Effect of Pruning on Tree Growth, Yield, and Wood Properties of *Tectona grandis* Plantations in Costa Rica

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Reduced plantation densities have the effect that obtaining natural pruning and stem straightness are less assured. The physiological process of self-pruning is replaced by manual pruning. Generally, plantations are denser and have more uniform spacing than natural forests. In many, if not most species, natural pruning is never a satisfactory option, even after branch senescence, if production of clear wood is a management objective. Natural pruning can only be considered on a species by species basis.

This study reports on the first results of a pruning trial for *Tectona grandis* L.F. plantations in Costa Rica. The treatments consisted of pruning heights of 3.0, 4.0, and 5.0 meters, and the Control without pruning. Differences among treatments in DBH and total height were significant at 3.2, 5.2, and 6.1 years of age, but not at 7.3 years.

Under an intensive pruning regime, a teak tree at rotation (20 years) may yield over 40% of knot-free volume (over 60% of the merchantable tree volume). Current findings open a scope for new management options, aiming at improving stem form and wood quality by means of an intensive pruning regime, without having a detrimental effect on tree growth and stand yield.

Keywords teak, heartwood volume, stem form, knot-free volume, wood quality
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1 Introduction

International grading rules establish strict standards for classifying high-quality timber, which include the appearance of knots (number, frequency, diameter, sound or unsound). Yield and market prices decrease considerably for trees without pruning interventions, since lumber must be almost knot-free in order to obtain a high monetary value. Knots are widely considered as the most determinant defect for wood quality classification, in large part, because they influence the origin and magnitude of other defects such as pith eccentricity, stem form deviations (from the geometric cylinder shape), and bending (Rosso and Ninin 1998).

There are few reports on teak pruning, mainly because natural pruning has been considered to produce sufficient knot-free volume. Recent studies on teak in India suggest that pruning before the first thinning is not beneficial for teak. Studies have also shown that late pruning is useless; therefore, it is logical to prune between the second and third thinnings (Jha 1999).

Studies on pruning have been carried out species other than teak. For example, the effect of pruning intensity on tree growth was studied in a plantation of *Pinus elliottii* Englem. in Rio Grande do Sul, Brazil. The pruning treatments resulted in great losses of volume production: there was a 12% loss with 40% pruning intensity and a 14% loss with 60% pruning intensity, at the age of 13 years). Therefore, pruning intensities below 40% of the total height are recommended (Schneider et al. 1999). In another study, survey data of maritime pine (*Pinus pinaster* Aiton) branching habits (based on surveys in young plantations, aged 11 to 17 years) indicated an average of 18 branches between the heights of 2.5 and 5.5 m above ground level, many of which were 2.2 to 3.0 cm in diameter. Therefore, in good quality plantations, pruning enhances overall growth rates and results in the production of knot-free stems (Alazard 1996).

In Costa Rica, as in many other countries, no official classification norms have been developed to differentiate and grade wood quality improvements by means of pruning. Consequently, few plantation owners are receiving a premium price for clear wood. The important property requirements of fast-grown *Tectona grandis* L.F. plantations include straight bole with least taper, reduced flutes and buttresses, and knot-free volume. Unsound hollow knots and deep flutes are the two major factors influencing sawn wood grade. However, no adequate data are available for timber grown with intensive silvicultural practices including pruning (Bhat 1998).

Torres et al. (1995) carried out a silvicultural evaluation of forest plantations in Costa Rica, finding that pruning is more often considered a cleaning activity rather than a silvicultural technique. Frequently, drastic pruning (the removal of almost all the branches) of young trees is practiced by small-scale farmers as well as by medium-size companies. There are few recommendations regarding pruning intensities for forest plantations in Costa Rica. However, in general, it is recommended that up to 50% of the trees' total height be pruned just after the first thinning (Keogh 1987, Chaves and Fonseca 1991), or according to commercial log sizes, i.e. up to 2.5 m sections (Murillo and Camacho 1997). Galloway (1993) recommends a first pruning in species that form large branches when tree height is only 3.0 meters and, in the case of teak, 4.0 meters. The second pruning takes place after the first thinning. Pruning should be done to the height of complete log lengths, since it is unlikely that someone will pay a premium price for a half-pruned log. Pruning is primarily an economic decision and the extra effort for extensive pruning must be rewarded with a premium price.

The present trial was designed according to the pruning methodology developed for *T. grandis* plantations in Costa Rica by Pérez et al. (2003). According to this study, independently of the site quality, the first pruning, of up to 2.0–3.0 m, should be carried out when trees reach a total height between 4.0 and 5.0 m (at approximately 2.0 years of age on high quality sites). In a second intervention, trees should be pruned up to 4.0–5.0 m when the stand reaches between 9.0 and 10.0 m of total height (at approximately 3.0 years of age on high quality sites). In a third intervention all the branches up to 7.0 m (or higher if the last usable section exceeds this height and the plantation quality assures an eventual attractive return on investment) should be pruned when trees reach 12 m of total height (at approximately

4.0 years of age on high quality sites). The authors suggest that the pruning of *T. grandis* in Costa Rica can be economically feasible for rotations of 15 years and more if performed adequately and in a timely manner.

As there are no reports about pruning trials established for *T. grandis* in Costa Rica, this study can be considered as one of the first approaches towards the definition of the optimum pruning regimes for this species. This study aims at evaluating the first results of a pruning trial with different intensities for *T. grandis* plantations in Costa Rica, based on the hypothesis that medium-intensity pruning increases wood quality without detrimentally affecting tree growth and stand yield.

2 Methodology

2.1 Site Description

The experiment was established on a 2.2-year-old *T. grandis* plantation, property of Precious Woods Costa Rica, located in the northwest region of Costa Rica. The mean annual rainfall is 2231 mm year^{-1} with a five-month dry period. The average annual temperature is 27.5 °C, ranging from highs of 34.9 °C to lows of 18.5 °C. The relative humidity averages 76%, where May and October are the most humid months (at 78% and 87%, respectively) (Instituto Meteorológico Nacional 1996). The terrain has a less than 5% gradient, at 15 m.a.s.l. The specific site conditions – flat, with good natural drainage and fertile soils – are excellent for teak growth, as demonstrated by the excellent diameter and height growth (22.4 cm and 17.0 m, respectively, at 7.3 years of age).

The plantation was established in April of 1995, with a stand density of 952 trees ha^{-1} (3.5 m × 3 m spacing). The seed origin is unclear as stated by Keogh et al (1978). The primary maintenance activity implemented in the first two years was weeding, together with the removal of secondary apical shoots during the first year.

2.2 Trial Design

At the establishment of the trial, the plantation (aged 2.2 years) was highly uniform with a mean DBH of 7.6 and a standard deviation of ± 0.12 cm, and a mean total height of 7.1 ± 0.12 m. The trial consisted of a complete block randomized design with four treatments and three replications. Each plot contained 25 trees (15.0 m × 17.5 m, 262.5 m^2), planted at 3.5 × 3.0 m spacing. A buffer zone of two lines was left between treatments and around the experiment. Each line received the exact same pruning intensity as the treatment they were bordering. The treatments were:

1) Control, no pruning of branches
2) Pruning up to a height of 3.0 m
3) Pruning up to a height of 4.0 m
4) Pruning up to a height of 5.0 m

At the age of 5.2 years, a second pruning up to a height of 7.0 m was carried out on all treatments except the control. In order to simulate an intensive management regime, at the age of 6.1 years the trial was thinned for the first time and the stand basal area of all treatments was reduced to 15 m^2 ha^{-1}. For scaling from tree to stand level, the number of trees found in the plot of 262.5 m^2 was projected to the area of one hectare (10 000 m^2). Any variable which required being scaled in per hectare values was first calculated individually, e.g. heartwood content per tree, then each value was added and multiplied by "38.1", which corresponded to the scaling factor from the plot area to a hectare (10 000 m^2/262.5 m^2).

2.3 Stem Analysis and Knot-free Volume Projections

Diameter at breast height (DBH) and total height were measured at 2.2 years of age and afterwards at ages of 3.2, 5.2, 6.1, and 7.3 years. Thirty-six trees from the thinning carried out at the age of 6.1 years were selected to measure total volume per tree and to carry out stem analyses, in order to determine heartwood content, stem taper, and stem form factor.

Cross-sectional stem samples (disks) were taken from each felled tree at 0.3 m and at 1.3 m from the base. Starting at the height of 2.0 m, sections were taken along the stem at 2.0 m intervals. First, heartwood mean diameter was calculated as the average of two cross-sectional measurements (direction North-South and East-West) for each stem section. Second, total mean diameter (with and without bark) was calculated following the same procedure. Next, heartwood, sapwood and bark cross-sectional area (cm^2) were calculated as a geometric circle. Finally, the total volume (cm^3) of sapwood, heartwood and stem (with and without bark) was calculated using the Smalian formulae (Clutter et al. 1983). The last stem section, from the last-taken disk to the tip of the tree was calculated as a geometric cone. Analysis of Variance and Duncan's test were carried out for each variable using the Systat 10.

Projections of knot-free volume of a pruned tree were carried out using the pruning regime recommended by Pérez et al. (2003), the volume equations of Pérez and Kanninen (2003), and the growth projections developed for teak in Costa Rica by Pérez and Kanninen (2005). A growth scenario was selected considering the growth in DBH and total height at different ages through rotation. Then, a profile of an average tree was projected at ages 2.0, 4.0, and 5.0 years where the first, second, and third pruning should take place. Finally, the stem volume was calculated at the different ages where each pruning should take place, calculating the gain in knot-free volume between pruning interventions and through rotation. It was possible to estimate the stem volume up to the different pruning heights and the eventual production of knot-free volume with each pruning intervention using the variable top diameter and top height volume equations of Pérez and Kanninen (2003).

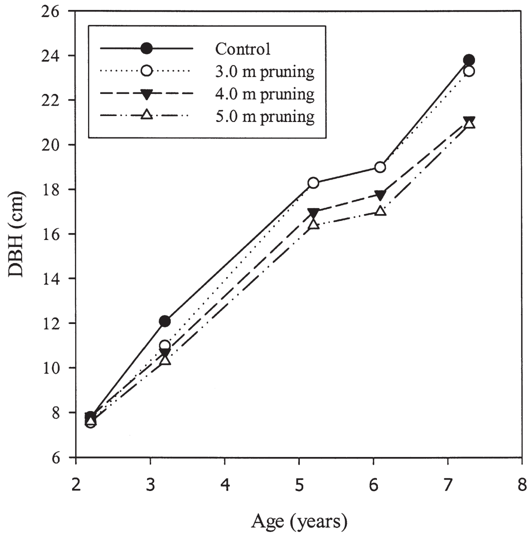

Fig. 1. Stand development in terms of DBH for the different treatments of the pruning trial established for *T. grandis* in Costa Rica.

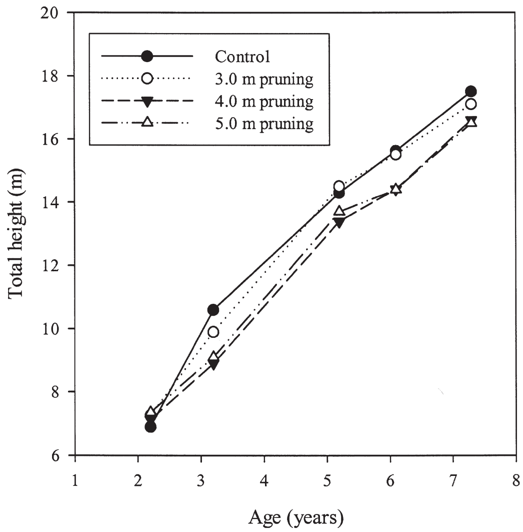

Fig. 2. Stand development in terms of total height for the different treatments of the pruning trial established for *T. grandis* in Costa Rica.

3 Results

3.1 Tree Growth and Stand Yield

The initial values of DBH, total height, and stand density were highly uniform among treatments and replications, with coefficients of variation < 7.1%. The stand growth and yield fall into the category of "high quality site", according to reports for *T. grandis* in Costa Rica (Chaves and Fonseca 1991, Pérez and Kanninen 2005, Vásquez and Ugalde 1995), with peak current annual increments of 4.4 cm in DBH and 3.4 m in total height (Figs. 1 and 2). The initial stand density was 952

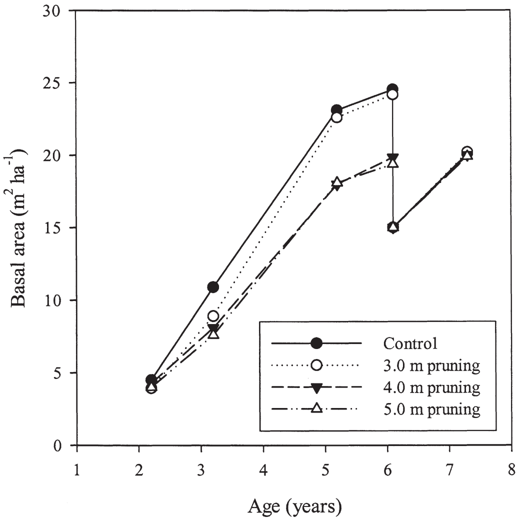

Fig. 3. Stand development in terms of basal area for the different treatments of the pruning trial established for *T. grandis* in Costa Rica. The trial was thinned to 15 $m^2 ha^{-1}$ between the two last measurements.

trees ha^{-1}, with a basal area between 4.0 and 4.6 $m^2 ha^{-1}$. At the age of 5.2 years, the basal area varied between 18.0 and 23.1 $m^2 ha^{-1}$ (Fig. 3).

The analysis of variance for the first measurement after pruning (3.2 years of age) showed significant differences ($P<0.05$) among treatments for DBH, total height, basal area and total volume per hectare (Table 1). DBH was higher in the Control and statistically different from the other treatments except for 3-m pruning. Differences in total height were significant between the Control and 3-m pruning, and between these two and 4-m and 5-m pruning treatments. Differences in volume per hectare were statistically significant between the Control and the 4-m and 5-m pruning. Basal area was statistically different between the control and 5-m pruning.

At the age of 5.2 years (3 years after pruning), differences between average DBH values of the Control and the 3-m pruning treatments, and those of the 4-m and 5-m pruning treatments were statistically significant ($P<0.008$). Differences in total height between the Control and the 4-m pruning were also statistically significant according to Duncan's test. The tallest trees were produced in treatment 3-m pruning, although the height difference was statistically significant only with treatment 4-m pruning. The Duncan's test showed two groups statistically different for the variable DBH; the Control and 3-m pruning presented the highest DBH values while the lowest were found in 4-m and 5-m pruning. Differences in total volume per hectare varied between 33 and 38%, when comparing the Control and 3-m pruning with 4-m and 5-m pruning.

Very similar results were obtained at 6.1 years of age. Differences among treatments were statistically significant for DBH and total height, and similar groupings were obtained from Duncan's test. The effect of pruning intensity was evident even four years after trial establishment. At this age (6.1 years) an important decrease on tree current annual increment in growth was detected, indicating a strong competition among trees and the urgent need for thinning, which was executed immediately, reducing the stand basal area to 15 $m^2 ha^{-1}$.

Table 1. Duncan's test for the stand variables DBH, total height, and basal area.

Treatment	Measurement at 3.2 years of age				Measurement at 5.2 years of age			Measurement at 6.1 years of age		
	DBH (cm)	Total height (m)	Basal area ($m^2 ha^{-1}$)	Total vol. ($m^3 ha^{-1}$)	DBH (cm)	Total height (m)	Basal area ($m^2 ha^{-1}$)	DBH (cm)	Total height (m)	Basal area ($m^2 ha^{-1}$)
Control	12.1 a	10.6 a	10.9 a	53.8 a	18.3 a	14.3 ab	23.1 a	19.0 a	15.6 a	24.5 a
3.0 m pruning	11.0 ab	9.9 b	8.9 ab	42.0 ab	18.3 a	14.5 a	22.6 a	19.0 a	15.5 ab	24.2 a
4.0 m pruning	10.7 b	8.9 c	8.1 ab	33.7 b	17.0 b	13.4 b	18.0 a	17.8 ab	14.4 b	19.8 a
5.0 m pruning	10.3 b	9.1 c	7.6 b	31.9 b	16.4 b	13.7 ab	18.1 a	17.0 b	14.4 ab	19.4 a

Duncan's grouping: means with the same letter are not significantly different.

A last measurement was carried out at the age of 7.3 years, finding no significant differences for any of the variables. However, the initial differences accumulated during the first three years after pruning were still present, as well as the differences between the Control and 3-m pruning with 4-m and 5-m pruning (24 vs. 21cm in DBH and 0.332 vs. 0.256 m^3 in total volume per tree).

3.2 Wood Quality

Total volume per tree differed significantly among treatments ($P<0.07$); 3-m pruning differed significantly from 4-m and 5-m pruning, but not from the Control, presenting differences of up to 40% in tree total volume (Table 2). Similarly, the heartwood volume was found to be greater in the 3-m pruning than in the rest of the treatments, but was not statistically different from the Control. 3-m pruning presented 142% more heartwood volume than 4-m and 5-m pruning, and 35% more than the Control. No significant differences were found for sapwood volume, although, 3-m pruning and the Control showed between 17 and 20% more sapwood than the other treatments.

In the present study, stem form tended to vary slightly among treatments, however differences were statistically significant. The 3-m pruning yielded the highest taper factor (1.82 cm m^{-1}), i.e. the least cylindrical stem form of all treatments (Table 2); results were statistically different ($P<0.05$) from the 4-m and 5-m pruning but not from the control. The stem form factor varied between 0.434 and 0.464 (3-m and 5-m pruning, respectively) but showed no significant differences.

Heartwood volume was higher in the 3-m pruning and varied between 14% and 25% (5-m and 3-m pruning, respectively). The Control presented 20% of heartwood volume, while the high-intensity treatment (5-m pruning) contained only 14%. Before thinning at age 6.1 years, the Control and the 3-m pruning treatment presented the highest stand total volume, with 166 and 162 $m^3 ha^{-1}$, respectively. The 4-m and 5-m pruning treatments reached an average total volume of 128 $m^3 ha^{-1}$. The 3-m pruning yielded the highest heartwood volume of the trial (45.4 $m^3 ha^{-1}$). The lowest values (21.2 and 21.7 $m^3 ha^{-1}$) corresponded to the 4-m and 5-m pruning, while the Control showed an intermediate value of 37.8 $m^3 ha^{-1}$ (Fig. 4).

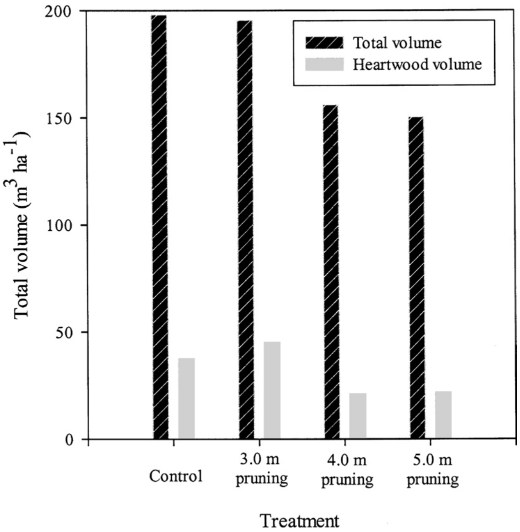

Fig. 4. Total and heartwood volume projected to stand level (per hectare values) at the age of 6.1 years for the different treatments of the pruning trial of *T. grandis* in Costa Rica.

Table 2. Duncan's test for tree volume and stem form variables at 6.1 years of age (4.0 years after pruning).

Treatments	Total volume ($m^3 tree^{-1}$)	Heartwood volume ($m^3 tree^{-1}$)	Sapwood volume ($m^3 tree^{-1}$)	DBH/total height ratio	Taper factor ($cm m^{-1}$)
Control	0.166 ab	0.034 ab	0.096 a	1.07 ab	1.69 ab
3.0 m pruning	0.183 a	0.046 a	0.097 a	1.20 a	1.82 a
4.0 m pruning	0.135 b	0.019 b	0.082 a	1.03 b	1.59 b
5.0 m pruning	0.131 b	0.019 b	0.081 a	1.03 b	1.57 b

Duncan's grouping: means with the same letter are not significantly different.

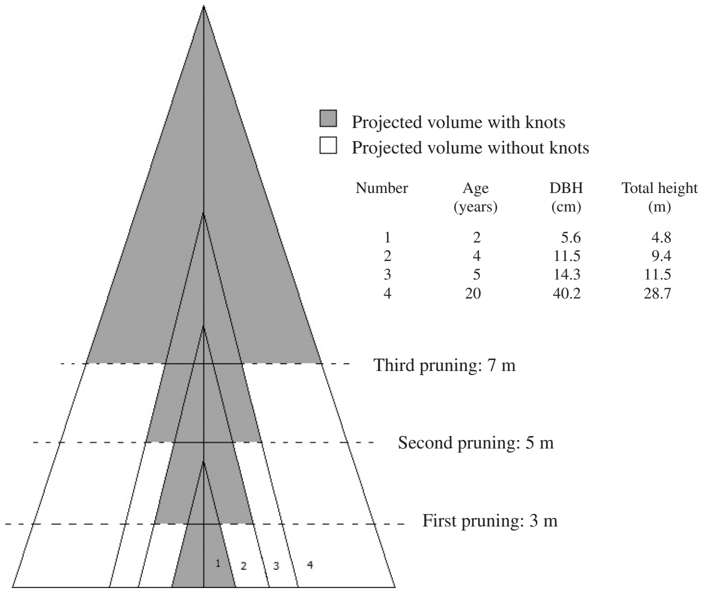

Fig. 5. Projected stem volume with and without knots according to the pruning system suggested by Pérez et al. (2003) for *T. grandis* in Costa Rica.

3.3 Estimation of Knot-free Volume

The projected volume without knots (See Fig. 5) was calculated using the growth projections of Pérez and Kanninen (2005) and the volume equations at variable stem diameter and tree height of Pérez and Kanninen (2003) for *T. grandis* plantations in Costa Rica. This figure shows the projections after each of the three pruning interventions suggested by Pérez et al. (2003), on which the present study was based in principle, and the average tree in a scenario of a 20-year-old rotation. According to this, a 20-year-old teak tree (under an intensive pruning program) will present a total knot-free volume of 0.839 m^3 vs. a total tree volume of 1.364 m^3.

The time it takes for different layers of wood to close the wound after pruning is not taken into consideration in this analysis, i.e. it is assumed that if the pruning interventions are executed properly and in a timely manner, the wounds will heal relatively quick and the loss of knot-free wood will be minimal. Next to validating these estimations, it would be important to determine the heartwood percentage out of the total knot-free volume, as heartwood increases considerably the price of teak timber.

4 Discussion

4.1 Tree Growth and Stand Yield

At trial establishment (2.2 years of age), trees were oversized in relation to the recommendations of Pérez et al. (2003) for the first pruning of teak in Costa Rica, reaching a mean height of 7.1 m and a mean DBH of 7.6 cm. The knotty core of 8.0 cm is still appropriate; however, an earlier pruning may be considered if branch size becomes a problem. Based on a previous study of foliage biomass for teak (Pérez 1996), it was estimated that the corresponding biomass removal for the currently implemented treatments (Control, 3.0 m, 4.0 m, and 5.0 m pruning) were, 0%, 49%, 72%, and 85%, respectively.

Annual diameter or volume growth rates of severely pruned trees may eventually recover to equal un-pruned tree growth rates, however cumulative growth rates are unlikely to recover lost growth (O'Hara 1991). Similar results were found on the present study, as the accumulated differences in the first three years after pruning were still present at age 7.3 years.

The usual objective of a project or company is to maximize the stand total and heartwood volume; a first pruning to 3.0 m high offers a feasible option for optimization, as the individual tree volume is not reduced as consequence of the increments in stand volume. However, at early plantation stages these positive improvements are not guaranteed, as other factors, such as density management, may influence future stand dynamics.

At early stages (5.0 years of age), *T. grandis* trees can produce over 15 branches with a diameter up to 6.0 cm along the stem, reducing the wood quality severely if an adequate pruning regime is not implemented (Pérez et al. 2003). Moreover, by that time the defect core diameter will be greater than 15 cm, the pruning would be more expensive, and the economic feasibility of the activity may be threatened, as the percentage of knot-free volume that will be produced afterwards may be insufficient for obtaining high returns on the investment.

According to Rosso and Ninin (1998), knots on 26-year-old teak in Venezuela cover up to 20% of the total log volume, increasing with increasing stem height (first two logs present between 4.0 and 13.0%). The authors also report an increment in stem bending, pith eccentricity, and ellipse-shape with increasing area of knots. Majid and Paudyal (1992) consider that pruning should be done at early stages in order to restrict knotty cores to a minimum. Moreover, early pruning (at 2.0 or 3.0 years of age for tropical species) should be done on all trees to avoid suppression by neighboring trees. In the case of *Acacia mangium* Willd. plantations, the authors proposed a first pruning up to 4.0 m, and a second pruning up to 6.0 m. The regime proposed by Gerrand et al. (1997) considers the previously mentioned criterion of the minimum defect core diameter, which according to them should be kept under 15 cm. Therefore, pruning should be executed early, when branches do not surpass 2.5 cm in diameter.

International grading rules do not allow the presence of knots in "special" grade timber. For first quality or grade 1, the permissible amount of knots is 1 per linear meter, with a maximum diameter of 1.25 cm. For the lowest grade within international standards (grade 3), a total of 3 knots per linear meter with a maximum of 3.81 cm of diameter is allowed (Tanteak 1995). Timber recovery rates reported for mature teak (70-year-old) in Malaysia vary between 23 and 30% for Prime (Grade 1), Standard (Grade 3), Serviceable (Grade 5), and Utility (Grade 6) grades (Tze 1999). By means of an intensive pruning regime that reduces the number, frequency, and diameter of knots, the timber recovery and the grading may be improved considerably, as logs of higher quality will result in a higher timber recovery rate.

4.2 Wood Quality

Heartwood formation is a growth-regulating process to develop and to maintain an optimum sapwood volume. In this way the nutritional balance in the living part of the tree is conserved, as the sapwood on heartwood formation reabsorbs the essential elements. The presence of heartwood influences the utilization of wood in different ways and affects its uniformity. This contributes to the uncertainty between forest inventory and the quality of wood available for use (Hillis 1987).

Differences in total volume as product of the different pruning regimes were more evident in terms of heartwood volume than in terms of sapwood volume, showing the 3.0 m with the highest individual tree growth and heartwood content. Pruning of branches may have reduced the efficiency of sapwood in certain areas, enabling the formation of heartwood; all this without a detrimental effect on tree growth as the removed foliage represented less than 50% of the total (Pérez et al. 2003).

For species other than teak, Margolis et al. (1988) consider that the unstained center of the stem, which can be interpreted as heartwood, may be temporarily immobilized sapwood rather than true heartwood; this explains the difficulty to establish the boundary between heartwood and sapwood, and could be used eventually as an indicator of stress. These authors report an increment in heartwood area in heavily pruned *Abies balsamea* (L.) Mill. trees, while Långström and Hellqvist (1991) found that a reduction in growth but an increment in heartwood area (immobilized sapwood) in 25-year-old *Pinus silvestris* L. were direct results of a pruning regime.

The 3.0 m pruning treatment produced trees with a better DBH/total height relationship but with a less cylindrical stem form than the other treatments. An explanation for this inconsistent behavior is that trees in this treatment had similar total height values but greater DBH than trees in the other treatments; therefore taper is greater although presenting a better DBH/total height ratio. These findings do not have an economical impact as trees are still young, but they open a scope for new management options, where the stem taper and the stem form factor can be improved by means of pruning, although at the expense of a slight decrease in DBH.

5 Conclusions

Present results show the importance of implementing intensive pruning regimens, as inadequate interventions may threaten the growth, yield, and wood quality of *T. grandis* plantations. In addition, within the concept of an intensive management system, it is of primary importance to develop a silvicultural strategy which includes both thinning and pruning and which clearly recognizes the relationship between these operations.

Pruning up to 3.0 m high in the first intervention produces trees with high individual growth and heartwood formation, with a better DBH/total height relationship, and results in the most suitable pruning intensity option for reaching maximum stand total and heartwood volume.

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