

Measuring and Modelling Oil Palm Trunk Growth**

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ABSTRACT

The trunk represents an important component of the vegetative dry matter of oil palm. This paper describes the approaches taken to model trunk growth as part of a comprehensive model of oil palm dry matter production and development, and the problems and limitations encountered. Several approaches are described including the independent simulation of trunk height and biomass, determination of height from biomass and determination of trunk biomass from total vegetative dry matter production by means of partition coefficients.

The results of the modelling exercise are presented and recommendations are made to fill gaps in information needed to improve simulation.

ABSTRAK

Batang merupakan komponen penting dalam bahan kering vegetatif sawit. Artikel ini menerangkan pendekatan yang diambil bagi memodelkan tumbesaran batang sebagai sebahagian dari model menyeluruh pengeluaran dan pembangunan bahan kering sawit serta masalah dan batasan yang dihadapi. Pelbagai pendekatan diterangkan termasuk simulasi ketinggian batang dan biojisim yang tersendiri, penentuan ketinggian dari biojisim dan penentuan biojisim batang dari jumlah pengeluaran bahan kering vegetatif dengan cara koefisien partisi.

Keputusan kerja membuat model dibentangkan dan beberapa cadangan dibuat bagi mengatasi kekurangan maklumat yang diperlukan untuk memperbaiki simulasi.

Keywords: modelling, oil palm, trunk, biomass, height, diameter.

INTRODUCTION

The trunk represents an important component of the vegetative standing biomass of oil palm. It acts to support fronds, developing inflorescences and fruit bunches, to provide a conduit for the passage of water, mineral nutrients and assimilates within and between the crown and roots, fronds and apex, and serves as a storage organ for reserve nutrients and assimilates. It is also a source of adventitious root production at its base.

In common with many other palm species, the single trunk of the oil palm displays continuous, indeterminate, vertical growth as a consequence of the permanent vegetative condition of the apical meristem. The trunk grows throughout the life of the palm and very old palms may reach heights in excess of 100 m. Initially, the growth is mainly radial, giving rise to a basal bulge at just above ground level that acts to enhance anchorage. After this initial growth phase, which may last for one to about three years after planting, the shoot apex attains a diameter of about 40 to 60 cm and from thereon vertical growth predominates. The absence of secondary thickening in palms, as in other monocots, restricts lateral growth, and under uniform growing conditions the trunk diameter above the basal bulge is generally considered to remain constant with age. This is not entirely correct, as is discussed further in this paper, but it is a useful approximation that has been exploited for practical assessments of biomass production (Corley *et al.*, 1971a; Corley and Breure, 1981).

The growth in height of the trunk has important implications for the planter. As palms increase in height, cultural operations such as harvesting of bunches, frond pruning and application of crop protection chemicals to the foliage become increasingly difficult. The

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**This is the first of a series of papers describing aspects of mechanistic simulation modelling of oil palm considered in constructing the oil palm growth model, OPRODSIM (Oil Palm Production Simulator). The term oil palm as used in this paper refers to present commercial *dura x pisifera* materials of *Elaeis guineensis*. *E. oleifera* and inter-specific hybrids are not considered.

difficulty of harvesting tall palms is generally the main reason for plantings having a limited life and for the need to replant. Because of this, there is a marked advantage in using planting materials that have low rates of vertical growth and breeders normally endeavour to incorporate this character into their new progenies.

Three main factors affect trunk vertical growth. They are palm age, genotype and environmental conditions (which include effects of agronomic practices). Considerable variation in height of individual palms is common within planting materials, and in commercial fields such heterogeneity has been considered beneficial for overall yield (van Kraalingen, 1985). Favourable growing conditions (adequate water, nutrients, *etc.*) which promote growth will also presumably increase height. Planting density is another factor that affects height since close spacing leads to increased height.

This paper describes the approaches taken to model trunk growth and development as part of a comprehensive, mechanistic model of oil palm dry matter production (Henson, 2005). It identifies some weaknesses and discrepancies in current information that need resolving by further experimentation. The main factors considered in this study are palm age and planting density.

TRUNK MEASUREMENTS

Trunk biomass is commonly determined using the non-destructive approach proposed originally by Corley *et al.* (1971a). For this method the trunk volume is required. Volume is calculated as height x cross-sectional area ($\pi \times r^2$) where r is the trunk radius. Height is assessed by measuring from ground level to the point of insertion of a standard frond. Frond 33 is often used as it is easily located though it may underestimate the true height as it is likely to be below the growing point (Breure and Powell, 1988). (This is not important when the annual increase in height is the prime concern, as in breeding trials.) The trunk is treated as being a cylinder of constant diameter. The diameter is measured, normally at breast height, but at least above the basal bulge using a pair of large calipers, following any necessary removal of the adhering bases of pruned fronds.

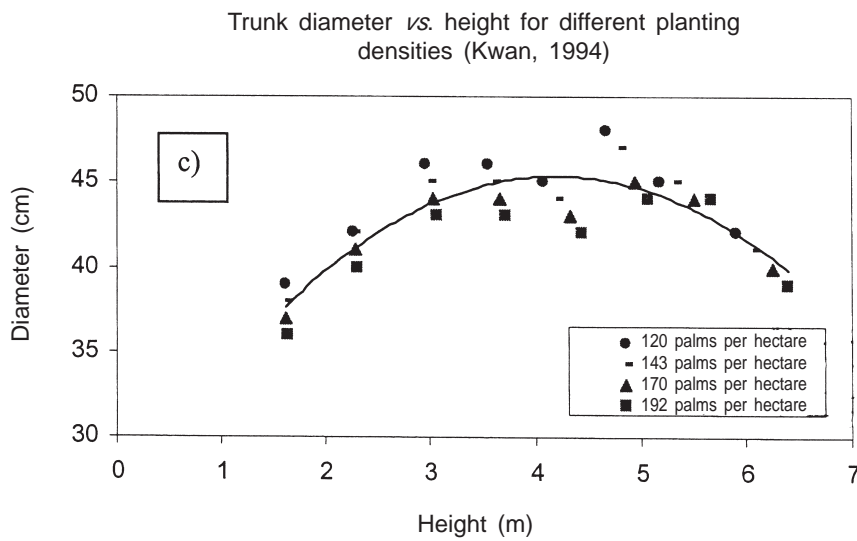
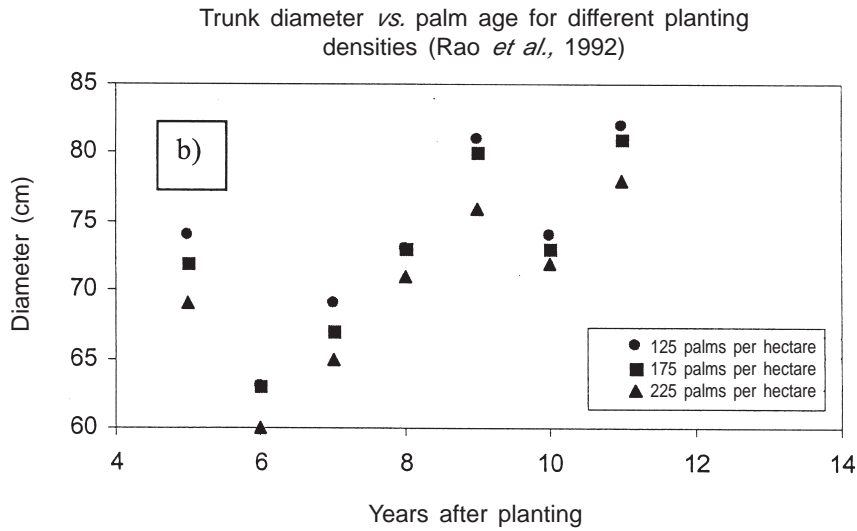
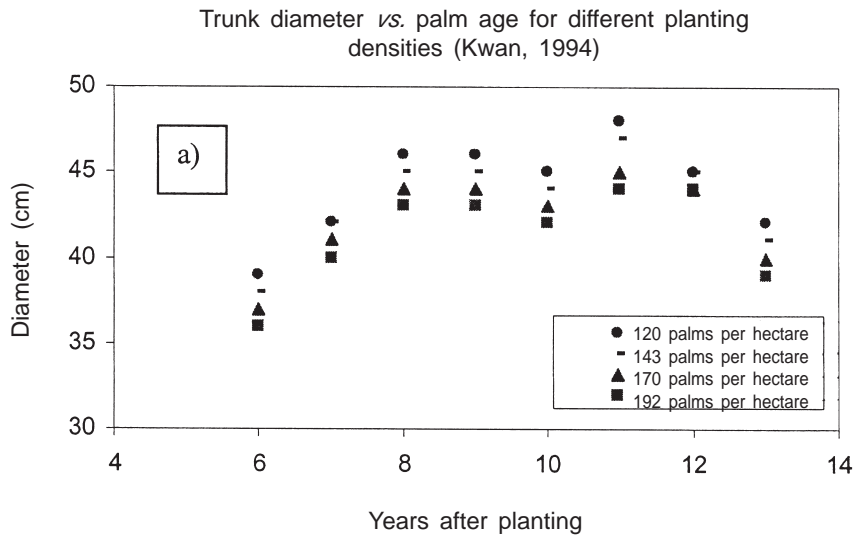
Although the trunk diameter, and hence radius, is assumed constant with height, this is not strictly correct. Changes in growing conditions can give rise to diameters changing

irregularly over time (Rees, 1964), although this is less common in the favourable Malaysian environment than in, *e.g.* the West African palm groves mentioned by Harley (1977). Otherwise, the diameter decreases gradually with height so that, in effect, the trunk is tapered (Rees, 1964; Killmann and Lim, 1987). The change is usually small (Rees, 1964) and can be ignored if the diameter is measured approximately mid-way between the ground and the lower fronds, a point giving an approximate mean of the gradually decreasing diameter (Henson *et al.*, 2003).

Corley and Breure (1981) considered it normally to be unnecessary to repeat diameter measurements in successive years and the diameter at breast height should not change. However, the mean diameter (*i.e.* the average for the whole trunk) may change as the palm ages. (This is implied from the observations of tapering.) While any changes with age may also be due to the measurement technique differing over time (it is not easy to standardize procedures over the 10 or more years life of a trial), the studies illustrated in *Figure 1* show common trends. Rao *et al.* (1992) and Kwan (1994) both found increases in trunk diameter in the early years after planting (YAP) although the earliest measurements of Rao *et al.* (1992) at five YAP were in this respect anomalously high (perhaps due to measuring at too low a height, thus including the basal bulge?). As height obviously must increase with age then diameter changes in a similar way when plotted against height (*Figures 1c* and *d*).

The same data also show that diameter decreases with planting density. This is true even at five YAP before any effect of planting density on trunk height becomes evident. A significant decrease in mean trunk diameter with planting density was also found by Henson *et al.* (2003).

The increase in height with planting density is well documented (*e.g.* Corley, 1976; Rao *et al.*, 1992; Corley and Tinker, 2003), though the effects are often not discernable for several years (>8 YAP; Donough and Kwan, 1991). Changes in trunk volume do not seem to have been much discussed. Relative changes in height, diameter and volume in the density trials of Kwan (1994) and Rao *et al.* (1992) are shown in *Figures 2* and *3*, respectively. These results are not entirely consistent but show that, in general, height increases and diameter decreases with planting density while trunk volume is either unaffected or declines. This



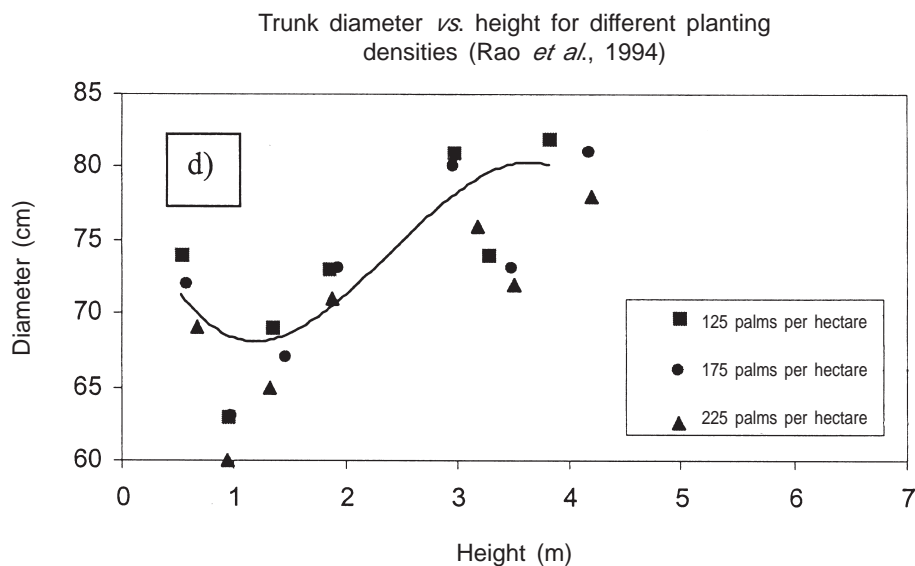


Figure 1. Relationships between trunk diameter and palm age (a, b) and trunk diameter and trunk height (c, d) in two planting density trials.

Notes: In (a) and (c), results are shown for four planting densities with measurements taken from the sixth to the 13th year after planting (YAP). In (b) and (d), results are shown for three planting densities for the fifth to 11th YAP. Note differences in the ranges of the vertical scales.

suggests that taller trunks may not necessarily represent greater biomass. More data are required to substantiate this conclusion.

Trunk biomass is the product of volume and tissue density. Corley *et al.* (1971a) derived an equation, based on destructive sampling (Corley *et al.*, 1971b), relating mean trunk density (D) to age, where:

$$D \text{ (kg m}^{-3}\text{)} = 7.62 \times \text{YAP} + 83 \quad (1)$$

and YAP = years after planting.

This formula has been widely used to estimate trunk biomass and biomass production from volume calculations. The alternatives are destructive sampling of the whole trunk, normally involving determination of fresh weight in the field followed by sub-sampling for dry matter content (*e.g.* Rees and Tinker, 1963; Gray, 1969; Corley *et al.*, 1971b; Khalid *et al.*, 1999), or taking core samples from standing palms (Henson *et al.*, 2003).

A comparison of tissue density calculated from Equation 1, with the density determined using core samples, showed that the two methods agreed to within 5%, 10% and 18% for three planting densities when palms were

sampled 17 YAP (Henson *et al.*, 2003). In the same paper, trunk densities derived from the destructive sampling data of Khalid *et al.* (1999) for 23-year-old palms were shown to be within a mean of 9% of the values calculated using Equation 1. Hirsch (1980) found the density of eight-year-old palms in the Ivory Coast to be 133 kg m⁻³, not too dissimilar from the value of 144 kg m⁻³ calculated by Equation 1.

MODELLING TRUNK HEIGHT GROWTH

For oil palm growth modelling it would be useful to be able to predict changes with age in both height and biomass of the trunk as well as their responses to planting density and other growth conditions.

The extent of variation in height is indicated in Figure 4 which shows height data assembled from several sources. These data show that trunk height at different sites can vary by as much as 2 m as early as 15 YAP. Some of this variation will be methodological, depending on the criteria chosen to define height. The general form of the curve describing these samples is sigmoidal with the maximum growth rate occurring at about 15 YAP. The curve may be biased by the predominance of points in the early years and the relatively few data for older palms.

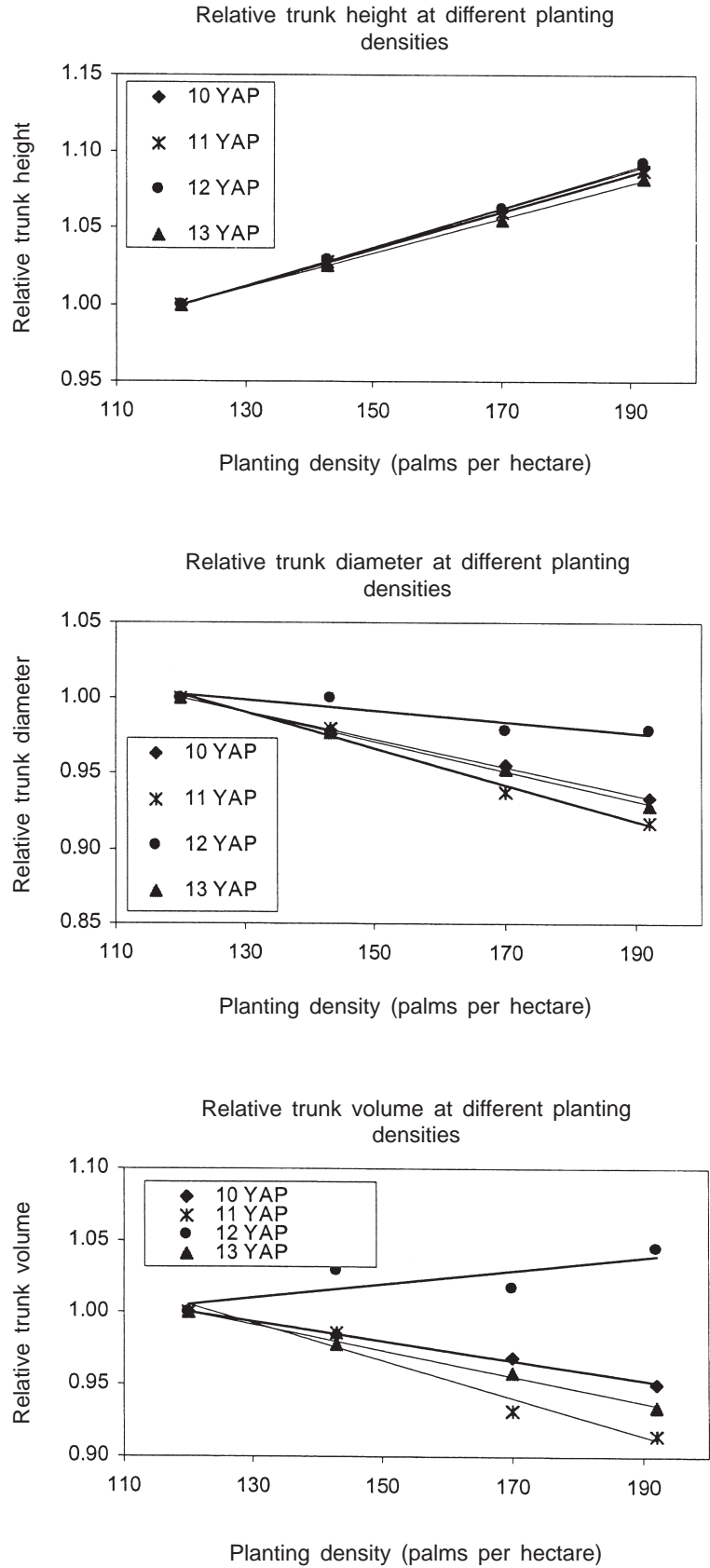


Figure 2. Relative changes in trunk height, diameter and volume with planting density for palms 10, 11, 12 and 13 years after planting (YAP) in the density trial of Kwan (1994).

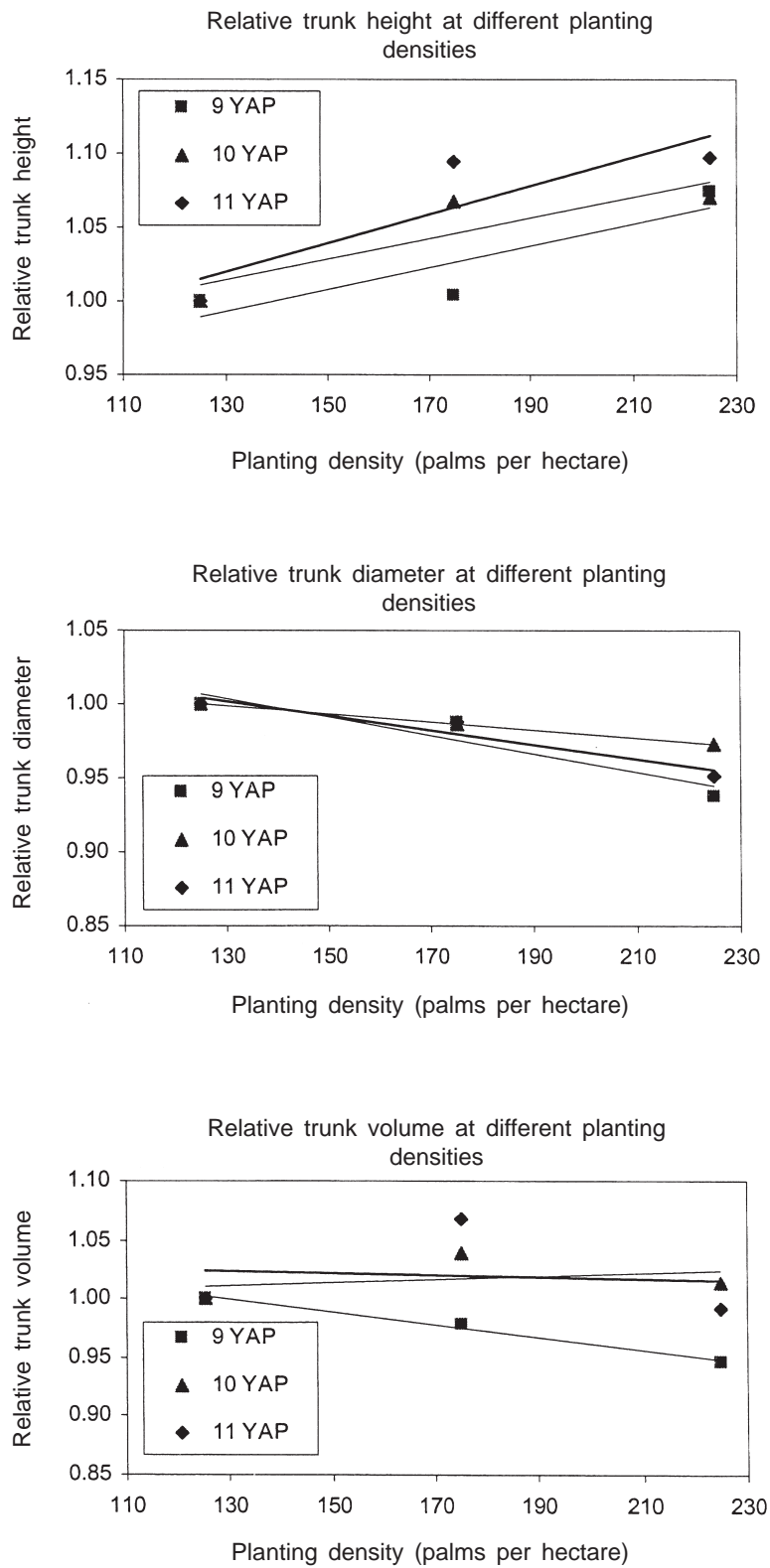


Figure 3. Relative changes in trunk height, diameter and volume with planting density for palms 9, 10 and 11 years after planting (YAP) in the density trial of Rao et al. (1992).

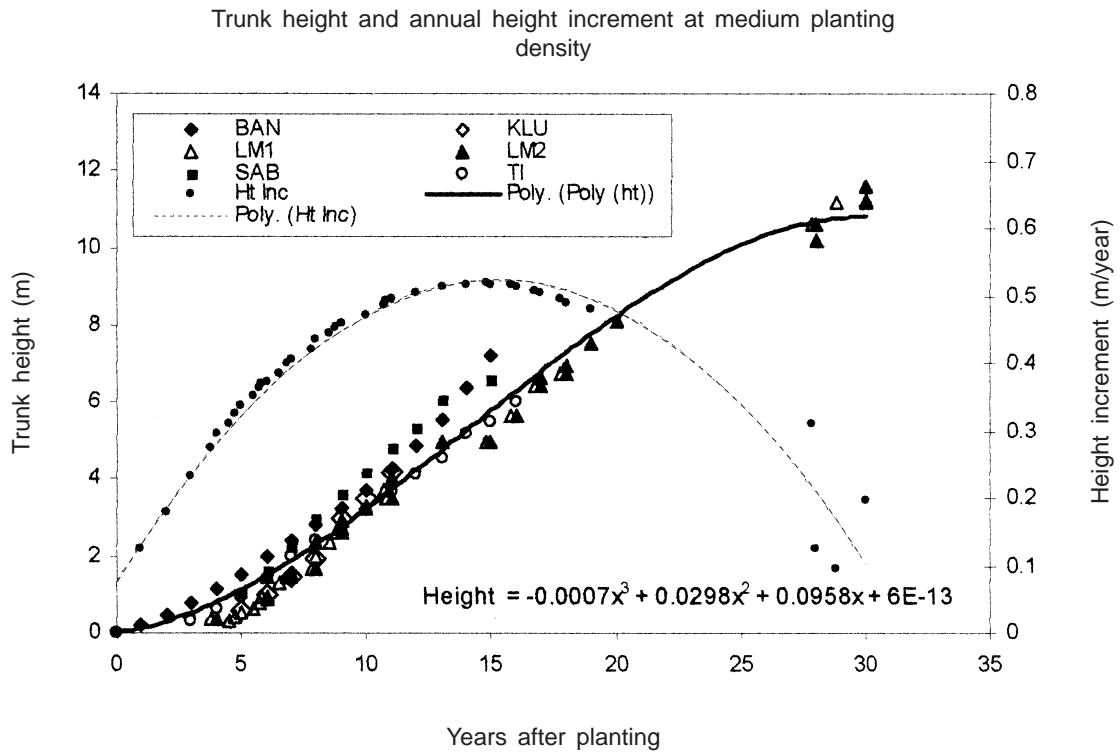


Figure 4. Changes in trunk height and height increment (Ht Inc) with palm age.

Notes: Height data were assembled from several sources with data for very low or high planting densities excluded. The third-order polynomial shown was fitted to the height data from which mean annual height increments were calculated and then plotted as points. A second-order polynomial curve was fitted to the height increment points. Data sources and details are as follows:

Label	Site	Reference
BAN	Banting, Selangor, Malaysia	Ng <i>et al.</i> (1968)
KLU	Kluang, Johor, Malaysia	Rao <i>et al.</i> (1992)
LM1	La Mé, Ivory Coast	Jacquemard (1979)
LM2	La Mé, Ivory Coast	Jacquemard and Baudouin (1988)
SAB	Ulu Dusun, Sabah, Malaysia	Kwan (1994)
TI	Teluk Intan, Perak, Malaysia	Henson and Mohd Tayeb (2003)

It is well established that trunk height increases with planting density (PD) (Corley, 1976; Breure, 1982; 1988; Rao *et al.*, 1992; Donough and Kwan, 1991; Kwan, 1994; Henson and Mohd Tayeb, 2003). While the effect is not particularly large, it is nevertheless sufficient to influence the cost of harvesting and replanting decisions (Donough and Kwan, 1991). Changes in height due to PD do not, however, become generally noticeable until about nine YAP (Kwan, 1994; Henson and Mohd Tayeb, 2003; *Figure 5*), which is about the time the canopy begins to overlap.

The magnitude of the density effect differs with site and was less in the Sabah trial on alluvial soil than in Perak on a peat soil (*Figure 5*). These and other results (Rao *et al.*, 1992) cover only the first 15-16 YAP or less, and comparable data have not been located for older palms.

Equations relating trunk height to age have been formulated by Jacquemard (1979), Jacquemard and Baudouin (1988) and Breure and Powell (1988). The latter workers found that height (H) between three and 10 YAP was a linear function of age where:

$$H \text{ (cm)} = -150 + 67 \times \text{YAP} \quad (2)$$

Here, height was measured to the base of frond 25 and resulted in a value of over 5 m at 10 YAP, which is greater than that found in most other studies (*Figure 4*). Equation 2 cannot be extrapolated to older palms due to non-linearity of the growth curve over the full lifetime of a planting.

Jacquemard and Baudouin (1988) derived a logistic growth equation where:

$$H = c \exp(-b t^k) \quad (3)$$

Here, t is time (YAP) and c , b and k , experimentally-determined constants. As in *Figure 4*, the annual height increment at first increases, reaches a peak and then decreases with age. By varying the parameters, curves may be generated differing in the initial point of growth acceleration, the height and age at the point of inflection and the growth rate at the end of the palm's economic life. Curves generated to represent four contrasting rates of trunk growth under standard planting density for inland soils (148 palms per hectare) are shown in *Figure 6*. These alternatives could be taken to represent either different genotypes or environments. They differ somewhat from the general growth

curve of *Figure 4* but accommodate the variation between the groups of palms represented therein.

The effect of planting density is introduced based on a linear regression of height on relative PD from the seventh YAP onwards using data from the trial in Perak (Henson and Mohd Tayeb, 2003). Alternatively, a multiple linear regression may be formulated (C Teh, per. comm.) to relate height to PD. The standard PD, for which no density adjustment is required, is taken as 148 palms per hectare. Prior to seven YAP, height is assumed to be unaffected by PD and no adjustment is necessary. For older palms, heights calculated from Equation 3 [height (std)] are adjusted using the following equation:

$$H = \text{height (std)} \times (0.004 \times \text{PD}) + 0.4169 \quad (4)$$

Examples of the response to PD are shown in *Figure 7*.

MODELLING TRUNK BIOMASS

Examples of standing trunk biomass obtained by both destructive and non-destructive measurements are shown in *Figure 8*. Data are in tonnes dry matter per hectare, adjusted where necessary for small differences in PD to a standard of 148 palms per hectare. Only data for median (*i.e.* commercial) densities are included. There is relatively little scatter of these data and a curve fitted though all points gave an r^2 of 0.967. This curve is used as one of the options to simulate trunk growth in the OPRODSIM model (Henson, 2005). Using this option, vegetative biomass (dry matter) production (VBP) is a sum of separate growth curves for fronds, trunk and roots.

The default (standard) simulation method in the model to derive VBP and its components is based on the relationship between VBP and leaf area index (LAI). A series of calculations is involved, as described elsewhere (Henson, 2006), starting with a growth curve, representing changes over time in the dry weight of the average sized frond on the palm. The area (m^2) of the frond (FA) is next obtained as a product of dry weight (kg) and the specific leaf area ratio (SLAR; $\text{m}^2 \text{kg}^{-1}$). LAI ($\text{m}^2 \text{m}^{-2}$) is calculated from $\text{FA} \times \text{TFNP} \times \text{PD}$ where TFNP = total frond number per palm. VBP is calculated from LAI using a third-order polynomial fitted to data from a number of experiments (Henson, 2006).

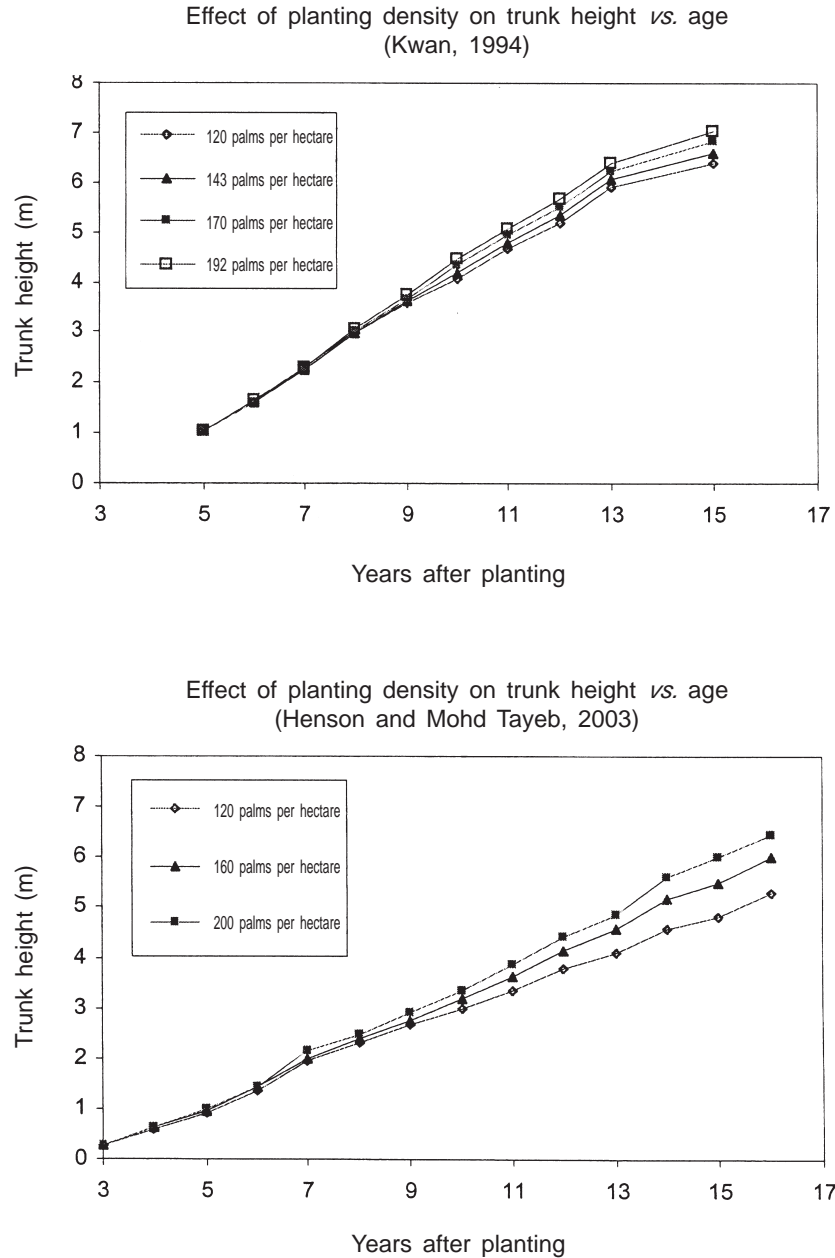


Figure 5. Changes in trunk height with age for different initial planting densities in two trials. Data of Kwan (1994) are from a trial in Sabah on a coastal alluvial soil and those of Henson and Mohd Tayeb (2003) from a trial in Perak on a peat soil.

The VBP so obtained is then partitioned between fronds, trunk and roots. This requires a decision regarding the appropriate partition coefficients. Data on these are rather sparse since few studies have evaluated root production, but this can be estimated in some cases. Table 1 gives examples of the coefficients either directly obtained or calculated from published data.

Table 1 reveals considerable variation in the allocated fractions, with the value for the trunk ranging from 0.09 (Dufrene, 1989; note high root mass) to 0.23 (Lamade and Setiyo, 1996; note differences between genotypes). A mean value of 0.1 is produced when running OPRODSIM using separate vegetative organ growth curves. This compares with the standard option of the model, which employs a default

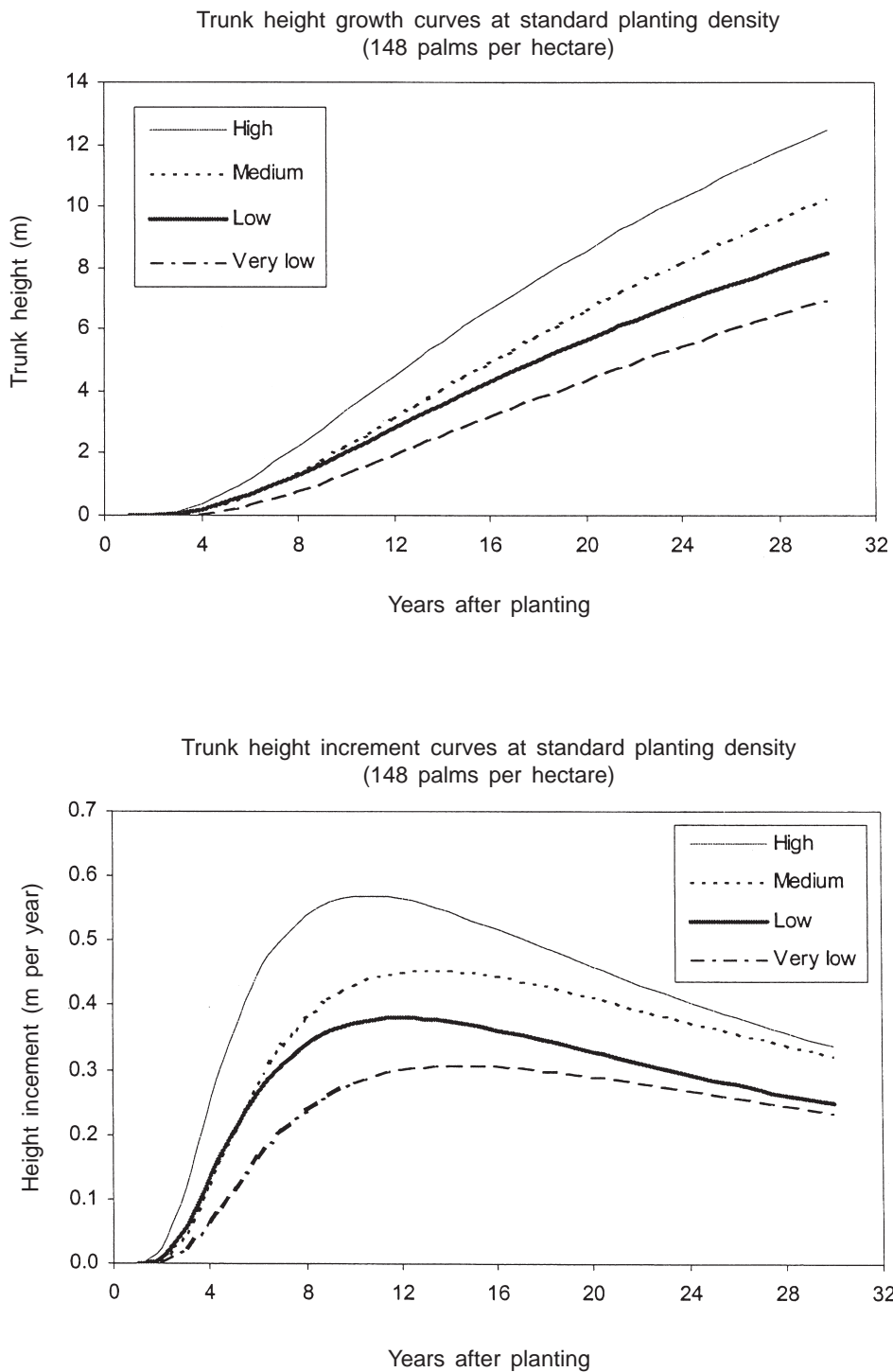


Figure 6. Trunk height and height increment curves generated from the logistic growth equation (Equation 3) of Jacquemard and Baudouin (1988).

Note: Parameter values used in the equation were as follows:

Parameter	Curve			
	Very low	Low	Medium	High
b	15	13	14	12
c	30	30	40	40
k	0.685	0.685	0.685	0.685

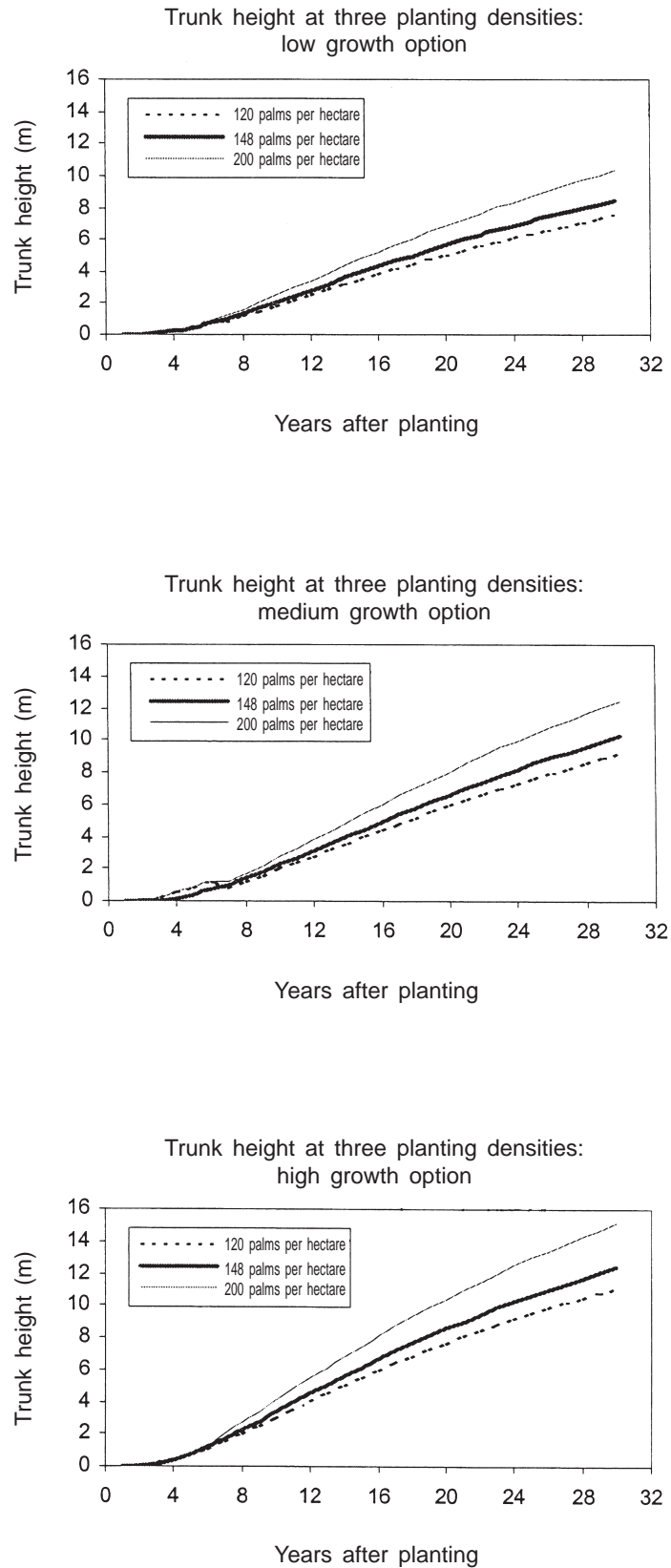


Figure 7. Effects of planting density on trunk height growth.

Note: Curves shown are for planting densities of 120, 148 and 200 palms per hectare using the low, medium and high growth rate options.

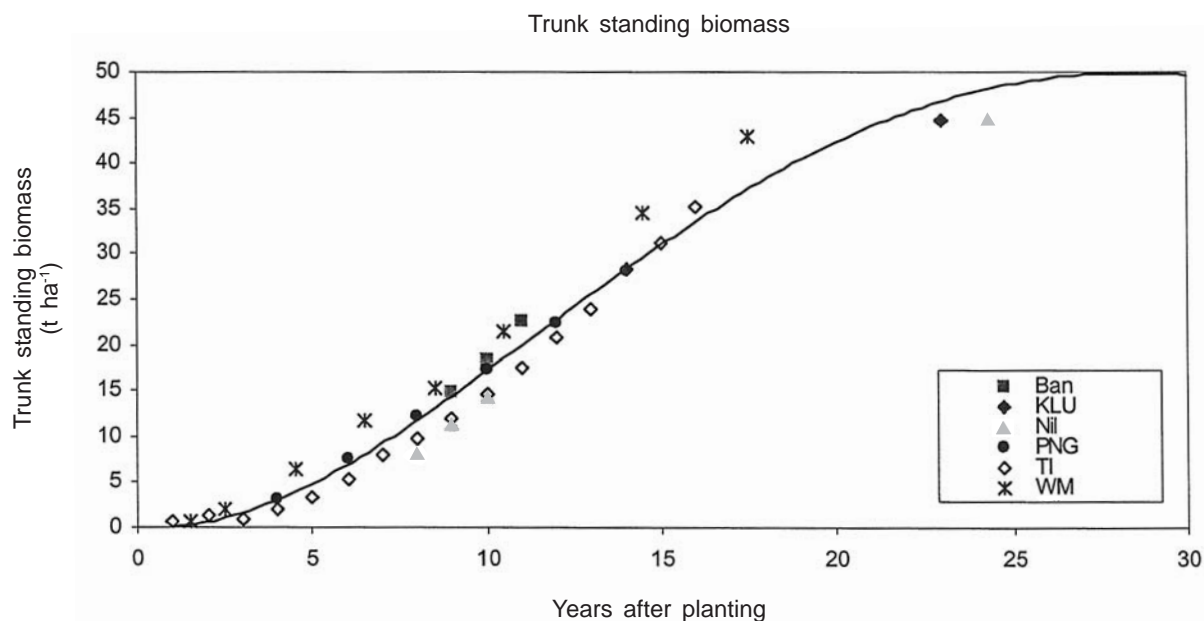


Figure 8. Changes in trunk standing biomass with palm age.

Notes: Data obtained using both destructive (d) and non-destructive (nd) methods were assembled from several sources. Data for very low or high planting densities were excluded. The fitted curve is a fourth-order polynomial ($y = 0.0001x^4 - 0.0114x^3 + 0.3002x^2 - 0.2645x$, $r^2 = 0.967$). Data sources and details are as follows:

Label	Site	Method	Reference
Ban	Banting, Selangor, Malaysia	nd	Henson (unpublished)
KLU	Kluang, Johor, Malaysia	d	Khalid <i>et al.</i> (1999)
Nil	Nilai, Negeri Sembilan, Malaysia	nd	Henson (unpublished)
PNG	Dami, Papua New Guinea	nd	Breure (1988)
TI	Teluk Intan, Perak, Malaysia	nd	Henson and Mohd Tayeb (2003)
WM	West Malaysia, coastal	d	Corley <i>et al.</i> (1971b)

value for the trunk of 0.12. However, a facility to vary the coefficient is provided.

Using separate vegetative organ growth curves in the model results in changes in the partition coefficients over time. These generally reflect those derived from the data of Corley *et al.* (1971b) (Figure 9). Temporal changes in the coefficients used with the standard option for running OPRODSIM are now included in the model.

The trunk standing biomass (TSB) is equal to the cumulative trunk production as no

turnover by trunk tissue is allowed for. Figure 10 compares the cumulated standing trunk biomass and annual trunk biomass production (TBP) simulated by the two model options with data of Corley *et al.* (1971b). The modelled data using separate organ growth curves are more similar to the measured data than are data produced by the other option in the model. This is not unexpected as the data of Corley *et al.* (1971b) were included when deriving the standard biomass curve. The results again point to the need to render the partition fractions for the model's default option, age-dependent.

TABLE 1. EXAMPLES OF PARTITIONING OF VEGETATIVE BIOMASS PRODUCTION BETWEEN FRONDS, TRUNK AND ROOTS COMPARED WITH THE DEFAULT VALUES USED OR PRODUCED BY OPRODSIM*

Source	Notes	Fraction of total VBP		
		Roots	Trunk	FronDS
Corley <i>et al.</i> (1971b)	West Malaysia; means for 1.5 to 27.5 YAP; RT calculated	0.15	0.10	0.75
Breure (1988)	Papua New Guinea; 6 to 9 YAP	0.18	0.13	0.69
Dufrene (1989)	Ivory Coast; 13 YAP; deep sandy soil	0.45	0.09	0.46
PORIM (1995)	West Malaysia; inland site; 9 YAP	0.19	0.20	0.61
Lamade and Setiyo (1996)	Sumatra; c. 9 YAP; material: La Mé	0.34	0.17	0.50
	Sumatra; c. 9 YAP; material: BJ	0.17	0.23	0.61
Henson and Chang (2000)	West Malaysia; coastal site; 10 YAP	0.21	0.18	0.61
Henson and Mohd Tayeb (2003)	West Malaysia; peat; mean, 3 PD; mean 3-16 YAP; RBP calculated	0.14	0.17	0.68
OPRODSIM	Standard option (fixed fractions)	0.18	0.12	0.70
	Alternative option; PD 148; mean, 3 to 25 YAP	0.17	0.10	0.73

Note: *Abbreviations: RT, root turnover; YAP, years after planting; PD, planting density; RBP, root biomass production; VBP, vegetative biomass production.

LINKING HEIGHT AND BIOMASS

Preferably, height should be derived directly from the biomass. The relationship between these, however, will depend on the mean trunk tissue density and trunk diameter, the latter characteristic having already been shown to be quite variable.

Using Equation 1 to derive trunk density and then calculating height from the biomass using a constant trunk diameter over time, in some cases leads to the anomaly of height decreasing above a certain age (*Figure 11*). This suggests either that the density/age relationship from Equation 1 is not valid for the entire age range¹ or that the diameter is not constant, as already indicated in *Figure 1*.

In the absence of major discrepancies between tissue densities derived by different

methods, it seems reasonable to use Equation 1 but to vary the diameter with age so as to avoid negative impacts on height. Unfortunately, diameter data are lacking for palms above 15 YAP. Therefore, the likely changes in diameter were calculated, using the standard height curves in *Figure 6*, representing very low, low, medium and high growth rates, and the tissue density calculated from Equation 1. The biomass used was that given by the curve in *Figure 8*. As indicated in *Figure 12*, this exercise resulted in very large and improbable diameter values for the early years but these sharply declined to give more realistic values and to assume a gradual, significant, linear trend from about 10 YAP. Heights were then calculated from biomass using either the actual diameters or diameters calculated from the (extrapolated) linear regressions (a procedure which thus ignored the trends during the first nine YAP). The heights thus derived, using OPRODSIM

¹ Corley *et al.* (1971a) do not state the age range of the palms for which tissue density was obtained but Gray's (1969) data, given in Corley *et al.* (1971b), and likely to have been used for this purpose, were, with one exception, all for palms below 20 YAP.

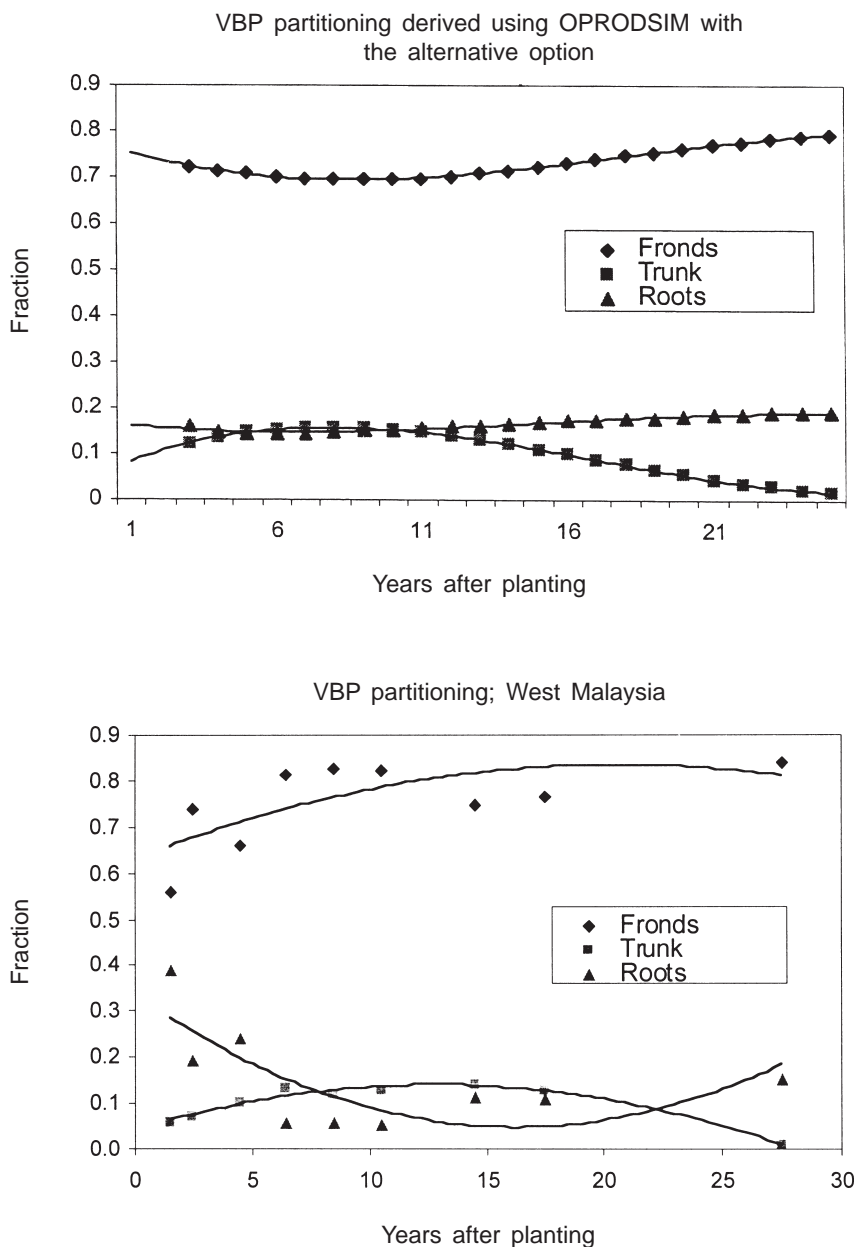


Figure 9. Changes over time in the partitioning of vegetative biomass production into fronds, trunk and root biomass.

Notes: The upper graph shows the partitioning resulting from the use of separate organ growth curves in the model OPRODSIM. The lower graph is based on data of Corley *et al.* (1971b) for palms on coastal alluvial soils. Curves are fitted polynomials.

biomass output for standard and alternative methods of deriving VBP, are shown in Figure 13. Use of the linear regressions, as opposed to the raw diameter data, had only a small absolute effect on height in the early years and did not appreciably change the height reached at 25 YAP.

A further approach is to ignore the standard density estimates (Equation 1) and

calculate density by relating heights derived from Equation 3 (Figure 6) directly to biomass (Figure 8). The densities which emerge will depend on the assumed trunk diameter. Such calculations (*e.g.* Figure 14) lead to very high densities in the early years and to densities that decline, rather than increase, with age; both in marked contrast to the trend given by Equation 1.

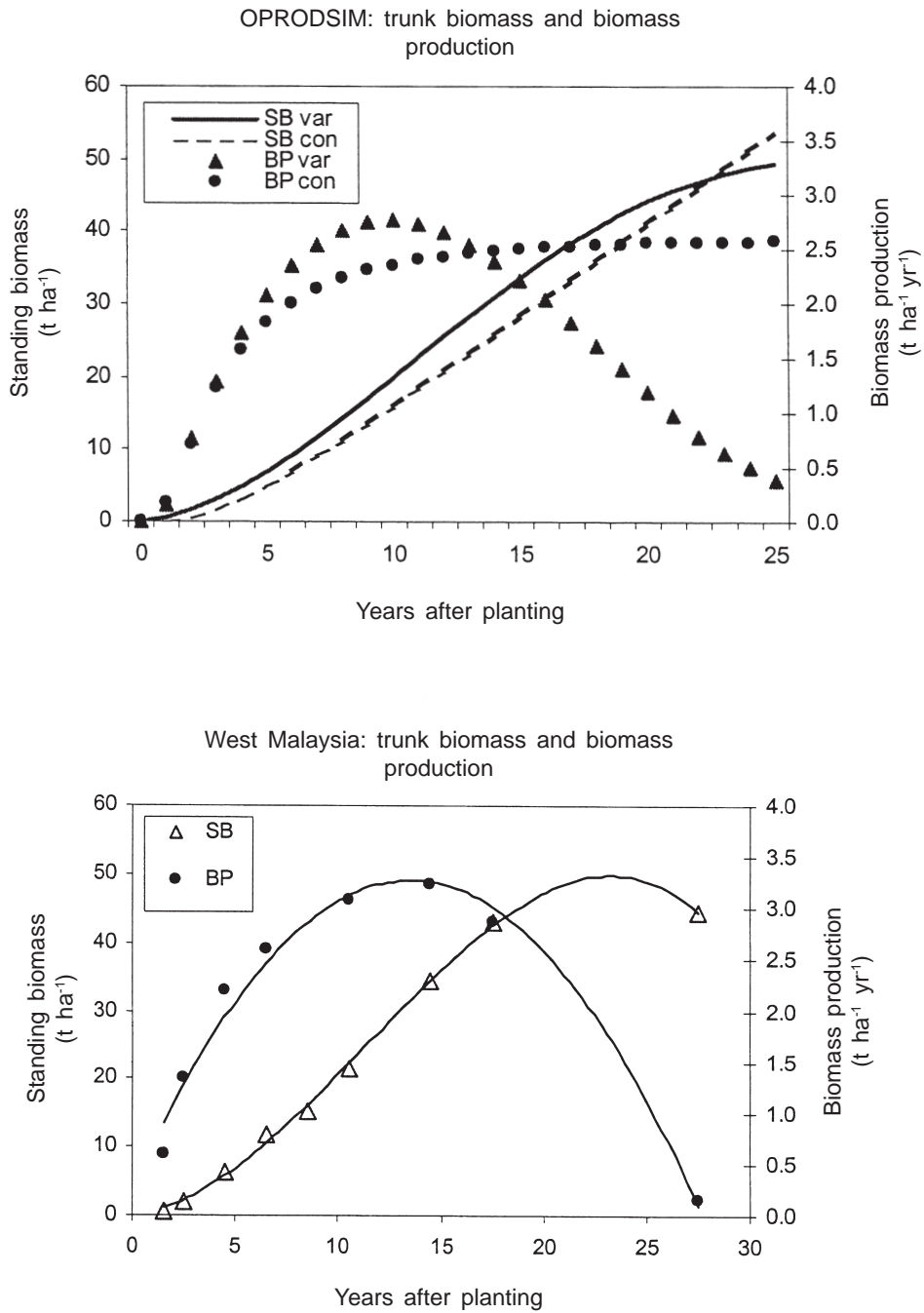


Figure 10. Changes over time in trunk standing biomass (SB) and annual trunk biomass production (BP).

Notes: In the upper graph, curves were simulated for an inland site at a planting density (PD) of 148 palms per hectare with the model OPRODSIM, using either a constant (con) vegetative biomass production (BP) partition coefficient of 0.12 or an equation generated from the data in Figure 8 (var). In the lower graph, data are plotted from Corley *et al.* (1971b) with one anomalous data point (8.5 years after planting) omitted to prevent distortion of the BP curve. Data from Corley *et al.* were calculated assuming a PD of 148 palms per hectare.

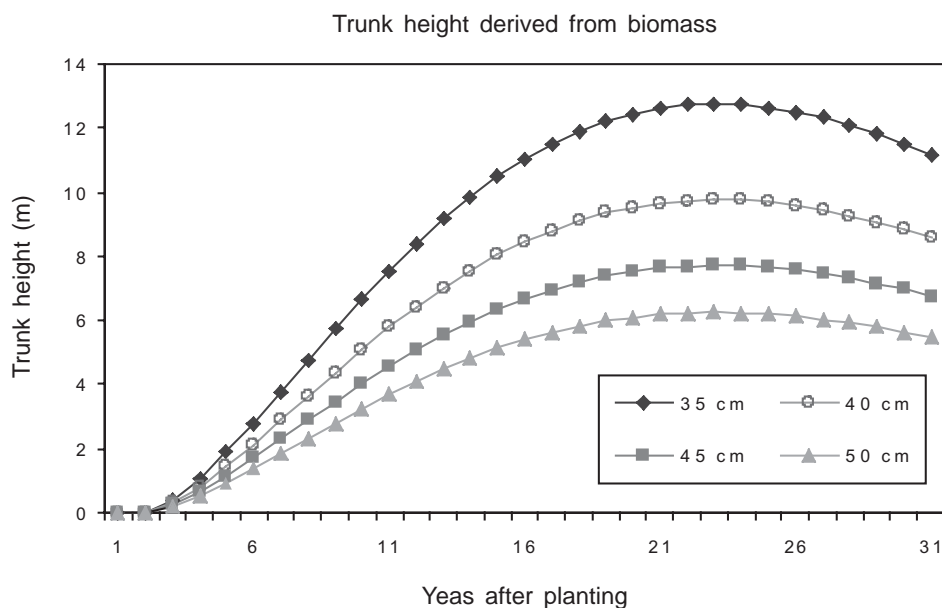


Figure 11. Trunk height calculated from biomass and trunk density for four trunk diameters (35, 40, 45 and 50 cm).

Notes: Biomass used was that shown in *Figure 8* (polynomial curve); trunk density was derived from Equation 1 and the diameter was assumed constant over time. Maximum trunk height was attained 22 years after planting.

HEIGHT AND FROND EMISSION RATE

Height could be defined by the frond emission rate² if the internode length were known. The relationships between trunk height, internode length and the rate of frond emission are, however, ill-defined. An increased rate of frond emission is not necessarily associated with increased height increment if internode lengths decrease. Several studies show that while trunk height increases with planting density, frond emission decreases (Breure, 1982; Rao *et al.*, 1992; Kwan, 1994; Henson *et al.*, 2003). As a consequence, the mean internode length increases. However, there is considerable variation in internode lengths when these are calculated from heights and frond emission rates (*e.g. Figure 15*), probably due to measurement errors being compounded. There are also differences due to genetic factors.

Better information on the factors controlling internode length would be useful as this could lead to another means of estimating height independently of biomass.

GENERAL DISCUSSION

There are appreciable data from which to predict changes in trunk biomass and height. Unfortunately, there are few studies in which both parameters have been determined for the same palms and very few data for either character are available for palms over 20 YAP.

The relationship between height and biomass depends on two factors, namely, trunk diameter and tissue density. While the empirical equation of Corley *et al.* (1971a) can be used to derive density, there is no established way to predict diameter. Although Corley and Breure (1981) found trunk diameter to have a low coefficient of variation compared with other vegetative measurements, and considered it a relatively stable character, the data in *Figures 1 to 3* indicate that it may change during the life of the palm in addition to being influenced by planting density. The range of trunk diameters presented by various workers also differ considerably, suggesting the methods used may have differed (*e.g. Figure 1*). The height at which

² Frond emission is commonly referred to as frond production but this term refers more strictly to frond initiation at the apex, the rate of which cannot be directly determined.

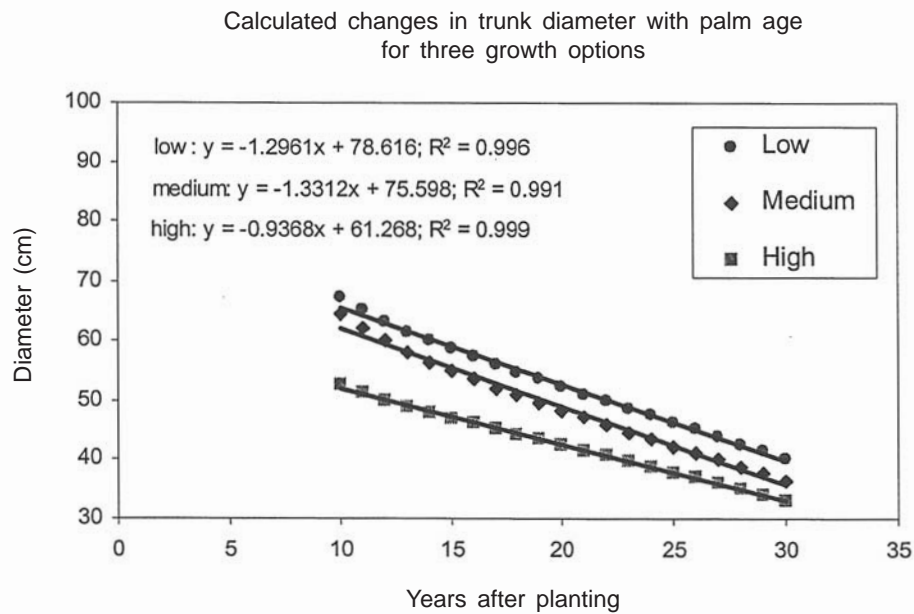
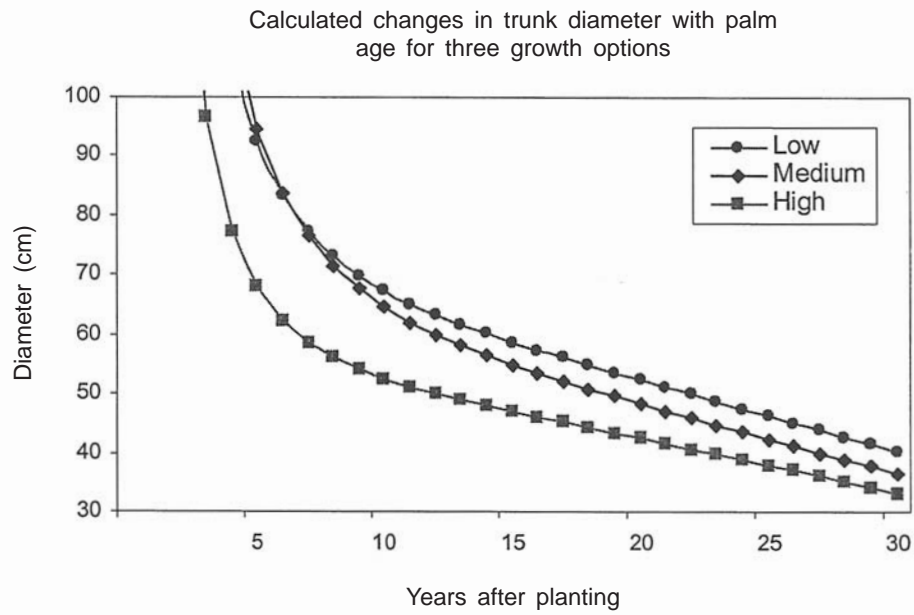
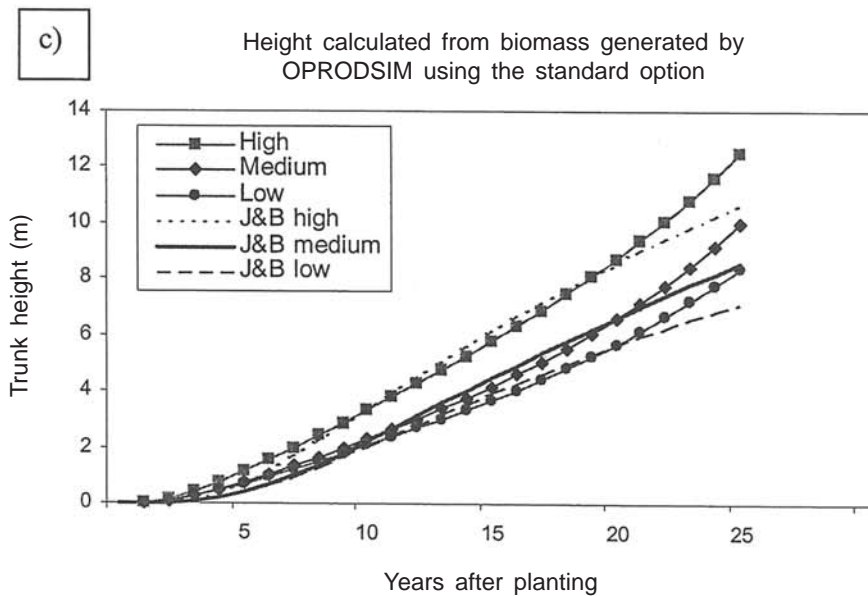
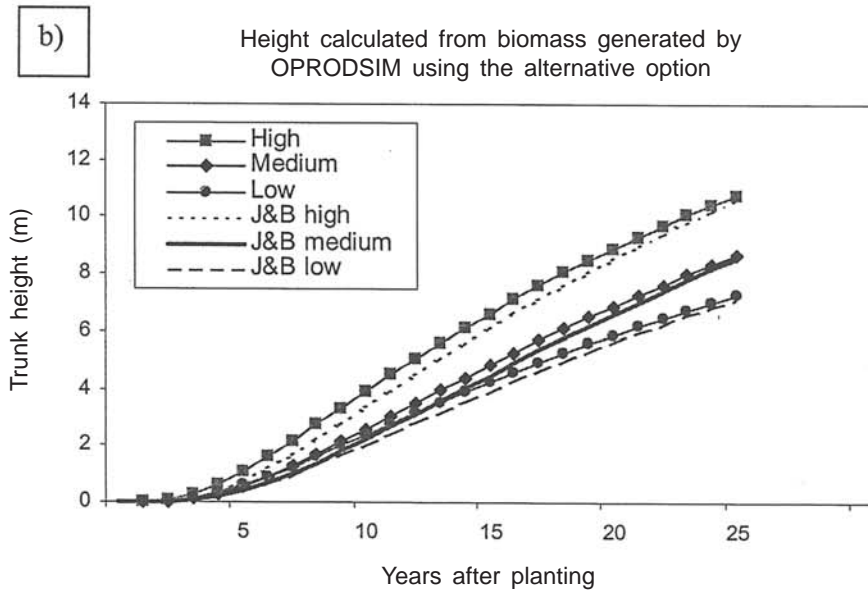
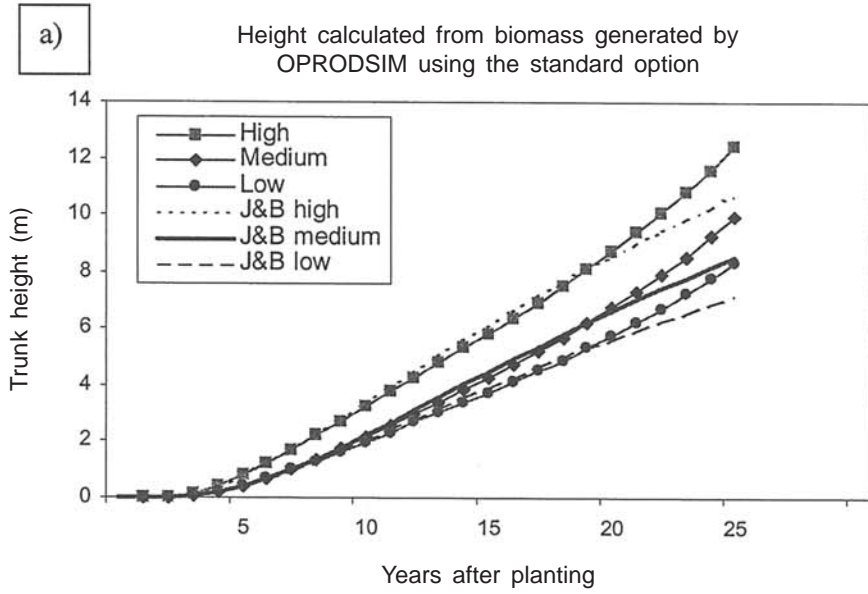


Figure 12. Trunk diameters calculated for three height growth options using trunk biomass data represented by the curve in Figure 8.

Notes: The upper graph omits improbably high values. The lower graph shows the regressions applied to the linear portions of the data together with the equations.



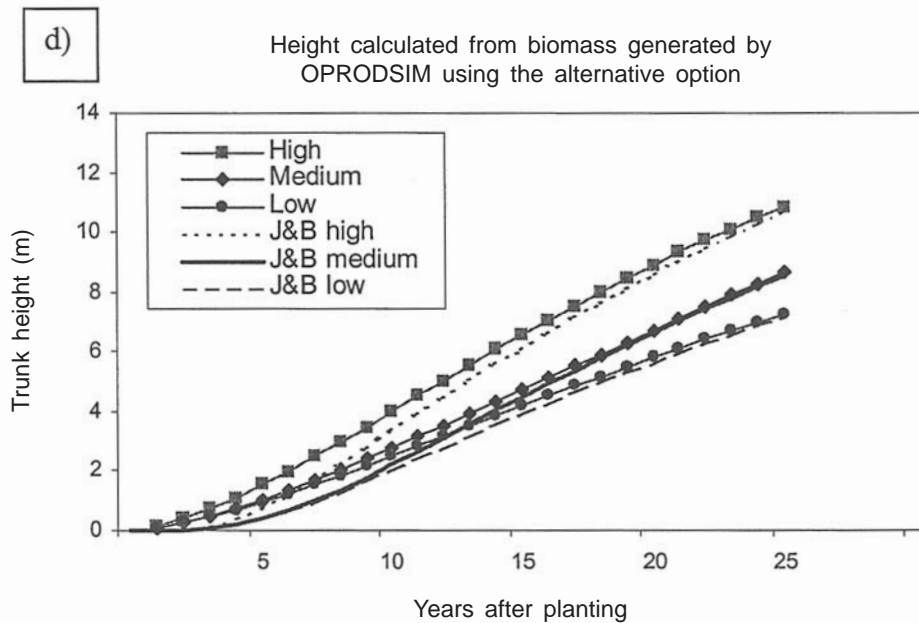


Figure 13. Trunk heights calculated for three height growth options using the trunk diameters shown in Figure 12 and trunk biomass data generated with OPRODSIM.

Notes: In (a) and (b), the full diameter vs. year curves were used, and in (c) and (d), the linear plots shown in the lower graph of Figure 12 were used. Results are shown for both the standard (a, c) and alternative (b, d) options of the model. The curves generated independently from versions of Equation 3 (J&B curves) are shown for comparison. Note deviations from the J&B curves in the early years, especially with use of the linear plots and the alternative option.

the measurements are taken and differences arising during removal of old frond bases, are the most likely cause of discrepancies. While changes in diameter can occur when new trunk tissue is being formed, there is supposed to be little or no further change subsequently (Rees, 1964). Thus, it seems difficult to explain the early increases in diameter with age such as those shown in Figure 1. However, Kwan (1994) stated that the diameter was measured just below the crown (frond 41), which may still be undergoing radial growth. The subsequent decline in diameter could reflect the onset of inter-palm competition resulting in greater vertical, and reduced, radial growth.

The effects of density on height are sometimes quite small but, nevertheless, may have economic impact (Donough and Kwan, 1991). It is therefore important that they be taken into account when modelling height growth.

The question arises as to whether increased height at high PD represents greater biomass. Henson *et al.* (2003) attempted to

answer this by taking into account trunk diameter and tissue density. The results of this rather small, preliminary study indicated there to be no significant difference in total biomass with PD if tissue density, calculated by Equation 1, was used. There were, however, significant differences when using tissue density obtained from core samples, with the biomass increasing with PD. These results need confirming as do other data reviewed here, such as the reduction or stability of trunk volume across planting densities (Figures 2 and 3) and the increase in internode length, a symptom of etiolation, with increasing PD (Figure 15).

SOME CONCLUSIONS AND IMPLICATIONS FOR MODELLING

It is apparent that there are different possibilities for modelling trunk growth. With the present information the following approaches are now favoured. Firstly, biomass may be calculated directly (using the empirically-derived curve: Figure 8) or by the

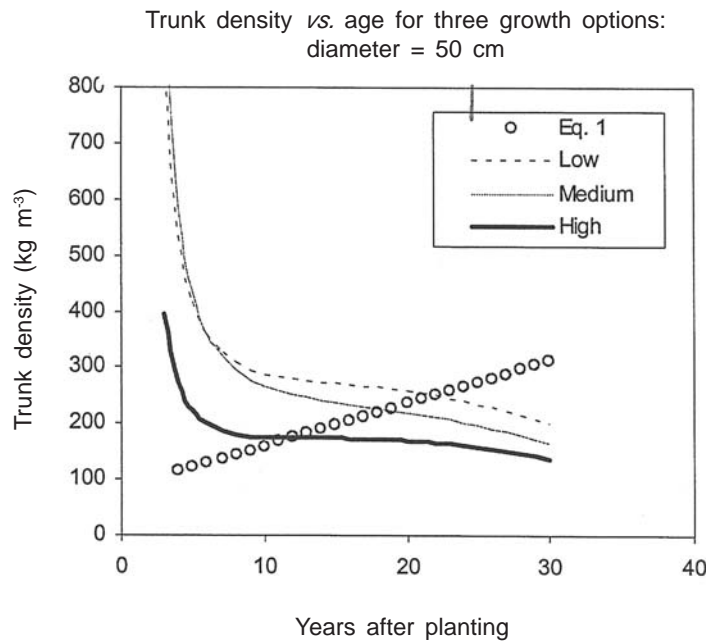
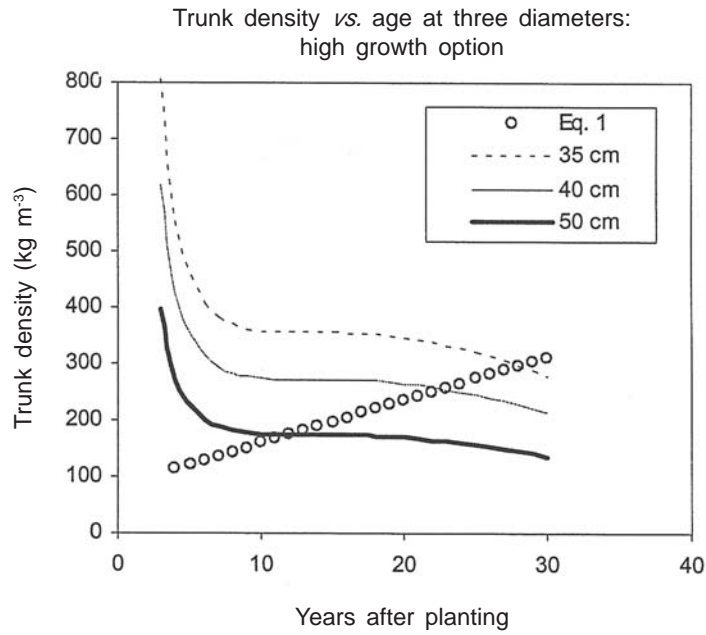


Figure 14. Trunk densities calculated using the standard biomass curve in Figure 8 and height curves generated by Equation 3 (Figure 6), compared with the densities derived from Equation 1 (Eq. 1).

Notes: The upper graph shows densities for three trunk diameters (cm) using the high growth-rate option. The lower graph shows densities for three trunk height growth-rates and a diameter of 50 cm.

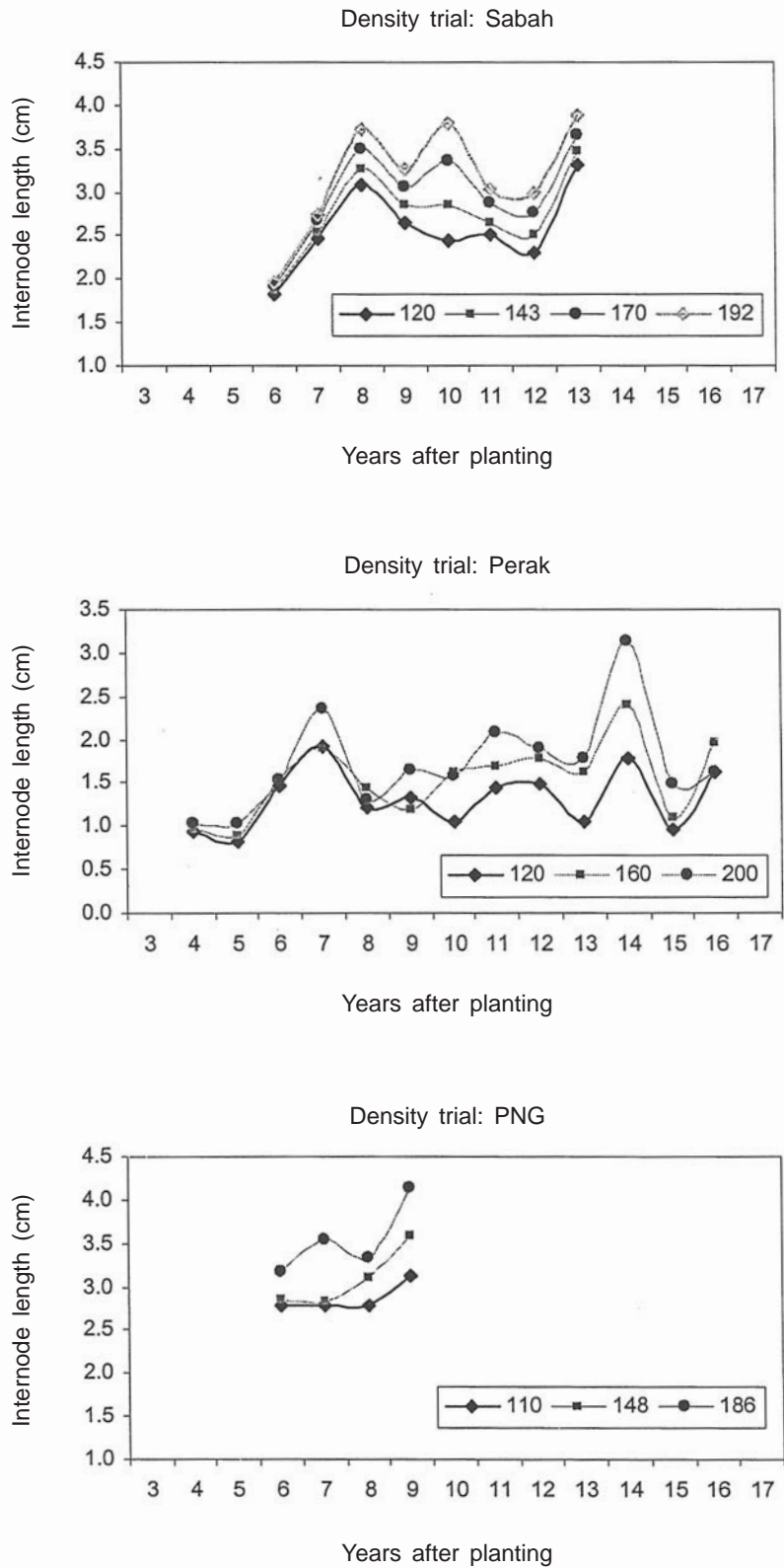


Figure 15. Changes in internode length with time calculated from trunk height and frond emission rates.

Notes: Data for Sabah are from Kwan (1994), for Perak from Henson and Mohd Tayeb (2003) and for PNG (Papua New Guinea) from Breure (1982). To facilitate comparison, the horizontal and vertical scales are the same in all the graphs.

partitioning of total VBP. However, if the latter is adopted then time-dependent partition coefficients should be used in preference to fixed values to more accurately reflect observed changes in height increment (*Figure 10*).

Height should be derived from biomass rather than independently calculated. The derivation should be based on age-dependent changes in tissue density and trunk diameter. The tissue density can be derived from Equation 1 and the trunk diameter from the linear portion of the curves shown in *Figure 12*. The latter result in some deviation from the expected heights in the early years (*Figure 13*) but this is only of minor importance given the lack of precision in measuring trunk height at this stage and the much closer correspondence found at the more critical period during later years when harvesting becomes problematic and when a prediction of the palm height might be useful. Details of the calculations to obtain height from biomass are given in *Appendix 1*.

Further work and data are needed for palms > 20 YAP regarding biomass, height and diameter changes, all determined for the same palms. More studies could also be done to measure internode length, which offers an alternative means of modelling height growth.

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Suggested procedure for deriving trunk height from standing trunk biomass

1. Calculate trunk biomass per palm (TBPP)
 $\text{TBPP (kg)} = (\text{TSB}/\text{PD}) \times 1000$ where TSB is the trunk standing biomass (t per hectare) and PD is planting density (palms per hectare).
2. Calculate trunk density (D) (Equation 1)
 $\text{D (kg m}^{-3}\text{)} = 7.62 \times \text{YAP} + 83$ where YAP = years after planting.
3. Calculate trunk volume (TVOL)
 $\text{TVOL (m}^3\text{)} = \text{TBPP}/\text{D}$
4. Calculate trunk diameter (TDIAM) according to preferred height growth option
 - i. very low: $\text{TDIAM (cm)} = -1.8075 \times \text{YAP} + 96.857$
 - ii. low: $\text{TDIAM (cm)} = -1.2961 \times \text{YAP} + 78.616$
 - iii. medium: $\text{TDIAM (cm)} = -1.3312 \times \text{YAP} + 75.598$
 - iv. high: $\text{TDIAM (cm)} = -0.9368 \times \text{YAP} + 61.268$
5. Calculate trunk cross-sectional area (TCSA)
 $\text{TCSA (m}^2\text{)} = [\pi \times (\text{TDIAM}/2)^2]/10\ 000$
6. Calculate trunk height (H)
 $\text{H (m)} = \text{TVOL} / \text{TCSA}$