for unthinned, thinned-only, and thinned coppice-treated are 16.5, 19.0 and 28.7 m^3 ha^{-1}, respectively. MAIs for selected trees and potential sawlogs in unthinned forest are only 13.7 and 12.8 m^3 ha^{-1}, respectively. The largest 150 trees ha^{-1} in unthinned forest, irrespective of quality or form, are accumulating much less volume per tree whilst using a major part of the site resources.

Effect of rainfall on growth

The growth of trees fitted with dendrometers reflected seasonal rainfall patterns (Fig. 6). Growth rates of trees in treated forest increased within 6 mo of thinning, and of thinning and fertiliser application. During short periods of water stress (i.e. summer periods around 110, 160 and 230 weeks following fertiliser application) the growth of smaller trees in unthinned forest fitted with dendrometers slowed to almost nothing (<1 mm per period), most likely due to competition for water. During these periods, trees in thinned forest, and in the thinned and fertilised plots, continued to grow.

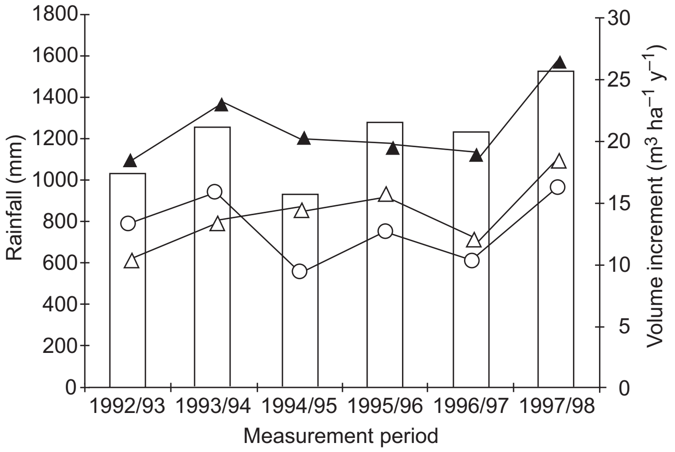

Figure 7. Annual (May–April) rainfall (columns) and total volume increment of potential sawlog trees (largest 150 trees ha^{-1}) during the rainfall periods for unthinned (▲), thinned-only (Δ) and thinned and coppice-treated (o) stands

Rainfall data from nearby Cabbage Tree Creek (Bureau of Meteorology Statistics) reveal that in most years rainfall is evenly distributed throughout the year. Mean annual rainfall averaged over 50 y is 1090 mm. Variation in seasonal and annual rainfall was seen to affect growth of individual trees and of the forest. Summer droughts (1993/94 and 1994/95) exacerbated competition between trees for short periods, and lower-than-average annual rainfall (1994/1995 and 1996/1997) affected annual growth (Fig. 4). During these drier periods, growth of trees in thinned and thinned-and-fertilised forest was less affected by the reduced rainfall. Examination of data for rainfall (Fig. 7) in periods coinciding with those in which tree growth was measured show that growth (of potential sawlog trees (largest 150 ha^{-1})) reflects rainfall in the same period. In unthinned forest at Towser Creek, tree volume increment was reduced when rainfall in the previous measurement period was reduced. The trend is evident over the 6 y, but it is most apparent for the drier periods of 1994/1995 and 1996/1997 (Figs 4 and 7). Growth in measurement periods, however, was not well correlated with the rainfall recorded during the same period (r^2 values of 0.51, 0.50 and 0.61 for unthinned, thinned-only, and thinned and coppice-treated plots, respectively).

Effect of fertiliser application on basal area growth

The addition of fertiliser (100 kg N ha^{-1} and 100 kg P ha^{-1}) to the adjacent area of the thinned-only forest dramatically increased basal area growth of trees fitted with dendrometers (Fig. 6). This treatment was for demonstration purposes and was not replicated. The basal area growth of potential sawlog trees in the fertilised stand increased by 60% over that of trees in thinned-only forest and was still 30–40% greater than of those in forest where coppice had been removed (data not shown). The rest of the trees in the stand (potential pulpwood trees and small sawlogs) showed a larger response to fertiliser addition, growing 97% faster than trees in the thinned-only plots and 150% faster than trees in unthinned forest.

Discussion

Increased productivity for potential sawlogs

East Gippsland mixed-species forest (dominated by *E. sieberi*) near the end of a sawlog rotation at 80–100 y (Mueck and Peacock 1992) will contain about 150 trees ha^{-1} (Incoll 1974). However, natural selection during the rotation may not always favour growth of the best potential sawlog, and wildfire will also downgrade wood quality. Under natural conditions as few as 20 trees ha^{-1} (P. Geary, NRE *pers. comm.* 1992) of the final crop trees may be high-value sawlog trees. The remainder are lower-class logs or defective logs suitable only for pulpwood. During the development of the stand, some of the best trees (in form and vigour) occur close together, and their growth as individuals will be impeded. Thinning offers the potential to select potential high-value sawlog trees as final-crop trees and to accelerate their growth.

After being thinned to about 250 trees ha^{-1}, the forest suffered no significant loss in total basal area increment, with most of the retained trees growing rapidly. Connell and Kellas (2001) reviewed the growth of a number of eucalypt forests (*E. sieberi, E. regnans, E. diversicolor, E. delegatensis*) after older-age commercial thinning. Reducing initial basal area by about 50% increased basal area growth of the largest trees by 30–90% compared to the growth of similar-size trees in control plots. Stoneman *et al.* (1997) found similar responses to thinning of jarrah (*E. marginata*), with additional significant responses to the addition of fertiliser. *Eucalyptus sieberi* trees in thinning experiments in south-eastern New South Wales showed basal area responses to thinning of up to 35% when compared to similar-size trees in control plots after 5 y (Jurskis and Turner, unpublished).

Whilst it is evident from this study that trees of all size classes in thinned forest are growing faster (Figs 3 and 5) than similar-size trees in unthinned forest, it is the growth rate of the 'potential sawlogs' (largest 150 stems ha^{-1}) which is of the greatest interest and provides the greatest potential value. The economic benefits of the response accrue not only from larger-diameter sawlogs, but also from increased sawlog:pulpwood ratios and more efficient harvesting and utilisation (Connell *et al.* 1997). In the period 1992–1998 about 46% of stand production in unthinned forest was contributed by 'potential sawlog' trees, whilst after thinning the figure was 77% (from Table 2).

Smaller trees have the potential to reduce sawlog and pulpwood increments on larger, more valuable trees. However, in thinned forest where forest structure or lack of suitable trees would otherwise create a larger gap, a small healthy tree of good form will grow well (Fig. 5) and has the potential to become a small sawlog late in the rotation or to provide pulpwood at the second commercial thinning.

Accurate measurement of height is difficult in natural eucalypt forests due to angles of the tree crowns and their structure. It was assumed for the purpose of assessment that the lowest live branch supporting the green crown was the merchantable size limit (about 13 cm dbhob). Because of these factors volume estimates should be regarded only as indicative.

Coppice growth 6 y after thinning contributed little to volume increment, but the contribution of surviving coppice stems will increase as the stand develops. The long-term stability of these coppice stems is unknown; any gains in basal area and therefore volume will be negated if the stems fall down later in the rotation. Removal of coppice competition following thinning enhances growth of retained trees in the short term and will have a relatively greater effect on the larger, more valuable trees in the latter part of the rotation.

Thinning prescriptions used in these forests (Dept of Conservation and Environment 1992) recommend a stocking of about 250 stems ha^{-1} to allow for a possible second commercial thinning whilst maintaining desirable form and branching characteristics. We did not observe any increase in the development of epicormic shoots following thinning, although epicormic shoots did develop on some trees in both thinned and unthinned forest.

Even in the presence of vigorous coppice, stems of all size classes in thinned and fertilised forest had greater growth than did those in all other treatments. Coppice regeneration developed differently on the fertilised site, as there were fewer stems at any measurement period, but stems were taller and larger in diameter than coppice stems in thinned-only plots. These findings suggest the presence of a nutrient limitation even in this productive forest (MAI about 14 m^3 ha^{-1} calculated over 34 y), and better exploitation of the additional water available to trees after thinning. During dry periods, growth of trees in thinned and thinned-and-fertilised forest was less affected by the reduced rainfall.

Coppice management

In a post-thinning coppice study in similar silvertop ash forests of varying productivity, Forrester *et al.* (2003) found that, after 3 y, coppice contributed up to 33% of total basal area of thinned regrowth forest, the exact figure depending upon the intensity of thinning. The coppice contribution to stand basal area increased with (a) an increase in thinning intensity (more light and less competition for resources) and (b) a reduction in site quality (larger competitive trees retained inhibited coppice growth on higher quality sites).

Removal of developing coppice stems from the thinned forest would be costly, although the observed 19% improvement of volume growth suggests it may be an economic option. Inhibiting or preventing coppice growth at the time of commercial thinning has the potential to be much more cost effective.

Coppice was initially removed with the back of an axe head or by driving the blade of an axe or a machete deep into the shoot and levering the coppice shoots off the stump, as well as damaging the bark surrounding the base of the shoot. The use of plastic bags to seal the stump created a sealed 'hot house' effect, which most likely created a pathogenic soup in the trapped moisture (some bags held litres of water in the folds of plastic around the stump). Subsequent high summer temperatures and humidity caused decay and finally death of the developing coppice shoots inside the bags.

The application of plastic bags to cut stumps or the manual removal of shoots following thinning is unlikely to be economic. However, the damaging of cut stumps during harvesting is worth some consideration. Machine tracks and tyres damage cut stumps and therefore there is usually less coppice regrowth in outrows where machines make a number of passes. It has also been observed that if the machine operator snaps off a stem (either a single-stemmed tree or multi-stemmed coppice) there is little coppice regeneration from the damaged stump.

Operationally the same effect could possibly be achieved by partially cutting the stem with the chainsaw within the harvesting head and then breaking the rest of the stem during directional felling. Usually the stem breaks downward, exposing more of the stump to the elements and destroying more of the bark/sapwood interface. The extent of any consequent wear and tear on equipment has not been investigated.

Another option for current commercial thinning operations using Waratah-style grapple harvesters is to test the use of poisons such as Glyphosate® added to the oil lubricating the chain of the hydraulically-operated chain saw. The immediate application of glyphosate to the cut stump during the cutting action could be very efficient, and the poison would be applied under conditions of osmotic tension for the most effective uptake. It may be impossible to deliver a lethal dose under such automated conditions but an inhibitory dose may suppress coppice growth sufficiently for retained trees to gain greater dominance. The extent of root-grafting in these forests would need careful consideration. Observations in a number of spacing trials employing chemicals show it is possible to suppress or kill one stem of a double-leadered tree or a coppice clump, using sub-lethal doses. These options require further investigation.

It is probable that coppice competition will continue to inhibit growth of retained stems in thinned-only forest as site resources become more limited over time. It is likely that some of the coppice and suppressed stems will form an intermediate layer in the stand, continuing to grow slowly as a potential pulpwood crop. Some loss of potential volume is likely in the years after thinning as stems die. In forests which have been thinned with a second commercial thinning in mind there is likely to be an opportunity to harvest these and other stems whilst retaining the final highest-value sawlog trees (about 150 stems ha^{-1}).

Conclusions

Sawlog yield can be increased by investing in silvicultural treatment of selected areas of regrowth forest of *E. sieberi*. Commercial thinning to reduce basal area to about 50% can almost double growth rates of retained trees, with the potential sawlog trees growing 50–80% faster than similar trees in unthinned forest for at least 6 y following thinning.

The growth and persistence of coppice regeneration and small trees in thinned forest may be suppressed by expansion of the crowns of the dominant retained trees, but it is likely that the rapid growth of small trees and coppice stems will retard the growth of the more valuable crop trees for some time.

Removal of coppice competition following thinning can enhance growth of retained trees by a further 20–30% even in the early years following thinning, and is likely to have a greater relative effect on the larger, more valuable trees in the latter part of the rotation.

Coppice regeneration could be a potential pulpwood resource for a second commercial thinning operation in these forests. However, factors such as inadequate persistence and stability of coppice stems on old stumps, inherent and potential defect in coppice stems, and butt tension wood could bring about substantial losses in potential growth or indeed sawn recovery if grown to sawlog size. The economic benefit of retention, suppression or removal of coppice requires longer-term analyses which can be provided in due course by this research.

Commercial thinning operations incorporating the removal of competing coppice regeneration give forest managers increased options for the future utilisation of the stand in delivering:

- subsequent commercial harvests of larger trees of higher quality, through further thinning, some years prior to the end of rotation, and/or
- larger, more valuable trees at the end of a rotation of normal length, or
- trees of sawlog size and quality at the end of a shortened rotation.

In the economic analysis of the long-term benefits of these or other silvicultural treatments, expected future increased premiums for larger logs, and retention of trees promising a higher grade of log, will be important considerations.

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