THINNING INCREASES SAW-LOG VALUES IN FAST-GROWING PLANTATIONS OF *ACACIA* HYBRID IN VIETNAM

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BEADLE CL, TRIEU DT & HARWOOD CE. 2013. Thinning increases saw-log values in fast-growing plantations of *Acacia* hybrid in Vietnam. High stockings at plantation establishment of fast-growing species can lead to rapid compromise of individual tree growth. This study examined the possibility of early thinning for *Acacia* hybrid to realise saw-log potential defined as log volume > 15 cm small-end diameter under-bark at harvest. A 2.5-year-old *Acacia* hybrid plantation located near Dong Hoi in Central Vietnam and established at 1000 stems ha^{-1} was subjected to four thinning treatments, namely, an unthinned control (871 stems ha^{-1} at time of thinning) and 600, 450 and 300 stems ha^{-1}. Significant diameter responses to thinning were observed after 6 months and sustained until at least 2 years after thinning and these were associated with significant differences in total basal area between treatments during the same period. However, by 18 and 25 months after thinning there were no significant differences in periodic basal area increment between treatments. This experiment showed that sites supporting mean annual increment (MAI) > 25 m^3 ha^{-1} and thinned to 600 stems ha^{-1} when the trees had mean diameter at breast height of 9 cm led to about 20% of the commercial log volume reaching minimum saw-log size within 5 years from planting. Our results support the view that thinning *Acacia* hybrid in these environments can rapidly realise saw-log values and increase the value of these plantations to smallholders.

Keywords: Acacias, basal area, clonal forestry, diameter, sawn timber

BEADLE CL, TRIEU DT & HARWOOD CE. 2013. Penjarangan meningkatkan nilai balak gergaji di ladang hibrid *Acacia* cepat tumbuh di Vietnam. Stok tinggi semasa penubuhan ladang spesies cepat tumbuh mengakibatkan masalah dalam pertumbuhan pokok individu. Kajian ini meninjau kemungkinan penjarangan awal hibrid *Acacia* agar dapat mencapai potensi balak gergaji yang ditentukan oleh isi padu balak pada diameter bawah kulit hujung kecil > 15 cm semasa penuaian. Ladang hibrid *Acacia* berusia 2.5 tahun yang terletak berhampiran Dong Hoi di Vietnam Tengah dan mempunyai stok asal 1000 batang ha^{-1} didedahkan kepada empat jenis rawatan penjarangan iaitu kawalan yang tidak dikenakan penjarangan (871 batang ha^{-1} semasa penjarangan) serta 600 batang ha^{-1}, 450 batang ha^{-1} dan 300 batang ha^{-1}. Gerak balas diameter yang signifikan dicerap selepas enam bulan dan kekal begitu sekurang-kurangnya dua tahun selepas penjarangan. Keputusan ini dikaitkan dengan perbezaan signifikan luas pangkal antara rawatan semasa kajian. Bagaimanapun, menjelang 18 bulan dan 25 bulan selepas penjarangan, tiada perbezaan signifikan diperhatikan dalam peningkatan luas pangkal antara rawatan. Kajian ini menunjukkan bahawa tapak yang menghasilkan tambahan min tahunan > 25 m^3 ha^{-1} dan dijarangkan sehingga 600 batang ha^{-1} apabila pokok mencapai min diameter aras dada 9 cm, dapat menghasilkan 20% isi padu balak komersial yang mencapai saiz balak gergaji minimum dalam masa lima tahun setelah ditanam. Keputusan kami menyokong pendapat yang menyatakan bahawa hibrid *Acacia* yang ditanam di persekitaran sebegini dapat mencapai nilai balak gergaji dengan cepat dan meningkatkan nilai ladang bagi pekebun kecil.

INTRODUCTION

The exploitation of species with very high early growth rates in plantations managed for solid wood must respect two fundamental requirements. The first is good form, at least in the lower part of the stem to be harvested for solid-wood products; the second is the trade off between total production (basal area) and individual log diameter (as indicated by diameter at breast height, dbh) so that solid-wood values at harvest are maximised and matched to the targeted market. Form is usually captured by establishing the plantation

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at stockings which encourage the formation of straight, single stems and small branches (Cameron 2001, Beadle et al. 2008). In species such as tropical acacias, singling, a type of form pruning that removes competing leaders at age 4 to 6 months, may also be necessary (Kha 2001). Once a straight stem of the required length has developed, a thinning strategy is implemented to reduce intraspecific competition and extend the benefits realised from high early growth rates (Schönau & Coetzee 1989, Beadle et al. 2008), and to manage the trade-off between stand volume and log diameter referred to above, and wood quality (Nutto & Touza 2005).

Producing timber from plantations that meets saw-log specifications usually necessitates at least one thinning (Lamprecht 1989), although multiple thinnings may be preferable to protect trees from excessive sway (Cameron & Thomas 2008), particularly if the final crop is to be based on trees of large diameter (Beadle 2006). In plantation systems, there is a long history of application of thinning to regulate stand density and increase diameter of retained trees. Early thinning has been demonstrated to improve future log quality and value without compromising stand stability and long-term financial viability (Cameron 2001). In very fast-growing tropical acacia plantations, early thinning may mean as early as at age 2 years when stands are already reaching canopy closure.

Clones of *Acacia* hybrid, the natural hybrid between *Acacia auriculiformis* and *A. mangium*, are the most widely established plantation species in Vietnam. By late 2009, the estate of *Acacia* hybrid was > 0.23 Mha. The popularity of *Acacia* hybrid has resulted from the selection and rigorous testing of clones that demonstrate consistently high growth rates across a range of lowland site types in northern, central and southern Vietnam (Kha et al. 2012). This rapid expansion of the *Acacia* hybrid plantation estate from the late 1990s, when superior clones were first approved by the Government of Vietnam for operational plantation forestry in Vietnam (Kha 2001), has been accompanied by an examination of silvicultural inputs to increase wood production primarily for pulpwood (Dung et al. 2005, Son et al. 2006).

The final stocking of a plantation will determine log size at harvest. Stockings for *Acacia* hybrid plantations managed for pulpwood in Vietnam have ranged from 1000–2500 stems ha^{-1}, with initial spacing of 3 m × 2 m (1667 stems ha^{-1}), perhaps the most commonly advocated by extension services and adopted by growers. Rotation length for pulpwood is from 4 to 8 years (Son et al. 2006). During the last decade, *Acacia* hybrid has been planted by some growers with the objective of producing a substantial proportion of the harvest volume as small saw logs. These growers use similarly high initial stockings and grow plantations on rotations of 6 to 10 years without thinning. This practice has compromised the diameter growth of individual trees because of intense between-tree competition, resulting in small log diameters at harvest. Growth increments of *A. mangium* established at 1667 stems ha^{-1} in Thailand were severely reduced in the absence of thinning once the stand had reached the age of 14 years (Kamo et al. 2009).

Studies conducted on Vietnamese sawmills that process *Acacia* saw logs show that a 2-m log length is typical for *Acacia* saw logs (CE Harwood & PH Hai, personal communication). The minimum log small-end diameter under-bark (sed_{ub}) for profitable mill operation is either 18–20 cm for horizontal band-saw systems where the log is dogged to hold it on a rail-mounted saw-carriage or 15 cm for vertical bandsaws where the logs are hand-sawn by pushing/pulling across a saw-bench. The typical thickness of sawn boards produced in Vietnam is around 30 mm (green); a log with 15 cm sed_{ub} can yield three such boards, and one with 18–20 cm sed_{ub}, four or five. *Acacia* hybrid growers will benefit financially if their plantations yield a high proportion of saw logs at final harvest that meet these specifications because of the higher price paid for saw logs than for pulpwood. For example, in 2008 saw logs with sed_{ub} > 20 cm fetched USD80 m^{-3} delivered to local sawmills, those > 15 cm fetched USD70 m^{-3}, while pulpwood with sed_{ub} down to 4 to 5 cm, delivered to usually more distant woodchip mills fetched USD40 m^{-3} (CE Harwood & PH Hai, personal communication).

This study examined responses to thinning at age 2.5 years in an *Acacia* hybrid plantation in central Vietnam which was established at 1000 stems ha^{-1}. The main question asked was 'how does thinning intensity affect the growth response of the retained trees and the recovery of saw-log volume?' Differences in tree diameter and basal area increments were used to evaluate how thinning could be used to maximise both wood volume (basal area) and wood value (as influenced by log size).

MATERIALS AND METHODS

Site

The experimental site was provided by the Forestry Enterprise of the Long Dai Company and was situated west of Dong Hoi town, Quang Binh province in central Vietnam (17° 20' N, 106° 8' E) at an elevation of 70 m above sea level. The mean annual rainfall and temperature are 2000 to 2300 mm and 24 to 25 °C respectively, and the mean humidity is 85%. The most distinct feature of the climate is the change from a hot and dry season (March–August) to a cooler wet season (September–February) associated with tropical cyclonic systems. The soil is a yellow-brown ferallitic clay-loam of moderate fertility and depth in excess of 60 cm.

The plantation was established to a random mixture of eight clones of *Acacia* hybrid, namely, BV10, BV16, BV32, BV71, BV72, BV73, BV74 and BV75. The trees were planted in December 2003. Initial spacing was 4 m × 2.5 m and planting density, 1000 stems ha^{-1}. At planting time, each seedling was fertilised with 200 g N:P:K (16:16:8) and 400 g of microorganism-enriched biofertiliser. Weeds were controlled by manual slashing at least two times per year during the first 3 years of growth. The plantation remained free of severe weed competition throughout the experiment.

Experimental design and treatments

The thinning trial was established in late May 2006, 2.5 years after planting. A randomised complete block design was used, with four replications of four thinning treatments: 300, 450 and 600 stems ha^{-1} and unthinned control. Average stocking in the four control plots at this time was 871 stems ha^{-1}, with a range of 84.1 to 96.8% survival. The plantation was very uniform with respect to tree size. Gross plot size was 28 m × 22.5 m (7 rows × 9 trees per row, 0.063 ha) and net plot size after excluding one buffer row was 20 m × 17.5 m (5 rows × 7 trees per row, 0.035 ha). A selection-thinning method, applied to the thinned net plots, first removed trees of poor form and then those of smaller diameter. However, no more than two adjacent trees were removed in any one row of the net plots, except in the 300 stems ha^{-1} treatment. Immediately after thinning, mean dbh of the 16 net plots ranged from 8.8 to 10.0 cm. At thinning, all retained trees in the plots were lift pruned to 2.3 m using pruning shears. The buffer rows surrounding each net plot received the same thinning and pruning treatments.

Measurements

Just before thinning, dbh (to nearest 0.01 m with a tape), total height (h, to nearest 0.1 m) and crown diameter (d_c, to nearest 0.1 m) were measured. During the experiment, dbh and h were measured approximately every 6 months (1st June and 15th December 2006, 10th July and 12th December 2007, and 10th July 2008) for 2 years. Height was measured using a Hastings height ruler (first four measurements) or a digital hypsometer (fifth measurement). The Hastings height ruler only measured up to 12 m and it was necessary to estimate the height of the trees with h > 12 m in 2007. Crown diameter was the mean of canopy widths measured along the row axis and in a perpendicular direction across the row axis.

Total tree volume under-bark to 5-cm diameter (V) at age 55 months was estimated from dbh. A regression of tree volume was developed by sampling 15 trees with dbh of 13 to 22 cm in a 9-year-old *Acacia* hybrid plantation with a stocking of 891 stems ha^{-1} at the Forest Science Institute of Vietnam's research station at Dong Ha, 100 km south of Dong Hoi. A summation of sectional volumes of 2-m log lengths using Smalian's formula and the relationship between bark thickness and tree height were used to determine V. The linear regression was

$$V = ((247.9 \times dbh) - 2188)/10{,}000$$

where V and dbh (m^3 and cm respectively) accounted for 94% of variance in volume. A second regression was developed for a subset of the 11 sample trees having dbh in the range 15 to 22 cm to predict the percentage of log volume accruing to saw logs with length of at least 1.2 m and log sed_{ub} of at least 15 cm. The linear regression was

$$\text{Percentage of saw log} = ((11.55 \times dbh) - 165.9) \times 100$$

where dbh, in cm, accounted for 96% of the variance in percentage saw log. These equations were considered sufficiently accurate to predict tree volumes and percentage of saw log for individual trees in the thinning experiment where dbh at 55 months ranged from 11 to 21 cm.

Saw-log volume was based on tree volume to 15 cm sed_{ub}; the balance of tree volume to 5 cm sed_{ub} was considered to be pulp logs. Wood value was based on average prices paid at the mill gate in 2008 in central Vietnam, USD40 m^{-3} for pulp-logs and USD70 m^{-3} for saw logs (20 cm > sed_{ub} > 15). The majority of the saw logs were in this size category. The value of trees thinned at age 2.5 years was not included in this assessment.

Analysis

Plot mean values of dbh, h and crown diameter were calculated. Plot basal areas (m^2 ha^{-1}) were calculated by summing the basal areas of all individual trees in each plot. Periodic increments of each variable were calculated for the intervals between successive measurements up to age 55 months. The significance of differences between thinning treatments for each variable on each assessment date and each successive increment was determined using univariate analysis of variance, with replicate set as the blocking factor and thinning treatment as a fixed effect treatment factor, using the statistical package Genstat (Release 11).

RESULTS

Survival

Tree losses were minimal between thinning and 25 months after thinning. However, 28 months after thinning, a typhoon uprooted or broke the stems of > 50% trees (Table 1).

Diameter distribution, dbh and basal area

The distribution of dbh across the four thinning treatments at age 30 months at the time of thinning in May 2006 was narrow (Figure 1). In the 871 (unthinned), 600, 450 and 300 stems ha^{-1} treatments, 87, 92, 94 and 93% of

Table 1 Tree survival (%) in the four thinning treatments

Stocking (stems ha^{-1})	May 2006	Dec 2006	Jul 2007	Dec 2007	Jul 2008	Feb 2009
300	100	100	100	100	100	42.2
450	100	100	100	98.5	98.5	38.5
600	100	98.8	98.8	96.5	96.5	35.3
Unthinned	100	98.4	98.4	97.5	97.5	48.4

Mean stocking in the unthinned treatment at the time of thinning was 871 stems ha^{-1}; note the large reduction in stocking caused by a typhoon on 31 October 2008, 28 months after thinning trees respectively were in the 9 to 11 cm (8.6 to 11.5 cm) diameter classes. The corresponding percentages in the 10-cm (9.6 to 10.5 cm) diameter class were 39, 48, 49 and 38%. The mean dbh immediately after thinning at age 30 months were 9.4, 9.4, 9.4 and 9.9 cm in the 871, 600, 450 and 300 stems ha^{-1} treatments respectively. However, the difference between the 300 stems ha^{-1} treatment and the other three treatments was not significant (Figure 2).

After 6 months, a significant difference ($p < 0.01$) in dbh between treatments had developed and remained significant ($p < 0.001$) on the three subsequent measurement dates. Twenty-five months after thinning (age 55 months), mean diameters were 14.5, 15.9, 16.3 and 17.1 cm in the 871, 600, 450 and 300 stems ha^{-1} treatments respectively (Figure 2). Differences in periodic increment in dbh were also significant for each of the four intervals between assessments up to age 55 months.

The average mean basal area of the experimental plots just before thinning was 6.1 m^2 ha^{-1}. Mean basal area values in the 871, 600, 450 and 300 stems ha^{-1} treatments at age 55 months (i.e. 25 months after thinning) were 14.1, 11.9, 9.6 and 7.4 m^2 ha^{-1} respectively (Figure 3a); the corresponding cumulative increments over the same period were 8.0, 7.6, 6.4 and 5.0 m^2 ha^{-1} (Figure 3b). There were significant differences in basal area ($p < 0.001$) between treatments throughout the 2-year period of the experiment and in basal area increment until ($p < 0.001$), but not after ($p > 0.05$), age 43 months (18 months after thinning). During the interval between

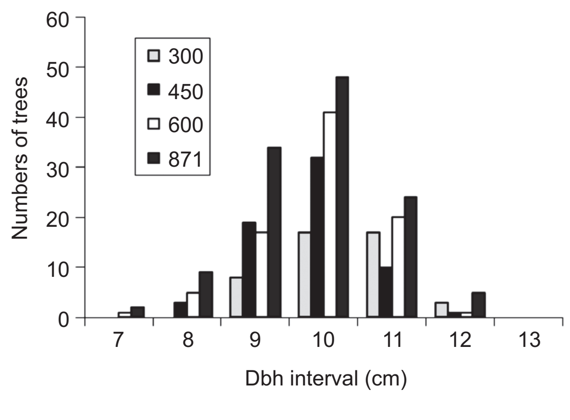

Figure 1 The number of trees in each diameter (dbh) class just after thinning; thinning treatments are in stems ha^{-1}

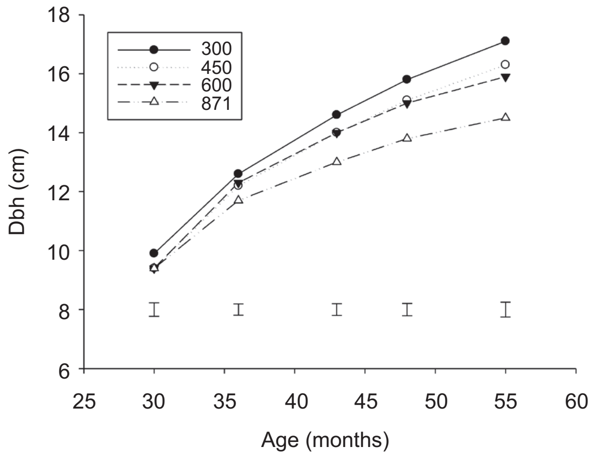

Figure 2 Mean dbh expressed as a function of stand age; stand was thinned at age 30 months and then measured at approximately 6-month intervals for 2 years; error bars are standard errors of difference; thinning treatments are in stems ha^{-1}

18 and 25 months after thinning, basal area increments were 1.31, 1.40, 1.36 and 1.09 m^2 ha^{-1} in the 871, 600, 450 and 300 stems ha^{-1} treatments respectively.

Height and crown diameter

Mean h when the plots were thinned was 9.4–9.9 m across treatments (Figure 4). Twenty-five months after thinning, mean h values were 17.3, 17.5, 17.2 and 16.6 m in the 871, 600, 450 and 300 stems ha^{-1} treatments respectively. There were no significant differences in h between treatments. The reduced increment in h between ages 43 and 48 months was in part caused by tops being blown off some trees (Figure 4). However, the large increase in h between ages 48 and 55 months suggested that height measurements might have been systematically underestimated, particularly at age 48 months, because of the limitations of the Hastings height ruler.

Mean d_c at thinning varied between 2.8 and 2.9 m. Significant differences ($p < 0.05$) in d_c developed 13 and 18 months after thinning, but only between the unthinned control and other treatments. Crown diameter was least in the unthinned treatment (data not shown).

Volume, product recovery and wood value

Total standing volume of wood in the 871 stems ha^{-1} (unthinned) stand at age 4.5 years was 118.6 m^3 ha^{-1}. Mean annual increment was 26.4 m^3 ha^{-1} (Table 2). In the 300 stems ha^{-1} treatment, standing volume was 65.8 m^3 ha^{-1}. Recoveries of saw logs in the 871 and 300 stems ha^{-1} treatments were 10.4 and 22.9 m^3 ha^{-1} respectively, and the corresponding percentage recoveries were 6.7 and 31.6% (Table 2).

Two years after thinning, saw-log values were similar in the 600, 450 and 300 stems ha^{-1} treatments. Due to the higher pulpwood yield in the treatments with higher stockings, wood value delivered to the mill gate was similar for the 871 and 600 stems ha^{-1} treatments, and lower for the 450 and 300 stems ha^{-1} treatments (Table 3).

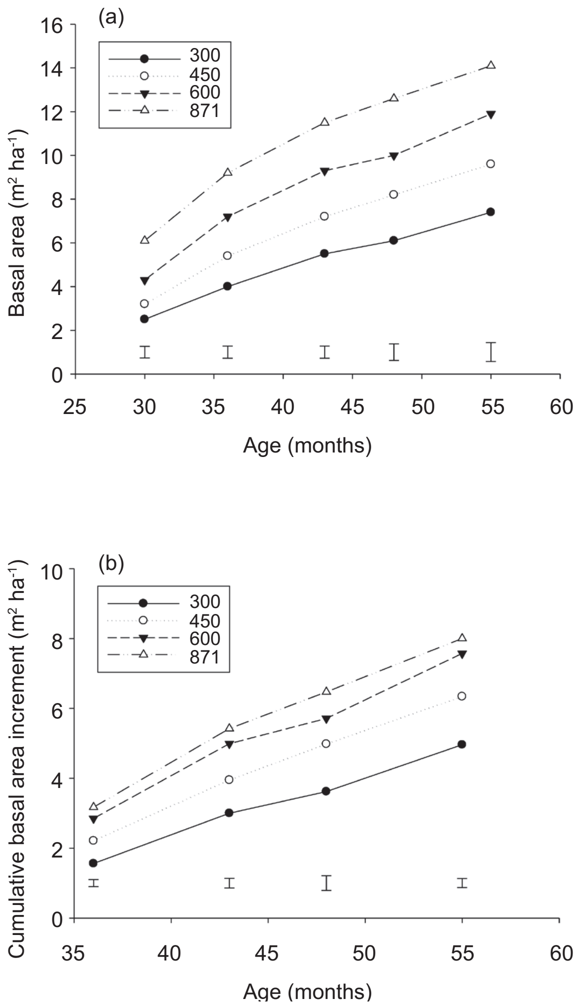

Figure 3 (a) Mean total basal area and (b) cumulative basal area increment at breast height expressed as a function of stand age; stand was thinned at age 30 months and then measured at approximately 6-month intervals for 2 years; error bars are standard errors of difference, thinning treatments are in stems ha^{-1}

DISCUSSION

This trial has shown that significant responses in diameter growth can occur in young, fast-growing *Acacia* hybrid plantations from as early as 6 months after thinning. This response to thinning, and the thinning rates examined, led to doubling in the potential volume of saw logs in the thinned treatments compared with unthinned control treatment 2 years after thinning. These results are now discussed in the context of inter-tree competition at an early age being a determinant of the balance between wood volume and wood value in *Acacia* hybrid plantations.

There was a strong diameter response to thinning when stand basal area had reached 6 m^2 ha^{-1} and the mean dbh was 9–10 cm. Significant diameter response just 6 months after treatment indicated that competition between trees for resources when the stand was thinned at age 2.5 years was already intense and, thus, compromised individual tree growth (Beadle 2006). In a 5-year-old *Acacia* hybrid plantation in southern Vietnam, significant increases in diameter after thinning from 1333 to 475 stems ha^{-1} were observed 2 years after treatment (Son et al. 2006). However, it was not clear whether this represented a delayed response because the stand was older at thinning. The onset of thinning response and the period over which it is sustained is likely to be a complex function of tree species, stand age, site quality and the growing environment (Medhurst et al. 2001), all of which influence tree vigour, intensity of competition and current rates of growth at thinning. *Acacia* hybrid behaves as a pioneer species which is expressed in plantations through very high early growth rates. Not only was the thinning response within months at Dong Hoi, it was maintained for at least 2 years after thinning. Throughout this time diameter increments of unthinned (871 stems ha^{-1}) and the 300 stems

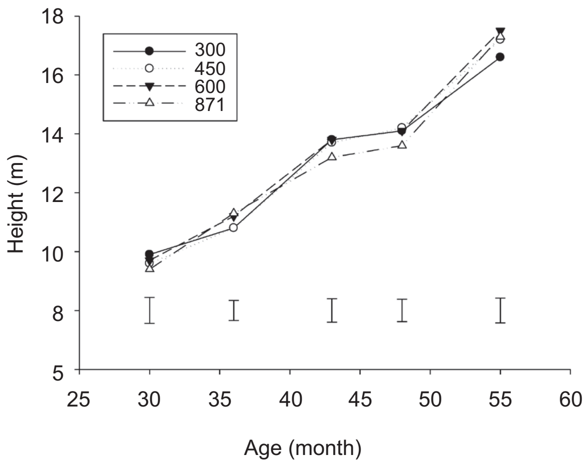

Figure 4 Total height expressed as a function of stand age; error bars are standard errors of difference; thinning treatments are in stems ha^{-1}

ha^{-1} treatments were diverging. Diameter increments of the 600 and 450 stems ha^{-1} treatments were intermediate but very similar until age 48 months. The reason for this lack of difference was unclear but the divergent trend emerging thereafter suggested that inter-tree competition was becoming more intense at the higher than lower stocking.

Periodic basal area increment was initially proportional to basal area just after thinning (Figure 3). Such a relationship was anticipated given that the percentage reductions in total basal area at thinning were substantial, viz, 29.1, 46.7 and 59.4% in the 600, 450 and 300 stems ha^{-1} treatments respectively. Differences in total basal area remained significant throughout the 2-year experiment. However, 25 months after thinning, these percentage reductions compared with the unthinned control had narrowed to 15.6, 32.0 and 47.2% respectively. At 18 and 25 months after thinning, there were no significant differences in periodic basal area increment between treatments. The latter measurement was the first after thinning that was associated with a smaller increment at 871 than at 600 stems ha^{-1}. Similar patterns of response in basal area increment to thinning have also been found in eucalypt plantations, though with different timing (Medhurst et al. 2001).

The rapid reduction in periodic basal area increment from 5.4 m^3 ha^{-1} in the first year to 2.6 m^3 ha^{-1} in the second year after thinning in the 871 stems ha^{-1} treatment clearly demonstrated the rapid rate at which growth rates declined in *Acacia* hybrid, even at modest initial stockings like 1000 stems ha^{-1}. However, even in the thinned treatments, basal area increments were less in the second than in the first year after thinning. Just how quickly such changes will undo the benefits to individual tree growth gained from thinning, and whether the period of rapid diameter increment can be prolonged by a subsequent thinning, remain unresolved. There is an expectation that the basal area of thinned stands will approach those of unthinned stands (Hasenhauer et al. 1997), except where rates of thinning are very high (Whyte & Woollons 1990). Two years after thinning, there was no indication that this was occurring in this *Acacia* hybrid stand.

Height growth was not affected by thinning treatment. Height:diameter (h:dbh) ratio just after thinning was approximately 100:1.

Table 2 Potential product recovery (m^3 ha^{-1}) from the four thinning treatments at age 4.5 years, two years after thinning

Stocking (stems ha^{-1})	Total volume (m^3 ha^{-1})	Pulpwood volume (m^3 ha^{-1})	Saw-log volume (m^3 ha^{-1})	Saw log (%)
300	65.8	42.9	22.9	31.6
450	84.7	64.0	20.6	22.4
600	104.1	81.6	22.5	18.8
871	118.6	108.2	10.4	6.7

Saw-log volume was based on tree volume to 15 cm small-end diameter under-bark (sed_{ub})

Table 3 Value (USD ha^{-1}) of wood products (m^3 ha^{-1}) from the four thinning treatments at age 4.5 years two years after thinning, delivered to the mill gate

Stocking (stems ha^{-1})	Pulpwood (@ USD40 m^{-3})	Saw log (@ USD70 m^{-3})	Total (ha^{-1})
300	1716	1603	3319
450	2560	1442	4002
600	3264	1575	4839
871	4328	728	5056

Twenty-five months after thinning, the ratio was 97:1 in the 300 stems ha^{-1} treatment and increased with stem density to 119:1 in the 871 stems ha^{-1} unthinned treatment. Thinning is normally associated with a decrease in h:dbh because of reduced competition for light (Pinkard & Neilsen 2003). However, height growth is normally unrestricted as diameter growth slows in response to the intensification of inter-tree competition (Gerrand et al. 1997). In the *Acacia* hybrid at Dong Hoi, decreasing diameter growth with increasing stem density led to an increase in h:dbh except at the highest rate of thinning where there was no change in h:dbh 2 years after treatment. Wind-throw is often associated with thinning (Forrester & Baker 2007) because of the loss of mutual support between trees (Kramer 1977). Early thinning during a period of rapid growth, as in this experiment, before critical values of h:dbh are exceeded should promote the re-establishment of stand stability in the shortest possible time as well as arresting, if not reversing, deleterious changes in h:dbh (Cremer et al. 1982, Wood et al. 2007). At Dong Hoi, there were negligible tree losses until a typhoon, which occurred when the trees were 59 months, caused very severe wind-throw and stem breakage. This appeared unrelated to thinning rate or any differences that might have developed in stand stability between treatments after thinning. Nevertheless there remains some concern that in this fast-growing species, h:dbh ratios exceed those recommended, even after thinning, to minimise risk of wind-throw (Cremer et al. 1982).

The trees were thinned before reaching canopy closure and crown diameter increased until age 36 months in all treatments. The significant difference between treatments that was evident at age 43 months was associated with decrease in canopy diameter and rapid crown lift in the 871 stems ha^{-1} treatment which was probably associated with canopy closure and the intensification of competition between trees. In the thinned treatments, crown diameter remained fairly constant after age 30 months. Thinning also extends the period that lower canopies remain well lit, delivering benefits to tree growth from the significant increases in photosynthetic activity in the lower canopy (Tang et al. 1999, Medhurst & Beadle 2005).

There was a marked and significant increase in the proportion of saw logs in the thinned treatments. This result has major implications for wood processors as many sawmills in Vietnam can profitably process acacia saw logs once log diameter is > 15 cm sed_{ub}. This experiment showed that sites supporting MAI > 25 m^3 ha^{-1} and thinned to 600 stems ha^{-1} when trees have mean dbh = 9 cm will lead to about 20% of the commercial log volume reaching minimum saw-log size within 5 years from planting. There was also no significant difference in the total value of wood harvested at this age between this treatment and the 871 stems ha^{-1} unthinned control. As pulpwood is harvested to 4–5 cm sed_{ub} in Vietnam, trees thinned at age 2.5 years can offer commercial return. For the more intensively thinned 450 and 300 stems ha^{-1} treatments, a rotation longer than 5 years would be required before returns from managing for saw log values more than offset those from managing for pulpwood.

This plantation was established at 1000 stems ha^{-1}. This is at the low end of planting densities commonly used to establish acacia plantations in Vietnam. Previous experiments with tropical acacias in Vietnam have shown that although volume increment may be higher at higher stockings during the first 3 years of growth (Dung et al. 2005), the best overall volume growth at age 5 years was attained at a stocking of 1111 stems ha^{-1} (Tinh 2002). Dung et al. (2005) suggested the most suitable stocking at planting for *Acacia* hybrid should be 1111–1667 stems ha^{-1}. In a plantation capable of MAI > 25 m^3 ha^{-1} and managed for saw logs, the current experiment supports the view that initial stockings no higher than 1000–1111 stems ha^{-1} are sufficient to best manage the rapid development of intraspecific competition on individual tree growth in *Acacia* hybrid, and to provide a significant growth response from retained trees to an early commercial thinning for pulpwood. It is useful to note that at stockings of > 1300 stems ha^{-1}, there would have been no saw logs with sed_{ub} > 15 cm on this site at age 5 years. Assuming a basal area of 15 m^2 ha^{-1}, slightly higher than that recorded for the 871 stems ha^{-1} treatment at age 55 months, mean dbh would have been 12–13 cm.

Typhoons regularly cause substantial damage to acacia stands in Central Vietnam. Consequently, there is a trade-off between the opportunity to grow a stand over an extended rotation of 8–10 years or more with two or more successive thinnings to produce a high proportion of high-value, large diameter saw logs, and the risk of losing the additional investment in stand management and obtaining lower volume production from salvage logging if storm damage occurs during the rotation. Smallholder growers who need to borrow to establish plantations tend to be risk-averse and will seek to minimise rotation length to reduce their costs (M Blyth, personal communication). These growers are recommended to establish plantation at stockings of 1000 or 1111 stems ha^{-1} and carry out single thinning to 600 stems ha^{-1} at age 2–3 years to realise about 20% of final harvest volume as saw logs > 15 cm sed_{ub} for rotations as short as 5 years, with an option of extending the rotation with a second thinning.

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REFERENCES

Beadle CL. 2006. Developing a strategy for pruning and thinning *Acacia mangium* to increase wood value. Pp 79–86 in Potter K, Rimbawanto A & Beadle C (eds) *Heart Rot and Root Rot in Acacia Plantations.* Proceedings No 124. 7–9 February 2006, Yogyakarta.

Beadle C, Volker P, Bird T, Mohammed C, Barry K, Pinkard L, Wiseman D, Harwood C, Washusewn R, Wardlaw T & Nolan G. 2008. Solid-wood production from temperate eucalypt plantations: a Tasmanian case study. *Southern Forests* 70: 45–57.

Cameron AD. 2001. Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. *Forestry* 75: 25–35.

Cameron A & Thomas K. 2008. Effect of thinning on the development of compression wood in stems of Corsican pine. *European Journal of Forestry* 127: 247–251.

Cremer KW, Borough CJ, Mckinnell FH & Carter PR. 1982. Effects of stocking and thinning on wind damage in plantations. *New Zealand Journal of Forestry Science* 12: 244–268.

Dung PT, Ngoc NV, Phuc HV, Le NT, Nhuan NT, Tung PV & Binh NT. 2005. *Techniques for the Intensive Establishment of Selected Clones of Acacia Hybrid in Old Alluvial Soil in Binh Phuoc Province for Pulpwood.* Project Report. Forest Science Institute of Vietnam, Hanoi. (In Vietnamese)

Forrester DI & Baker TG. 2007. Growth response to thinning in a productive *Eucalyptus globulus* plantation in Victoria, Australia. Pp 30–37 in Jiang Xiaomei et al. (eds) *Proceedings of the International Conference on Plantation Eucalyptus.* 28 November–1 December 2005, Zhanjiang.

Gerrand AM, Neilsen WA & Medhurst JL 1997. Thinning and pruning eucalypt plantations for sawlog production in Tasmania. *Tasforests* 9: 15–34.

Hasenhauer H, Burkhart HE & Amateis RL. 1997. Basal area development in thinned and unthinned loblolly pine stands. *Canadian Journal of Forestry Research* 27: 265–271.

Kamo K, Vacharangkura T, Tiyanon S, Viriyabuncha C, Thaingam R & Sakai M. 2009. Response of unmanaged *Acacia mangium* stands to delayed thinning in north-east Thailand. *Journal Tropical Forest Science* 21: 223–234.

Kha LD. 2001. *Studies on the Use of Natural Hybrids Between Acacia mangium and Acacia auriculiformis in Vietnam.* Agriculture Publishing House, Hanoi.

Kha LD, Harwood CE, Kien ND, Baltunis B, Hai NG & Thinh HH. 2012. Growth and wood basic density of *Acacia* hybrid clones at three locations in Vietnam. *New Forests* 43:13–29.

Kramer H. 1977. Thinning in Norway spruce stands in the Federal Republic of Germany. *South African Forestry Journal* 111: 49–53.

Lamprecht H. 1989. *Silviculture in the Tropics: Tropical Forest Ecosystems and Their Tree Species Possibilities and Methods for Their Long-Term Utilization.* Deutsche Gesellschaft für Technische Zusammenarbeit, Eschborn.

Medhurst JL & Beadle CL. 2005. Photosynthetic capacity and foliar nitrogen distribution in *Eucalyptus nitens* is altered by high-intensity thinning. *Tree Physiology* 25: 981–991.

Medhurst JL, Beadle CL & Neilsen WA. 2001. Growth in response to early-age and later-age thinning in *Eucalyptus nitens* (Deane and Maiden) Maiden plantations. *Canadian Journal of Forest Research* 31: 187–197.

Nutto L & Touza C. 2005. High quality *Eucalyptus* sawlog production. Pp 658–666 in Borralho NMG, Pereira JS & Marques C (eds) *Eucalyptus in a Changing World. Proceedings of the International Union of Forestry Research Organisations Conference.* 11–15 October 2005, Aveiro.

Pinkard EA & Neilsen WA. 2003. Crown and stand characteristics of *Eucalyptus nitens* in response to initial spacing: implications for thinning. *Forest Ecology and Management* 172: 215–227.

Schönau APG & Coetzee J. 1989. Initial spacing, stand density and thinning in eucalypt plantations. *Forest Ecology and Management* 29: 245–266.

Son NH, Quat NX & Nam DH. 2006. *Planting Techniques for Tree Species for Raw Materials.* Statistic Publishing House, Hanoi. (In Vietnamese)

Tang Z, Chambers JL, Guddanti S & Barnett JF. 1999. Thinning, fertilization and crown position interact to control physiological responses in loblolly pine. *Tree Physiology* 19: 87–94.

Tinh KT. 2002. Relationship between space and growth of *Acacia* hybrid in Tri An, Dong Nai province. MSc thesis, Thu Duc Agriculture and Forestry University, Ho Chi Minh City.

Whyte AGD & Woollons RC. 1990. Modelling stand growth of radiata pine thinned to varying densities. *Canadian Journal of Forest Research* 20: 1069–1076.

Wood MJ, Ellis L & Volker PW. 2007. Towards the prediction and management of windthrow in *Eucalyptus* plantations across Tasmania, Australia. Pp 10–18 in Jiang Xiaomei et al. (eds) *Proceedings of the International Conference on Plantation Eucalyptus.* 28 November–1 December 2005, Zhanjiang.