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Predictors of tree growth in a Dipterocarp-based agroforest: a critical assessment

Grégoire Vincent[*,1], Hubert de Foresta[2], Rachmat Mulia

International Center for Agroforestry Research, P.O. Box 161, Bogor 16001, Indonesia

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Abstract

Growth records from three 1 ha plots of old-growth agroforest that have been monitored for 3–7 years in Sumatra are analysed. These plots of damar agroforest show typical multi-species composition. Tree species were grouped into five sets according to species ecology and average growth rate. Variables used in the multiple linear regression to predict average annual increment were crown form index, crown position (CP) index and initial girth. Crown form (CF) index is indicative both of photosynthetic capacity and of general vigour of the tree. Crown position index is indicative of the amount of light available to a tree. Results show that crown form is the most effective predictor of growth and that initial girth, and crown position only marginally increase the percentage of variance accounted for in most cases. About 40–50% of the variance is explained by using the above mentioned variables depending on the sites. The significance of these results is discussed and some methodological improvements to the monitoring techniques currently in use are suggested. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Dipterocarp forest; Sumatra; Crown scores; Tree growth modelling

1. Introduction

Damar agroforest are multi-species, multi-strata agroforests made up of a mosaic of individually owned and managed plantations (see for instance (Michon et al., 1995; Michon et al., 2000)). Damar (*Shorea javanica* K. and V.), the main species is planted and tapped for its resin. It is also used as a source of timber. Other planted trees include fruit trees such as *Durio zibethinus* Murr., *Lansium domesticum* Correa, legume trees such as *Parkia speciosa* Hassk., *Archidendron pauciflorum* (Benth.) Nielsen. Many other tree species are left to grow from natural regeneration when they are thought not to compete with trees of economic value. The present trend is to actively tend a growing number of timber species. Little is formally known on the functional ecology and optimal management of such complex agroforests. Our objective here is to give a first account of long-term measurements that have been carried out in the last 8 years. Data from three permanent 1 ha plots are analysed.

The variables used to predict annual girth increment are the following: crown position (later referred to as CP), crown form (CF), a species grouping (five groups) and initial girth (size).

[*] Corresponding author. Tel.: +62-251-625-415; fax: +62-251-625-416.

E-mail address: g.vincent@cgiar.org (G. Vincent).

[1] Visiting Scientist from Institut de Recherche pour le Développement.

[2] Present address: Institut de Recherches pour le Développement, France.

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2. Materials and methods

2.1. Study site

Three 1 ha plots were delineated in old-growth damar agroforests in Lampung, the southern province of Sumatra, Indonesia (latitude 5° 11′ S, longitude 103° 55′ E). Average annual rainfall is 3500 mm, with a peak in October/November with about 400 mm/month and a minimum in June/July with about 200 mm/month. Variation between years is important and in the last decade, there has been at least 3 years characterised by unusually severe dry seasons (1991, 1994 and 1997). The three sites are located in three different villages in the Krui district (west Lampung). Land unit in the area is defined (National Coordination Agency for Surveys and Mapping, 1989) as moderately dissected rolling marine terraces, acid tuffs and fine felsic sedimentary rocks, slopes ranging from 8 to 15%. A total of 10 randomly scattered soil samples were taken in each plot at two depths (0–10 and 10–25 cm). Standard chemical analyses were carried out, a summary of which is presented in Table 1. These inceptisols appear moderately acid, relatively nutrient rich soils with no outstanding differences between the three experimental sites. The rather low *P* values (Bray method) are common in such soils and are probably not limiting for heavily mycorrhizal forest vegetation. Site 1 has lower pH-KCl value and also higher Al^{3+} content still well below 50% of the CEC. These sites differ more in terms of species composition and other management aspects than in chemical soil characteristics as can be seen in Table 2.

2.2. Girth measurements

Measurements were made using a tape. Position of measurement was marked by red paint on the tree trunks. Usual height of measurement is 1.3 m above ground level for all species, except for tapped damar trees. In sites 2 and 3, the damar trees were measured about 50 cm above the highest tapping hole to avoid the bias linked to trunk deformation in the tapping zone. For a limited number of trees, during period of measurement height of tapping may have increased above height of initial measurement. In site 1, damar tree girth was measured at 1.3 m above ground level as no deformation of trunk was visible due to a different tapping technique. Only trees with diameter at breast height (DBH) $\geq$5 cm are monitored. At time of first measurement of any tree (whether at the initiation of the experiment or when a new tree would enter the monitoring process) tree location, crown position and crown form are recorded. Each tree was identified to species level.

Dates of measurements on each site are shown in Table 3. Girth increment is recorded in centimetre while initial girth which is used as a predictor is recorded in metre.

2.3. Species grouping

The total number of species identified in the three plots comprises of 113, most of which are only represented by very few individuals (42 species are represented by a single individual). Hence species were grouped for growth analysis. Criteria used for

Table 1
Chemical characteristics of top soil in three sites of damar agroforests in Krui—Sumatra[a]

	Gunungkemala		Pahmungan		Penengahan	
Soil depth (cm)	0–10	10–25	0–10	10–25	0–10	10–25
pH-H_2O	5.55 (0.38)	5.06(0.22)	5.71 (0.34)	5.39 (0.36)	5.83 (0.42)	5.33 (0.42)
pH-KCl	4.60 (0.44)	3.86 (0.19)	4.91 (0.38)	4.26 (0.43)	5.09 (0.42)	4.35 (0.41)
C (%)	5.54 (2.02)	1.84 (0.64)	4.46 (1.60)	1.82 (0.73)	4.30 (1.36)	1.75 (0.47)
N (%)	0.43 (0.13)	0.21 (0.07)	0.36 (0.16)	0.15 (0.04)	0.39 (0.09)	0.19 (0.04)
C/N	12.98 (2.13)	8.76 (1.27)	17.93 (6.53)	11.85 (2.36)	10.82 (1.41)	9.02 (0.62)
P Bray (ppm)	9.33 (6.31)	4.91 (2.73)	4.91 (1.79)	3.57 (1.22)	3.60 (0.96)	2.17 (0.87)
CEC (me/100 g)	30.38 (5.54)	25.38 (6.63)	19.60 (6.51)	14.86 (3.72)	19.98 (4.08)	13.84 (4.29)
SAT (%)	76.73 (14.65)	58.38 (23.59)	73.91 (15.84)	61.33 (19.38)	82.11 (6.96)	58.18 (12.40)

[a] S.D. in parenthesis.

Table 2
Some characteristics of three experimental plots of damar agroforest

Characteristic	Site		
	1: Gunungkemala	2: Pahmungan	3: Penengahan
Altitude (m a.s.l.)	100	50	25
Previous land-use	Secondary vegetation	Coffee/pepper plantation	Fruit tree garden
Estimated age (years)	>70	>70	>70
Distance from village	Far: 5 km	Medium: 1.5 km	Close: 0 km
Number of owners for each study plot	2	2	13

Table 3
Monitoring frequency in three plots of damar agroforest

Site	Girth measurement	Crown scoring
1: Gunungkemala	1993–2000, except 1994	1994
2: Pahmungan	1993–2000	1993, 1997, 1999
3: Penengahan	1994, 1997	1994

grouping species were autecology when known (mainly successional status and sensitivity to drought which was assessed by analysing growth time series using the same dataset) and average growth rate also estimated using the same dataset. Average growth rate of species on any site was estimated for species which had more than five individuals present throughout the growing period.

All rare species for which no reliable estimate of growth rate was available were lumped into one group called ''miscellaneous'' which composition differs significantly between sites. Another group was formed with damar (*Shorea javanica*), the most common species in all plots to which was added *Parkia speciosa* showing similar low sensitivity to prolonged dry season and relatively low growth rate. A third group, ''duku'' was formed by *Lansium domesticum*, *Baccaurea dulcis* (Jack) Muell. Arg. and *Durio zibethinus*. The first two species have similar size and ecology, and both thrive in the middle story. *Durio zibethinus*, a common fruit tree of bigger size, was put into this group on the basis of its similarly low growth rate and high sensitivity to drought. The fourth group labelled ''fast growing'' consists in fast growing species such as a number of *Macaranga* and *Ficus* species. The last group labelled ''medium fast growing'' regroups some valued timber tree species such as *Pterospermum javanicum* Jungh., *Alstonia angustiloba* Miq., *Cinnamomum porrectum* (Roxb.) Kosterm., as well as other species such as *Artocarpus elasticus* Reinw. ex Bl. and *Archidendron* sp.

Data related to plot structure are synthesised in Table 4. They show considerable differences between sites in terms of total number of damar trees, species composition and total basal area. Note that basal area of the damar group (and consequently total basal area) is merely indicative as the damar trees were not measured at same height in all plots. To correct for the bias due to bole tapering the average tapering coefficient was estimated from a set of 1356 damar trees—measured in the framework of a study on timber harvesting in damar agroforests and applied to the trees which were measured above 1.3 m to extrapolate girth at 1.3 m. Given the high variability found for this tapering coefficient (CV = 0.78) though, basal area figures given here should be considered as approximate figures. The damar group is the most numerous group in the three sites. All sites have a high proportion of trees in the ''miscellaneous'' group. For growth analyses trees in ''fast growing'' group were excluded on sites 2 and 3 due to their small number (Table 5). Palm trees as well as a small treelet (*Leea indica* (Burm. f.) Merr. which was abundant on one site only) were also excluded from analysis. Palm trees do not show appreciable girth increment (no secondary stem growth). *Leea* enters our monitoring only at its maximum size.

A measure of similarity in species composition within the groups across sites is given in Table 6. Percentage of similarity is computed as shown in Eq. (1).

$$100\sum_{n}\min\left(\frac{y_{ni}}{\sum_{n}y_{ni}},\frac{y_{nj}}{\sum_{n}y_{nj}},\frac{y_{nk}}{\sum_{n}y_{nk}}\right) \quad (1)$$

Table 4
Number of trees of more than 5 cm DBH, and basal area (m^2/ha) per group in three 1 ha stands of damar agroforest as in 1993

Group	Site					
	1: Gunungkemala		2: Pahmungan		3: Penengahan	
	Trees	B. A.	Trees	B. A.	Trees	B. A.
Damar	247	38.61	214	17.17	124	9.92
Duku	34	1.83	86	3.61	102	11.79
Medium fast growing	54	0.74	51	2.96	70	0.80
Fast growing	21	0.18	7	0.89	3	0.10
Miscellaneous	73	0.49	42	0.57	91	2.97
Excluded (see text)	8	0.10	2	0.09	30	0.18
Total	437	41.96	402	25.3	420	25.9

where y_{ki} is the abundance of the k-th species at site i (either in a particular group or across all species).

This formulation is slightly different from the percentage of similarity proposed by Jongman et al. (1995) insofar as the measure they derive for quantitative data from the Sorensen similarity index does not correct for unequal sample size whereas we are concerned here about species relative frequency per group and not group size.

It can be seen from Table 6 that apart for the ''damar'' group, groups composition differ significantly between sites. The most heterogeneous group is 'miscellaneous' where only one species among the 73 belonging to this group is present on all three sites.

2.4. Crown indices

Following the pioneering work of the Uganda Forest Department (Dawkins, 1958, cited in Alder and Synnott, 1992), two types of crown indices have been used: the crown form index and the crown position index. These indices were initially developed for natural forest and are here used in a tropical agroforest environment.

The crown form index tries to capture the photosynthetic potential of a tree. It is an architectural characteristic and will tend to reflect the development history of the tree. Crown form scale is defined as follows (Alder and Synnott, 1992):

- perfect = 5, the best size and development generally seen, wide, circular in plan, symmetrical;
- good = 4, very near ideal, sylviculturally satisfactory, but with some slight defect of symmetry or some dead branch tips;
- tolerable = 3, just sylviculturally satisfactory, distinctly asymmetrical or thin, but apparently capable of improvement if given more space;

Table 5
Number of observations per group in three experimental plots used for analysis of growth[a]

	Site 1	Site 2	Site 3
Damar	248	230	99
Duku	39	132	83
FG	61	9	3
MFG	135	87	36
Miscellaneous	219	53	91
Total	702	511	312

[a] Number of observations may include trees recruited during the course of the monitoring period and hence be higher than corresponding figures in Table 4.

Table 6
Similarity in species composition between experimental sites in % (see text for details)

Groups	Similarity			
	Site 1–2	Site 2–3	Site 1 and 3	Site 1–3
Damar	97.07	97.08	99.99	97.07
Duku	45.92	86.23	41.61	41.61
FG	–	–	–	–
MFG	32.24	30.17	25.74	13.15
Miscellaneous	18.30	18.01	1.63	1.15
No grouping	54.17	63.47	42.46	40.22

- poor = 2, distinctly unsatisfactory, with extensive dieback, strong asymmetry and few branches but probably capable of surviving;
- very poor = 1, definitely degenerating or suppressed, or badly damaged, and probably incapable of increasing its growth rate or responding to liberation.

The crown position index, which depends on the relative position of the crown within the canopy, reflects the light conditions prevailing at a particular moment. Crown position scale is defined as follows (Alder and Synnott, 1992):

- emergent = 5, crown plan exposed vertically and free from lateral competition at least within the 90° inverted cone subtended by the crown base;
- full overhead light = 4, crown plan fully exposed vertically but adjacent to other crowns of equal or greater height within the 90° cone;
- some overhead light = 3, crown partially exposed vertically but partly vertically shaded by other crowns;
- some side light = 2, crown plan entirely vertically shaded but exposed to some direct light due to a gap or edge of overhead canopy;
- no direct light = 1, crown plan entirely shaded vertically and laterally.

In this study, crown position and crown form were measured once for every tree, at the beginning of the monitoring of its growth, except on site 2 where repeated measurements were taken (see Table 3). On the latter site a weighted average of crown index is used. When used as categorical variables average values of crown scores were categorised as follow:

- if crown score average value >4.5 then re-coded as 5;
- if crown score average value >3.5 and $\leq$4.5 then re-coded as 4;
- if crown score average value >2.5 and $\leq$3.5 then re-coded as 3;
- if crown score average value >1.5 and $\leq$2.5 then re-coded as 2;
- if crown score average value $\leq$1.5 then re-coded as 1

A number of competition indices based on individual tree position and tree relative size were also tested either alone or in combination with the other predictors. Those competition indices all performed very poorly possibly due to low precision in tree positioning. Corresponding results are, therefore, not presented here.

2.5. Data analysis

Girth records were carefully checked prior to statistical analysis by using exploratory graphic analysis. A few outlyers obviously corresponding to measurement errors were detected and those records were discarded. The amount of trimmed data was less than 1% of the total dataset. Girth records indicating shrinking of trunk were not systematically discarded, except when specific additional information (e.g. observed bark fall) would justify it. Negative increments were found to be often associated with tree death during the next following 1 or 2 years. The average annual increment over the total growing period was then computed for each tree. Only the average annual increment is analysed here.

The different models tested were applied first to a subset of the data, restricted to the trees present throughout the monitoring period, and subsequently to the full dataset. The full dataset would include those trees appearing after the onset of experiment or disappearing before the end of the monitoring period (Table 5). Conclusions are essentially similar and we report only the results of the analysis carried on the full dataset.

All calculations revealed a linear increase of the variance of the residuals with increasing average increments. In order to stabilise the variance the square root of the average increment was used as the dependent variable (Tomassone et al., 1993). Negative increments were replaced by zero. On the whole r^2 values were slightly reduced by such a transformation but tendencies were not altered.

3. Results

Results are presented in three parts. Part 1 describes the data structure and in particular examines the degree of colinearity between predictors used in the model. Part 2 reports on growth prediction using different statistical models. Part 3 presents complementary

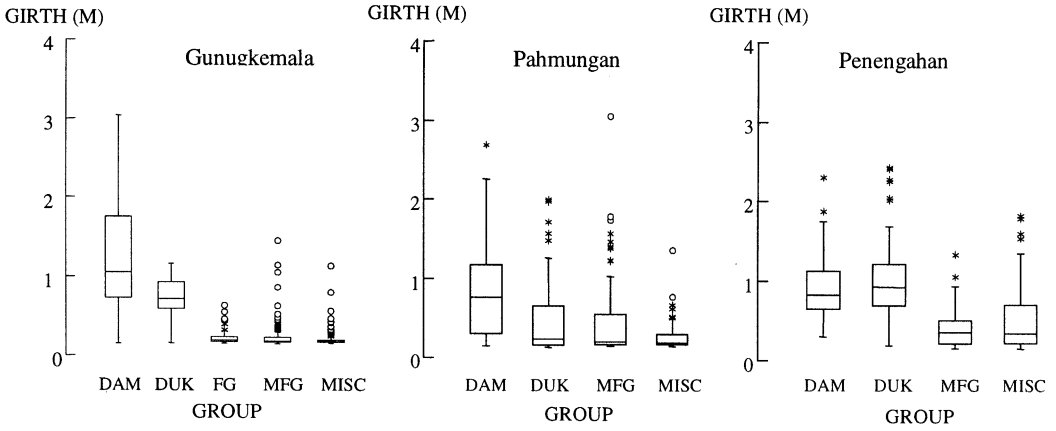


Fig. 1. Box-plot of girth values per group of species in three permanent plots of damar agroforest; see groups definition in text.

analyses carried out with the specific objective of assessing the precision of the predictors used.

3.1. Data structure

Fig. 1 uses a box-plot representation to compare the girth distribution between groups and across site of the trees entering monitoring. Except in site 3 (Penengahan) where the ''duku'' group is slightly ahead, median girth value is much higher for the ''damar'' group than all other groups. Also note that the ''miscellaneous'' group has a low median in all sites as it is predominantly composed of small understorey vegetation. Both the mean and variance of initial size differ between groups.

Fig. 2(a–c) depicts crown scores (crown form and crown position) as used in the general linear models analysed in part 2. Note that on site 2 (Pahmungan) those scores are the weighted mean of scorings taken at three different times whereas on the other sites this was done only once per tree during the whole growth monitoring period. The CP distributions appear to be left skewed especially on site 1 where basal area is highest. CF distribution is more symmetrical only slightly right skewed on site 2.

Figs. 3 and 4 depict the relation between size (initial girth) and crown scores. Not surprisingly bigger trees tend to have a higher crown position score reflecting their better access to light. As expected no consistent relation between size and crown form is apparent. On site 1 though trees with high crown form scores appear to be significantly bigger than in other crown form categories.

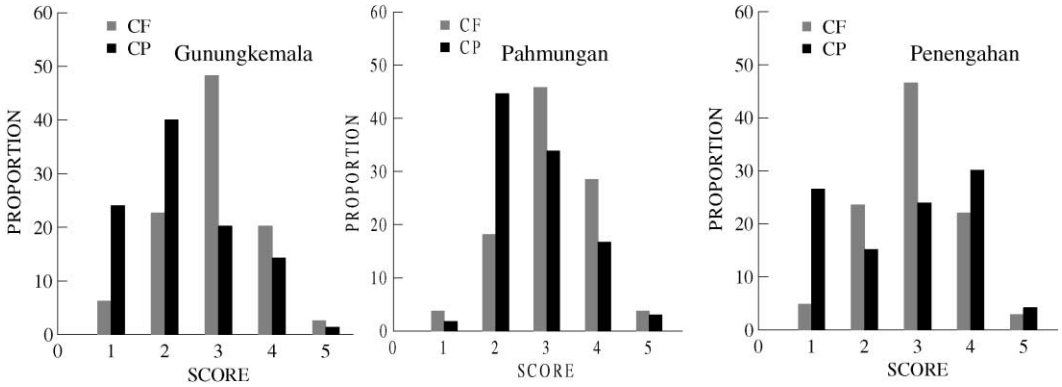


Fig. 2. Histogram of tree crown scores from three 1 ha plots of damar agroforest.

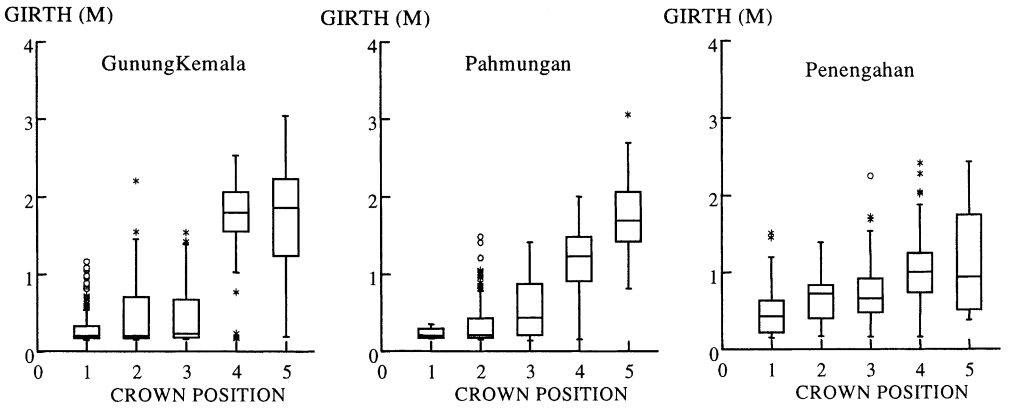


Fig. 3. Box-plot of girth values per crown position category in three 1 ha plot of damar agroforest.

Independence between crown form and crown position was tested using Pearson's χ^2 statistic. Independence hypothesis was rejected for sites 1 and 3 and accepted on site 2. Spearman's ρ correlation was positive but low (respectively, 0.15 and 0.09) in both cases where independence was rejected.

Finally, distribution of crown scores per group are reported in Table 7. The unbalanced distribution of crown scores is obvious, extreme values of crown scores being rare in most groups even when data from all sites are pooled together.

3.2. Growth analysis

The strategy adopted was to gradually complexify the initial simplest model that would include only the four elementary predictors CP, CF, IG and group, by testing interaction between the group factor and the other predictors. An interaction term being considered for inclusion in the final model common to all sites only if found highly significant in at least one site.

Final common model used for single sites

$$\mathrm{Sqrt(GirthInc)} = \mathrm{CP} + \mathrm{IG} + \mathrm{group} + \mathrm{group} \times \mathrm{CF}$$

When data from all three sites were pooled together a dummy variable coding for site was added. An interaction site × group term was also found significant as expected due to dissimilarity in composition between groups.

Model used for combined sites

$$\mathrm{Sqrt(GirthInc)} = \mathrm{CP} + \mathrm{IG} + \mathrm{CF} + \mathrm{site} + \mathrm{group} \times \mathrm{site} + \mathrm{group} \times \mathrm{CF}$$

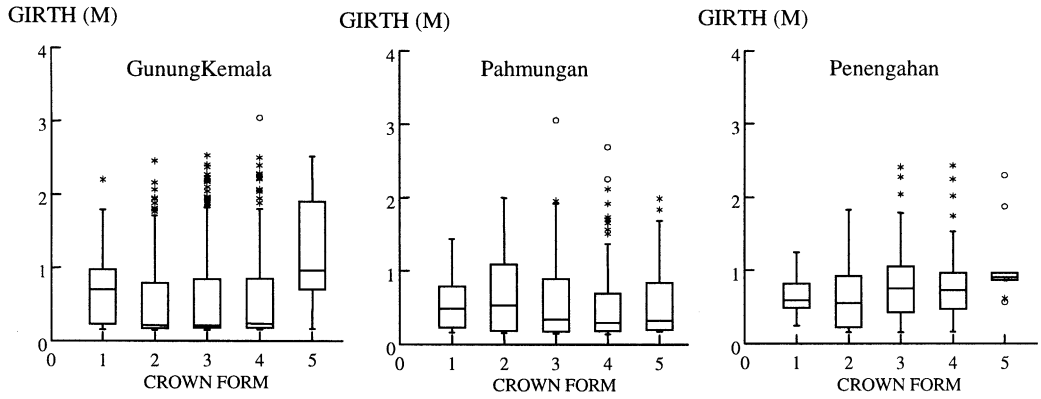


Fig. 4. Box-plot of girth values per crown form category in three 1 ha plots of damar agroforest.

Table 7
Frequencies of crown form scores and crown position scores per group[a]

	Dam	Duk	FG	MFG	Miscellaneous
Frequencies of crown form scores per group					
1	50	4	4	5	15
2	150	32	13	53	75
3	263	120	31	125	174
4	100	81	13	70	89
5	14	17	0	5	10
Frequencies of crown position scores per group					
1	30	41	11	59	119
2	165	105	33	105	144
3	155	71	15	72	73
4	200	35	1	18	23
5	27	2	1	4	4

[a] All sites.

Parameter estimates and associated null hypothesis probability values are given in Table 8 for main effect of numerical predictors and Table 9 for the group × CF interaction term, respectively. Group least square means are given in Table 10.

Main effect parameter estimates are rather consistent across sites. CP effect estimates are consistently less than CF effect estimates, CP effect being not significant in site 3. Estimates of CF effect are also more homogeneous than estimates of CP effects across sites. Groups estimated means vary quite a lot across sites which is consistent with the fact that a significant site × group interaction effect was found when data from all sites were pooled. However, ranking between groups is almost the same across sites, the only discrepancy being due to the miscellaneous group (the most dissimilar between sites in terms of species composition) which sometimes ranks before damar or after. Estimate of initial girth effect is consistently negative revealing a trend of slower growth of bigger trees.

Groups are most often significantly different from each other, each group being statistically significantly different from any other on at least one site (Table 10).

A significant effect of group × crown form interaction was expected and included in the model as the additional girth increment associated to an increase of one unit of crown form score should be higher for a faster growing species. In other words, CF effect would arguably be more effectively modelled as a multiplicative factor. In fact, this interaction was found to be significant only on site 2 (Table 9) and the estimates per group do not seem to support the above interpretation (Table 10), slow growing groups not necessarily showing lower CF effect. This suggest that those

Table 8
Parameter estimates and *P* values (Fisher test) of main effect of the predictors in the three sites

	Site							
	1: Gunungkemala		2: Pahmungan		3: Penengahan		All sites[a]	
	Estimate	*P* value	Estimate	*P* value	Estimate	*P* value	Estimate	*P* value
CF	0.217	0.000	0.327	0.000	0.273	0.000	0.261	0.000
CP	0.083	0.000	0.185	0.000	0.012	0.618	0.076	0.000
IG	−0.251	0.000	−0.355	0.000	−0.075	0.335	−0.242	0.000

[a] Including dummy variable site and site × group interaction.

Table 9
Parameter estimates and *P* values in brackets (Fisher test) of group × crown form interaction term

	Damar	Duku	FG	MFG	Miscellaneous
Gunungkemala (0.071)	0.032	−0.001	0.067	−0.004	−0.094
Pahmungan (0.002)	0.061	−0.137	–	0.001	0.075
Penengahan (0.060)	−0.108	0.065	–	0.125	−0.082
All sites (0.083)	0.028	−0.020	0.023	0.028	−0.059

Table 10
Means and standard error (S.E.) of groups (square root of yearly girth increment)[a]

Group	Site							
	1: Gunungkemala		2: Pahmungan		3: Penengahan		All sites	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Damar	1.146 a	0.041	1.393 a	0.026	1.134 a	0.049	1.224 a	0.022
Duku	1.099 a	0.095	1.258 b	0.034	0.867 b	0.055	1.069 b	0.035
Fast growing	1.978 b	0.056	–	–	–	–	1.956 c	0.058
Medium fast growing	1.644 c	0.039	1.776 c	0.040	1.758 c	0.082	1.707 d	0.031
Miscellaneous	1.546 c	0.033	1.421 a	0.053	0.999 b, a	0.052	1.297 a	0.028

[a] Values within a column followed by the same letter are not significantly different ($P > 0.05$) from each other.

estimates may not be very reliable and that they may be very sensitive to the unbalanced data structure (Table 7). Group × IG although highly significant on site 3 (contributing by 3% points to the explained variance) was not included in the common model selected. Indeed the wide range of variation of IG and the low number of trees per group makes the estimate very sensitive to the diameter distribution in a particular group, thus, seriously limiting its robustness. As a matter of fact the estimates for the group × IG interaction term were very different across sites and inclusion of this term for sites where it was not found to be significant seriously affected the corrected mean per group (data not shown). Finally, group × crown position interaction was not significant in any site and not included in the model whereas it was expected that group with different light requirement would react differently to particular crown position scores.

3.3. Critical examination of the predictors used

3.3.1. Crown scores

Crown scores were treated as a numerical variable hence assuming a linear effect on girth increment. This is probably a reasonable assumption for crown form but more debatable for crown position which is supposed to reflect light conditions experienced by the tree. Indeed relation between light level and growth performance may not be linear nor even monotonic. The above models were rerun using crown scores as categorical variables. By doing so, the overall reduction in variance was only marginally increased (between 0.5–2% points depending on site). Categorical plots of corrected means per crown scores either per site (Fig. 5) or per group when data from all three sites were pooled together (Fig. 6) show that linear approximation is indeed a reasonable

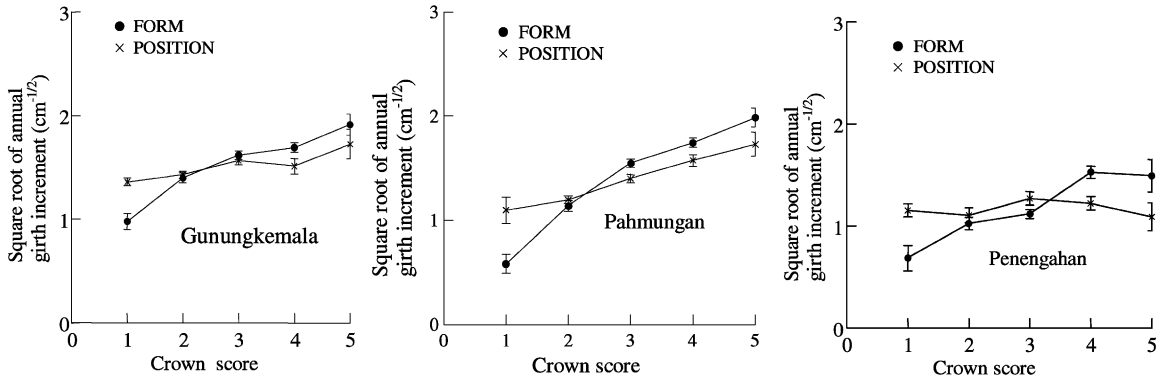


Fig. 5. Plot of adjusted means of the square root of girth increment for crown score category in three 1 ha plot of damar agroforest in Sumatra (estimated from model without interaction terms).

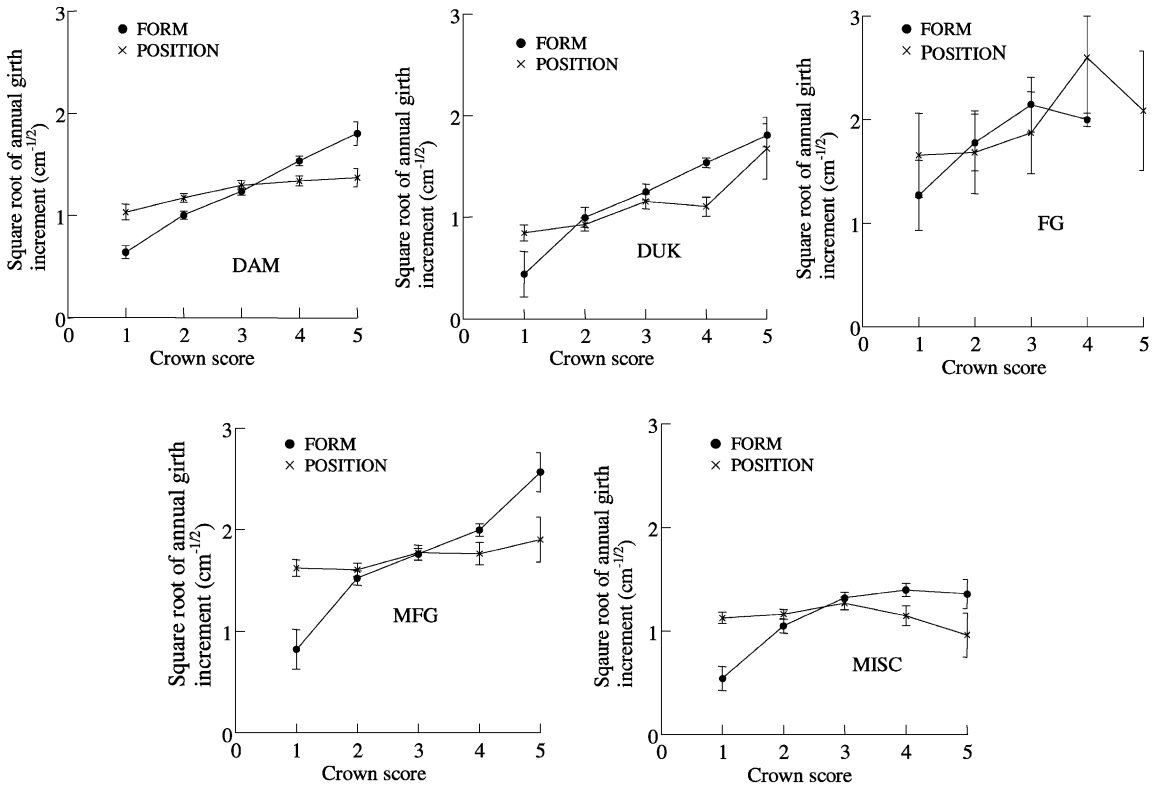


Fig. 6. Plot of the adjusted means of the square root of annual girth increment per crown form and crown position by group (data from three 1 ha plots of damar agroforest—Sumatra); fitted model: Sqrt[Inc] = CF + CP + IG + group + site + group × site + group × CF + group × CP); see text for groups definition.

simplification for both types of crown indices. Note that group × CP effect remained not significant when CP was treated as categorical variable (data not shown).

Using the data from site 2 where repeated measurements of crown scores were available (Table 3), a simple model of evolution of crown score over time was developed. Changes of categories between two dates were coded as the difference between scores at those two dates. A tree remaining in the same category would score a 0, a tree showing a decrease in crown class from 4 to 2 would score 2 etc. The mean is close to 0 and the variance of the resulting distribution σ_Y^2 was related to time between measurements yielding the following estimates:

$$\sigma_Y^2 = 0.341 + 0.074\,\text{Year for crown form score}$$

$$\sigma_Y^2 = 0.199 + 0.066\,\text{Year for crown position score}$$

where year is the number of years between successive measurements (cf. Fig. 7). The variance of the distribution in year 0 provides an estimate of the error in crown scoring (under the strong hypothesis that the process of crown alteration is a random process with no memory). The uncertainty on these predictors appears to be significant leading to some concern about repeatability of the crown scoring. Assuming a zero mean and a normal distribution with a variance of 0.341 for CF (respectively, 0.199 for CP) means that about 40% for CF (respectively, 26% for CP) of crown scores are mis-recorded. The probability that the error in scoring is more than one crown class though is low (less than 0.01). This simple model also reveals that after 6 years of growth the variance of the "error" distribution has more than doubled, thus, indicating that precision of predictor would definitely benefit from repeated assessment of crown scores carried out at regular intervals.

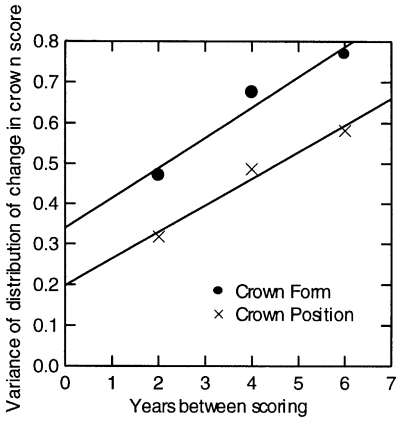


Fig. 7. Variance of the distribution of changes in crown categories is modelled as a linear function of time. Interpolated value of variance at year 0 yields an estimate of error in crown scoring.

A specific test of repeatability of crown scoring was done on a subset of the trees on site 1 by two of the authors to test the validity of the above error model. After scoring 50 trees jointly to get tuned they independently assessed crown scores of another 100 trees. The error made in CF and CP was respectively, 38 and 26%. No difference in scoring being more than one class. Those estimates are very close indeed to the predictions of the simple error model.

3.3.2. Grouping

Efficiency of grouping was assessed by comparing the model using species as a predictor instead of group in the same model as above (except that no interaction term is considered). It appeared that by using species instead of groups an increase of 7–13% points in the variance accounted for was achieved depending on the sites (data not shown). This is a very significant increase but it implied multiplying by 5–10 the number of degrees of freedom used by the model. Because of the important number of species with very few individuals, it is likely that in such a model some variability is unduly attributed to species.

4. Discussion

About 50% of the total variance is left unexplained using the models described here. This is comparable to other recently published results (Gourlet-Fleury, 1997; Rautiainen, 1999) of similar studies but questions about the sources of the remaining variance remain. Possible underground competition was tested using a variety of competition indices but did not prove significant. Possible spatial pattern in the residuals was examined to detect a spatial pattern in fertility but was also inconclusive. A closer look at the variables used seems, therefore, necessary.

4.1. Girth measurements

Residual mean square error (Table 11) is lowest in site 2 where repeated measurements of both girth and crown scores are available, intermediate in site 1 where only girth measurements were regularly repeated and highest in site 3 where girth measurements have been repeated only once. This trend probably directly reflects the link between quality of predictors and frequency of measurements.

Table 11
Total r^2, mean square error and contribution of each predictor to the percentage of variance explained (r^2) given that other predictors exist in the model (conditional) and as a single predictor (alone)[a]

Model 1	Site					
	1: Gunungkemala $r^2 = 0.511\ 9$ (M.S.E. = 0.169)		2: Pahmungan $r^2 = 0.513$ (M.S.E. = 0.138)		3: Penengahan $r^2 = 0.374$ (M.S.E. = 0.213)	
Predictor	Conditional	Alone	Conditional	Alone	Conditional	Alone
CF	0.078	0.127	0.265	0.307	0.114	0.122
CP	0.012	0.021	0.047	0.006	0.001	0.003
IG	0.015	0.217	0.063	0.034	0.002	0.012
Group	0.118	0.407	0.113	0.130	0.191	0.240
Group × CF	0.006		0.015		0.016	

[a] Main factors' contribution is estimated conditionally to a model with no interaction.

Carrying girth measurement on a yearly basis and limiting analysis to the average growth over a period of a few years tended to limit measurement errors by cross checking between successive years, and spreading remaining error over a larger period of growth. This strongly advocates for repeated measurement to be carried out which will also provide a dynamic view of growth through time series analysis (not reported here). Nevertheless, annual measurements will not correct for errors due to bark fall, slight displacement of the ring of paint when paint marks have to be refreshed, etc. Dendrometer bands would probably help to deal with the above mentioned problems and may reduce the uncertainty on the girth measurements. Nevertheless, they also present some drawbacks such as the need for the dendrometer bands to be checked often for fast growing trees, the risk that they be removed by third parties (particularly in the present smallholder context), and the lack of reliability of the first year of measurements (Cameron and Lea, 1980; Keeland and Sharitz, 1993).

4.2. Species grouping

In dealing with many different species and many rare species, grouping species is inescapable. This is always a delicate procedure (Vanclay, 1991; Favrichon, 1994) and its use means that some variability due to inter species differences is almost necessarily neglected by the model. This might have been an important source of the unexplained residual variability. The implicit hypothesis in the process of grouping is that of ''homogeneity'' of the response of the species to the covariates measured. This is obviously difficult to test for in a systematic way. Absence of interaction between group and CP may reflect that species grouping is not consistent with regard to species light requirement. The grouping technique adopted here, based on available knowledge of autecology, should nevertheless, limit this source of error at least for the few well known species. The fact that not every combination of groups and CP level is to be found (incomplete design) and some combinations have only very few observations (unbalanced design) also limited the power of the experimental design (cf. Table 7). On the other hand, this difference in CP distribution may itself convey ecologically meaningful information but again would only be available for the very common species.

Differences in species composition (and species relative abundance) between sites probably account for part of the discrepancy in estimates of mean per group across sites (Table 10), as well as differences in estimates of interaction of group with the other predictors (see Section 3.2). This is certainly the case for the ''miscellaneous'' group for which composition varies greatly between sites. The ''miscellaneous'' group has a much lower mean in site 3 (Table 10) which itself is probably responsible for the highly significant site $\times$ group interaction detected.

A statistically more efficient grouping (possibly using an equally small number of groups) could have been achieved by grouping species based only on their mean growth rate (corrected for the other predictors) maximising between-group relative to within-group variance. This would not necessarily have led to compatible grouping between sites though and would not have taken into account available information about species autecology. A classification based solely on observed growth rates would probably require a very large dataset if the objective were to generate reasonably stable groups with ecological significance.

Finally, the lack of interaction between group and CP (see also Section 3.2) may also indicate that CP is not a reliable parameter in the context of the damar agroforest.

4.3. Crown scores

Contrary to crown form index which is subjective and appears more prone to error in recording (see Section 3.3.1), the crown position classification is objective and should depend on the observer only in limit cases. Nevertheless, although most often statistically highly significant (Table 9) CP only marginally contributes to reduction of variance. This was unexpected as it was previously reported to be well correlated with growth in tropical rainforests (Alder and Synnott, 1992; Moravie et al., 1999). Crown exposure was also shown to be a good predictor of tree girth increment in northern hardwood stands (Cole and Lorimer, 1994).

One major concern is that CP scores may not accurately represent light conditions experienced by a tree. Consider a small tree that is entirely vertically

shaded but with no close neighbours surrounding it. It might still receive considerable lateral light, this is even more likely to be the case if the shading tree is much taller than target tree, a common situation in damar agroforest. Nevertheless, it would fall in category 2 (sidelight only). On the other hand, a heavily shaded tree with a small canopy gap above it (category 3, some overhead light) may receive far less light. It might even be true for a tree in category 4 (full overhead light) which, if all surrounding trees are higher than the target tree, may receive less light than a tree on the edge of a gap. The criteria used to score the crown position are convenient because objective but probably poorly reflect actual light level in a damar agroforest context. A more precise estimate of light condition should be based on assessing how much of the sky vault above crown plan is free from neighbouring crowns. This can be done with a reasonable precision at ground level using specially designed instruments such as the canopy densiometer (Lemon, 1957). It is clearly problematic to estimate for a point hanging 10 m above the observer.

Another limitation to the crown position index is that it does not consider degrees in shading properties of canopy. For example, a single upperstory layer of damar tree even though continuous, may allow as much as 50% of the light to reach next story (crown porosity to light estimate based on photograph analysis). Thus, presence or absence of shading may be too crude a simplification. Another possible reason why CP does not perform as well in damar agroforest as in natural forest might be that light availability is on average higher and, therefore, does not have the same constraining character. The average canopy openness measured at ground level using regularly spaced hemispherical photographs in three stands of lowland natural forest in Sumatra was found to be between 2.7 and 4.3% (number of observation at least 60 on each site) (Trichon, 1996). Similar analysis performed on our site 2 (number of observations 37 randomly spread over 1 ha) gives an average value of 9.6% (unpublished).

CF on the other hand showed high correlation with annual increment despite the fact that CF scoring is qualitative and subjective. It seems that previous studies in natural forests could not show clear correlation between CF and annual increment (Alder and Synnott, 1992). According to our field experience, estimation of CF requires some knowledge about the tree species such as whether it will seasonally shed its leaves, what its normal physiognomy and architecture is, etc.... in order to be reliable. While these estimations are almost impossible to implement in case many species are unknown, like in a natural diverse rainforest, high correlation between CF and annual growth in our study seems to indicate that this parameter is well suited to the conditions of an agroforest where a few well-known species dominate forest composition.

Finally, another shortcoming of our dataset is that CP (and CF) have not been reassessed regularly except on site 2.

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