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Growth and yield models for teak plantations in Costa Rica

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Abstract

Volume equations for commercial teakwood, site index curves and provisional empirical yield tables were developed and presented for teak (*Tectona grandis* L.f.) at Bosque Puerto Carrillo S.A. plantations in Guanacaste, northwestern Costa Rica. These plantations were established in 1986 and are the first serious teak plantation projects under rational and intensive silvicultural management in Central America. Height curves for three site indices: 23, 21 and 19 m at a reference age of 10 years were built. Yield tables proposed for an average thinning regime correspond to the three site indices defined. The silvicultural model has been developed using data from the yearly inventories of Bosque Puerto Carrillo. Hence, the obtained silvicultural model should be validated and adjusted, if necessary, at the end of the first rotation.

Keywords: *Tectona grandis*; Volume equations; Site index; Silvicultural model; Yield tables; Central America

1. Introduction

Teak (*Tectona grandis* L.f.) is one of the most important tropical hardwood species in the international market of high-quality timber. Its high durability, good dimensional stability and aesthetic qualities make it a very valuable timber species for forestry plantations. Its impressive rates of growth (when optimal sites are chosen) and the high demand of this hardwood for yachting, building and furniture industries make it a very profitable option for both public and private forestry schemes (Troup, 1921; Tewari, 1992).

As the sustainable supply of teak from natural forests shrinks and the demand continues to increase, the general trend in the future of teak growing will be towards increasing production and utilizing more plantation-grown teak (Pandey and Brown, 2000). This suggests a need for enhanced knowledge regarding diverse aspects of teak plantation establishment as well as silviculture, management, utilization and the ecological aspects of both plantations and natural stands (Seth and Kaul, 1978; Krishnapillay, 2000). Several countries are interested in improving financial returns from teak plantations through the utilization of thinnings and small roundwood. Objective studies are therefore being conducted on development techniques for small roundwood, reconstituting small sawn wood as larger material, and market opportunities for small-dimension timber or components (Pandey and Brown, 2000).

Teak is native to India, Myanmar (Burma), Thailand and Laos, but this broadleaved tree species grows nowadays in the whole intertropical region (excluding desert areas of Africa).

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Teak was introduced in Central America in 1926 with seeds that were sent from Colombo (Sri Lanka) to the Botanical Garden of Panama. Then, seeds were exported, in the next 20 years, to countries of Central America (de Camino et al., 1998).

Reforestation in Costa Rica has been extensive in the last two decades due to international cooperation projects and national incentives. In recent years, 135,000 ha have been reforested with *Euclyptus deglupta*, *Bombacopsis quinata*, *Gmelina arborea*, and *T. grandis*. More than 25,600 ha were plated with teak but this species has not always been established on sites suitable for its ecological requirements. These plantations are the first serious reforestation projects under rational and intensive silvicultural management. Teak has since acclimatized well and has been widely grown in both industrial plantations and small community woodlots.

Several papers have been devoted to various teak issues in recent years: Troup (1921), Kadambi (1972), Chaves and Fonseca (1991) and Tewari (1992). Very useful information on silviculture has been extracted from studies developed by Seth and Kaul (1978), Keogh (1987, 1990, 1996), Centeno (1997), Krishnapillay (2000) and Pandey and Brown (2000). Studies carried out by Laurie and Ram (1939), Miller (1969), Maître (1983), Abayomi (1984), Islam (1988), Keogh (1996), Akindele (1991), Phillips (1995) and Zambrano (1995) yielded relevant information for the development of growth models and yield tables for teak of various regions.

There is undisputed potential for growing teak to timber size on good soils in Central America, with resulting economic benefits. A regional approach to research with this species has much to offer in this region of small countries and islands that share many common ecological zones. However, local knowledge on the growth and yield characteristics of this species, which will help in assessing that potential, is still lacking and in some cases the available information shows not very realistic figures. It is thus necessary to make use of the best material available in the short term, even though this may not give optimum silvicultural prescriptions.

The main aim of this study was to develop provisional growth and yield models for teak plantation management in northwestern Costa Rica and serve as a basis for future studies on silvicultural models for teak in Central America. Our four concrete objectives are:

1. to estimate tree volume for commercial wood (minimum diameter of 10 cm under bark);
2. to develop a preliminary site index classification for teak in northwestern Costa Rica;
3. to assess the volume growth under clear-felling system for rotations of 25 years in northwestern Costa Rica;
4. to provide basic data for future teak plantation management in Central America.

2. Material and methods

2.1. The study area

This research has been carried out on three forest estates located in the northwestern peninsula of Nicoya (Guanacaste province), on the Pacific coast of Costa Rica (Fig. 1). The area of study is located approximately on the 10° north parallel, thus barely belonging to the tropical zone or zone II according to Walter (1997).

In the study area (average altitude of 300 m above sea level and relative proximity to the sea), mean annual temperatures oscillate between 26 and 29 °C. Total annual rainfall varies between 1800 (inland areas) and 2450 mm (coastland areas). This part of Costa Rica is affected by trade (NE and E) winds

Fig. 1. General location of teak Bosque Puerto Carrillo S.A. plantations in Costa Rica.

Table 1
Main characteristics of the three Bosque plantations

Plantation	Area (ha)	Plantation year (s)	Number of experimental plots	Altitude (m a.s.l.)	Slope (%)	Soil texture	Soil type
Puerto Carrillo	1165	1986–1991	117	100–500	15–30	Clay	Cambisols
Palo Arco	1620	1991–1992	163	500–600	0–30	Sand–clay	Calcic-cambisols
Moravia	272	1993	38	25–400	Flat	Sand–clay	Calcic-cambisols
Total	3057	–	318	25–600		–	–

mainly during the May–November period. However, during the December–April period, sea breezes and west equatorial (W and SW) winds are predominant and bring extensive rainfall to the Province of Guanacaste. These three plantations sites are good representations of the teak plantations in Costa Rica (Van der Linden and Patricio, 1999, unpublished information). Table 1 shows the most important data of them.

These three plantations sites have been divided into four zones according to ecological differences (mostly slope), geographical situation and plantation date:

- Zone 1: flat terrain in Palo Arco plantations.
- Zone 2: Palo Arco plantations with more than 15% of slope.
- Zone 3: Moravia plantations.
- Zone 4: Puerto Carrillo plantations, mostly high slope.

2.2. Data collection and analysis

Data were collected from a total of 318 permanent plots on the three plantations (four ecological zones) defined above. The plot number in each site plantations was proportional of the surface plantation. Each plot consisting of a rectangular area of about 500 m^2 was coded with both name and number.

All the teak trees within the plot were measured for diameter at breast height (dbh) and total height every year.

One tree was chosen at random within each plot to estimate the commercial volume. On 285 trees in total, dbh was first measured before felling and total height after felling. Afterwards, the main stem was cut in logs of 2 m, thus measuring the commercial volume of the tree (minimum diameter of 10 cm under bark). Two perpendicular diameters under bark were taken at each end of the logs. Only logs with both ends over 10 cm under bark were collected during harvest because industry accepts only logs of that size. Since the lower stem usually has a very irregular shape at the base, the commercial volume estimations obtained from these measurements would not need to be adjusted by any transformation-related coefficient.

The information included in the yearly inventories shows the evolution of stand variables such as mean diameter, mean and top height, basal area, total and commercial volume per hectare and thinned commercial volume per hectare.

2.2.1. Tree volume estimation for commercial teakwood

The total volume of each tree (dm^3) was computed using Smalian's formula, due to its simplicity and the convenience of measurements taken on the sampled trees:

$$V_{\log} = \sum_i \frac{\pi}{160}[(D_{i1} + D_{i2})^2 + (d_{i1} + d_{i2})^2] \quad (1)$$

where D_{i1}, D_{i2} are the diameters corresponding to the biggest log section and d_{i1}, d_{i2} those of the smallest one (in cm, both under bark). The log length was always 2 m.

Thus, the total volume of each tree was calculated as the sum of all the separate volumes of its commercial logs.

Table 2 shows the number of sampled trees and the ranges of diameter, height and commercial volume for each ecological zone.

As a consequence of their ecological differences, data coming from each zone were considered separately for statistical analysis. A later analysis seeking significative differences (95% confidence intervals) among volume equations for each ecological zone was carried out through the comparison of volume

Table 2
Main characteristics of the four ecological zones defined within Bosque plantations and ranges of dendrometric data

Zone[a]	Sampled trees		Ranges		
	N	%	dbh (cm)	h (m)	v (dm^3)
1	109	34.27	12.9–27.2	13.8–23.1	32.3–358.4
2	61	19.18	10.1–23.1	12–21.9	19.9–174.9
3	35	11.02	10–21.8	14.4–21.4	37.8–288.8
4	113	35.53	15.3–24.9	12.3–23.2	59.6–287.1
Total	318	100	10–27.2	12–23.2	19.9–358.4

[a] Zone 1: flat terrain in Palo Arco plantations; zone 2: Palo Arco plantations with more than 15% slope; zone 3: Moravia plantations; zone 4: Puerto Carrillo plantations, mostly high slope.

equation analysis. For that purpose, we constructed indicator variables to allow us to compare the simple regression models, to test whether we could use a single model across groups.

Commercial volume (dm^3) was the chosen dependent variable in all cases and dbh (cm) and/or height (m) were the chosen independent variables. The dependent variable was tested for normality using the Shapiro–Wilk statistic. Three models with dbh as the sole independent variable were tried, while four models with both dbh and height as independent variables were used (Table 3).

Data were used to select equations through linear, polynomial (classical least squares methods) and non-linear regression techniques (Marquard method). The best models was chosen according to a set of statistics including the following issues:

- Coefficient of determination (R^2).
- Statistical significance of the coefficients.

Table 3
Mathematical models tried on teak samples to estimate tree commercial volume[a]

One-variable models (volume $= f(\text{dbh})$)
$V = a + bD^2$
$V = a + bD + cD^2$
$V = aD^b$
Two-variable models (volume $= f(\text{dbh}, \text{height})$)
$V = a + bD^2H$
$V = a(D^2H)^b$
$V = aD^bH^c$
$V = a + bD^2 + cH + dD^2H$

[a] D: dbh (cm); H: total height (m).

- Minimum residual sum of squares value (RSS) and their distribution (this should be close to normality).
- It was also taken into consideration that new models should have similar expressions to those already developed, when possible. Thus, linear models developed for commercial volume equations by Miller (1969), Keogh (1987) and Cartwright and Marshall (1994, unpublished) were considered as the best options when doubt arose.
- Simple and biologically meaning expressions.

Statgraphics Plus ver. 6.0 statistical software package was used for statistical analysis.

2.2.2. Site index

Site index, considered as the mean top height/ plantation age rate, was the basis for classifying plantations into site classes. The material used consisted, basically, of yearly inventories of the experimental plots carried out by Bosque's Department of Silviculture.

Three different models were used, following other studies on site index equations, such as Keogh (1979), Akindele (1991) and Montero et al. (2001). The equations used were those developed by Richards (1959) (Eq. (2)), Bailey and Clutter (1974) (Eq. (3)), and Hossfeld (Zeide, 1993, Eq. (4)):

$$H_0 = a(1 - e^{-b(t-d)})^{1/c} \quad (2)$$

$$\ln(H_0) = a + b\frac{1}{t} \quad (3)$$

$$H_0 = \frac{t^2}{a + bt + c_i t^2} \quad (4)$$

where H_0 is the top height; t the age (years); a, b, c, d, the parameters; c_i a parameter specific of each station. The value of $1/c_i$ is the superior asymptote of top height for i station.

The guide-curve method was used in the present study for the development of a site index equation. The whole series of age–top height data of Bosque's yearly inventories was used for this purpose, making no differences among zones (see above), and thus obtaining an equation that shows an average behavior (i.e. the guide curve).

Anamorphic curves were drawn from the guide curve, using the top height reached at a reference age (Garcia, 1983, 1984), which has been established at 10 years (Bermejo, 2001, unpublished) for this study.

The "shape" and general tendency of these guide curves around year 25 (i.e. its asymptotic behavior) were the basic factors taken into consideration. The best guide curve thus obtained was defined as the average site quality class. Then, two more site quality classes were defined, one above (best class) and one below (worst class).

2.2.3. Yield tables

The material used for the development of yield tables consisted of yearly inventories and results obtained in previous stages: volume equations and site index curves.

The development of these tables requires different expressions representing relationships among stand variables. The variables used in this study are: age (years), number of stems per hectare, mean dbh (cm) and height (m), basal area (m^2/ha), total and individual commercial volume (m^3/ha and m^3/stem). In preparing these models, the methodology used in yield tables (Laurie and Ram, 1939; Maître, 1983; Montero et al., 2001) was followed.

The first relationship is of $H_0 = f(\text{age})$, which was obtained during the development of site index curves (H_0 is top height). Different expressions were used for different site quality classes.

N (number of stems/ha) is obtained considering a constant rate of reduction that depends on both initial and final stand densities. Initial densities for all the site quality classes is 1111 stems/ha (3 m × 3 m of plantation), final densities at 25 years (considered rotation) vary inversely with site quality, and five thinnings is considered to be the optimum silvicultural treatment (Keogh, 1987, 1990; de Camino et al., 1998). The natural mortality is included in the crop removed with thinning.

The rate of reduction for each site quality class has the following expression:

$$r = \sqrt[5]{\frac{1111}{\mathrm{fd}}} \tag{5}$$

where fd is the final density of the stand before the final felling.

Given N and H_0, the quadratic mean diameter (D_g) was calculated as

$$D_g = f(H_0, N) \tag{6}$$

Basal area (G) was calculated on the basis of N and D_g figures:

$$G = \frac{\pi}{40\,000} D_g^2 N \tag{7}$$

Mean tree volume of the main stand before the thinning (V_m) is obtained by using the double-entry table (above section). The volume per hectare (V) was calculated as the product of the number of tress per hectare (N) by the mean tree volume per age and site quality:

$$V = V_m N \tag{8}$$

The relation between the mean tree volume in the removed crop and main crop (V_{me}/V_m) was calculated with the data of yearly inventories and information obtained from Miller (1969), de Camino et al. (1998) and Laurie and Ram (1939).

The volume removed is estimated from the number of tree removed (N_e) and the mean tree volume (V_{me}). The different expressions used to estimate D_{ge} are the following:

$$V_e = V_{me} N_e \tag{9}$$

$$V_e = a G_e H_0 \tag{10}$$

$$G_e = \frac{\pi}{40\,000} D_{ge}^2 N_e \tag{11}$$

Mean annual volume increment (M) was determined as the ratio of the model volume yield to age, where VT is the total volume and t the age of the stand:

$$M = \frac{\mathrm{VT}}{t} \tag{12}$$

The periodic annual increment (P) model was obtained as a derivative of volume yield with respect to age:

$$P = \frac{\mathrm{VT}_{(t)} - \mathrm{VT}_{(t-i)}}{i} \tag{13}$$

where t is the age of the stand and i the period between thinning.

From these, the ages of maximum M and P were determined.

3. Results

The data used in this study only represent half of the rotation age for teak plantations; a validation would be

Table 4
Data of the trees used for developing volume equations (mean and standard deviation are shown for each variable)

Zone[a]	Final number of trees used		dbh (cm)		Height (m)		Volume (dm^3)	
	N	%	Mean	σ_d	Mean	σ_h	Mean	σ_v
1	99	34.7	18.7	2.5	18.8	1.90	153.8	71.4
2	54	18.9	17.2	1.9	17.1	2.0	93.3	29.7
3	29	10.2	17.6	1.8	17.1	1.6	124.6	35.5
4	103	36.2	20.2	1.9	18.0	1.8	164.5	46.3
Total	285	100	18.7	2.4	17.9	1.9	140.3	56.3

[a] Zone 1: flat terrain in Palo Arco plantations; zone 2: Palo Arco plantations with more than 15% slope; zone 3: Moravia plantations; zone 4: Puerto Carrillo plantations, mostly high slope.

necessary to develop definitive growth and yield table models. Extrapolation beyond the period of the data gathered presents some problems that we assume and take into account in the discussion.

3.1. Volume equations for teak wood

Table 4 shows the result of filtering the samples. Trees with abnormal values (mean $\pm$ 2 standard deviation) were eliminated after considering that (a) there was some sort of mistake in the data-gathering process or (b) they were clearly non-representative trees from the sampled population. Thus, a final total of 285 trees were used for the development of the volume equations after eliminating 10.38% of the initial sample (33 trees).

The model chosen as the best option for all cases was number 4, noting that this is the type of volume equation developed by Cartwright and Marshall (1994) for Bosque and by Keogh (1987) for Costa Rica. These equations have a high coefficient of determination, small standard error and well-distributed residuals, which are indicators of a good fitting. They have also a clear biological significance. The allometric model, number 5, works very well for the considered range of the combined variable D^2H. However, it gives volume overestimations for trees near the end of the 25-year rotation. The expressions for the volume equations obtained above are given in Table 5.

A commercial volume formula was also obtained for quick and gross volume calculations for all Bosque plantations. The result is the following:

$$V = -26.7721 + 0.02566\,\mathrm{dbh}^2\,h \qquad (14)$$

where V is the teak commercial volume (dm^3/stem, up to 10 cm diameter under bark), dbh the mean diameter at breast height (cm) and h the total height (m).

In the comparison of regression models the a coefficients showed significant differences (95% of confidence interval). The slope coefficient (b) for the four models, however, did not show significant differences.

3.2. Site index

Hossfeld (Zeide, 1993) equation was chosen since both Richards' (1959) and Bailey and Clutter's (1974) give very poor height values once the age of the stand

Table 5
Commercial volume equations chosen for Bosque plantations (dbh > 10 cm)[a]

Equation	a	b	R^2	SS	RSS	σ_v	d.f.	σ_a	σ_b
Zone 1: Palo Arco (flat)	−37.5322	0.02737	0.84	334.287	63.050	25.49	97	8.48	0.0012
Zone 2: Palo Arco (sloping)	−14.8739	0.02155	0.70	42.722	18.018	18.60	52	10.27	0.0019
Zone 3: Moravia	20.9638	0.01924	0.64	22.582	12.758	21.74	27	15.53	0.0028
Zone 4: Puerto Carrillo	−20.2924	0.02476	0.79	172.960	45.604	21.25	101	9.67	0.0013
All Bosque plantations	−26.7721	0.02566	0.80	722.309	178.335	25.10	283	5.16	0.0007

[a] R^2: coefficient of determination; SS: sum of squares due to regression; RSS: residual sum of squares of the error; σ_v: standard deviation of volume; d.f.: degrees of freedom of the error; σ_a and σ_b: standard deviation of coefficients a and b in the model $V = a + bD^2H$.

Table 6
Site indices and c_i parameters values for teak in Costa Rica

Si (top height at the age of 10 years, m)		c_i (quality parameter)		Maximum height ($1/c_i$, m)	
Limits	Average	Limits	Average	Limits	Average
18		0.0475		21.05	
	19		0.0446		22.42
20		0.0420		23.81	
	21		0.0396		25.25
22		0.0374		26.74	
	23		0.0355		28.17
24		0.0337		29.67	

Table 7
Results of the relationship between top height (H_0) and age for different quality sites

Age (years)	Quality 23, H_0	Quality 21, H_0	Quality 19, H_0
3	8.6	8.3	8.0
5	15.3	14.4	13.4
8	21.0	19.3	17.6
12	24.3	22.1	19.3
25	26.5	23.9	21.3
25	27.0	24.3	21.7

reaches 8–10 years. Hossfeld's equation resulting for the mean or guide curve is as follows:

$$H = \frac{t^2}{0.6926 + 0.0108t + 0.0396t^2} \quad (15)$$

This gives a mean height of 21 m for a base age of 10 years. Thus, site quality class 21 is defined as "average" for Guanacaste. Three anamorphic curves proceeding from the guide curve were defined, each separated at the age of 10 years by 2 m. Qualities used were 23, 21 and 19, showing that at 10 years of age the corresponding mean heights reach 23, 21 and 19 m, respectively.

Table 6 shows the site indices (Ic_i) and values of parameter c_i for the three site quality classes in according with the next expression:

$$c_i = \frac{1}{Ic_i} - 0.008006 \quad (16)$$

when Ic_i is the height reached at base age (10 years).

Fig. 2 shows the mean data from inventories in each ecological zone and the three adjusted models we tried. Moravia, Palo Arco and Puerto Carrillo plantations show site quality indices of 23, 21 and 19, respectively.

3.3. Yield tables

The results of the first relationship ($H_0 = f(\text{age})$) are presented in Table 7 where for each age the top height is given in function of the site index defined in the above section.

The second relationship (number of trees/ha) for each age was defined through the rate of reduction and included possible natural mortality. In this rate the final density of the stand before the final felling was calculated for each site quality in function of the information given in Keogh (1987, 1990) and de Camino et al. (1998) as well the data available in our plantation.

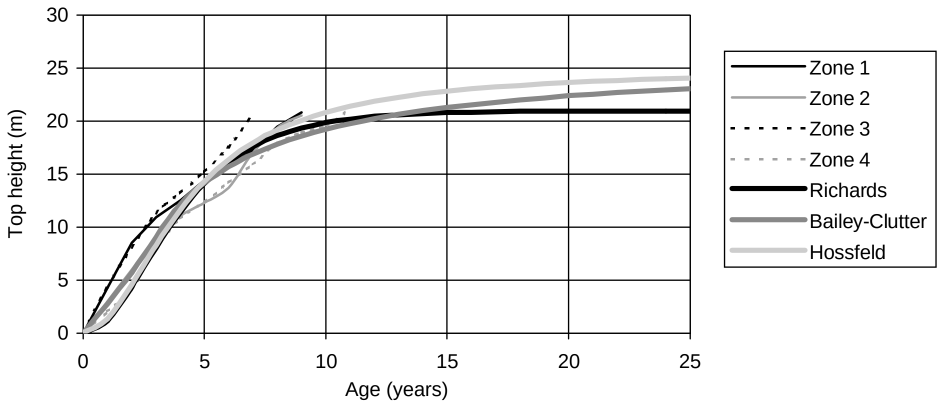

Fig. 2. Guide curves obtained from the inventory data and average series of Bosque zones.

Table 8
Yield tables for *T. grandis* L.f. in Northwestern Costa Rica[a]

Age (years)	H_0	Main crop before thinning					Crop removed					Main crop after thinning					Total crop		
		N	D_g	G	V	Hart	N	D_g	G	V	Vt	N	D_g	G	V	Hart	VT	MAI	CAI
Quality 23																			
3	8.6	1111	7.5	4.9	0	34.9	399	0	0	0	0	712	9.4	4.9	0	43.6	0	0	0
5	15.3	712	15.2	13.0	49.8	24.5	256	12.1	2.9	12.5	12.5	456	16.8	10.1	37.3	30.6	49.8	9.9	24.9
8	21.0	456	22.7	18.5	114.0	22.3	164	19.5	4.9	28.7	41.2	292	24.4	13.6	85.3	27.9	126.5	15.8	25.6
12	24.3	292	29.0	19.3	137.2	24.1	105	24.8	5.1	34.5	75.8	187	31.1	14.2	102.7	30.1	178.5	14.9	13.0
20	26.5	187	35.9	19.0	157.1	27.6	67	31.8	5.3	39.4	115.2	120	38.1	13.7	117.7	34.4	232.9	11.6	6.8
25	27.0	120	43.9	18.2	133.2	33.8											248.4	9.9	3.1
Quality 21																			
3	8.3	1111	7.2	4.6	0	36.1	357	0	0	0	0	754	8.8	4.6	0	43.9	0	0	11.3
5	14.4	754	14.2	11.9	30.2	25.3	242	9.4	1.7	6.78	6.78	512	16.0	10.2	23.4	30.7	30.2	6.0	15.1
8	19.3	512	20.5	16.9	76.8	22.9	165	15.7	3.2	17.3	24.1	347	22.4	13.7	59.5	27.8	83.6	10.4	17.8
12	22.1	347	25.5	17.7	107.6	24.3	111	21.1	3.9	24.1	48.2	236	27.3	13.8	83.5	29.5	131.7	11.0	12.0
20	23.9	236	30.7	17.4	146.3	27.2	76	28.7	4.9	33.0	81.2	160	31.5	12.5	113.3	33.1	194.5	9.7	7.8
25	24.3	160	36.1	16.4	136.0	32.5											217.2	8.7	4.5
Quality 19																			
3	8.0	1111	6.9	4.2	0	37.5	335	0	0	0	0	776	8.3	4.2	0	44.9	0	0	9.9
5	13.4	776	13.1	10.5	27.2	26.8	234	9.1	1.5	5.73	5.733	542	14.5	9.0	21.43	32.1	27.2	5.4	13.6
8	17.6	542	18.6	14.7	55.3	24.4	163	13.6	2.4	11.6	17.37	379	20.3	12.3	43.65	29.2	61.0	7.6	11.3
12	19.3	379	22.2	14.7	98.5	26.6	114	20.7	3.8	20.7	38.12	265	22.8	10.8	77.79	31.8	115.9	9.7	13.7
20	21.3	265	27.0	15.2	119.0	28.8	80	25.9	4.2	25.1	63.26	185	27.4	10.9	93.84	34.5	157.1	7.9	5.2
25	21.7	185	31.5	14.4	115.3	33.9											178.5	7.1	4.3

[a] H_0: top height (m); N: number of stems/ha; D_g: quadratic mean diameter at breast of height (cm); G: basal area (m^2/ha); V: commercial volume (m^3/ha); Vt: commercial volume accumulated in thinnings (m^3/ha); Hart: Hart–Becking index; VT: total commercial volume (m^3/ha); MAI: mean increment of volume (m^3/ha per year); CAI: current increment of volume (m^3/ha per year).

The relation between V_{me} and V_m (V_{me}/V_m) was 0.70 for the second and third thinning and 0.75 for the fourth and fifth thinning. We can observe that this fraction has increased with the age. The reason is that silvicultural treatments like thinnings reduce size differences between trees in the stand. The thinning increases stand uniformity, reducing the range of diameter distribution, overall if low thinning treatments are applied, as in this case happens.

Yield tables are given for an average silviculture regime and the three qualities adjusted (Table 8). At the end of Table 8, figures of commercial total volume (accumulated), mean and current annual increments of commercial volume are shown. Total crop, which includes both standing and felled trees, is also shown.

In order to calibrate density in the model proposed here, the Hart–Becking index (Wilson, 1979), or relative spacing, was used. The index is defined as the relationship between the mean spatial distance between trees and the top height of the stand, expressed as a percentage. The following expression is used to determine this index in forest plantations:

$$S = \frac{10^4}{H_0\sqrt{N}} \tag{17}$$

where S is the Hart–Becking index, H_0 the top height (m) and N the number of trees per hectare. The philosophy is to maintain constant the density and the relative spatial distance between trees. This spatial distance is expressed as a percentage of top height, when the top height increased, the absolute spatial distance increased too, but not the relative spatial distance between trees. In Table 8 we could appreciate the Hart–Becking index range from 22 to 27 before thinning and 27–34 after thinning. Values appropriated for plantations with not high density.

The mean tree volume is obtained by using a general double-entry equation estimated in the above section (Eq. (8)). The volume by hectare was obtained

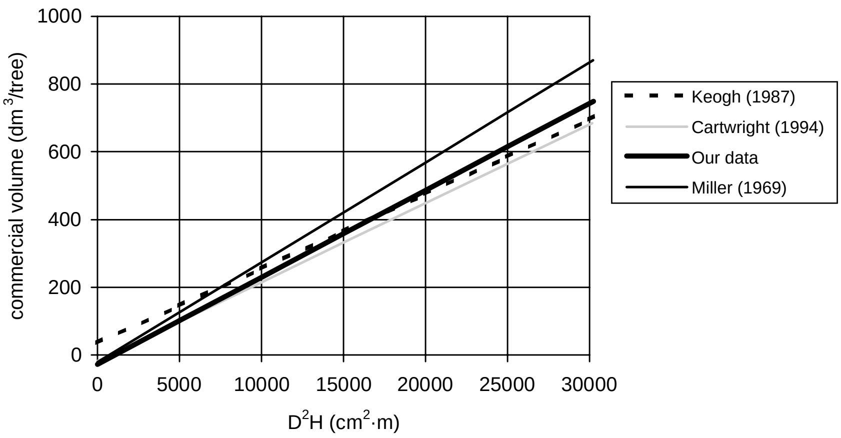

Fig. 3. Comparison of teak commercial volume equations given for Central America by Miller (1969), Keogh (1987), Cartwright and Marshall (1994), and our data.

as the product of the number of trees per hectare by the mean tree volume.

The quadratic mean diameter (D_g) was calculated using the following equation:

$$D_g = -3.034 + 0.964H_0 + \frac{2510.28}{N}, \qquad R^2 = 0.698 \tag{18}$$

$$V_e = 0.28G_eH_0 \tag{19}$$

The estimation of removed basal area was estimated through Fig. 3 compares the teak commercial volume equations given by Miller (1969), Keogh (1987), Cartwright and Marshall (1994), and our data for Central America.

Fig. 4 shows the evolution of mean and current annual increments of commercial volume for different qualities of teak plantations in northwest Costa Rica.

Commercial volume and basal area for the main stand after thinning and for total crop for different site qualities are shown in Fig. 5. These figures provide useful information for forest management and enable rapid and schematic comparisons to be

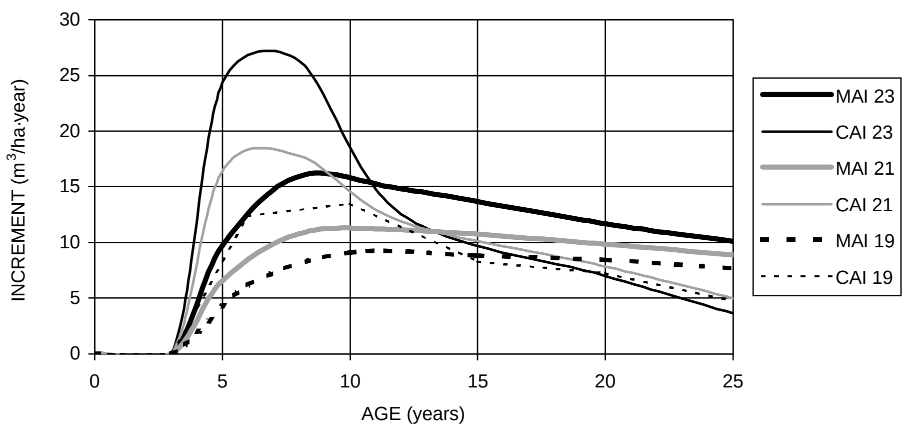

Fig. 4. Current and mean annual increments of commercial volume for different site index of teak plantations in Guanacaste (Costa Rica) (MAI: mean annual increment of commercial volume; CAI: current annual increment of commercial volume).

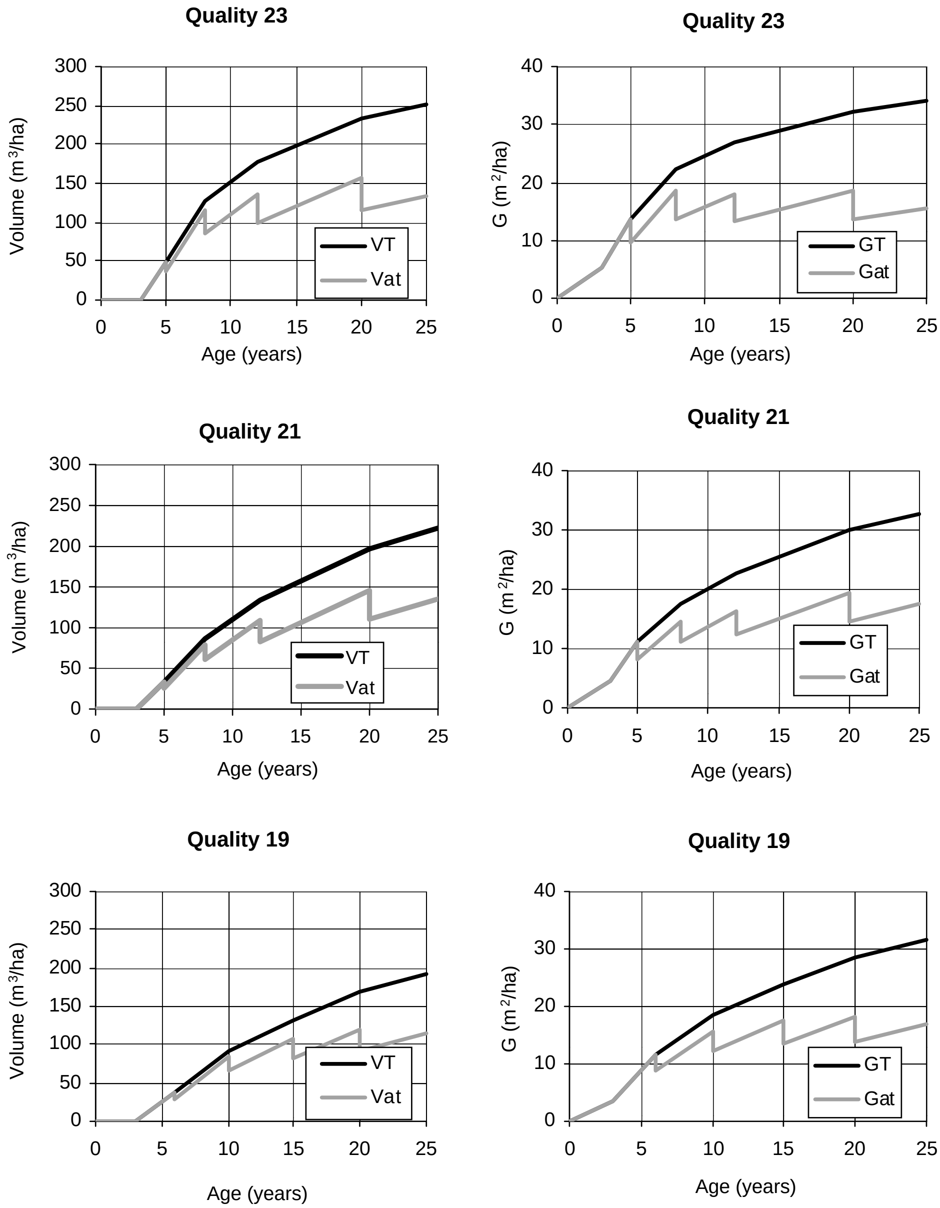

Fig. 5. Commercial volume (m^3/ha) and basal area (m^2/ha) for main stand after thinning (Vat and Gat) and for total crop (VT and GT) for different site qualities. Results for plantations of *T. grandis* in Guanacaste (Costa Rica).

made of the evolution of these important variables, according to site quality, thinning regime and stand age.

Fig. 6 shows the evolution of tree density after thinning for teak plantations for the three quality sites.

4. Discussion

A comparative study was carried out of *T. grandis* L.f. volume equations, site quality curves and yield tables given by this study and those coming from other works developed in Central and South America

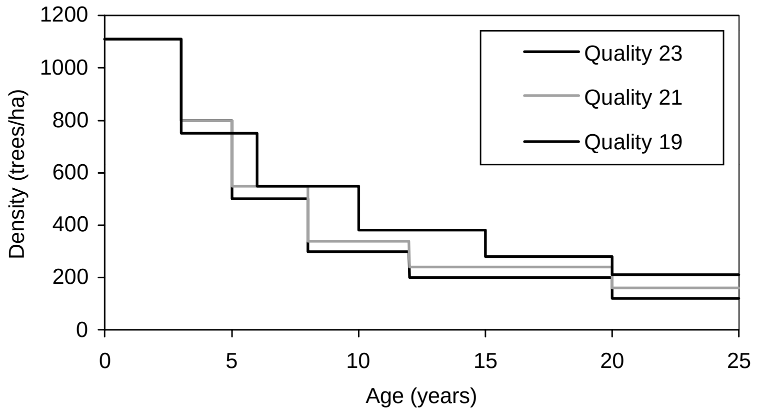

Fig. 6. Density (trees/ha) before (first) and after (second) thinning according to site quality for teak plantations in Guanacaste (Costa Rica) and average silviculture.

(Miller, 1969; Keogh, 1987; Cartwright and Marshall, 1994; Nieuwenhuyse et al., 2000) and other parts of the world (Malende and Temu, 1990; Murugesh et al., 1997; Nunifu and Murchison, 1999).

4.1. Volume equations for teakwood

Volume equations developed for Bosque in 2000 maintain the expressions obtained by Cartwright and Marshall (1994). We recommend the use of separate formulae for the development of the yearly inventories since the interception coefficients show significative differences (95% of confidence interval).

As far as the general volume equation is concerned, only a slight increase in the slope of the linear function now gives higher commercial volume figures, as compared to that of Cartwright and Marshall (1994). Since the linear model has been chosen in the study carried out by Keogh (1987) for teak in Costa Rica and for a sample with diameters ranging from 18 to 53 cm (height range is unknown), this is the model we have considered to be the most appropriate.

Fig. 3 compares volume equations given by Keogh (1987), Cartwright and Marshall (1994) and Miller (1969) with our data. All the curves show quite similar shape and behavior.

Nevertheless, this linear model should be confirmed in the future with a sample covering the whole ranged variation of the D^2H variable throughout the full rotation length.

4.2. Site index

The site quality curves obtained in this study clearly show that Guanacaste is an excellent territory for teak growing. The three quality classes given here could be placed around the best quality (Class I) obtained by Miller (1969), Keogh (1979) and Akindele (1991) in similar studies (see Fig. 7). Similar results were obtained too by Somarriba et al. (1999) for teak linear plantations in the Nicoya peninsula.

Using this site quality classification in Guanacaste, an idea of the future development of a given teak plantation can be obtained by cross-indexing the top height at an age of 5–6 years (measurements taken earlier might be not precise enough, because curves are not well differentiated at early ages). We can then assign site indices to different planting zones and use yield tables according to such qualities.

Again, a more detailed study on quality should be carried out at the end of the first rotation with the aim of confirming whether Hossfeld's chosen model still remains the most appropriate one for Bosque plantations.

Authors from other parts of the world (Nwoboshi, 1983; Murugesh et al., 1997; Nunifu and Murchison, 1999; Malende and Temu, 1990) use lineal models or log–log models for site index classifications. These works thus estimate a lower height growth for the first years of age in comparison with our data. However their height growth estimates show no upper limit (the site models do not present asymptote). That is why our

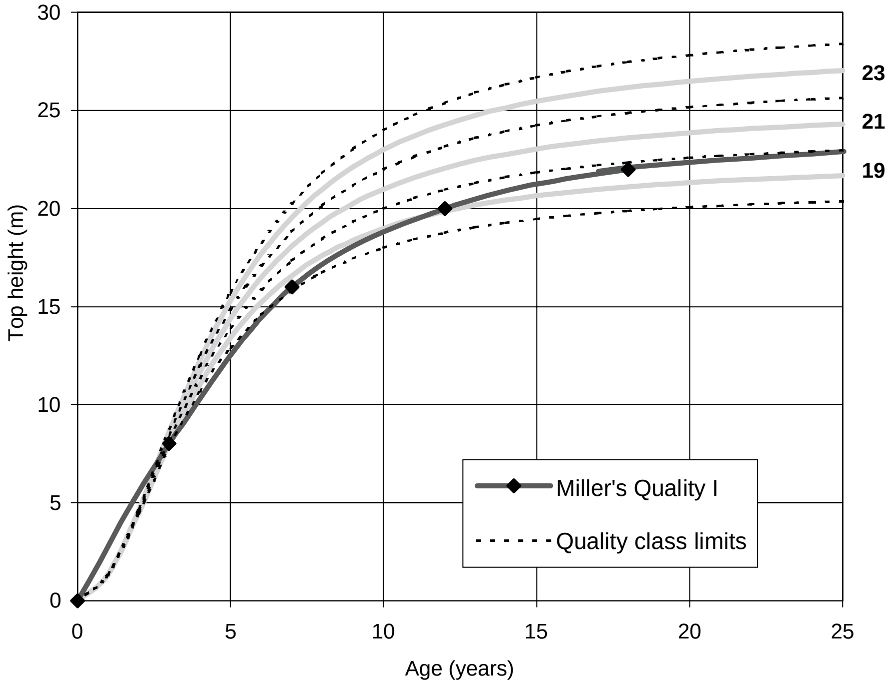

Fig. 7. Site quality curves for plantations of teak in Costa Rica and comparison with quality I of Miller (1969).

site index models seem to be more appropriate, at least for American plantations.

4.3. Yield tables

Our yield tables have been compared to those developed for Trinidad by Miller (1969) and those used by Bosque up until the present day. Our tables (see Table 8) are similar to those used in the recent past, thus showing coherence with previous studies and data. The new model adds a new division, with three categories, instead of the two categories defined by the old one. The new criterion for our yield table use is, moreover, based on a site quality study, which the old tables lacked. Our new tables are fully detailed in their explanation of how every major silvicultural variable progresses with time, thus providing a more useful management tool from the long-term point of view.

Considering that Bosque plantations cover a wide spectrum of sites, we affirm that the proposed silvicultural model, though developed from Bosque data, can be used in all those areas of Guanacaste suitable for teak growing.

Productivity figures, such as commercial volume of the total stand at the end of the rotation and maximum mean/current increments achieved, clearly draw the line of maximum expectations in Guanacaste. While some teak planting schemes planned for this region claimed to reach mean increments of 49 m^3/ha per year with 20-year rotations (Centeno, 1997), this is heavily against figures obtained in this study. Pandey and Brown (2000) warns against this trend in overestimating teak possibilities that is currently damaging the image of teak before angry investors who do not get what they were told at the end of the rotations. Excellent crops and economic returns can be obtained from teak plantations with a suitable scientific silviculture and environmentally sound management. Results of 8.6 m^3/ha per year (commercial volume) for 25-year rotations in Guanacaste, as is the case for average quality sites in this study, are good enough and need no further inflation for becoming a good investment.

Table 8 shows this species grows very fast during the first years after plantation. By the age of 10 years it reaches 85% of its potential height and 50% of potential diameter. Current and mean annual diameter and height increment reach their maximum values very soon (5 years), and the current volume increment reaches its upper value at 8 years of age. *P* equals *M* (biological rotation period) at an age of 11 years, in medium and high site quality and at 15 years in low quality sites. Somarriba et al. (1999) have obtained similar results in Costa Rica.

As has already been stated, for volume equations and site quality indices, our yield tables should be validated at the end of the first rotation (2015–2020), though significative differences are not foreseen.

Our yield table is valid for stands with the following silvicultural treatments:

- Density plantation: 1111 trees/ha (3 m × 3 m).
- First thinning systematic at 3 years old (top height 8 m). The results density will be 750 trees/ha approximately.
- First commercial thinning at 5–6 years old (mean height = 15 m).
- Other three thinnings with rotation every 5 years.
- Final felling at 25 years old.

5. Conclusions

The site index model presented in this work could be provisionally adopted for teak plantation management in Costa Rica. At a reference age of 10, average site index of 23, 21 and 19 m are estimated for teak in the region for site classes I, II and III, respectively.

Growth and yield models seem to be the best tools for designing a thinning regime, and are also helpful in matters concerning forest inventorying and management. They are also a necessary tool in the resource planning essential to forest policy design. Our yield models might be used in the following cases:

- site index classification of the inventory units;
- the estimation of periodic increment in inventories for forest management;
- the estimation of volumes with a fair degree of accuracy, when inventories are not possible;
- production forecasting for regional scale planning.

Our silvicultural model is based on data from the first half of the rotation and other models developed for teak. Therefore, it should be validated at the end of the first 25-year period.

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