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ABOVEGROUND BIOMASS OF *TECTONA GRANDIS* PLANTATIONS IN COSTA RICA

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PÉREZ CORDERO, L. D. & KANNINEN, M. 2003. Aboveground biomass of *Tectona grandis* plantations in Costa Rica. There are few studies on biomass distribution for *Tectona grandis* plantations in Costa Rica. This paper reports the distribution of total aboveground biomass *of T. grandis* and its relationship with diameter at breast height (dbh), age and stand density in plantations across Costa Rica. Foliage, branch, stem and total aboveground biomass were highly correlated both with dbh ($r > 0.91$) and with age ($r > 0.85$). Foliage dry biomass represented between 1 and 6% of the total tree dry biomass, while 5 to 30% corresponded to branches and 70 to 90% to stem dry weight. Per hectare aboveground biomass tended to increase with increasing age class (young, intermediate and mature). Foliage dry biomass varied between 3 and 9 Mg ha^{-1}, branch dry biomass between 11 and 54 Mg ha^{-1}, stem dry biomass between 70 and 221 Mg ha^{-1}, and total aboveground dry biomass between 84 and 284 Mg ha^{-1}. Significant relations between crown diameter and aboveground biomass with dbh, age and stand density, useful for the management of stand competition, are the main results of this study.

Key words: Allometric models - crown diameter - intensive management - stand density

PÉREZ CORDERO, L. D. & KANNINEN, M. 2003. Biojisim atas tanah ladang *Tectona grandis* di Costa Rica. Terdapat beberapa kajian tentang taburan biojisim bagi ladang *Tectona grandis* di Costa Rica. Artikel ini melaporkan tentang taburan jumlah biojisim atas tanah *T. grandis* dan hubungan dengan diameter aras dada (dbh), umur dan kepadatan dirian di ladang Costa Rica. Daun, dahan, batang dan jumlah biojisim atas tanah mempunyai korelasi yang tinggi dengan dbh ($r > 0.91$) dan umur ($r > 0.85$). Biojisim kering daun mewakili antara 1 dan 6% daripada jumlah biojisim kering, manakala 5 hingga 30% merupakan ranting dan 70 hingga 90% merupakan biojisim kering batang. Biojisim atas tanah sehektar cenderung untuk meningkat dengan peningkatan kelas umur (muda, pertengahan dan matang). Biojisim kering daun berubah-ubah antara 3 dan 9 Mg ha^{-1}, biojisim kering dahan antara 11 dan 54 Mg ha^{-1}, biojisim kering batang antara 70 dan 221 Mg ha^{-1} dan jumlah biojisim kering atas tanah antara 84 dan 284 Mg ha^{-1}. Hubungan yang bererti antara diameter silara dan biojisim atas tanah dengan dbh, umur dan kepadatan dirian, merupakan keputusan utama yang diperoleh dalam kajian ini.

Introduction

Fast-growing and high-yielding tree plantations are an increasingly significant source of wood in the tropics. In these areas, improved wood productivity is an important economic goal. *Tectona grandis* has gained a worldwide reputation on

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account of the attractiveness and durability of its wood. Market demands have prompted the establishment of plantations within and beyond its native countries (Hoare & Patanapongsa 1988, Monteuuis & Goh 1999, Bhat 2000).

Tectona grandis is a valuable and fast-growing tree species that has been widely used in plantation programmes throughout Central America. Approximately 223 000 ha of *T. grandis* plantations have been established in Central America (Pandey & Brown 2000). In Costa Rica, teak plantations cover a total area of 40 000 ha (Arias & Zamora 1999). With this large hectarage it is necessary to develop appropriate silvicultural techniques for the management of teak.

The size and spatial distribution of the canopy are causally related to the amount of light intercepted by the leaves. This relationship has been used to develop better understanding of how the productivity of plantations can be measured in terms of conversion of light energy into biomass (Beadle 1997). Therefore it is important to study plantation densities appropriate to crown development that optimises tree growth (Suri 1975).

Measurements of biomass productivity for different plant communities under the same or different management and habitat conditions are needed to assess the limits to potential production of ecosystems. Total biomass productivity and percentage contribution of each tree component vary with forest type, species, density, age, site condition and management practices (Ola-Adams 1993). Studies of the crown composition and total biomass distribution of *T. grandis* plantations in Central America are lacking.

Biomass quantification is a time-consuming activity, especially the measurement of certain biomass components, such as foliage or branch biomass. Therefore, there is a need to develop useful, indirect methods for estimating the difficult-to-measure variables.

This paper reports the distribution of total aboveground biomass and the crown development with diameter at breast height (dbh), age and stand density of *T. grandis* plantations across Costa Rica. The observed relationships can undoubtedly be very helpful for the indirect estimation of aboveground biomass and for the density management of forest plantations.

Materials and methods

Materials for this study were collected from private plantations in Costa Rica (Figure 1), including the following sites and provinces: Samara and Tempisque (Guanacaste); Jicaral, Parrita, Quepos, Palmar Norte and Buenos Aires (Puntarenas); Guapiles and Guacimo (Limon); and San Carlos (Alajuela).

For this study 16 plantations from 10 different sites were selected, representing different climatic conditions (Table 1), plantation densities (initial densities between 1111 and 2500 trees ha^{-1}, actual densities between 170 and 1600 trees ha^{-1}), and ages (8 to 47 years). One or two plots of 400 m^2, with 50 to 80 trees each, were established on each plantation. The age was obtained from the registers recorded by the owner and corroborated through stem analysis (growth ring counting).

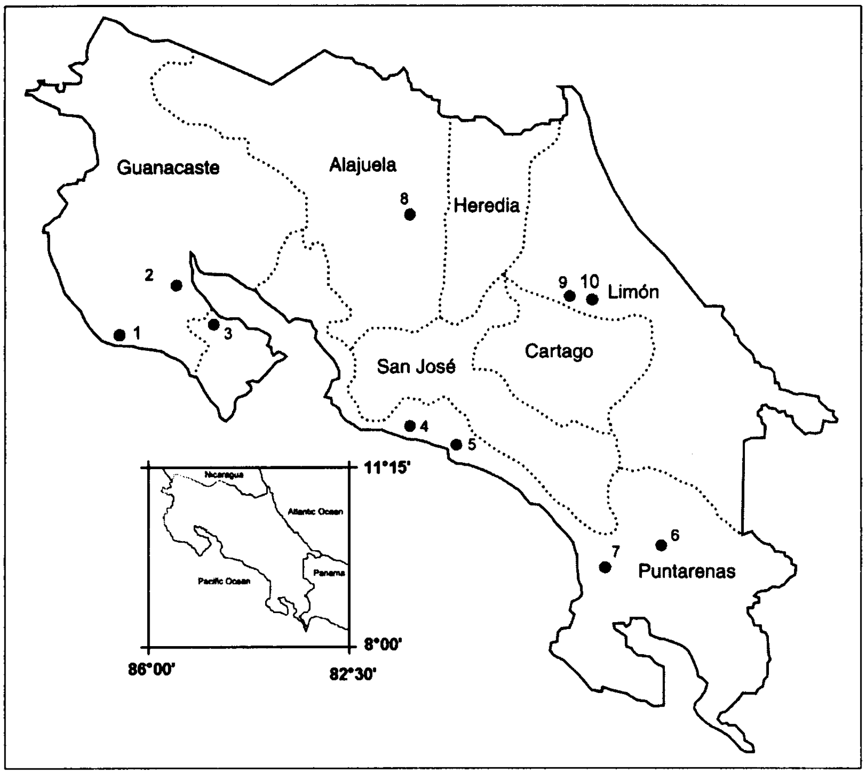


Figure 1 Location of the *Tectona grandis* plantations evaluated in Costa Rica. (For site codes, see Table 1)

Table 1 Bioclimatic variables of the sites where *Tectona grandis* trees were harvested

Site code	Location	Elevation (m)	Precipitation (mm year^{-1})	Mean annual temperature (°C)	Slope (%)	Dry month*
1	Samara	100	1705	26.1	15	5
2	Tempisque	30	1901	27.1	2	6
3	Jicaral	85	1659	26.8	5	6
4	Parrita	23	3117	26.0	13	3
5	Quepos	70	3900	25.9	5	3
6	Buenos Aires	300	3627	27.0	2	4
7	Palmar Norte	80	3644	27.0	5	3
8	San Carlos	90	3393	26.1	2	1
9	Guapiles	250	4107	26.0	2	0
10	Guacimo	220	4200	26.0	11	0

* months with rainfall less than 100 mm

From these plots, a total of 40 trees were felled for biomass measurements. A higher sample was intended, but the owners allowed the harvesting of only few trees. In most cases, a dominant and an average tree were selected on each plot. In some others, between one and three individuals were felled. Before the felling, dbh and crown diameter of each tree were measured. After the felling, the quantified variables were:

(1) foliage and branch fresh weight (kg),
(2) total height (H) of the tree (m), and
(3) diameter (cm) at different heights.

Stem cross-sectional samples were taken at the base and at the dbh of each felled tree. From the height of 2.0 m onwards, sections were taken along the stem at every 2.0 m. Diameter was measured on each stem section. Total volume (m^3) was calculated using the Smalian formulae (Alder 1980) for each stem section (i.e. 0.0–1.3 m, 2.0–4.0 m, 4.0–6.0 m, etc). The last stem section (from the last disc to the tip of the tree) was calculated as a geometric cone.

For the determination of dry biomass content, branch and foliage samples of 1.0 and 0.5 kg respectively were taken from each tree at the different stem sections. Green weight was recorded and the samples were then oven-dried (65 °C) at the laboratory to constant weight. These samples were used to determine dry weight and moisture content. Stem volume was calculated using the dry density values previously determined for each sample tree (averaging 0.60 g cm^{-3}).

Different models, such as linear, logarithmic, exponential and logistic, were tested for best-fit of the relationships between aboveground biomass as well as crown diameter, and dbh, age and stand density. Multiple regression analyses were carried out to analyse the combined effect of dbh, age and stand density on biomass distribution. The best models were selected based on the criteria of the model's biological logic, the adjusted coefficient of determination (r^2), the root mean square error (RMSE) of the fitted equation (Parresol 1999), the Akaike information criterion (Draper & Smith 1980), the Furnival index (Furnival 1961), and residual autocorrelation.

Finally, aboveground biomass per hectare was calculated using the allometric models developed in this study. For this, the first step was to calculate foliage, branch, and stem biomass of trees in each dbh class in the sample plots. The second step was to estimate biomass per hectare using the dbh distribution of each sample plot.

Results

Foliage, branch, stem and total biomass were highly correlated with dbh ($r > 0.91$), showing a clear increment with increasing dbh. The best allometric models to estimate aboveground biomass and crown diameter from dbh and age are presented in Table 2. The $\log_{10}$-$\log_{10}$ transformation allowed elimination of the residual autocorrelation and improved the models significantly in relation to the exponential logistic and non-transformed linear models. Multiple regression analyses did not improve the results obtained by single regression analyses; therefore, only simple linear and logarithmic models were selected as best models.

Table 2 Parameter values and regression statistics for the best allometric models developed in this study to estimate biomass components for *Tectona grandis* in Costa Rica

Model #	Variable	a	b	CF*	r^2	RMSE	FI**	AIC**	Confidence interval (95%)	
						Type I: $\log_{10} Y = a + b \log_{10}$ dbh (cm)				
1	Foliage dry biomass (kg)	- 2.138	2.272	1.11	0.83	0.1949	1.25	- 129	- 2.604 < a > - 1.671	1.928 < b > 2.616
2	Branch dry biomass (kg)	- 2.380	2.920	1.10	0.89	0.190	2.69	- 131	- 2.835 < a > - 1.924	2.585 < b > 3.256
3	Stem dry biomass (kg)	- 0.804	2.303	1.01	0.98	0.055	11.22	- 229	- 0.938 < a > - 0.671	2.205 < b > 2.401
4	Total dry biomass (kg)	- 0.815	2.382	1.01	0.98	0.055	14.06	- 227	- 0.952 < a > - 0.679	2.281 < b > 2.483
5	Crown diameter (m)	- 0.317	0.771	1.02	0.75	0.084	0.453	- 198	- 0.513 < a > - 0.121	0.627 < b > 0.916
						Type II: $Y = a + b$ dbh (cm)				
6	Foliage dry biomass (kg)	- 8.569	0.881	0.82	4.509	40.0	122		- 12.195 < a > - 4.944	0.743 < b > 1.019
7	Branch dry biomass (kg)	- 72.397	5.750	0.89	21.87	276.49	249		- 89.983 < a > - 54.811	5.081 < b > 6.420

* Correction factor (Sprugel 1983)
** Furnival index (Furnival 1961)
** Akaike information criterion (Draper & Smith 1980)

Foliage dry biomass increased exponentially with increasing dbh, varying between 0.9 and 38.1 kg. The best model fitting this relationship was logarithmic ($\log_{10}$-$\log_{10}$) (Figure 2a, Table 2). With a similar tendency and predictive model type, branch dry biomass ranged from 2.2 to 302 kg, with a maximum of 278 kg (Figure 2b, Table 2). The stem dry biomass varied between 27.0 and 1760 kg, without any trend towards an asymptote, and was best predicted also by a $\log_{10}$-$\log_{10}$ equation (Figure 2c, Table 2). Consequently, total aboveground biomass ranged from 30.1 to 2100 kg, increased exponentially with dbh and was modelled

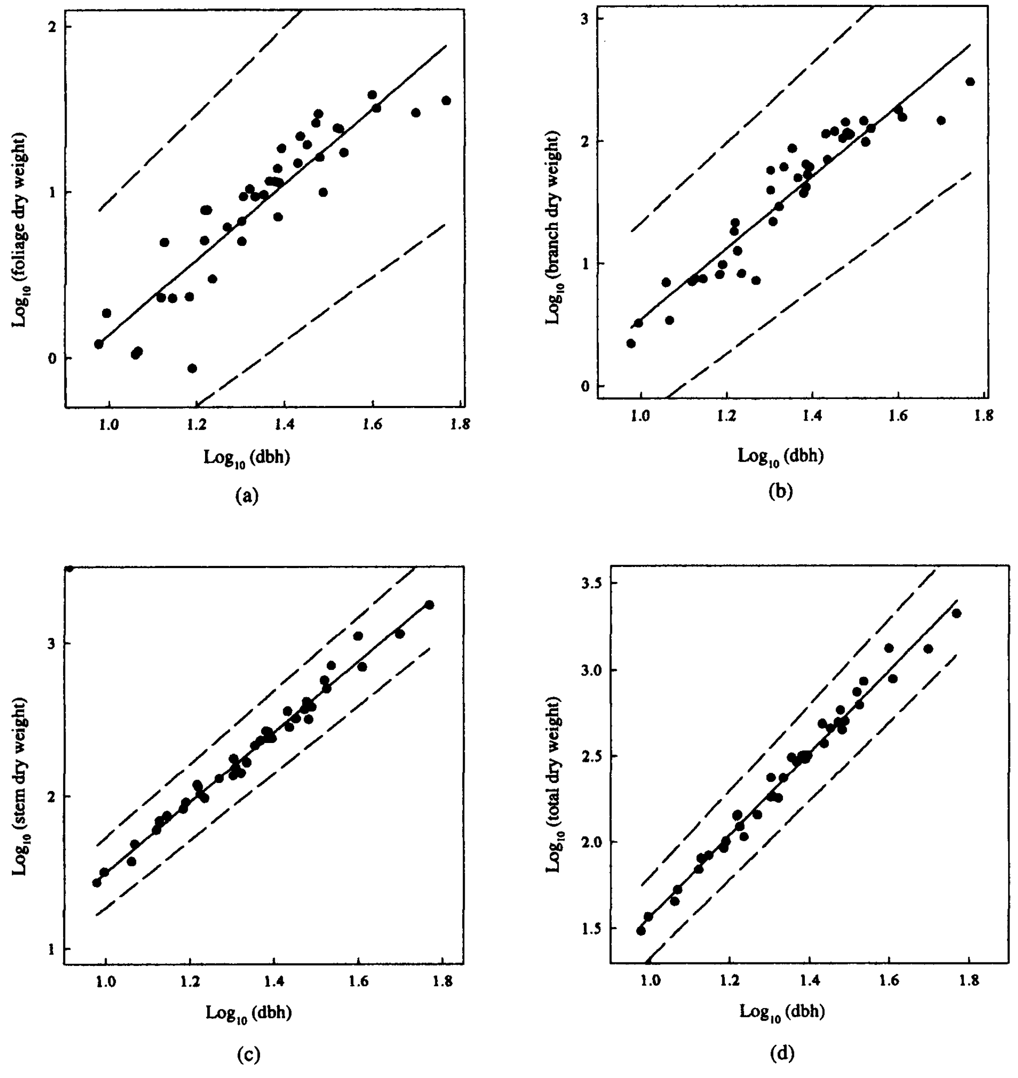
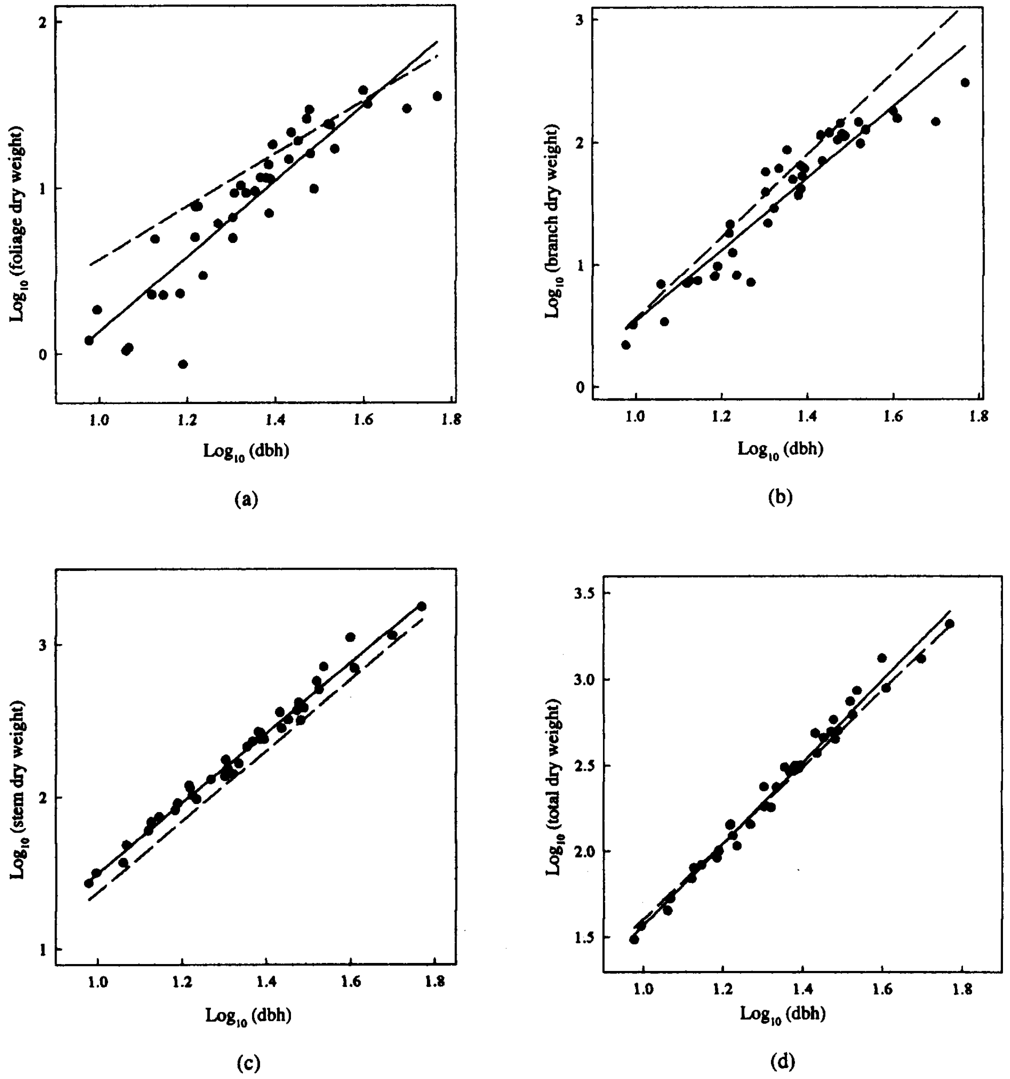


Figure 2 Relationship between (a) foliage dry weight, (b) branch dry weight, (c) stem dry weight, and (d) total aboveground dry weight and dbh of *Tectona grandis* trees harvested in Costa Rica. Dashed lines correspond to 95% confidence interval. Models 1 to 4 from Table 2 were used.

by a logarithmic equation as well (Figure 2d, Table 2). Foliage biomass and branch biomass were also estimated from dbh using simple linear models and were included as best models in Table 2. However, the regression statistics suggested the logarithmic models to be best. The best models found in this study were plotted against those developed by Negi *et al.* (1995) for teak in India (Figure 3), for comparison.

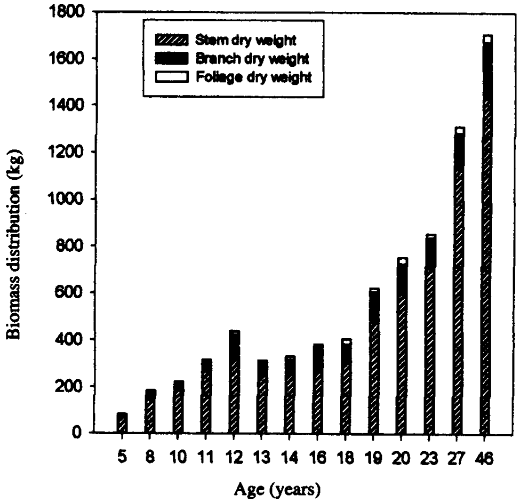


(a) (b)

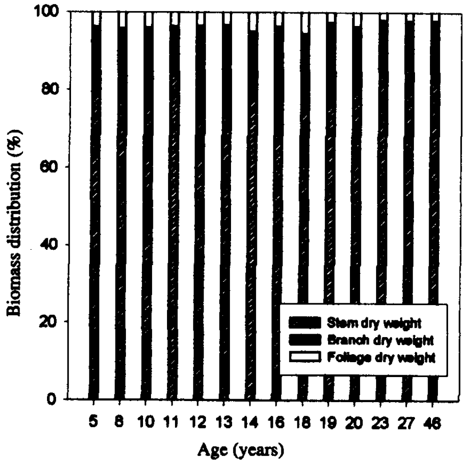
(c) (d)

Figure 3 Comparison of allometric models developed in this study (continuous line) vs allometric models developed by Negi *et al.* (1995) (dashed line) for the relationships between (a) foliage dry weight, (b) branch dry weight, (c) stem dry weight and (d) total aboveground dry weight and dbh in *Tectona grandis* plantations in Costa Rica and in India respectively. Dots correspond to sample data of this study.

Individual-tree foliage, branch and stem dry weight increased with increasing age (Figure 4a). In relative terms, foliage dry biomass represented between 1 and 6% of the total tree dry biomass, while 5 to 30% corresponded to branches and 70 to 90% to stem dry weight (Figure 4b). For individual-tree variable values see Appendix 1.



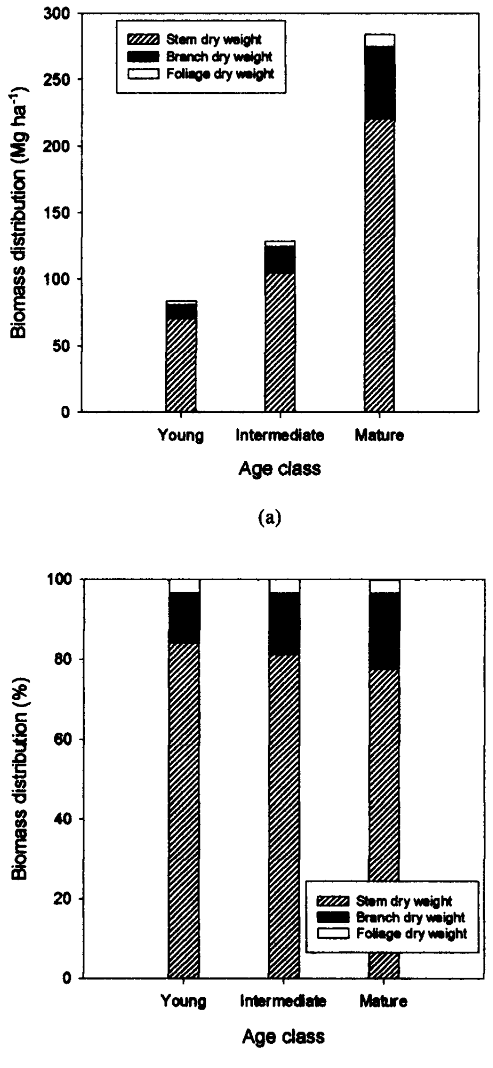
(a)



(b)

Figure 4 Biomass distribution (a) in absolute values, and (b) in per cent at different ages of *Tectona grandis* trees in Costa Rica

Per hectare aboveground biomass tended to increase with increasing age class (young, intermediate and mature). Foliage dry biomass varied between 3 and 9 Mg ha^{-1}, branch dry biomass between 11 and 54 Mg ha^{-1}, stem dry biomass between 70 and 221 Mg ha^{-1}, and total aboveground dry biomass between 84 and 284 Mg ha^{-1} (Figure 5a). In relative values the foliage biomass represented approximately 4% of the total aboveground dry biomass, while 16% corresponded to branches and 80% to stems (Figure 5b).



(a)

(b)

Figure 5 Per hectare biomass distribution (a) in absolute values, and (b) in per cent at different age classes of *Tectona grandis* in Costa Rica

Other relationships, such as the increment in crown diameter with increasing dbh (Figure 6, Table 2), or the decrease of foliage, branch, stem and total aboveground biomass with increasing stand density (Figure 7), were developed as possible tools to aid the management of stand competition. However, no strong correlation was found between biomass components and stand density ($r < 0.67$).

Discussion

The increase in foliage, branch and stem dry biomass with increasing dbh indicated that even at dbh of 60 cm, *T. grandis* still produced and accumulated biomass without reaching a maximum but with some fall-off in increment at the largest dbh values. Besides the tendency of the total tree biomass to increase with increasing dbh, there was also a clear increment of the biomass components with increasing age.

Foliage and branch biomass predictive models presented a mean error of estimate of 40% in relation to sample data. This difference between observed and predicted can be attributed to the considerable variation of foliage and branch weight between trees of similar dbh but at different plantation sites with specific thinning and pruning regimes. However, the stem and total dry weight were estimated with more accuracy, presenting a mean error of estimate of 12% in relation to the sample data. Improvements in accuracy could be obtained by increasing the number of sample trees from different regions, age, dbh and management regimes.

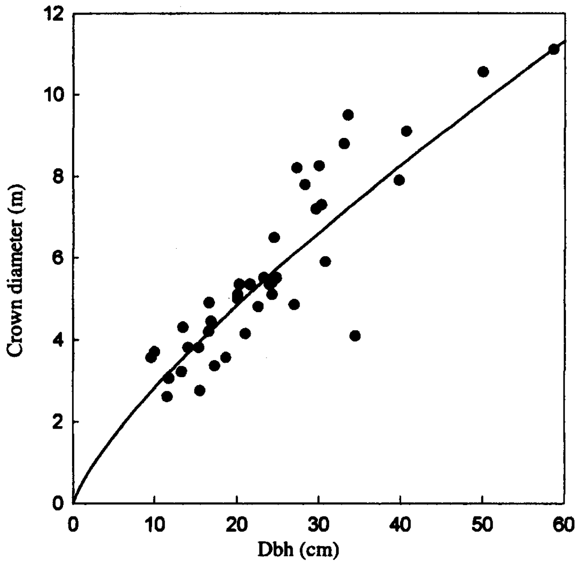
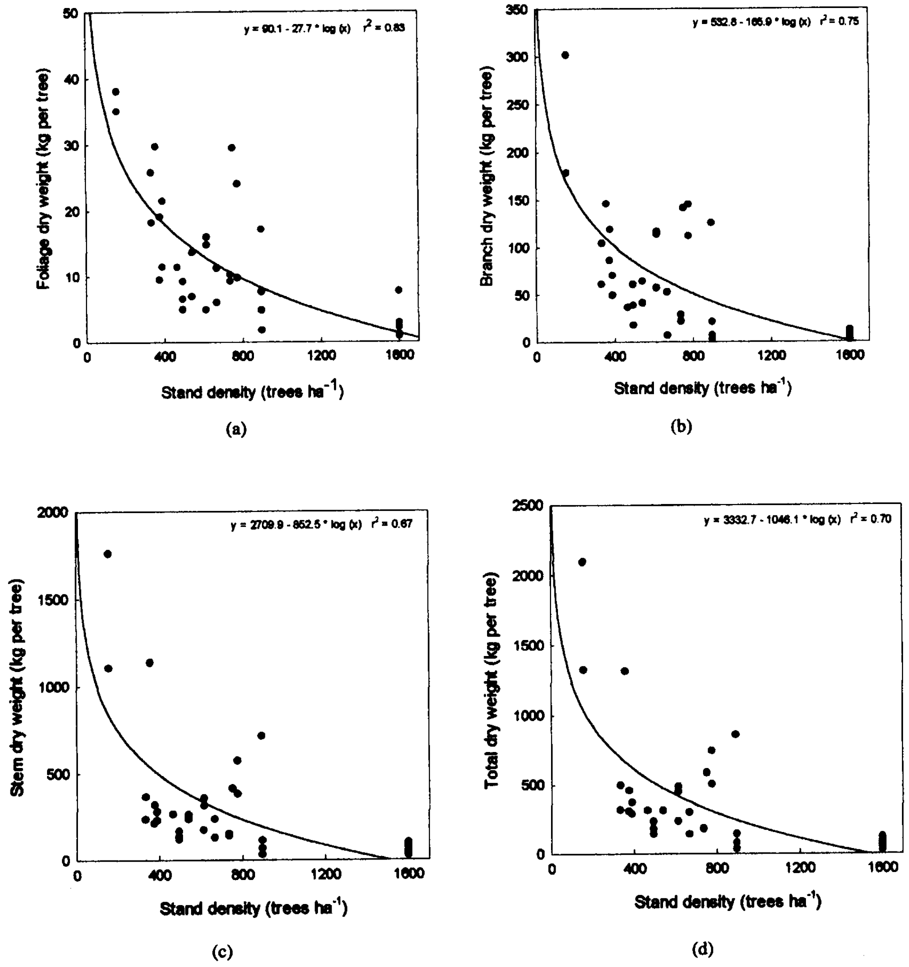


Figure 6 Relationship between crown diameter and dbh of *Tectona grandis* in Costa Rica. (For fitted model, see Table 2)



(a) (b)

(c) (d)

Figure 7 Relationship between (a) foliage dry weight, (b) branch dry weight, (c) stem dry weight, and (d) total aboveground dry weight per tree and stand density of *Tectona grandis* plantations in Costa Rica

Similar to our findings, Negi *et al.* (1995) confirmed that dbh can be used as a reliable parameter for the estimation of aboveground biomass for teak. In relation to our sample data, the model overestimated foliage biomass (up to 67% difference) mainly at lower dbh values, while the model for the prediction of branches overestimated values (overestimations up to 45%) at dbh > 30 cm. On the other hand, the models for the estimation of stem biomass and total biomass from dbh were very similar to those developed in this study and fitted well the observed values, with a mean difference of 22 and 12% between observed and predicted values respectively. Differences in growth rate, stand density, climatic conditions and tree size between the present study and that carried out in India may had influenced the significant variations in the estimation of biomass components, mainly foliage and branches.

The use of multiple regression analyses did not improve the fit of the single regression analyses, although single-tree biomass components was highly correlated with age ($r > 0.86$) and slightly correlated with stand density ($r < 0.68$). A reason for this may be the fact that some plantations of similar age presented much different actual densities. Moreover, just before the onset of this study, most of the sample plantations underwent different thinning regimes and, as a consequence, the actual stand density may not have influenced the biomass distribution and tree size as it normally would.

Biomass dry weight reported by Chelunor (1983) for 10- and 14-year-old *T. grandis* in Nigeria are similar to those found in Costa Rica at the same ages. Also similar to our results, from his study of 20-year-old *T. grandis* growing in Saugar, India, Kandya (1974) found that 63% of the biomass was stored in the stem, 31.9% in the branches, and the remaining 5.1% in the foliage. On the other hand, lower values, contrasting with our results in age-specific aboveground biomass, were reported by Karmacharya & Singh (1992) for *T. grandis* in a tropical dry region of India. We hypothesise that the reason for this may be the low growth rate of trees in that dry region (10.4 cm of dbh and 4.4 m of crown diameter at 30 years).

Per hectare total aboveground biomass currently found for *T. grandis* plantations in Costa Rica is similar to that reported by Negi *et al.* (1990) in Tripura (138 Mg ha^{-1} at 20 years), but lower than the values found by Ola-Adams (1993) in south-western Nigeria (378 Mg ha^{-1} at 18 years). While these results indicated that foliage biomass increased with increasing age, Karmacharya & Singh (1992) found that the proportion of foliage biomass per hectare decreased from 34 to 7% with increasing age (based on measurements at 4, 14 and 30 years).

Per hectare biomass production of tropical forest plantations (including teak) has been reported to increase with increasing precipitation (Lugo *et al.* 1988, Brown *et al.* 1989, Karmacharya & Singh 1992). Nevertheless, based on a 10-year rainfall data we obtained earlier, we found no statistically significant relationship between the two variables. Among others, the reasons for this may be differences in planting density, site class and pruning and thinning regimes between sites with similar rainfall.

The variation of aboveground biomass with plantation density and the estimation of crown diameter from dbh can be of great use for stand density management purposes. The relationship between dbh and foliage biomass can be linked to the relationship between crown area and dbh in order to determine the maximum plantation density of a stand at a certain age. Assuming, for example, a criterion of maximum crown area occupancy as a parameter for maximum area occupancy, a maximum stand density could be defined based on the required plantation average dbh. In contrast to the results of our study, Ola-Adams (1993) found that the stand density had no significant effect on the total stand dry weight of 18-year-old teak in south-western Nigeria.

Per tree aboveground biomass decreased with increasing stand density but increased with increasing tree age, as stand density is negatively correlated with age (on managed plantations with thinning interventions). Accordingly, older trees are in plantations with lower densities than younger ones and, therefore, present more individual-tree biomass. The same pattern was observed with per hectare biomass, which increased with increasing age, although no clear tendency was observed with stand density initially. However, when eliminating the effect of age, the residuals showed a clear trend of increase with increasing stand density. This implies that per hectare biomass in teak is influenced by stand density, presenting higher values with higher plantation densities, but with some exceptions where lower plantation densities presented higher per hectare biomass (e.g. in a 47-year-old plantation sampled in this study, where no constant and systematic thinning regime had been followed).

Our study showed difficult-to-measure or time-consuming variables (e.g. foliage biomass) can be estimated from easily-measured variables (e.g. dbh). Simple linear and logarithmic models developed in this study estimated foliage, branch, stem and total dry biomass as well as crown diameter from dbh. The estimation of foliage biomass from dbh could also be useful for estimations carried out in the dry season when *T. grandis* would have lost most of their foliage.

In the regression analyses, variable transformations improved the results when compared with original values of non-transformed variables. This type of logarithmic models have been successfully implemented for other tropical species (Glough & Scott 1989, Overman *et al.* 1994).

We recognise that more sample trees are needed to construct more accurate regression models, particularly in the older age classes (> 20 years). We also acknowledge that extrapolation beyond the range of actual observations is not statistically valid.

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Appendix 1 Individual-tree registers of the measured variables of the 40 trees sampled in the present study

Site code	Tree (#)	Age (year)	Plantation density (trees ha^{-1})	dbh (cm)	Total height (m)	Crown diameter (m)	Foliage dry weight (kg)	Branch dry weight (kg)	Stem dry weight (kg)
1	1	8	736	21.0	15.2	4.2	10.3	28.9	141
1	2	8	736	20.3	16.4	5.4	9.3	21.9	153
1	3	10	667	18.6	19.8	3.6	6.1	7.2	130
1	4	10	667	24.5	22.0	6.5	11.3	52.8	238
2	5	14	389	27.3	21.1	8.2	21.5	70.4	281
2	6	14	389	23.3	20.3	5.5	11.5	49.5	230
2	7	18	333	29.6	20.3	7.2	25.8	104.1	367
2	8	18	333	24.8	20.1	5.5	18.2	61.0	238
2	9	20	line planting	33.5	23.4	9.5	23.8	97.7	503
2	10	20	line planting	40.7	23.3	9.1	31.7	154.8	697
3	11	11	466	24.0	20.1	5.5	18.2	61.0	238
3	12	12	750	30.0	24.7	8.3	29.5	141.3	414
4	13	13	541	24.3	20.9	5.4	13.7	64.2	238
4	14	13	541	24.3	23.1	5.1	7.0	41.5	264
4	15	45	156	58.7	31.9	11.1	35.1	301.9	1759
4	16	46	156	39.8	33.3	7.9	38.1	178.4	1108
5	17	16	375	28.3	21.2	7.8	19.1	118.6	320
5	18	16	375	22.6	21.5	4.8	9.5	86.2	213
5	19	19	775	30.8	24.8	5.9	9.8	111.5	383
5	20	19	775	33.1	24.8	8.8	24.0	145.0	572
6	21	27	357	50.0	32.1	10.6	29.8	146.0	1138
7	22	23	893	34.4	29.3	4.1	17.1	125.4	714
8	23	5	1600	9.5	13.3	3.6	1.2	2.2	27
8	24	5	1600	14.0	17.7	3.8	2.2	7.4	74
8	25	5	1600	15.3	19.0	3.8	2.3	8.0	82
8	26	5	1600	11.5	13.5	2.6	1.0	6.9	37
8	27	5	1600	17.2	18.0	3.4	2.9	8.2	96
8	28	5	1600	13.2	17.9	3.2	2.3	7.1	60
8	29	5	1600	11.7	16.4	3.1	1.1	3.4	48
8	30	5	1600	15.5	17.8	2.8	0.9	9.7	91
8	31	5	1600	16.8	19.4	4.5	7.7	12.5	103
9	32	5	896	16.6	18.6	4.9	7.7	21.4	115
9	33	5	896	13.4	16.5	4.3	4.9	7.4	68
9	34	5	896	9.9	12.4	3.7	1.8	3.2	32
9	35	12	613	20.1	19.4	5.1	5.0	57.1	175
9	36	12	613	30.3	21.0	7.3	16.0	116.5	316
9	37	12	613	27.0	21.1	4.9	14.8	113.6	358
10	38	8	494	16.5	18.8	4.2	5.0	18.0	119
10	39	8	494	21.6	18.9	5.4	9.2	60.8	166
10	40	8	494	20.1	18.3	5.0	6.6	39.1	136