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Stand growth scenarios for *Tectona grandis* plantations in Costa Rica

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Abstract

Management scenarios with rotation lengths of 20 and 30 years were developed for different site qualities (high, medium and low) under two different management options (high individual tree growth versus high stand growth) for teak (*Tectona grandis* L.f.) in Costa Rica. The scenarios are based on data collected in different regions in Costa Rica, representing different site conditions, offering a variety of possible management options for high-quality teak yield.

Three competition indices were used for modeling the competition and for the definition of intensities and the plantation age at thinning. The maximum site occupation (MSO) and the Reineke density index (RDI) provide conservative stand density management limits, resulting in the need to execute several thinning frequently. The competition factor (CF) matches the field observations and seems to be more appropriate for the growth characteristics of the species.

Final stand densities varied between 120 and 447 trees ha^{-1}, with mean diameter at breast height (dbh) of 24.9–47.8 cm, and mean total heights between 23.0 and 32.4 m, depending on rotation length and site quality. The mean annual increment of total volume (MAI_{Vol}) at the end of the rotation varied from 11.3 to 24.9 m^3 ha^{-1} $year^{-1}$, accumulating a total volume over rotation of 268–524 m^3 ha^{-1}.

The most suitable scenario for teak plantations for high-quality sites is the 30-year-rotation scenario with five thinnings of intensities between 20 and 50% (of the standing trees) at the ages of 4, 8, 12, 18 and 24 years. After the sectioning of the merchantable stem in 4-m length logs, the merchantable volume varied between 145 and 386 m^3 ha^{-1}, with an estimated heartwood volume of 45–195 m^3 ha^{-1}, both depending on rotation length and site quality.

Keywords: Competition factor; Individual tree growth; Stand growth; Site quality; Merchantable volume

1. Introduction

Fast grown forest species require a timely and intensive management schedule to obtain high yield and high-quality timber, thus success can only be

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achieved by performing intensive and on time silvicultural interventions. Besides the wood esthetic characteristics, sufficient size is an important quality criterion in saw milling. A minimum size is required in many processes and high log diameter usually means high sawing yield (Persson, 1986). An efficient way to increase productivity of forest plantations is to optimize the stand density and rotation age (Jayaraman and Zeide, 2003).

Tectona grandis has gained a worldwide reputation on account of the attractiveness and durability of its wood. Teak is suitable for multiple end uses, including construction, furniture and cabinets, railway sleepers, decorative veneer, joinery, ship and vehicle body building, mining, reconstituted timber, etc. (Bhat, 2000). Market demands have prompted the establishment of plantations within and beyond its native countries (Hoare and Patanapongsa, 1988; Monteuuis and Goh, 1999; Bhat, 2000). In Costa Rica, the species was introduced in 1940 and was prompted at the beginning of 1980 by the Costa Rican government, effort that lead to a reforestation area of 40,000 ha by the year 1999 (Arias and Zamora, 1999; Keogh et al., 1978).

In Costa Rica and other countries in Central America, most of the forest plantations have not reached the expected productivity. The main causes for this are inappropriate site selection, use of poor planting material and lack of appropriate silvicultural programs. Development of management scenarios for timber production is particularly necessary in the case of advance-aged, fast-grown forest plantations (over 15 years) approaching the commonly expected rotation period in Costa Rica and Central America (between 20 and 30 years).

Increased yield, higher uniformity and shorter rotations are strong incentives for developing *T. grandis* intensively managed plantations. However, no adequate data are available on intensive silvicultural practices for high-quality teak culture (Bhat, 1998). Although many reports are available on growth and yield of teak, only few of them provide efficient tools and procedures for the intensive management the tropics. These include, e.g. Dupuy and Verhaegen (1993) and Dupuy et al. (1999) for Côte DÍvoire, Adegbehin (2002) for Northern Nigeria, Phillips (1995) for Sri Lanka, Vánclav and Skoupý (1972) for Bangladesh and Gonzales (1985) for Philippines. However, they report growth and yield of stands but they do not contain formulations of criteria for developing management guidelines.

Alternative density management regimes for forest plantation can be developed using density management diagrams (Jack and Long, 1996). Kumar et al. (1995) developed these diagrams for teak plantations in Kerala (India), aiming at optimizing teak production under different management objectives. In Costa Rica, Bermejo et al. (2004) developed growth and yield models for a teak plantation in a specific site in the northwestern region (Guanacaste Province).

Annual growth records of teak stands are scarce in the tropics because of the absence of permanent sample plots. In addition, the climatic conditions cause the formation of false rings (Priya and Bhat, 1998).

The aim of this study was to generate density management scenarios for the intensive management of *T. grandis* plantations in Costa Rica, using competition indices as guidelines for defining the timing and intensity of thinnings.

2. Materials and methods

T. grandis plantations were evaluated in different regions of Costa Rica (Fig. 1), including the following sites (and provinces): Carrillo, Garza and Tempisque (Guanacaste); Jicaral, Parrita, Quepos, Palmar Norte and Buenos Aires (Puntarenas); San Carlos (Alajuela); Guapiles (Limon). Over 150 plots of approximately 80 trees each (including missing trees) were measured, with ages between 1 and 47 years. In total, 10,707 trees were measured for this study.

The development of growth functions for diameter at breast height (dbh) and total height with age was based on a fitted curve (Chapman–Richards model). For this, dominant trees (approximately 3800 observations) were selected from the database, corresponding to the fourth Quartile (>85th percentile). The reason for this data selection was to develop different scenarios based on the potential growth of the species under intensive management, i.e. discarding plantations with no adequate management and low growth rates. Fig. 2 shows the dbh and total height growth curves used for developing the management scenarios. The curves on each figure represent the growth in a site

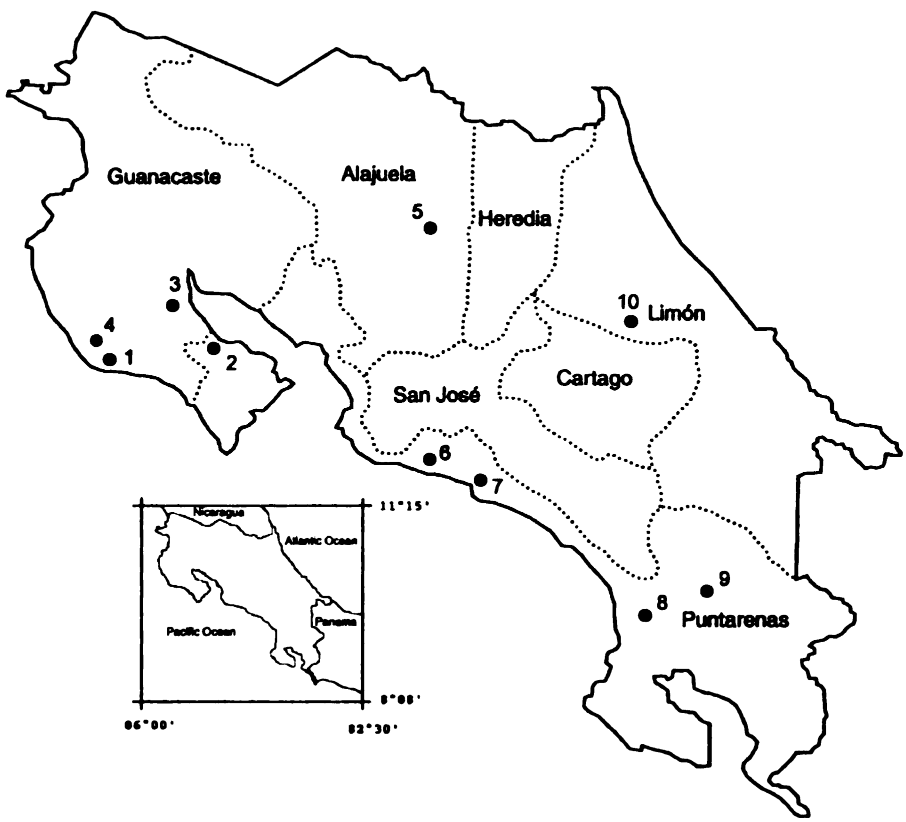

Fig. 1. Location of the *T. grandis* plantations evaluated in Costa Rica (for site codes, see Table 1).

class I (100% of the potential), in a site class II (80% of the potential) and in a site class III (60% of the potential). Anamorphic curves were constructed because the lack of sufficient data for stratification of soil, terrain and other climatic factors, did not allow the construction of polymorphic curves. The growth curves used in this study are not based on consecutive measurements in permanent sample plots only, but

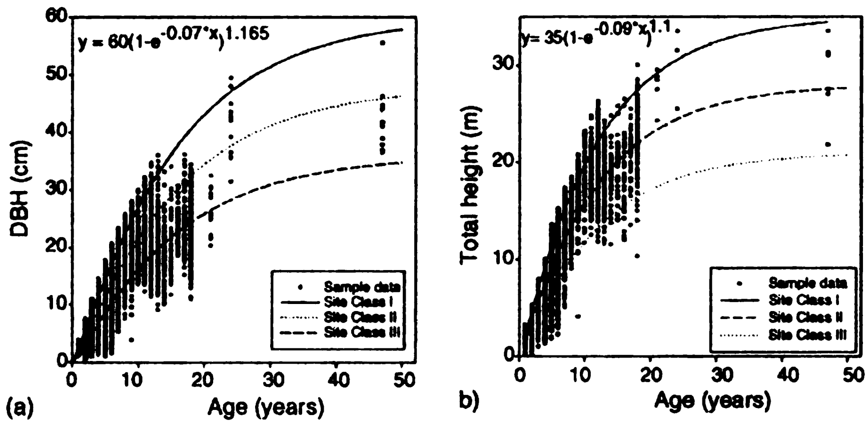

Fig. 2. Fitted curve for the relationship between (a) age and dbh and (b) age and total tree height used for the development of the scenarios for *T. grandis* plantations in Costa Rica. Data correspond to field measurements of individual dominant trees (>percentile 85). Curve for site class I corresponds to 100% of the potential, site class II corresponds to 80% of the potential and site class III to 60% of the potential.

rather on data from both temporal and permanent plots at different plantation ages.

Management scenarios with rotation periods of 20 and 30 years of age were developed for three different site qualities (high, medium and low) under two different management objectives (high individual tree growth versus high stand growth).

In growth and yield models, competition or growth modifiers are usually defined as a function of stand basal area or other variables indicating stocking density of the stand (Monserud and Sterba, 1996; Hilt and Teck, 1988; Wykoff and Monserud, 1988). In this study, three different indices for stand density competition were used for defining the intensities and the plantation age at thinning.

Predictions of stand development depend largely on ecological concepts. Qualitative silviculture applies principles, concepts and models from population ecology, production ecology and biometrics to assess and make predictions relating to various aspects of stand development. It also relates how density influences stand structure, canopy dynamics and production efficiency (Jack and Long, 1996).

Based on these ecological criteria, and following the methodology used by Alder (1979), a curve of maximum observed current annual increment of dbh (CAI_{dbh}) values was plotted against stand basal area (BA). An exponential function was fitted to points of maximum CAI_{dbh} line.

A second index used in this study contemplates the relationship between the size and the spatial distribution of the canopy with the amount of light intercepted by the leaves, followed by an appropriate plantation density definition for an optimum crown development and the consequent optimization of tree growth (Beadle, 1997; Suri, 1975). Crown closure is commonly assumed to represent the threshold of strong competitive interaction and stand development (Jack and Long, 1996). Finally, a third density index was based on the concept of maximum number of trees possibly encountered in a stand and their negative correlation with the average diameter. The curve representing this relationship assumes a straight-line form when plotted on logarithmic paper and is termed the "reference curve" (Reineke, 1933).

The first index consisted of a competition factor (CF), based on the reduction of current annual increment of dbh as a function of different stocking densities, expressed in terms of basal area. The CF was defined as:

$$CF = 1 - (a \times 10^{b \times BA}) \quad (1)$$

where CF is the competition factor (relative values between 0 and 1) and BA is the stand basal area ($m^2\,ha^{-1}$). $a = 0.003$ and $b = 0.160$.

It was assumed that CAI_{dbh} is maintained close to its maximum at low stand densities, decreasing rapidly (non-linearly) with increasing stand density. The CF values range from 1 (no growth reduction) to 0 (no growth at all). The relationship between stand basal area and CAI_{dbh} is shown in Fig. 3a, while the CF

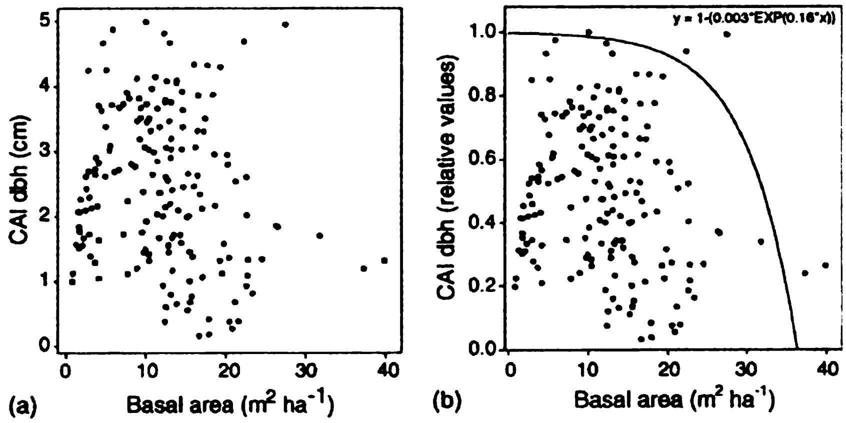

Fig. 3. Relationship between (a) current annual increment of dbh (CAI_{dbh}) and (b) relative CAI_{dbh} and stand basal area. Relative CAI_{dbh} is the fraction of the maximum observed value (5.0 cm $year^{-1}$). The fitted curved is the competition factor—CF (equation (1)). Dots correspond to field data obtained from those plots where consecutive measurements were available in order to determine the CAI_{dbh}.

Table 1
General data of the research sites where the *T. grandis* plantations were evaluated in Costa Rica

Site code	Location	Precipitation (mm year^{-1})	Dry months*	Elevation (m)	Mean annual temperature (°C)	Age (years)	DBH (cm)	Total height (m)	Density (trees ha^{-1})
1	Carrillo	1659	6	100	26.1	8–10	17–26	15–24	600–800
2	Jicaral	1659	6	85	26.8	11–18	22–32	19–28	450–750
3	Tempisque	1901	6	30	27.1	14–20	21–29	20–27	300–400
4	Garza	2205	6	90	25.9	6	18–24	16–23	700–850
5	San Carlos	3393	1	90	26.1	7	15–25	14–24	400–1550
6	Parrita	3117	3	25	26.0	13–47	24–60	21–35	150–550
7	Quepos	3900	3	70	25.9	19	28–35	24–30	375–450
8	Palmar Norte	3644	3	80	27.0	23	30–37	26–32	600–900
9	Buenos Aires	3627	4	300	27.0	27	40–55	28–35	300–500
10	Guapiles	4107	0	250	26.0	5–12	10–25	11–24	400–900

* Months with rainfall less than 100 mm month^{-1}.

developed from the relationship of Fig. 3a, using a maximum CAI_{dbh} of 5.0 cm year^{-1} and a maximum standing Basal Area of 36 m^2 ha^{-1} (where CAI_{dbh} equals zero) is presented in Fig. 3b.

The second index consisted of maximum site occupancy (MSO) based on the maximum crown area occupancy in the stand. The MSO model was defined as:

$$\mathrm{MSO} = \frac{(a/\mathrm{CA})}{N} \tag{2}$$

where MSO is the maximum site occupancy (relative values between 0 and 1), CA the crown area of the mean tree (m^2), a the area of one hectare (m^2) and N is the initial stand density (trees ha^{-1}).

The crown diameter was estimated from dbh using the model developed by Pérez and Kanninen (2003a), and the crown area was calculated as a geometric circle. It was assumed that the maximum stand density ("maximum density", trees ha^{-1}) was reached when the site was fully occupied by the crowns. Plantation density was kept within the maximum density limits using the MSO of the standing trees.

The maximum site occupancy is expressed in relative values. We assumed the initial stand density (N) to be the maximum stand density at all stages, therefore, any possible densities greater than N (at early stages trees have very small dbh values and the model gives possible stand densities greater than N trees ha^{-1}) will be considered as equal to N and consequently MSO = 1.0.

The third competition index corresponds to the Reineke density index—RDI (Reineke, 1933), defined as:

$$\mathrm{RDI} = N \times \left(\frac{a}{\mathrm{dbh}}\right)^{b} \tag{3}$$

where RDI is the Reineke density index (values from 1 to 1049 for *T. grandis* in Costa Rica), N the stand density (number of trees per hectare), dbh is the diameter at breast height (cm); $a = 25$ and $b = -1.9175$.

Limits for each density zone were previously developed for *T. grandis* in Costa Rica by Camacho and Blanco (1997), and were calculated also using our database, coinciding in a maximum RDI of 1049 (Table 2). Kumar et al. (1995) obtained a maximum

Table 2
Reineke density index limits for each density zone expressed as a percentage of the maximum RDI for *T. grandis* in Costa Rica

Zone	RDI %	Lower limit	Upper limit
I (Sub utilization)	0–15	0	156
II (Individual tree growth maximization)	16–35	157	366
III (Stand growth maximization)	36–55	367	576
IV (Self thinning stage)	56–100	577	1049

Maximum RDI value corresponds to that estimated by Camacho and Blanco (1997) and by the authors for *T. grandis* in Costa Rica.

RDI of 1200 with a dataset used for the construction of a density management diagram for *T. grandis* in Kerala, India, while Valencia (1994) obtained a maximum RDI of 1077 for *Pinus douglasiana* in Mexico. The former allows slightly higher stand density upper limits than those used for teak in Costa Rica, while the latter suggests that fast growing species in general may result in similar maximum RDI values.

The three competition indices were plotted against stand BA for comparison purposes (Fig. 4). The competition factor allowed a maximum BA of 30 m^2 ha^{-1} with a growth reduction of maximum 20%, while the Reineke density index allowed a maximum BA of only 20 m^2 ha^{-1} before exceeding the upper limit of zone II (maximum individual tree growth) and the maximum site occupancy permitted a total BA of 22 m^2 ha^{-1} for a full site occupancy. When comparing the RDI, the MSO and the CF, it was evident that both RDI and MSO are basically linear functions of BA, whereas CF is a non-linear one. In terms of site occupancy allowance, the RDI was "less-tolerant" than the MSO and both were "less-tolerant" than the CF (RDI < MSO < CF).

The volume equations for *T. grandis* in Costa Rica developed by Pérez and Kanninen (2003b) were used for the estimation of total and merchantable volume of the trees. An equation for estimating heartwood volume developed for *T. grandis* in Costa Rica by Pérez and Kanninen (2003c) was used for the estimation of heartwood proportion from the merchantable volume. For practical purposes, it was assumed that the heartwood percentage was similar between total and merchantable volume, i.e. the volume classified and discarded as "non-merchantable" contains only sapwood, as heartwood formation is minimal at stem diameters lower than 15.0 cm.

The construction of the management scenarios was based on the dbh and total height growth curves of Fig. 2a and b. An initial stand density of 1111 trees ha^{-1}, two rotation periods of 20 and 30 years, under high-, medium- and low-quality classes yielded different stand density management options. Finally, two different production objectives, i.e. high individual tree growth and high stand growth, set the main factors defining the management regime of each scenario using the competition factor (equation (1); Fig. 3). A maximum reduction on dbh growth was allowed, this according to the production objectives of the scenario. The maximum site occupancy criterion (equation (2)) and the Reineke density index (equation (3)) were used for comparing the competition levels allowed by the CF.

A thinning was carried out every time the CF reduced the dbh growth in maximum 20 and 50% (Fig. 2), for high individual and high stand growth objectives, respectively. On each thinning intervention, the basal area was reduced from 20–24 m^2 ha^{-1} (which correspond to the values reached near the upper limits of competition) to 14–17 m^2 ha^{-1} (which

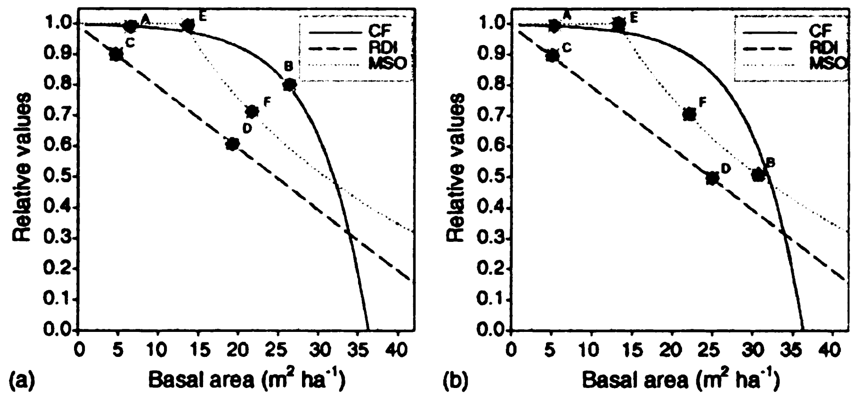

Fig. 4. Comparison between the competition factor (CF)—equation (1), the maximum site occupancy (MSO)—equation (2) and the Reineke density index (RDI)—equation (3), used in the growth scenarios to define the stand competition with increasing stand basal area for high individual tree growth (a) and for high stand growth (b). For comparison purposes, the stand competition indices are presented in relative values with increasing BA. Sections (A–B), (C–D) and (E–F), correspond to the competition interval of each factor applied to the present scenarios for *T. grandis* in Costa Rica.

corresponded to an acceptable minimum BA growth and recovery in a reasonable period of time). Based on these criteria, the BA could recover from the thinning in about 4–5 years, which we considered a reasonable period of time for carrying out subsequent interventions. In addition, the extracted volume was sufficient to make the thinning intervention economically attractive in terms of extracted volume.

At last, validation of the growth scenarios was carried out with an independent dataset obtained from consecutive measurements of a thinning trial (Kanninen et al., 2004).

3. Results

Management scenarios with rotation periods of 20 and 30 years of age were developed for three different site qualities (high, medium and low) under two different management options (high individual tree growth versus high stand growth). At the end of the rotation, stand densities varied between 120 and 447 trees ha^{-1}, with mean dbh of 24.9–47.8 cm and mean total heights between 23.0 and 32.4 m. The mean annual increment in total volume (MAI_{Vol}) at the end of the rotation varied from 11.3 to 24.9 m^3 ha^{-1} $year^{-1}$, accumulating a total volume over rotation from 268 to 524 m^3 ha^{-1}. The summary of the stand growth scenarios is presented in Table 3.

The 30-year-rotation scenario in the high-quality site and with the objective of high individual tree growth is considered the most suitable scheme for teak plantations in Costa Rica under high input management practices. In this scenario, the stand is managed with five thinnings of intensities between 20 and 50% of the standing trees (Table 4a; Fig. 5a). The final harvest at 30 years would be of 120 trees ha^{-1}, with a mean dbh of 47.8 cm, and a total height of 32.4 m. This would yield a total stand volume of 212 m^3 ha^{-1}, for an accumulated total volume (including thinnings) of 501 m^3 ha^{-1} (Table 4a).

Table 4b shows a 30-year-rotation scenario with the objective of high stand growth. In this scenario, four thinnings are carried out with intensities between 40 and 50% of the standing trees (Fig. 5b). The total volume harvested in this scenario is different from the previous one, as there are fewer but more intensive thinning interventions. The accumulated total volume reached 524.3 m^3 ha^{-1}, with a total volume at harvest of 190 m^3 ha^{-1}.

From the 1111 harvested trees during rotation (20 and 30 years), between 1067 and 2931 logs of 4 m length and 15 cm of minimum diameter could be obtained depending on the scenario (Table 5). After the sectioning of the merchantable stem in 4 m length logs, the sellable volume varied between 145 and 386 m^3 ha^{-1}, with an estimated heartwood volume of 45–195 m^3 ha^{-1} (30–50%), depending on the length of the rotation period and the site quality.

The validation of the competition factor indicated that for that precise plantation project used for validation, the proposed competition factor is not optimum, since the maximum basal area is 30 m^2 ha^{-1} and not 36 m^2 ha^{-1}. As a consequence, competition starts at early site occupancy levels with a correlated stronger reduction in CAI_{dbh} (Fig. 6a). The validation of the growth scenarios indicated that the management guidelines and the growth response in BA fit within the independent data (Fig. 6b).

4. Discussion

The maximum site occupancy, the competition factor, and the Reineke density index were used for modeling the competition and for the definition of intensities and the plantation age at thinning. Competition factors of this type were scarce in the literature, being the index of competition for light or the Beer–Lambert's Law cited by Waring (1983), the most similar index to that used in the present study. A competition index has been proposed previously by Wilson (1979), and implemented by Bermejo et al. (2004) to calibrate density of *T. grandis* plantations in Costa Rica. The Hart–Becking index, however, relates the stand density with the top height of the stand and does not provide a reduction factor for tree growth as a consequence of inter tree competition.

The MSO and the RDI were not strictly followed, as too many interventions and too often (every 2 years) would be necessary, which we considered economically unfeasible to implement for fast growing tree plantations in Costa Rica. The RDI limits were surpassed in all the scenarios with the objective of high individual tree growth, while in the scenarios with the objective of high stand growth, the RDI

Table 3
Summary of the stand growth scenarios for *T. grandis* in Costa Rica

Scenario	Age	Thinning number	Number of trees	Thinning intensity	dbh	Total height	Remaining basal area	Extracted basal area	Remaining volume	Extracted volume	Accumulated volume
High-quality; 30 years; maximum dbh	4	1	556	50	11.5	9.4	5.8	5.8	35.6	35.6	35.6
	8	2	333	40	21.8	16.8	12.4	8.3	104.1	69.4	105.0
	12	3	200	40	29.7	22.2	13.8	9.2	125.9	83.9	188.9
	18	4	150	25	38.3	27.5	17.3	5.8	165.4	55.1	244.0
	24	5	120	20	44.0	30.6	18.2	4.6	178.0	44.5	288.5
	30	Final cut	0	100	47.8	32.4	0.0	21.5	0.0	212.5	501.0
High-quality; 20 years; maximum dbh	4	1	611	45	11.5	9.4	6.4	5.2	39.2	32.1	32.1
	8	2	336	45	21.6	16.8	12.3	10.1	103.1	84.4	116.5
	12	3	225	33	29.5	22.2	15.4	7.6	139.8	68.8	185.3
	16	4	169	25	35.6	26.0	16.8	5.6	158.2	52.7	238.0
	20	Final cut	0	100	40.2	28.7	0.0	21.5	0.0	206.8	444.8
High-quality; 30 years; maximum volume	6	1	556	50	16.5	13.4	11.8	11.8	89.0	89.0	89.0
	10	2	333	40	24.2	19.7	15.4	10.2	132.7	88.5	177.4
	14	3	200	40	30.0	24.2	14.2	8.0	129.2	71.4	248.8
	21	4	120	40	37.8	28.7	13.5	9.0	128.3	85.5	334.3
	30	Final cut	0	100	45.3	32.4	0.0	19.4	0.0	190.0	524.3
High-quality; 20 years; maximum volume	6	1	556	50	16.5	13.4	11.8	11.8	89.0	89.0	89.0
	10	2	333	40	24.2	19.7	15.4	10.2	132.7	88.5	177.4
	15	3	200	40	31.6	25.2	15.6	8.0	144.0	71.4	248.8
	20	4	0	100	37.8	28.7	0.0	22.4	0.0	213.8	462.6
Medium quality; 30 years; maximum dbh	5	1	611	45	11.5	9.2	6.3	5.2	39.1	32.0	32.0
	10	2	367	40	21.0	15.8	12.7	8.5	105.5	70.3	102.3
	15	3	246	33	27.9	20.1	15.0	7.4	134.9	66.4	168.7
	21	4	184	25	33.7	23.4	16.4	5.5	153.5	51.2	219.9
	30	Final cut	0	100	38.9	25.9	0.0	21.9	0.0	210.3	430.2
Medium quality; 20 years; maximum dbh	5	1	611	45	11.5	9.2	6.3	5.2	39.1	32.0	32.0
	10	2	367	40	21.0	15.8	12.7	8.5	105.5	70.3	102.3
	15	3	246	33	27.9	20.1	15.0	7.4	134.9	66.4	168.7
	20	Final cut	0	100	32.9	23.0	0.0	20.9	0.0	194.6	363.3
Medium quality; 30 years; maximum volume	8	1	556	50	17.0	16.8	12.6	12.6	95.9	95.9	95.9
	12	2	372	33	23.1	22.2	15.6	7.7	133.1	65.6	161.5
	17	3	279	25	28.6	26.8	18.0	4.7	161.9	40.7	202.1
	22	4	209	25	32.5	29.7	17.3	5.8	160.5	53.5	255.6
	30	Final cut	0	100	36.6	32.4	0.0	22.0	0.0	208.5	464.1
Medium quality; 20 years; maximum volume	5	1	667	40	11.5	11.5	6.9	4.6	42.6	28.4	28.4
	10	2	400	40	20.9	19.7	13.7	9.1	113.2	75.5	103.9
	15	3	300	25	27.6	25.2	17.9	4.2	160.0	35.6	139.5
	20	Final cut	0	100	32.1	28.7	0.0	24.3	0.0	224.6	364.1
Low-quality; 30 years; maximum dbh	7	1	667	40	11.8	12.1	7.3	4.9	46.1	30.7	30.7
	13	2	400	40	19.4	18.6	11.8	7.9	94.9	63.2	93.9
	19	3	268	33	24.5	22.5	12.7	6.2	110.0	54.2	148.1
	30	Final cut	0	100	30.0	25.9	0.0	19.0	0.0	172.9	321.0
Low-quality; 20 years; maximum dbh	7	1	667	40	11.8	12.1	7.3	4.9	46.1	30.7	30.7
	13	2	400	40	19.4	18.6	11.8	7.9	94.9	63.2	93.9
	20	Final cut	0	100	25.2	23.0	0.0	19.9	0.0	174.2	268.1
Low-quality; 30 years; maximum volume	9	1	667	40	14.6	14.7	11.2	7.4	79.4	52.9	52.9
	16	2	447	33	21.8	20.8	16.6	8.2	138.9	68.4	121.4

Table 3 (*Continued*)

Scenario	Age	Thinning number	Number of trees	Thinning intensity	dbh	Total height	Remaining basal area	Extracted basal area	Remaining volume	Extracted volume	Accumulated volume
	22	3	299	33	25.7	23.8	15.5	7.6	136.1	67.0	188.4
	30	Final cut	0	100	29.1	25.9	0.0	19.9	0.0	180.6	369.0
Low-quality; 20 years; maximum volume	9	1	667	40	14.6	14.7	11.2	7.4	79.4	52.9	52.9
	14	2	447	33	20.2	19.4	14.3	7.1	117.0	57.6	110.5
	20	Final cut	0	100	24.9	23.0	0.0	21.7	0.0	189.2	299.7

Scenario: Stand growth scenarios for different site quality (high, low and medium), rotation cycle (20 and 30 years) and objective (high individual tree growth vs. high stand growth); age (years): age of the stand; thinning number: serial number of the thinning interventions; number of trees: stand density (trees ha^{-1}); thinning intensity (%): thinning intensity based on the number of standing trees; dbh (cm): mean diameter at breast height; total height (m): mean total height of the plantation; remaining basal area (m^2 ha^{-1}): remnant (standing) basal area after thinning; extracted basal area (m^2 ha^{-1}): extracted basal area in each thinning; remaining volume (m^3 ha^{-1}): remnant (standing) total volume after thinning; extracted volume (m^3 ha^{-1}): extracted total volume in each thinning; accumulated volume (m^3 ha^{-1}): accumulated total volume extracted in each thinning and in the final cut.

values remained within the limits calculated by Camacho and Blanco (1997) and by the authors of the present study for teak in Costa Rica.

In order to keep the stand within the limits of RDI and MSO, a constant thinning regime (every 2 years) would be necessary, while for the CF a management regime with less thinnings will keep the stand within the limits for high individual tree growth. For RDI and MSO, competition begins at BA of 15 m^2 ha^{-1} or less, while for CF the competition becomes evident (loss in annual growth > 10%) at BA 20 m^2 ha^{-1}. According to Kanninen et al. (2004), teak plantations in Costa Rica present their highest growth rate at BA between 17 and 20 m^2 ha^{-1}. Jayaraman and Zeide (2003) found that for teak plantations in Kerala (Southern India) the upper limit of RDI should be 475 (approximately at BA of 23 m^2 ha^{-1}) for achieving high stand growth, similar value to that obtained in the present study for the scenarios with the objective of high individual tree growth.

High individual tree growth or high stand growth were not intended to be achieved at expenses of site sub-occupancy or excessive site occupancy. High stand growth and yield should be achieved through moderate thinning interventions rather that accumulating volume to the end of the rotation period. This allows a high volume stocking without severe reductions in growth and yield as consequence of high stand competition levels.

The stand density at the end of rotation varied between 120 and 447 trees ha^{-1}, with a mean dbh

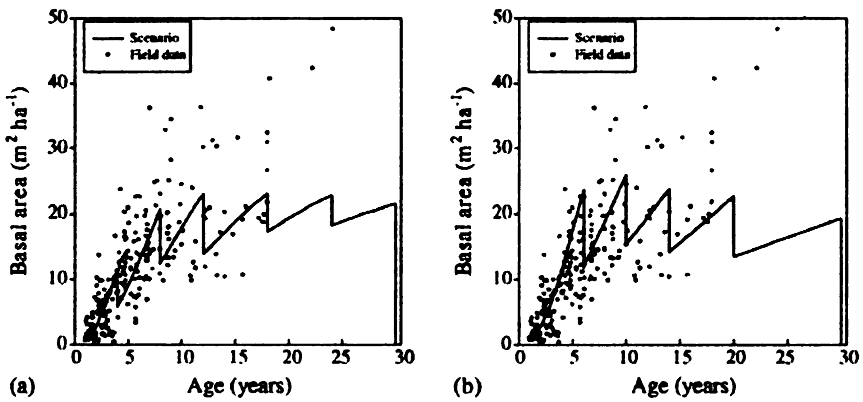

Fig. 5. Basal area management scenarios for *T. grandis* plantations in Costa Rica in a high-quality site, with rotation of 30 years, and with the objective of (a) high individual tree growth and (b) high stand growth. Dots represent the field observations.

Table 4a
Stand growth scenario for a high-quality site, with the objective of high individual tree growth, and with a rotation of 30 years for *T. grandis* in Costa Rica

Age	MSO	RDI	CF	Actual density	Thinning intensity	dbh	CAI dbh	Total height	CAI T. height	Remaining basal area	Extracted basal area	Remaining volume	Extracted volume	CAI volume
1	1.00	14	1.00	1111		2.6	2.6	2.4	2.4	0.6		0.1		0.1
2	1.00	63	1.00	1111		5.6	3.0	4.8	2.5	2.7		6.6		6.5
3	1.00	143	0.99	1111		8.6	3.0	7.2	2.4	6.4		30.9		24.2
4	1.00	251	0.98	1111		11.5	2.9	9.4	2.2	11.6		71.3		40.4
1st thinning														
4				556	50	11.5		9.4		5.8	5.8	35.6	35.6	
5	0.81	191	0.99	556		14.3	2.8	11.5	2.1	9.0		63.3		27.7
6	0.62	266	0.98	556		17.0	2.7	13.4	1.9	12.7		96.9		33.5
7	0.50	346	0.95	556		19.5	2.5	15.2	1.8	16.7		134.5		37.6
8	0.43	427	0.90	556		21.8	2.3	16.8	1.6	20.7		173.5		39.0
2nd thinning														
8				333	40	21.8		16.8		12.4	8.3	104.1	69.4	
9	0.37	310	0.96	333		24.1	2.3	18.3	1.5	15.2		130.7		26.7
10	0.32	363	0.94	333		26.2	2.1	19.7	1.4	17.9		158.0		27.2
11	0.29	415	0.90	333		28.0	1.9	21.0	1.3	20.6		184.8		26.8
12	0.26	463	0.83	333		29.7	1.6	22.2	1.2	23.1		209.8		25.1
3rd thinning														
12				200	40	29.7		22.2		13.8	9.2	125.9	83.9	
13	0.24	311	0.95	200		31.5	1.8	23.3	1.1	15.6		143.2		17.3
14	0.22	343	0.94	200		33.1	1.6	24.2	1.0	17.2		160.3		17.0
15	0.21	373	0.92	200		34.6	1.5	25.2	0.9	18.8		176.7		16.5
16	0.20	402	0.89	200		36.0	1.4	26.0	0.8	20.4		192.4		15.7
17	0.19	429	0.85	200		37.2	1.2	26.8	0.8	21.8		207.1		14.7
18	0.18	454	0.81	200		38.3	1.1	27.5	0.7	23.1		220.5		13.5
4th thinning														
18				150	25	38.3		27.5		17.3	5.8	165.4	55.1	
19	0.17	361	0.92	150		39.5	1.2	28.1	0.6	18.4		176.5		11.1
20	0.16	380	0.90	150		40.6	1.1	28.7	0.6	19.4		187.0		10.5
21	0.16	397	0.88	150		41.6	1.0	29.2	0.5	20.3		196.9		9.9
22	0.15	414	0.86	150		42.4	0.9	29.7	0.5	21.2		206.1		9.2
23	0.15	429	0.83	150		43.3	0.8	30.2	0.5	22.0		214.6		8.5
24	0.14	443	0.80	150		44.0	0.7	30.6	0.4	22.8		222.5		7.9
5th thinning														
24				120	20	44.0		30.6		18.2	4.6	178.0	44.5	
25	0.14	367	0.90	120		44.8	0.8	31.0	0.4	18.9		184.7		6.7
26	0.14	378	0.89	120		45.5	0.7	31.3	0.3	19.5		191.1		6.3
27	0.13	388	0.88	120		46.1	0.7	31.6	0.3	20.0		197.0		5.9
28	0.13	398	0.86	120		46.7	0.6	31.9	0.3	20.6		202.5		5.5
29	0.13	407	0.85	120		47.3	0.6	32.2	0.3	21.1		207.7		5.1
30	0.13	415	0.84	120		47.8	0.5	32.4	0.2	21.5		212.5		4.8
Final cut														
30				0	100	47.8		32.4		0.0	21.5	0.0	212.5	

Table 4b
Stand growth scenario for a high-quality site, with the objective of high stand growth, and with a rotation of 30 years for *T. grandis* in Costa Rica

Age	MSO	RDI	CF	Actual density	Thinning intensity	dbh	CAI dbh	Total height	CAI T. height	Remaining basal area	Extracted basal area	Remnant volume	Extracted volume	CAI volume
1	1.00	14	1.00	1111		2.6	2.6	2.4	2.4	0.6		0.1		0.1
2	1.00	63	1.00	1111		5.6	3.0	4.8	2.5	2.7		6.6		6.5
3	1.00	143	0.99	1111		8.6	3.0	7.2	2.4	6.4		30.9		24.2
4	1.00	251	0.98	1111		11.5	2.9	9.4	2.2	11.6		71.3		40.4
5	0.82	377	0.94	1111		14.2	2.7	11.5	2.1	17.6		123.9		52.6
6	0.66	498	0.81	1111		16.5	2.2	13.4	1.9	23.6		177.9		54.1
1st thinning														
6				556	50	16.5		13.4		11.8	11.8	89.0	89.0	
7	0.53	327	0.95	556		19.0	2.5	15.2	1.8	15.7		125.1		36.2
8	0.44	405	0.90	556		21.2	2.3	16.8	1.6	19.6		162.9		37.7
9	0.39	476	0.79	556		23.1	1.9	18.3	1.5	23.2		197.7		34.9
10	0.36	523	0.52	556		24.2	1.2	19.7	1.4	25.6		221.2		23.5
2nd thinning														
10				333	40	24.2		19.7		15.4	10.2	132.7	88.5	
11	0.32	362	0.90	333		26.1	1.9	21.0	1.3	17.8		157.3		24.6
12	0.29	407	0.83	333		27.8	1.6	22.2	1.2	20.2		180.5		23.2
13	0.27	446	0.72	333		29.1	1.3	23.3	1.1	22.2		200.6		20.1
14	0.26	474	0.54	333		30.0	0.9	24.2	1.0	23.6		215.3		14.7
3rd thinning														
14				200	40	30.0		24.2		14.2	8.0	129.2	71.4	
15	0.24	312	0.92	200		31.6	1.5	25.2	0.9	15.6		144.0		14.8
16	0.22	354	0.89	200		33.7	33.7	26.0	0.8	17.8		166.5		22.4
17	0.21	380	0.85	200		34.9	1.2	26.8	0.8	19.2		180.1		13.7
18	0.20	403	0.81	200		36.0	1.1	27.5	0.7	20.4		192.7		12.6
19	0.19	424	0.75	200		37.0	1.0	28.1	0.6	21.5		204.0		11.3
20	0.18	442	0.68	200		37.8	0.8	28.7	0.6	22.4		213.8		9.8
4th thinning														
20				120	40	37.8		28.7		13.5	9.0	128.3	85.5	
21	0.17	279	0.94	120		38.8	1.1	29.2	0.5	14.2		136.1		7.9
22	0.17	293	0.93	120		39.8	1.0	29.7	0.5	14.9		143.6		7.5
23	0.16	306	0.92	120		40.7	0.9	30.2	0.5	15.6		150.7		7.1
24	0.16	318	0.91	120		41.5	0.8	30.6	0.4	16.3		157.5		6.7
25	0.15	329	0.90	120		42.3	0.8	31.0	0.4	16.9		163.8		6.3
26	0.15	340	0.89	120		43.0	0.7	31.3	0.3	17.4		169.8		6.0
27	0.15	350	0.88	120		43.7	0.7	31.6	0.3	18.0		175.4		5.6
28	0.14	359	0.86	120		44.3	2.0	31.9	1.0	18.5		180.6		5.2
29	0.14	368	0.85	120		44.8	0.6	32.2	0.3	18.9		185.4		4.9
30	0.14	376	0.84	120		45.3	0.5	32.4	0.2	19.4		190.0		4.5
Final cut														
30				0	100	45.3		32.4		0.0	19.4	0.0	190.0	

Age (years): stand age; MSO (relative values): maximum site occupancy index based on the initial stand density; RDI (absolute values): Reineke density index, based on the upper limit of zone II for scenario in Table 4a and based on the upper limit of zone III for the scenario in Table 4b; CF (relative values): competition factor, relative value corresponding to the portion of dbh growth attainable, this in relation to the growth curve of Fig. 2a; actual density (trees ha^{-1}): plantation density; thinning intensity (%): thinning intensity based on the number of trees; dbh (cm): mean diameter at breast height; CAI dbh (cm $year^{-1}$): dbh current annual increment; total height (m): mean total height of the plantation; CAI T. height (m $year^{-1}$): current annual increment in total height (H); remaining basal Area (m^2 ha^{-1}): remnant (standing) basal area after thinning; extracted basal area (m^2 ha^{-1}): extracted basal area in each thinning; remaining volume (m^3 ha^{-1}): remnant (standing) total volume after thinning; extracted volume (m^3 ha^{-1}): extracted total volume in each thinning; CAI volume (m^3 ha^{-1} $year^{-1}$): current annual increment in total volume.

Table 5
Merchantable volume projections for the stand growth scenarios for *T. grandis* in Costa Rica

Scenario	Age	Thinning number	Thinned trees	Merch. volume	Volume of logs	Heartw. Vol. of logs	Log #1	Log #2	Log #3	Log #4	Log #5	Number of logs
High-quality; 30 years;	8	2	223	48	35	10	18.2					223
maximum dbh	12	3	133	71	71	28	27.1	20.5	15.0			399
	18	4	50	51	48	24	36.9	29.5	23.3	17.9		200
	24	5	30	42	41	22	43.5	35.4	28.8	23.0	17.7	150
	30	Final cut	120	203	191	111	47.8	39.4	32.4	26.3	20.8	600
Average log diameter							34.7	31.2	24.9	22.4	19.2	
Number of logs							556	333	333	200	150	1572
Total volume				414	386	195						
High-quality; 20 years;	8	2	275	57	42	11	18.4					275
maximum volume	12	3	111	58	59	23	27.6	20.8	15.3			333
	16	4	56	48	47	22	34.8	27.4	21.3	16.0		224
	20	Final cut	169	192	193	99	40.5	32.6	26.1	20.4	15.1	845
Average log diameter							30.3	27.0	20.9	18.2	15.1	
Number of logs							611	336	336	225	169	1677
Total volume				355	340	155						
High-quality; 30 years;	10	2	223	71	65	21	21.4	15.5				446
maximum dbh	14	3	110	65	70	28	28.1	21.7	16.5			330
	21	4	73	62	74	36	36.8	29.6	23.7	19.2		292
	30	Final cut	150	193	170	96	45.3	37.4	30.8	25.0	19.7	750
Average log diameter							32.9	26.1	23.7	22.1	19.7	
Number of logs							556	556	333	223	150	1818
Total volume				391	379	180						
High-quality; 20 years;	10	2	223	71	68	22	22.7	16.5				446
maximum dbh	15	3	110	65	61	25	31.7	24.8	19.1			330
	20	Final cut	223	188	179	83	38.3	30.8	24.7	19.2		892
Average log diameter							30.9	24.0	21.9	19.2		
Number of logs							556	556	333	223	0	1668
Total volume				324	308	131						
Medium quality; 30 years;	10	2	244	46	37	10	17.6					244
maximum volume	15	3	121	55	48	18	25.8	18.9				242
	21	4	62	46	43	19	32.8	25.1	18.8			186
	30	Final cut	184	193	188	94	39.2	30.8	23.9	17.9		736
Average log diameter							28.8	24.9	21.4	17.9		
Number of logs							611	367	246	184	0	1408
Total volume				340	316	141						
Medium quality; 20 years;	5	1	500	0	0	0						0
maximum volume	10	2	244	46	37	10	17.6					244
	15	3	121	55	48	18	25.8	18.9				242
	20	Final cut	246	172	163	71	31.8	24.3	18.1			738
Average log diameter							25.1	21.6	18.1			
Number of logs							611	367	246	0	0	1224
Total volume				272	248	98						

Table 5 (*Continued*)

Scenario	Age	Thinning number	Thinned trees	Merch. volume	Volume of logs	Heartw. Vol. of logs	Log #1	Log #2	Log #3	Log #4	Log #5	Number of logs
Medium quality; 30 years;	12	2	220	40	26	7	18.7					220
maximum volume	17	3	148	56	45	16	25.2	19.5				296
	22	4	75	49	48	20	32.3	26.0	20.8	16.2		300
	30	Final cut	224	213	209	101	39.4	32.5	26.8	21.7	17.1	1120
Average log diameter							28.9	26.0	23.8	19.0	17.1	
Number of logs							841	621	621	473	373	2931
Total volume				358	328	144						
Medium quality; 20 years;	10	2	267	49	32	8	18.7					267
maximum volume	15	3	100	44	43	16	26.7	20.9	16.1			300
	20	Final cut	300	197	193	82	32.3	26.0	20.8	16.2		1200
Average log diameter							25.9	23.5	18.5	16.2		
Number of logs							767	500	500	400	0	2167
Total volume				290	269	107						
Low-quality; 30 years;	13	2	266.6	37	29	7	17.1					267
maximum dbh	19	3	132	41	37	12	23.1	17.5				264
	30	Final cut	268	147	136	55	29.4	23.1	18.0			804
Average log diameter							23.2	20.3	18.0			
Number of logs							667	400	268	0	0	1335
Total volume				226	202	73						
Low-quality; 20 years;	13	2	267	37	29	7	17.1					267
maximum dbh	20	Final cut	400	136	116	39	23.9	18.2				800
Average log diameter							20.5	18.2				
Number of logs							667	400	0	0	0	1067
Total volume				173	145	45						
Low-quality; 30 years;	16	2	245	33	26	6	17.1					245
maximum volume	22	3	200	50	48	14	21.3	15.9				400
	30	Final cut	299	160	149	59	29.4	23.1	18.0			897
Average log diameter							22.6	19.5	18.0			
Number of logs							744	499	299	0	0	1542
Total volume				243	223	79						
Low-quality; 20 years;	14	2	267	44	31	8	18.2					267
maximum volume	20	Final cut	400	134	115	38	23.9	18.2				800
Average log diameter							21.1	18.2				
Number of logs							667	400	0	0	0	1067
Total volume				178	146	46						

Scenario: stand growth scenarios for different site qualities (high, low, medium), rotation cycles (20 and 30 years), and objectives (high individual tree growth vs. high stand growth); age (years): age of the stand; thinning number: serial number of the thinning; thinned trees: harvested trees in each thinning (tree ha^{-1}); Merch. Vol.: total merchantable volume with minimum diameter of 15 cm (m^3 ha^{-1}); volume of logs: total volume of the logs harvested in each intervention (m^3 ha^{-1}); Heartw. Vol. of logs: heartwood volume from the total volume of logs (m^3 ha^{-1}); log #: 4m-length logs are numbered consecutively from the base to the top of the tree as #1, #2, ..., the total amount under these columns refers to the diameter of the logs at smaller end; number of logs: number of logs harvested in each intervention.

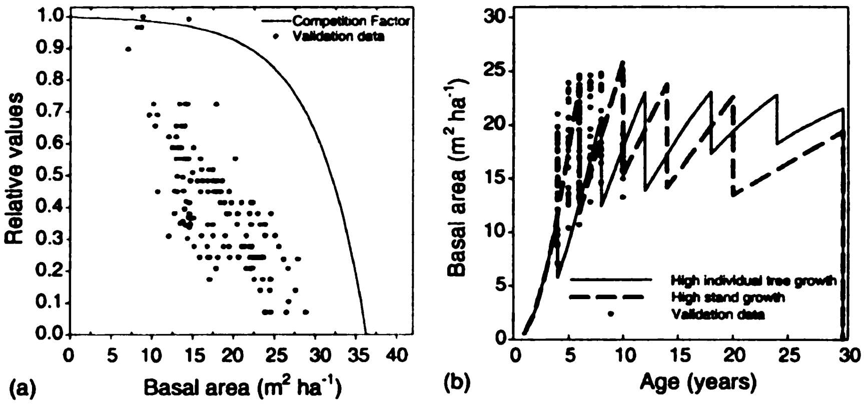

Fig. 6. (a) Validation of the competition factor and (b) the growth scenarios (using the scenarios of high-quality sites and 30 years rotation—Table 4, as example) with an independent dataset from a *T. grandis* plantation measured from year 4 until year 10 in Costa Rica.

between 24.9 and 47.8 cm, values perfectly achievable under 30-year-old rotations in Costa Rica. This statement is supported by data of two plantations (without silvicultural management) measured in the field, which indicate that teak plantations can grow up to 42 cm in dbh with 357 trees ha^{-1} at 27 years of age. Torres (2000) indicates that in Brazil, a mean dbh of 50.0 cm in a 25-year-rotation can be expected after four thinnings and with an initial planting density of 1666 trees ha^{-1}. Differences in growth and yield between present results and those reported elsewhere (including some results obtained during the field work of the present study) are caused by variations in site quality and management guidelines.

BA values up to 40 m^2 ha^{-1} were found in the field, while the maximum values in the scenarios reached 25.6 m^2 ha^{-1}. Maximum total volume (standing volume) recorded in the field reached 800 m^3 ha^{-1} (age 24 years) in some extremely dense plots, whereas in others with less competition the standing volume reached 500 m^3 ha^{-1} (age 22 years). In the present scenarios, the maximum standing volume at the end of rotation was 225 m^3 ha^{-1}, and the accumulated volume (including thinnings) reached 524 m^3 ha^{-1} as maximum, showing, therefore, attainable production rates for *T. grandis* in Costa Rica. Centeno (1997) suggests a maximum production of 500 m^3 ha^{-1} at 30 years in high-quality sites for teak in the Neotropics.

Results of thinning trial for teak in Costa Rica reported by Kanninen et al. (2004) indicate that teak stands can sustain up to 30 m^2 ha^{-1} without falling into extreme competition, i.e. self-thinning. According to present scenarios, if no thinning interventions are practiced, teak stands can support over 1111 trees ha^{-1} until year 8 before starting self thinning, and growing around 17 cm in dbh and 26 m^2 ha^{-1} in BA. The control plots of the thinning trial showed that with the initial stand density of 1600 trees ha^{-1} a maximum growth is reached at age 7 years with a mean dbh of 14 cm and a maximum BA of 28 m^2 ha^{-1}.

Vásquez and Ugalde (1995) consider that teak grown in medium quality sites of Costa Rica can be managed with BA between 15 and 20 m^2 ha^{-1}, while high-quality sites can hold over 20 m^2 ha^{-1}. Scenarios developed in this study reached maximum BA's of 25.6 m^2 ha^{-1}, with average MAI_{Vol} values of 11.2 m^3 ha^{-1} $year^{-1}$ and an overall productivity (including extracted volume by thinning) of 24.9 m^3 ha^{-1} $year^{-1}$, similar to those values found for Costa Rica in different studies (Rojas, 1981; Vásquez and Ugalde, 1995; Vallejos, 1996). *T. grandis* plantations have been reported to grow over 12 m^3 ha^{-1} $year^{-1}$ in Tanzania (Evans and Wood, 1994), 10 m^3 ha^{-1} $year^{-1}$ in Brazil (Centeno, 1997) and 3.4–11.5 m^3 ha^{-1} $year^{-1}$ in Ivory Coast (Dupuy and Verhaegen, 1993).

The thinnings in the scenarios with the objective of high individual tree growth reduced the BA from 20–23 to 12–17 m^2 ha^{-1}. On the other hand, the thinnings in the management scenarios with the objective of high stand growth reduced the BA from 22–26 to 13–18 m^2 ha^{-1}. Present results indicate that teak plantations in Costa Rica grow easily over 4.0 m^2 ha^{-1} $year^{-1}$ in medium and high-quality sites.

In relation to this, Centeno (1997) considers that teak stands should grow up to 20–22 $m^2 ha^{-1}$ and then be reduced to BA of 13–15 $m^2 ha^{-1}$. Torres (1982) proposes a thinning system for teak in Venezuela starting with 1000 trees ha^{-1}, stocking over 24 $m^2 ha^{-1}$ of BA and reducing it to 17 $m^2 ha^{-1}$. However, Bermejo et al. (2004) recommend thinnings to be carried out when the BA reaches 18–19 $m^2 ha^{-1}$ in high-quality sites, and bringing the BA values to 13–14 $m^2 ha^{-1}$ after the thinning.

T. grandis in Central and South America grows differently (often faster) than in many other countries, therefore, it is difficult to compare management prescriptions and their growth responses. For example, Ramnarine and Jhilmit (2003) indicate that teak is managed under 50-year-old rotation schemes, with six thinning interventions and the initial planting density of 2200 trees ha^{-1}, yielding a MAI_{Vol} of 7–10 $m^3 ha^{-1} year^{-1}$ in high-quality sites in Trinidad and Tobago. Ramnarine (1994) concluded that scenarios for teak plantations in Trinidad and Tobago must contemplate for a rotation of 20 years, a production of maximum 125 $m^3 ha^{-1}$ versus 100 $m^3 ha^{-1}$, with a tree mean dbh of 20 and 32 cm, for stands without thinning and stands with three thinnings, respectively.

In the future, measurements from permanent sample plots on growth or stem analysis should be used to improve the growth models. Unfortunately, such data is available in the tropics only in rare occasions. Bermejo et al. (2004) used permanent sample plots from a limited area and from limited ages (up to 11 years) for teak grown in Costa Rica. Contrary to this, many studies on growth and yield of teak plantations carry out in different regions, such as that of Kumar et al. (1995) in peninsular India, Dupuy et al. (1999) in Côte d́Ivoire, Malende and Temu (1990) in Tanzania, and Piñol (1994) in Philippines, were based on data from single measurements in temporal sample plots.

The validation of the competition factor evidenced the applicability of the scenarios in teak plantation management. The CF, although with a maximum BA capacity than that shown by the validation data, followed a similar pattern on reduction growth than that followed by the teak stand used for validation. The growth scenarios, both the high individual tree growth and the high stand growth objective, operated within the limits of the validation data. Calibration of models and scenarios with local data will certainly improve present projections and management guidelines.

5. Conclusions

(1) The maximum site occupation and the Reineke density index provide conservative stand density management limits, resulting in the need to execute frequent thinning interventions, which in practice may be economically unfeasible to perform. The competition factor matches the field observations and seems to be more appropriate for the growth characteristics of the species.
(2) Scenarios with the objective of high individual tree growth resulted in fewer number of merchantable volume and sawn logs, but with greater diameter and at younger ages than the scenarios aiming at high stand growth. Scenarios with the objective of high stand growth produced higher total volumes.
(3) The developed management scenarios are not intended to be optimum scenarios, i.e. they are possible options for reaching particular production objectives. The optimum may be obtained for instance by combining both management strategies, i.e. starting with a late and light thinning to reach initial high stand productivity and later on concentrate on individual growth maximization.
(4) As *T. grandis* in Central and South America grows differently (often faster) than in many other countries in the Tropics, it is difficult to establish comparisons of management regimes and growth responses to silvicultural practices and site conditions with other regions.

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