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Intensity and timing of the first thinning of *Tectona grandis* plantations in Costa Rica: results of a thinning trial

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Abstract

During the last two decades, the Costa Rican government has promoted the establishment of *Tectona grandis* plantations for sawn timber. However, there is a lack of knowledge on optimum spacing and on thinning regimes, in contrast to high expectations of final mean diameter at breast height (DBH) between 35 and 40 cm and stand volumes between 200 and 300 m^3 ha^{-1}. The aim of this study was to establish guidelines for plantation management in terms of appropriate intensity and timing of the first thinning (from approximately 4 thinnings recommended in 20–25-year-old rotation management systems).

A thinning trial was established in a 4-year-old *T. grandis* plantation that was originally established with initial spacing of 1600 trees ha^{-1}. The experimental design consisted of randomized complete blocks, with eight treatments and three replicates. Each treatment consisted of 80 trees in square blocks of 500 m^2. The treatments were of different thinning intensities (from 25% to 60% removal of standing trees, and the unthinned control) applied at two timings (at the ages of 4 and 6 years, and one treatment applied at the ages of 4 and 5 years) and an unthinned control in each replicate. The trees in each treatment were measured annually between age 4 and 8 years.

At the age of 8 years, the average DBH for all treatments was 17.5 cm (15.2–20.1 cm) and the total height averaged 18.8 m (17.7–19.5 m). The total volume (V_o) varied from 90 to 200 m^3 ha^{-1}, at corresponding BA between 12 and 28 m^2 ha^{-1}.The 60% thinning intensity applied at the age of 4 years, and the two consecutive 25% thinnings at the ages of 4 and 5 years gave the highest individual tree growth, while the control was the lowest.

The current annual increment (CAI) of DBH was highest in the 40 and 60% thinned treatments. The CAI of DBH and BA decreased rapidly with increasing age in every treatment. The values of CAI of V_o varied between 9 and 39 m^3 ha^{-1} $year^{-1}$. The high values of CAI of V_o were obtained at BA between 18 and 20 m^2 ha^{-1}. At BA of 18 m^2 ha^{-1}, V_o was between 120 and 150 m^3 ha^{-1} on a stand conformed by trees with an average DBH between 17 and 20 cm. The recovery of BA and V_o was faster in the treatments carried out at the age of 4 years than at 6 years, when measured 2 years after the thinning.

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In terms of the remaining stand volume (after thinning), tree size and rate of recovery, the best thinning was at the age of 4 years removing 40–60% of the trees, or consecutively at the ages of 4 and 5 years removing 25% of standing trees in each year.

Results of this thinning trial indicate that *T. grandis* plantations can be managed towards the production of high individual tree growth or towards the production of high stand growth, by means of varying the intensity and timing of the thinning interventions through rotation.

Keywords: Productivity; Stand competition; Intensive management; Basal area management

1. Introduction

Success in the management of plantations of fast-grown tropical tree species can only be achieved by performing intensive and timely silvicultural interventions (Ola-Adams, 1990; Lowe, 1976; Larson and Zaman, 1985). It is necessary to determine which spacing promotes early canopy closure to control weed growth and to reduce coarse branching as well as to optimize wood production on an individual and stand basis (Ola-Adams, 1990).

The size and spatial distribution of the canopy are causally related to the amount of light intercepted by the leaves. This relationship has been used to develop a better understanding of how the productivity of plantations can be measured in terms of conversion of light energy into biomass (Beadle, 1997). Therefore, it is important to link thinning to crown development in order to optimize tree growth (Suri, 1975). Larson and Zaman (1985) concluded after carrying out a study on spacing and thinning guidelines for *Tectona grandis* in Bangladesh that as teak trees get older they use canopy space less efficiently. This trend indicates that thinnings should become more intense and eventually more frequent as the stands mature.

On a study carried out on teak in Nigeria, Ola-Adams (1990) found that at different plantation spacings varying from 1.37 m $\times$ 1.37 m to 3.96 m $\times$ 3.96 m, the percentage of survival and the diameter at breast height (DBH) increased with increasing spacing, while merchantable height, stem volume, and basal area decreased with increasing spacing. Lowe (1976) also found that in a thinning experiment carried out in Nigeria, 20-year-old trees react positive in terms of individual tree growth 5 years after carrying a moderate and a heavy thinning in relation to the unthinned control, concluding that thinning reinforced rather than changed the pattern of discriminative growth within the stand, even for the heaviest thinning. Adegbeihn (1982) reports the effect of spacing (densities varying from 2600 to 748 trees ha^{-1}) on different tree and stand variables. The results show that whilst mean DBH, mean DBH of dominant trees, and basal area production are significantly affected by spacing, mean height, top height, and total volume production remain independent of the effect of this factor.

T. grandis has gained a worldwide reputation on account of the attractiveness and durability of its wood. Market demands have prompted the establishment of plantations within and beyond its native countries (Hoare and Patanapongsa, 1988; Monteuuis and Goh, 1999; Bhat, 2000). Approximately 223,000 ha of *T. grandis* plantations have been established in Central America (Pandey and Brown, 2000); in Costa Rica these plantations cover about 40,000 ha (Arias and Zamora, 1999), most planted during the last two decades. The Costa Rican government promoted the establishment of these plantations for high-yield and high-quality timber. However, yield is being found lower than anticipated (mean DBH of 35–40 cm and stand volume of 200–300 m^3 ha^{-1} at the age of 20 years). Despite the large-scale plantings, intensive management on a wide-spread basis is relatively new and the knowledge is little about the optimum spacing and thinning guidelines needed to maximize productivity. *T. grandis* appears to be a strongly site sensitive species and with strong discriminative growth (i.e. a quarter of the trees can account for more than half of the basal area increment as vertical dominance appears due to competition) (Lowe, 1976).

The aim of this study was to establish guidelines for the appropriate intensity and timing (with the objective of high individual tree growth and for saw timber production) of the first thinning (from approximately 4 thinnings recommended in 20–25 year-old rotation management systems) of *T. grandis* plantations in Costa Rica. The research was based on the hypothesis that an early and high-intensity thinning significantly increases the size of the remaining trees without a detriment on the extracted volume recovered in the short term. For hypothesis testing light, medium, and strong intensity thinnings (covering the range of intensities practiced on teak plantations in Costa Rica) were carried out at the time considered to be the best moment for this species, aiming at obtaining a matrix of possibilities for the intensive density management and for the selection of the best combination (time and intensity) for high individual tree growth management systems.

2. Materials and methods

2.1. The site

The thinning trial was established in San Carlos, Alajuela, on a site representing the typical warm, moist, and flat region of northern Costa Rica. The average annual temperature is approximately 26 °C with minor daily and annual fluctuations. The mean annual precipitation is 2900 mm with three dry months (rainfall 100 mm month^{-1}). The site is located at the altitude of 90 m a.s.l., at 84°23′ W and 10°30′ N, corresponding to the Tropical Wet Forest life zone (Holdridge, 1978). Soil texture is clay loam (>50% clay), with a pH of 5.2 and a slightly deficient nutrient status, with a particular deficiency of phosphorous (5.8 mg/L).

In an area originally cleared for farming, a 314 ha plantation of *T. grandis* was established in June 1994 with initial spacing of 2.5 m × 2.5 m (1600 trees ha^{-1}). Upon the commencement of the thinning trial at the age of 4 years (June 1998), trees had reached an average of 12.0 cm DBH and 14.5 m total height (*H*). The stand presented a full canopy closure but extreme competition was not evident (basal area less than 21.0 m^2 ha^{-1}). A first pruning (up to 3 m of height) was the only silvicultural intervention applied previously to the plantation area where the trial was established.

2.2. Experimental design and treatments

The experimental design consisted of randomized complete blocks, with eight treatments and three replicates. Previous to thinning, each treatment consisted of 80 trees (including missing trees) in square blocks of 500 m^2 (10 × 8 trees under a spacing of 2.5 m × 2.5 m), excluding the buffer zones consisting of two lines of trees between the treatments, each of them thinned according to the corresponding treatment they were bordering.

The trial consisted of different thinning intensities applied at two different timings (at 4 and 6 years of age, and one treatment thinned at 4 and 5 years of age). The treatments were:

(1) unthinned (1600 trees ha^{-1}) (Control);
(2) light thinning; removal of 25% of the original trees at the age of 4 years (25% 4th);
(3) moderate thinning; removal of 25% of the original trees at the age of 4 years and 25% of the original trees at the age of 5 years (25% 4th and 5th);
(4) moderate thinning; removal of 40% of the original trees at the age of 4 years (40% 4th);
(5) heavy thinning; removal of 60% of the original trees at the age of 4 years (60% 4th);
(6) light thinning; removal of 25% of the original trees at the age of 6 years (25% 6th);
(7) moderate thinning; removal of 40% of the original trees at the age of 6 years (40% 6th);
(8) heavy thinning; removal of 60% of the original trees at the age of 6 years (60% 6th).

The path followed by each treatment in terms of number of standing trees is presented in Table 1. All living trees were recorded and numbered with red paint. DBH and *H* were measured annually, using a diameter tape and a Suunto altimeter, respectively. When the thinnings were executed, preference was given to the retention of the most vigorous trees (dominants, straight stem, no diseases or stem defects, well-formed crown), although trees were selected as evenly spaced as possible. The last measurement was carried out in year 8, with the aim of evaluating the treatments on two different timings (ages 6 and 8 years) with a similar response period of 2 years after the corresponding thinning interventions (ages 4 and 6 years).

Table 1
Pre- and post-thinning results on stocking density, DBH, total height, basal area, and total volume in the different thinning treatments before and after each intervention

Age (years)	Control	25% 4th	40% 4th	60% 4th	25% 4th and 5th	25% 6th	40% 6th	60% 6th
	Stand density (trees ha^{-1})							
4	1493	1413	1420	1467	1480	1513	1467	1480
$4'$	1493	1160	940	640	1200	1513	1467	1480
5	1493	1153	940	620	1190	1513	1467	1480
$5'$	1493	1153	940	620	800	1513	1467	1480
6	1487	1140	900	580	780	1493	1467	1360
$6'$	1487	1140	900	580	780	1167	967	633
7	1467	1140	860	573	690	1153	953	620
8	1460	1153	873	567	680	1140	927	613
	DBH (cm)							
4	11.8	12.0	11.3	11.6	11.4	12.1	12.3	12.3
$4'$	11.8	12.4	11.9	12.7	11.8	12.1	12.3	12.3
5	13.2	14.1	13.9	15.6	13.6	13.4	13.7	13.6
$5'$	13.2	14.1	13.9	15.6	14.3	13.4	13.7	13.6
6	14.0	15.4	15.6	17.4	16.3	14.6	14.7	14.4
$6'$	14.0	15.4	15.6	17.4	16.3	15.4	15.9	16.0
7	14.9	16.3	16.6	19.3	17.8	16.1	17.0	17.4
8	15.2	16.5	17.2	20.1	18.9	16.6	17.5	18.3
	Total height (m)							
4	14.1	14.3	13.5	14.0	13.8	14.8	15.0	14.6
$4'$	14.1	14.6	14.0	14.6	14.2	14.8	15.0	14.6
5	15.9	16.1	15.5	16.2	16.1	16.0	16.2	15.9
$5'$	15.9	16.1	15.5	16.2	16.5	16.0	16.2	15.9
6	16.9	18.0	16.8	18.0	18.1	17.5	17.1	17.4
$6'$	16.9	18.0	16.8	18.0	18.1	17.9	17.5	17.9
7	17.4	18.6	17.8	19.1	18.8	19.1	18.8	18.8
8	17.7	18.8	18.2	19.4	19.2	19.5	18.8	18.8
	Basal area (m^2 ha^{-1})							
4	16.9	16.4	14.6	15.9	15.4	17.9	17.8	18.2
$4'$	16.9	14.4	10.7	8.2	13.3	17.9	17.8	18.2
5	21.2	18.5	14.5	12.0	17.5	22.0	22.2	22.3
$5'$	21.2	18.5	14.5	12.0	13.0	22.0	22.2	22.3
6	23.9	22.0	17.5	14.0	16.9	26.0	25.7	23.0
$6'$	23.9	22.0	17.5	14.0	16.9	22.4	19.5	13.1
7	26.8	24.6	19.0	17.1	18.0	24.5	22.1	15.2
8	28.0	25.8	20.7	18.2	19.4	25.6	22.7	16.4
	Total volume (m^3 ha^{-1})							
4	109	106	90	100	96	117	117	121
$4'$	109	64	68	62	88	117	117	121
5	146	132	102	89	121	153	156	157
$5'$	146	132	102	89	99	153	156	157
6	171	164	130	108	124	189	187	167
$6'$	171	164	130	108	124	167	146	98
7	198	188	145	138	137	187	169	119
8	209	199	159	149	156	197	177	131

($'$) After thinning.

Data were analyzed using Excel 2000. Average values of DBH (cm), total height (m), basal area (m^2 ha^{-1}), total volume (m^3 ha^{-1}) and their corresponding current annual increment (CAI) values were calculated for each treatment, on each replicate, and for each year of measurement. Total volume over bark (V_o) was calculated using the volume equations developed for *T. grandis* in Costa Rica by Pérez and Kanninen (2003). Analysis of variance (ANOVA) and other statistical analyses were carried out using the statistical software Systat 10.

3. Results

At establishment, the ANOVA revealed that some plots presented significant differences ($P < 0.05$) in DBH or in total height with others. However, this unexpected result was assumed to be part of the normal variation found in *T. grandis* forest plantations in Costa Rica and therefore not considered in the analyses.

In the first measurement, at the age of 4 years (before thinning), the average DBH was 11.8 cm, ranging from 11.3 to 12.3 cm. After thinning, the mean DBH increased to 12.2 cm and the range from 11.8 to 12.7 cm (Table 1, Fig. 1a). Mean total height averaged 14.3 cm (13.5–15.0 cm) and 14.5 cm (14.0–15.0 cm) before and after thinning, respectively (Table 1, Fig. 1b).

By the final measurement at year 8, the average DBH for all treatments was 17.5 cm (15.2–20.1 cm) and the total height averaged 18.8 m (17.7–19.5 m). The 60% thinning intensity applied at year 4 (60% 4th), and the two consecutive 25% thinnings at the ages of 4 and 5 years (25% 4th–5th) gave the highest values in terms of DBH, while the control gave the lowest (Table 1).

Significant differences in DBH were found at year 8, where the Control was lower than the rest of the treatments. The total height was not statistically different between the treatments, although the *H* of Control was lower than that of other treatments.

The basal area (BA) of the treatments carried out at year 4 ranged between 14.6 and 18.2 m^2 ha^{-1} (Table 1, Fig. 2a). The thinning with the highest intensity (60% of the standing trees) reduced the BA in 48%, decreasing from 15.9 to 8.2 m^2 ha^{-1}. At year 6, when the same treatments were repeated 2 years after, the BA of treatments without any intervention yet ranged between 23 and 26 m^2 ha^{-1}. The highest intensity thinning brought the BA from 23 to 13.1 m^2 ha^{-1} (43% extracted), similar to the highest intensity thinning performed at year 4. The recovery of the BA was faster in the treatments carried out at year 4 than those carried out at year 6, when both were measured 2 years after the thinning.

The corresponding volume development from the age of 4 to 8 years is presented in Table 1 and Fig. 2b. At both timings (age 4 and 6 years), the reduction in V_o corresponded to 10–40% of total volume. However, the treatments carried out at age 4 years recovered the extracted volume in 2 years (from age 4 to 6 years), but those of age 6 years could not achieve equal recovery during the same period of time (from age 6 to 8 years).

At the age of 8 years, the BA differed statistically ($P < 0.05$) between the Control and the rest of the treatments except the light thinning (25% of trees removal). The BA of the most intensely thinned treatment carried out at the age of 6 years (60% 6th) was statistically lower than that of the medium and light interventions, i.e. those with 25–50% intensity. Total volume was statistically different only between the Control and the treatments with medium- and high-intensity thinnings of both timings.

During the first year after the "early" thinning (from the age of 4 to 5 years), the CAI of DBH varied between 1.3 and 2.8 cm $year^{-1}$, being highest in the intensely thinned treatments. After the age of 4 years, the CAI of DBH decreased considerably in all treatments except one (treatment 25% 4th–5th). At the age of 8 years, the CAI of DBH ranged between 0.3 and 1.4 cm $year^{-1}$, decreasing therefore in average 60% in relation to the age of 4 years. The Current Annual Increment of *H* presented a similar pattern, ranging between 1.2 and 2.0 m $year^{-1}$at the age of 4 years, and between 0.2 and 1.0 m $year^{-1}$in the last measurement at the age of 8 years (Table 2).

The CAI of DBH decreased with increasing BA. However, this reduction started at relatively low values of BA: after 15 m^2 ha^{-1} the CAI of DBH was lower than 1.6 cm $year^{-1}$. The CAI of *H* also decreased with increasing BA from 1.5 to 0.7 cm $year^{-1}$ in all treatments except in treatment 60% 6th.

The CAI of BA decreased rapidly with increasing age in every treatment. Between the age of 4 and 5 years the CAI of BA ranged from 3.7 to 4.5 m^2 ha^{-1} $year^{-1}$, while between the age of 7 and

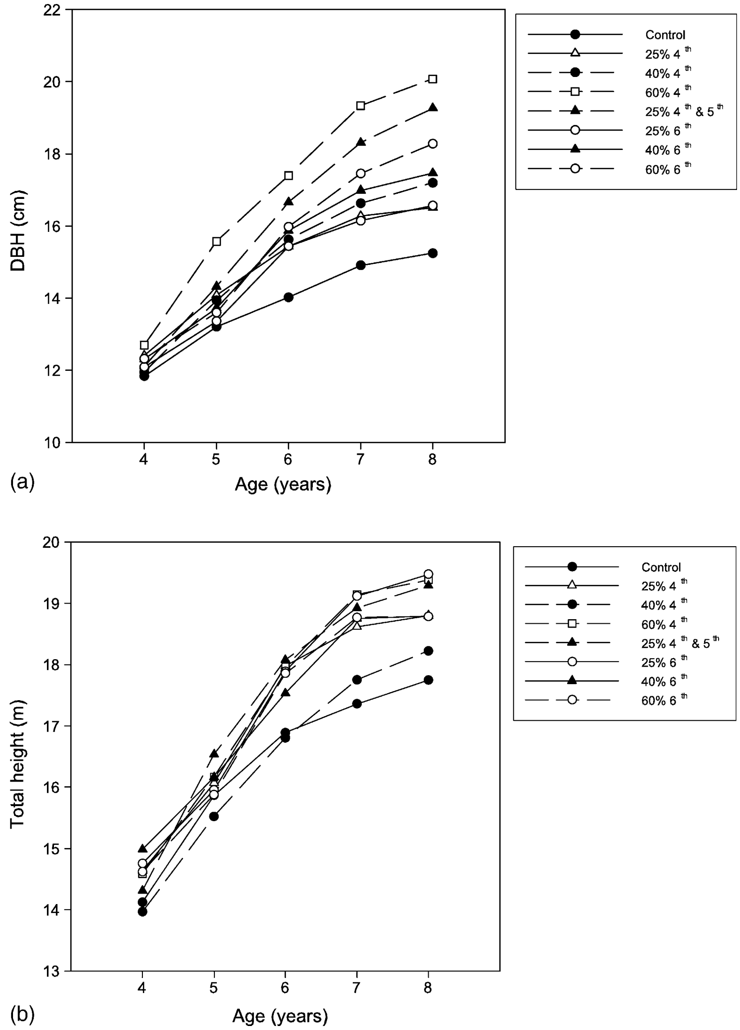

Fig. 1. Mean stand diameter (a) and height (b) after the thinning interventions from the age of 4 to 8 years for the different thinning treatments of *T. grandis* established in Costa Rica.

8 years, it was reduced to 0.6–1.7 $m^2\ ha^{-1}\ year^{-1}$ (reduction of 70%). Similar to this, the CAI of V_o decreased considerably with increasing age, from 26–39 $m^3\ ha^{-1}\ year^{-1}$ to 8.1–16.3 $m^3\ ha^{-1}\ year^{-1}$, which corresponded to a reduction of approximately 70%.

The CAI of BA decreased with increasing BA, reaching the maximum of 4.5 $m^2\ ha^{-1}\ year^{-1}$ at BA of 17.8 $m^2\ ha^{-1}$. The values of CAI of V_o varied between 9 and 39 $m^3\ ha^{-1}\ year^{-1}$ (Table 2). The highest values of CAI of V_o (>35 $m^3\ ha^{-1}\ year^{-1}$) were obtained at BA between 18 and 20 $m^2\ ha^{-1}$.

The V_o varied from 90 to 200 $m^3\ ha^{-1}$, at corresponding BA between 12 and 28 $m^2\ ha^{-1}$. As mentioned before, the highest CAI of BA occurred at BA of 18 $m^2\ ha^{-1}$, corresponding to a V_o of 120–150 $m^3\ ha^{-1}$. When the V_o for the eight treatments was plotted against DBH, different intensities and timings of thinning yielded different V_o to DBH combinations (Fig. 3).

4. Discussion

The thinned plots began to differentiate from the non-thinned ones, presenting differences up to 5 cm (30%) in DBH and 2 m (12%) in H at the age of 8

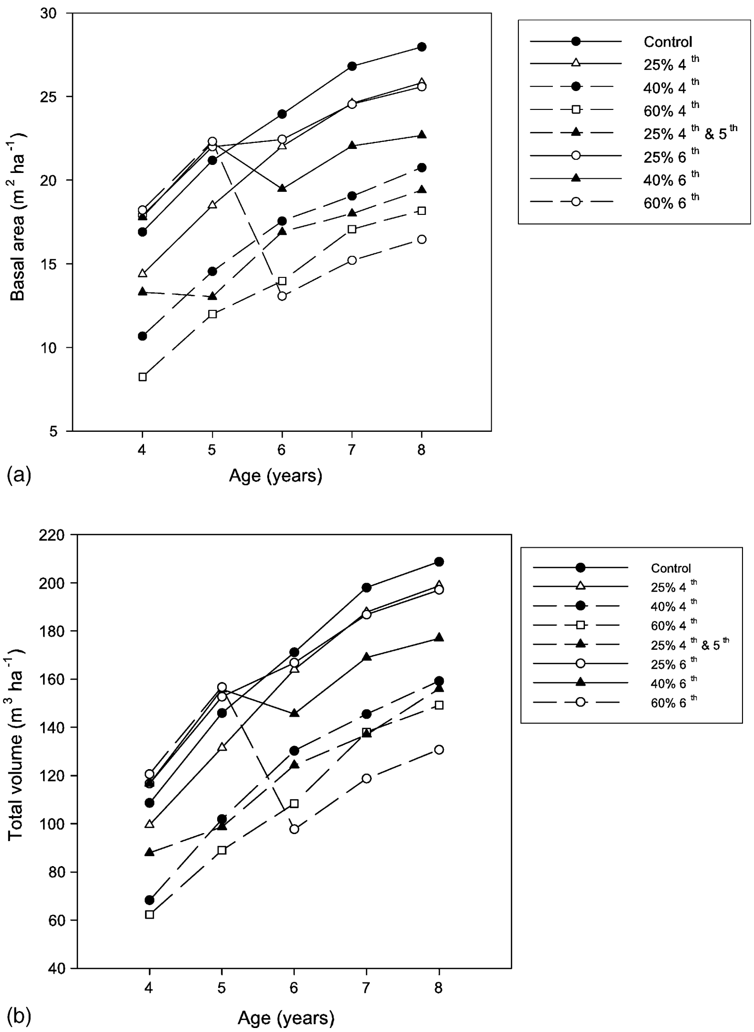

Fig. 2. Stand basal area (a) and stand total volume (b) after the thinning interventions from the age of 4 to 8 years for the different thinning treatments of *T. grandis* established in Costa Rica.

years. Similar results were found in another thinning trial established at the age of 4 years in a *T. grandis* plantation in Costa Rica by Chaves and Chinchilla (1991). Adegbeihn (1982) found significant differences in diameter growth but not in mean height growth in a *T. grandis* spacing trial established in Nigeria, supporting the view that diameter growth is sensitive to spacing. Gerrand et al. (1997) reported a significant response to thinning at the age of 6 years in a thinning trial of *Eucalyptus nitens* plantations for saw log production in Tasmania, expecting a continuation of the thinning response and resulting in a substantial reduction in rotation length.

Reductions in BA were up to 50% in the treatments where 60% of the standing trees were removed. The plots thinned at the age of 4 years recovered better than those thinned at the age of 6 years, when evaluated 2 years after the intervention (ages 6 and 8 years, respectively). This result indicates that the best moment for thinning is at the age of 4 years. Combining this result with the data on individual tree growth, our conclusion is that the best thinning

Table 2
Current Annual Increment (CAI) of DBH, total height, stand basal area, and stand total volume for the different thinning treatments

Age (years)	Control	25% 4th	40% 4th	60% 4th	25% 4th and 5th	25% 6th	40% 6th	60% 6th
	CAI DBH (cm year^{-1})							
4–5	1.3	1.6	2.0	2.8	1.7	1.3	1.4	1.3
5–6	0.8	1.3	1.6	1.8	1.9	1.2	1.0	0.8
6–7	0.9	0.8	1.0	1.9	1.4	0.7	1.1	1.5
7–8	0.3	0.5	0.9	0.7	1.4	0.4	0.5	0.8
	CAI Total height (m year^{-1})							
4–5	1.7	1.5	1.5	1.5	2.0	1.2	1.2	1.3
5–6	1.0	1.4	1.7	1.6	1.6	1.6	0.9	1.5
6–7	0.5	0.8	0.9	1.2	0.8	1.2	1.2	0.9
7–8	0.3	1.0	0.9	0.2	1.2	0.3	0.8	0.8
	CAI Basal area (m^2 ha^{-1} year^{-1})							
4–5	4.3	4.1	3.9	3.7	4.2	4.1	4.5	4.1
5–6	2.8	3.5	3.0	2.0	3.9	4.0	3.5	0.7
6–7	2.9	2.6	1.5	3.1	1.1	2.1	2.6	2.1
7–8	1.1	1.2	1.7	1.1	1.4	1.0	0.6	1.2
	CAI Total Volume (m^3 ha^{-1} year^{-1})							
4–5	37.4	67.1	33.6	26.5	33.4	36.1	39.0	36.1
5–6	25.2	32.5	28.5	19.5	25.5	36.6	31.7	10.3
6–7	26.9	23.8	15.2	29.6	12.8	20.1	23.3	21.1
7–8	10.8	11.0	13.7	11.1	19.0	10.2	8.1	12.0

regime is either to carry out the thinning at the age of 4 years and remove from 40 to 60% of the trees, or consecutively at the ages of 4 and 5 years and remove each year 25% of the initial number of trees. In other words, heavy thinning is better than light, and early thinning is better than late. Lowe (1976) carried out a *T. grandis* thinning experiment in Nigeria where a BA reduction from 32 m^2 ha^{-1} to 13 m^2 ha^{-1} was performed in the heavy thinning treatment, showing notorious improvement in terms of individual as well

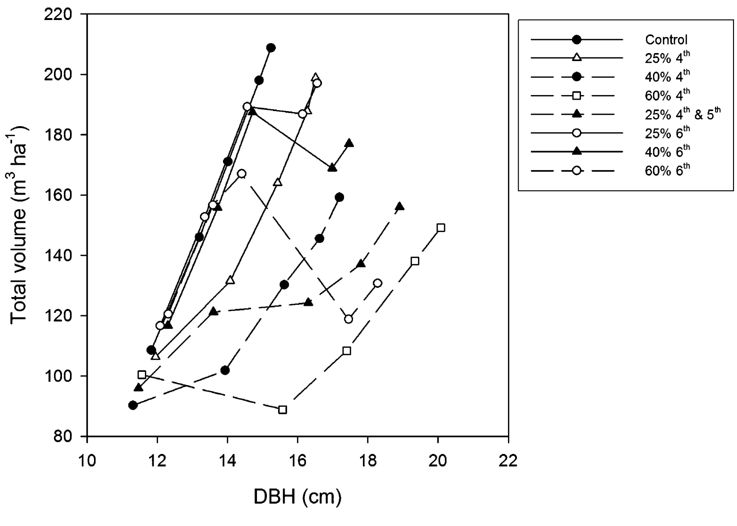

Fig. 3. Relationship between stand total volume and mean stand diameter (DBH) for different thinning treatments of *T. grandis* in Costa Rica.

as stand growth and suggesting that BA should be brought below 20 m^2 ha^{-1} in each thinning intervention.

Ola-Adams (1990) concluded after evaluating a spacing trial in Nigeria, that *T. grandis* should be planted at densities between 1189 and 1680 trees ha^{-1}, as individual tree growth declines on higher densities and stand growth potential is not reached on lower densities.

From our results, three different management regimes or options can be deduced: (1) 60% at the age of 4 years, (2) 40% at the age of 4 years, and (3) two consecutive thinnings at the ages of 4 and 5 years, each of 25% of the initial plantation density.

The first one (60% thinning intensity) requires more time than the other two options to recover the extracted BA (and V_o) and to increase the standing BA to adequate levels for a second thinning, but individual tree growth is significantly greater ($P < 0.05$) than in the other two cases. Therefore, this option can be recommended only if most of the remnant trees are of high quality and if there is no intention to use the removed trees commercially. In this regime, fewer interventions are needed over the rotation and a large (non-commercial) volume is extracted in the first intervention.

The second one (40% thinning intensity) recovers the extracted BA (and V_o) faster than the first option; a second commercial thinning can be performed approximately at the age of 8 years. The disadvantage of this in relation to the first option is that the remaining trees will be smaller (DBH and volume) than in the first option (Fig. 3).

The third option, which is the method used by the host company where this study took place, comprehends two consecutive thinnings at the ages of 4 and 5 years, where in each thinning 25% of the trees are removed. The results of this regime are similar to those of the 60% thinning intensity regime. However, two consecutive thinnings may result in higher management costs.

The highest BA found in the non-thinned treatments was 28 m^2 ha^{-1}, so we estimate that in this site, the maximum BA is approximately 30 m^2 ha^{-1}. If the management objective is to maximize individual tree size, stands under similar conditions should not reach this BA, since over 20 m^2 ha^{-1} competition increases and the growth of DBH decreases, particularly at BAs over 25 m^2 ha^{-1}. Other studies suggest that the critical point for the BA of *T. grandis* plantations varies between 15 and 32 m^2 ha^{-1} (Lowe, 1976; Keogh, 1979; Torres, 1982). However, if the objective is to maximize individual tree size, the upper BA limit will certainly have to be reduced to 25 m^2 ha^{-1} and less, for medium- and high-quality sites.

In both thinning interventions (ages 4 and 6 years), the reduction of total volume over bark (V_o) was of 10–40%. In plots thinned at the age of 6 years the reduction of V_o was more than double of those thinned at the age of 4 years.

The CAI of DBH and of H decreased markedly (in average 75% in CAI of DBH and of H) after the age of 4 years, even in thinned stands, which was unexpected for such a young *T. grandis* plantation. The growth values measured in our study at the age of 8 years were lower in DBH and similar in H than those reported for *T. grandis* in Costa Rica (Pérez et al., 2002; Ugalde, 1997; Vallejos, 1996; Vásquez and Ugalde, 1995). However, the initial stand density of our experiment (1600 trees ha^{-1}) was about 30% higher than the average stand density reported in Costa Rica, which may explain the difference in the results. In addition, we suspect that the reduction of growth may also be a consequence of either nutrient deficiency or other soil factors, such as drainage problems, compacted soil or low soil depth.

According to present results, the optimal CAI of BA can be obtained at a BA of approximately 18 m^2 ha^{-1} (Fig. 7). Both at lower as well as at higher BA values, the annual increment tended to decrease, suggesting an optimal BA range of 16–20 m^2 ha^{-1}. In another thinning trial established in Costa Rica, Chaves and Rodriguez (1995) found that for a 7-year-old *T. grandis* plantation the highest increment of DBH, total height, and BA corresponded to the treatments were the BA had been reduced to 17 m^2 ha^{-1}.

Based on the BA management criterion of 18 m^2 ha^{-1} for the first thinning to maximize annual tree and stand growth, the total stand volume should be managed between 120 and 150 m^3 ha^{-1} at the time of the first thinning. In sites similar to our study, this would yield, depending on the management regime, DBH values for the remaining trees between 17 and 20 cm at the age of eight (Fig. 3).

Similar interpretation of results was carried out by Yahya (1993) after evaluating an *Acacia mangium* thinning trial in Malaysia. According to the author, this species reacts favorably to thinning interventions with the improvement of the growth rates and crown size. However, it would be impossible to achieve an average diameter increment of 3 cm per year over the rotation time of 15 years. As a result, a reduction in the number of final crop trees and an increase in the rotation age were suggested.

Schönau and Coetzee (1989) reported the results of a factorial thinning experiment carried out in *Eucalyptus grandis* plantations in the Natal Midlands. The main factors were thinning intensity, commencement of first thinning, thinning frequency, and final stocking density. The results at 20 years of age indicated that the productivity ($m^3\ ha^{-1}\ year^{-1}$) was not influenced by any combination of factors, except those plots, which received 50% intensity thinning at 2 years interval starting before 6 years after planting.

The regime for the first thinning described above for *T. grandis* stands in Costa Rica would allow us to perform second, third, and fourth thinnings when the BA reaches values between 22 and 26 $m^2\ ha^{-1}$ (depending on site quality), and to reduce it to 15–18 $m^2\ ha^{-1}$ in each thinning. In such a case, the volume reduction in each thinning would be between 70 and 100 $m^3\ ha^{-1}$ (Pérez et al., 2002). This regime is similar to the density management regime developed for *T. grandis* plantations of Kerala by Kumar et al. (1995).

5. Conclusions

The 60% thinning intensity applied at the age of 4 years, and the two consecutive 25% thinnings at the ages of 4 and 5 years gave the highest values in terms of DBH, while the control was the lowest. The total height was not statistically different between the treatments, although the *H* of control was lower than that of other treatments. The total volume (V_o) varied from 90 to 200 $m^3\ ha^{-1}$, at corresponding BA between 12 and 28 $m^2\ ha^{-1}$.

The CAI of DBH was highest in the intensely thinned treatments. The CAI of DBH and BA decreased rapidly with increasing age in every treatment. The values of CAI of V_o varied between 9 and 39 $m^3\ ha^{-1}\ year^{-1}$. The high values of CAI of V_o were obtained at BA between 18 and 20 $m^2\ ha^{-1}$. At the BA of 18 $m^2\ ha^{-1}$, the V_o was between 120 and 150 $m^3\ ha^{-1}$, and the DBH of the remaining trees between 17 and 20 cm. The recovery of the BA and V_o was faster in the treatments carried out at the age of 4 years than those carried out at the age of 6 years, when both were measured 2 years after the treatment.

In terms of the remaining stand volume, tree size and rate of recovery, the best regime is either to carry out the thinning at the age of 4 years and to remove 40–60% of the trees, or consecutively at the ages of 4 and 5 years removing each year 25% of the initial number of trees. In other words, heavy thinning is better than light, and early thinning is better than late.

Present results are limited to recommend density management options for a first thinning on *T. grandis* plantations. Further evaluations of this thinning trial will provide useful information for the definition of the intensity and timing of the following thinning interventions (approximately 4 thinnings recommended on 20–25-year-old rotation management systems). Current findings dictate a base for intensive management practices in teak plantations, as it has been clearly evidenced that for saw timber production objectives, high-intensity thinnings offer great advantage over low-thinned or unthinned stands.

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