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RESEARCH ARTICLE

Reassessing the estimation of leaf area in oil palm (*Elaeis guineensis* Jacq.) by linear regression equation

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Abstract

The area of individual leaves in oil palm has been conventionally estimated from a regression equation that is based on the size and number of leaflets. The aim of the present study is to verify the accuracy of this equation, which became standard in oil palm research. Therefore, true leaf area, measured with a video camera, was estimated from the product of number of leaflets per leaf (n) with mean length (l) times mid-width (w) of six of the longest leaflets (nlw). The database was assembled, annually for the first 4 years after planting, from 2961 leaves of *dura* × *pisifera* testcrosses descending from six distinct *pisifera* origins. The regression coefficients of the regression lines of nlw plotted against true area did not show a trend with age of the palms or a difference among *pisifera* origins. The common regression equation fitted through all data of this study accurately estimated true leaf area of the testcrosses and also the areas of 2- to 3.5-year-old *dura* palms of three distinct origins as well as 18-year-old *tenera* palms. These outcomes are at odds with the conventional regression equation that overestimates the true leaf areas by about 24%. A more recently-developed variant underestimates true area of the young *tenera* and *dura* palms by 28%, while overestimating true area of old *tenera* palms by 19%. Possible causes for these deviations from true area are discussed. The paper argues that parameters depending on leaf area of previous physiological studies need to be reassessed.

Keywords: Estimating leaf area; Regression equations; *Pisifera* origins; Palm age; Oil palm

Introduction

In oil palm, as in other plants, dry matter is formed by the process of photosynthesis, using solar radiation absorbed by the green leaf surface. An accurate value of the area of individual leaves is thus essential for estimating light interception in breeding and agronomy experiments and for assessing physiological parameters related to the amount of intercepted light. Moreover, knowledge of the leaf area and, in particular mature leaf area (L-max), appeared to be crucial for estimating optimal planting densities (Breure, 2010).

Since measuring true leaf area is too laborious, obtaining estimates from linear regression equations became an approach. Hardon *et al.* (1969) were the first to develop a regression equation, in which size and number of leaflets per leaf are taken to estimate true leaf area.

The leaves of oil palm are closely pinnate, with 100 to 200 leaflets on each side of the rachis. To determine the total area of a leaf, one thus needs to measure the areas of all individual leaflets. In contrast to the study of Hardon *et al.* (1969), in which leaflet areas were roughly derived from

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the leaflet size, a more recent study of Henson (1993) measured the true area of leaflets by employing a TV camera and monitor (Delta-T Devices).

In the pioneer study of Hardon *et al.* (1969), three outcomes became manifest. The regression lines appeared to be (1) linear and (2) passed through the origin, while (3) the slopes of the regression lines (regression coefficients) clearly increased with age of the palms. Henson (1993) replicated the work of Hardon *et al.* (1969) for various age groups. He found that the formula of Hardon *et al.* (1969) grossly overestimates leaf area of palms of all ages studied. Although Henson's (1993) data did not show a clear trend in the regression coefficients as a function of palm age, Henson and Dolmat (2003), who used the same data pattern, still included age as a factor in the regression equation, as Hardon *et al.* (1969) did.

A different outcome of the regression coefficient per age group is of relevance, for example, when fitting a logistic growth curve through annual leaf area values as a function of time after planting (*cf.* Breure, 1985). From this curve, an asymptotically mature leaf area (L-max) was obtained, which could be applied to estimate optimal planting densities for *tenera* offspring derived from several *pisifera* origins (Breure, 2010). The results were contradictory, however. In contrast to the equation of Hardon *et al.* (1969) that was used in Breure's 2010 study, Mendham (1971) obtained a difference in regression coefficients between *dura* × *pisifera* progenies from two *pisifera* origins. Therefore, it makes sense to look at a difference in our regression coefficients between *pisifera* origins, which may be regarded as a replication of Mendham (1971).

Considering the importance of oil palm as a commercial crop, it is timely for future research to develop – and widely distribute – a more accurate formula, which can be considered as the major objective of this report. Currently, oil palm planting material is all of the *tenera* fruit form, which is produced by pollinating thick-shelled *dura* females with (commonly female-sterile) *pisifera* males. It is thus essential that the formula estimates leaf area for the different palm types.

As database of the present study, we used the true areas of all leaflets of one leaf, measured with a similar video camera as employed by Henson (1993), along with the same type of measurements for estimating leaf area as in previous studies. The linear regression equations were developed by using annual leaf measurements during the first 4 years after planting from a *dura* × *pisifera* progeny test, involving six distinct *pisifera* origins.

The objective of the present investigation is first of all to verify whether a trend in the regression coefficients as a function of palm age becomes manifest and whether there is a difference between *pisifera* origins. The second goal is to validate the estimated values from the regression equation of (1) Hardon *et al.* (1969), (2) Henson and Dolmat (2003) and (3) our study, with an additional data pool. In the latter not only testcrosses are involved, but also samples of *dura* palms of three distinct origins in the age of 2 to 3.5 years, along with a group of 18-year-old *tenera* palms. For details of the three regression equations, a reference is made to the Methods section.

Material and Methods

Plant material

The three experiments of the present study were located at an oil palm breeding station in North Sumatra.

Experiment 1 was a *dura* × *pisifera* (*tenera*) progeny trial that was planted at a density of 135 and 160 palms per ha, with one replicate per density, in 2010. The assembled data came from 392 progenies with 16-palm plots, derived from *pisifera* parents of six distinct origins: AVROS (58 plots), Ekona (58 plots), Ghana (212 plots) and Nigeria (246 plots), being origins described by Mayes *et al.* (2017), along with two less common origins: Compact (86 plots) *cf.* Sterling *et al.* (1988) and Evolution (124 plots) *cf.* Alvarado and Henry (2015).

One youngest, fully-grown, leaf from the same palm within each plot was measured annually for the first 4 years after planting. The number of palms that were measured could be less when the leaf was damaged, resulting in a total of 2961 leaf measurements. Because of the young age of the palms at the time of the measurements, interpalm competition was expected to be negligible. Therefore, the two density treatments are ignored in the present study.

Experiment 2 contained sets of identified *dura* lines of Deli origin as well as those of Tanzania (Richardson and Chavez, 1986) and Compact (Sterling *et al.*, 1988). The lines were planted in 36-palm plots with three replicates between 2007 and 2009. From each plot, two leaves were measured in 2011 when palms of the three origins were between 2 and 3.5 years old.

Experiment 3 was an observation trial that was planted with a mixture of AVROS and of Ekona *tenera* progenies in 1997. A random sample of 26 leaves from palms of AVROS and 17 leaves of Ekona were measured 18 years after planting.

Data collection

Leaf measurements

From each side of the rachis, 10 leaflets were cut off downwards from the point where the rachis ceases to be flat and becomes angular. This reference point can be easily recognized and was, for each origin, confirmed to be corresponding to the area of the (broad) zone of the largest leaflets. The longest six leaflets (three on each side) were taken and the length and mid-width measured. From each leaf, the number of leaflets were counted at one side of the rachis and multiplied by two. The method is described by Breure and Verdooren (1995).

True leaf area

Straight after removal of an intact leaf, all leaflets were cut off and, after repairing any damage, the leaflets were divided into three pieces for convenient measurement. The areas were measured with a Skype IDS μEye video camera where the pieces of leaflets were physically constrained by a glass plate and became entirely flat (see Supplementary Material Figure S1). The instrument was frequently calibrated, manually as well as automatically, by measuring a cardboard of known area, as recommended by Skype Company. Repeated measurements of the area of some leaflets during the recording period confirmed the accuracy of our outcomes.

Estimating leaf area

The true area (the sum of all individual leaflets) was estimated according to the following regression equation:

$$\text{Leaf area}\left(\mathrm{m}^2\right) = a + b(nlw),$$

where n *is* the number of leaflets, l and w are the mean length and mid-width (cm) of six longest leaflets, a is the intercept and b is the regression coefficient.

Data processing

In the present report, the standard procedure of calculating the regression equation is followed, as applied in previous studies (*cf.* Hardon *et al.*, 1969; Henson, 1993; Henson and Dolmat, 2003; Mendham, 1971). The regression coefficients of the regression lines for the six origins of Experiment 1 were determined annually for the first 4 years after planting.

Finally, we measured the true leaf area and estimated the area of the individual leaves not only for palms from Experiment 1 but also those from Experiments 2 and 3 by applying the equation developed in the present study and those of previous methods, which are described below.

The accuracy of the leaf area estimation is defined as the difference between the true and the estimated leaf area, the latter expressed as a percentage of true area.

Method of Hardon et al. *(1969)*

Their method was developed by using a total of 26 leaves in three age groups, sampled from commercial plantings of Deli *dura* palms.

Leaflet area was obtained from the regression of length times mid-width of the leaflet, using a regression coefficient (B_1) of 0.838.

Leaf area was estimated by summing the area of all, or an adequate sample, of leaflets of the leaf. They found a close relationship between this (alleged) true leaf area and the product of length (l) times mid-width (w) of six of the longest leaflets with the total number of leaflets per leaf (n). The regression coefficients (B_2) were 0.512, 0.529 and 0.573 for palms of 1–2, 4–6 and 8–11 years after planting.

Hardon *et al.* (1969) applied these regression coefficients (B_2) for estimating leaf area, as follows:

$$\text{Leaf area} = B_2[(l \times w) * n],$$

where $l \times w$ is the mean length times mid-width of the six longest leaflets and n is the number of leaflets.

Method of Henson and Dolmat (2003)

Their equation was based on data from a total of 158 leaves in five age groups of *tenera* palms of unspecified origin reported by Henson (1993), who, in contrast to Hardon *et al.* (1969), used *measured* leaflet areas by employing a TV camera and monitor (Delta-T device) instead of providing an *estimation*, as mentioned before. They adopted the close relationship between leaf area and the product of n and lw of the six longest leaflets that Hardon *et al.* (1969) found. Therefore, they estimated true leaf area from nlw but using an age-specific regression coefficient (b) for palms younger than 10 years as follows:

$$b = 0.205 + 0.0319 * t,$$

where $t =$ palm age (years).

Note that the latter equation results in a strong increment of the regression coefficients (b) from 0.24 for 1-year-old palms to 0.52 for palms older than 10 years.

Results

Regression coefficients of the linear regression lines per year and per origin obtained in Experiment 1

For each origin, the regression equations (with x = *nlw* and y = true leaf area) per year and over 4 years are calculated. Table 1 presents for AVROS, as an example, in the third column the regression coefficients of the regression lines traced through annual data and over 4 years.

Clearly, the regression coefficient for the 4-year data (0.454) is much higher than those for the separate years (range from 0.302 to 0.404). This difference is due to the increase in size of the (measured) youngest leaves with age during the early years after planting, resulting in a wider range (minima and maxima) of *nlw* (x) and true leaf area (y) for values over 4 years than for separate years (see the last four columns of Table 1). Only the regression equation over 4 years validly estimates true leaf area for each of the 4 years (see Supplementary Material Table S1).

The difference in regression coefficients is further clarified in Figure 1, which shows, for all six origins, the regression lines for individual years (solid lines) and the common lines over 4 years (dotted line) along with the respective regression equations. Note the high coefficients of determination of the regression lines (R^2), a statistical measure of how close the data are to the fitted regression line, ranging for the dotted lines from 0.907 to 0.974 (see the right-hand corner of

Table 1. The number of leaves measured and the regression coefficients of the regression lines relating true leaf area (LA) to *nlw*, along with the range (minima and maxima) of LA and *nlw*, per year and over 4 years, for AVROS origin

			LA		*nlw*	
			Range		Range	
Year	Number of leaves	Regression coefficient	Minimum	Maximum	Minimum	Maxima
1	58	0.307	0.63	1.78	1.82	5.36
2	55	0.404	1.99	4.59	4.50	10.69
3	53	0.335	3.66	6.56	8.95	16.50
4	51	0.302	5.13	8.95	11.27	19.64
Over 4 years	217	0.454	0.63	8.95	1.82	19.64

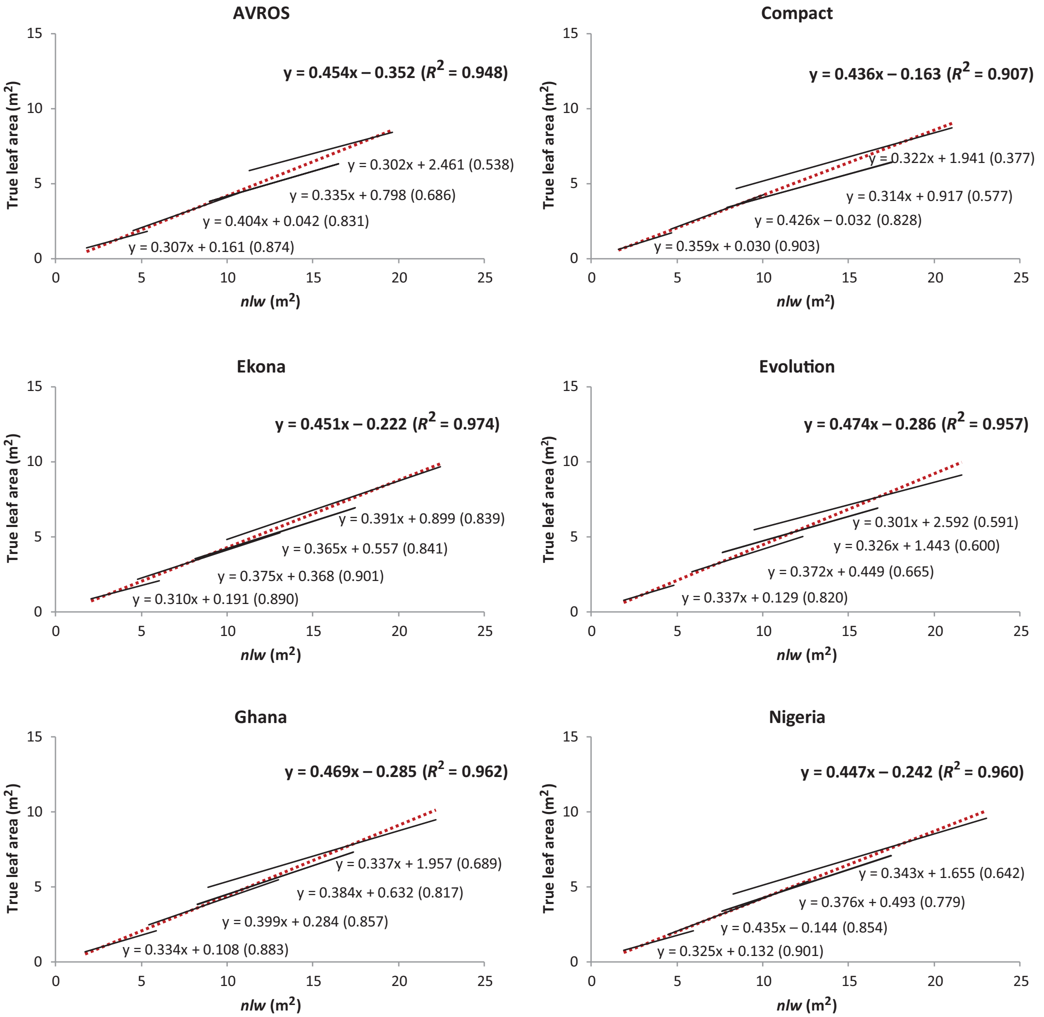

Figure 1. Linear regression lines and regression equations, relating true leaf area (y-axis) to the product of leaflet number (*n*) with length (*l*) and with mid-width of six of the longest leaflets (*nlw*, in x-axis), for palms of separate years (solid lines) and over all 4 years (dotted line) for six *pisifera* origins: AVROS, Compact, Ekona, Evolution, Ghana and Nigeria. The coefficients of determination are given in brackets.

Table 2. The number of measured palms, along with the regression coefficients of the regression lines traced through true leaf area (LA) versus *nlw* for the first 4 years after planting per origin. The last column presents the regression coefficients of the regression line over the 4 years

		Regression coefficients of regression lines through data for years 1, 2, 3 and 4 after planting				
Pisifera origin	Number of leaves	1	2	3	4	Regression coefficients of lines over all 4-year data
AVROS	58	0.307	0.404	0.335	0.302	0.454
Compact	86	0.359	0.426	0.314	0.322	0.436
Ekona	58	0.310	0.375	0.365	0.391	0.451
Evolution	124	0.337	0.372	0.326	0.301	0.474
Ghana	212	0.334	0.399	0.384	0.337	0.469
Nigeria	246	0.325	0.435	0.376	0.343	0.447
Over all origins	784	0.328	0.414	0.368	0.330	0.455

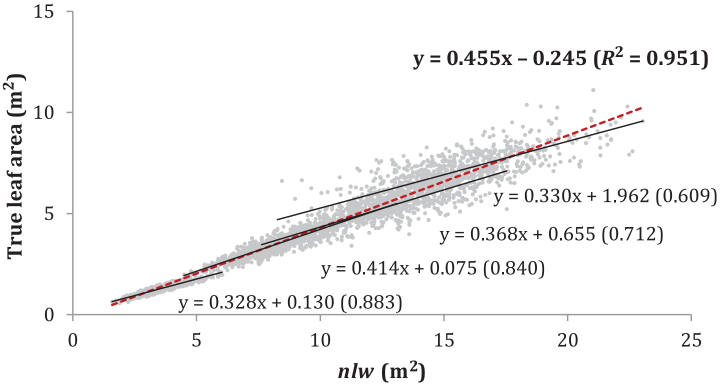

Figure 2. Linear regression lines and regression equations, relating true leaf area (y-axis) to the product of leaflet number (*n*) with length (*l*) and with mid-width (*w*) of six of the longest leaflets (*nlw*, in x-axis), for pooled data of six *pisifera* origins for each year (solid lines) and over all 4 years (dotted line). The coefficients of determination are given in brackets.

Figure 1). This shows the excellent fit of the common regression lines through all (annual) data of true leaf area plotted against *nlw* for the six origins.

Table 2 summarizes, for all origins, the total number of measured palms (at the start of the experiment) and the regression coefficients per year. The last column presents the regression coefficients of the lines traced through data over all the 4 years.

Trend in the regression lines of palm ages

Inspection of Table 2 reveals that there is no clear trend visible in the regression coefficients with palm age for any of the six *pisifera* origins. This shows that the influence of palm age on the regression coefficients is negligible.

Regression coefficients between origins

There are only small variations among the regression coefficients of the origins for each of the 4 years (see the vertical columns of Table 2). In other words, the regression coefficients are practically of the same order.

Table 2 also shows, on the bottom line, the regression coefficients over the six origins for the separate years. In the same way as for the separate origins over 4 years (Figure 1), regression lines over the six origins are fitted for the separate years (solid lines) and over 4 years (dotted line), as shown in Figure 2.

A common regression line through all data

The dotted line of Figure 2 through all data points, *nlw* plotted against true leaf area, shows that the following regression function of leaf area (see below) very well fits the observations of all origins, which is supported by the high R^2 (0.951):

$$\text{Leaf area} = -0.245 + 0.455\,nlw$$

The accuracy of the equation is also illustrated by the small 95% confidence interval of the regression coefficient, being a value within a boundary of 0.452 and 0.460.

Accuracy of estimating leaf area

As shown in Table 3, our estimate of leaf area from the common regression equation fitted through all measurements accurately corresponds, for each year, with the true leaf areas of samples from Experiment 1. By contrast, the equation of Hardon *et al.* (1969) overestimates the true leaf area in all years with a pronounced score of 40% difference in year 1, while averaged over the 4 years the value is 25%. The formula of Henson and Dolmat (2003), on the other hand, results in an underestimation with a mean of 27% over all 4 years.

The formula of our study also accurately estimates leaf areas of young *dura* of different origins from Experiment 2 (Table 4) as well as those of the older *tenera* palms from Experiment 3 (Table 5). The formula of Hardon *et al.* (1969), however, again overestimates the areas for both young *tenera* and *dura* palms (21.3%) as well as for those of old *tenera* palms (23.7%). The formula

Table 3. True leaf areas versus those estimated from the equation of Hardon *et al.* (1969), Henson and Dolmat (2003) and of our study (leaf area = −0.245 + 0.455 *nlw*), together with the percentage difference with true area, for the first 4 years after planting of Experiment 1

			Estimated leaf area (m^2) based on several equations					
Palm age (years after planting)	Number of leaves	True leaf area (m^2)	Present equation	% difference	Hardon *et al.* (1969)	% difference	Henson and Dolmat (2003)	% difference
1	778	1.24	1.30	4.7	1.73	39.5	0.93	−24.7
2	752	3.44	3.45	0.3	4.14	20.4	2.31	−32.7
3	718	5.33	5.52	3.5	6.71	26.0	3.94	−26.0
4	713	7.04	6.75	−4.1	8.15	15.8	5.25	−25.4
Mean			–	1.1	–	25.4	–	−27.2

Table 4. True leaf areas versus those estimated from the equation of Hardon *et al.* (1969), Henson and Dolmat (2003) and of our study (leaf area = −0.245 + 0.455 *nlw*), together with the percentage difference with true area, for young *dura* palms of Deli, Tanzania and Compact origins of Experiment 2

				Estimated leaf area (m^2) based on several equations					
Palm age (years after planting)	Origin	Number of leaves	True leaf area (m^2)	Present equation	% difference	Hardon *et al.* (1969)	% difference	Henson and Dolmat (2003)	% difference
3.5	Deli	388	5.22	5.27	1.0	6.42	23.1	3.97	−23.9
3	Deli	331	4.98	5.06	1.7	6.19	24.2	3.64	−26.9
2.5	Deli	67	3.93	3.92	−0.3	4.67	18.7	2.74	−30.4
2.5	Tanzania	51	3.30	2.97	−9.9	3.61	9.3	2.14	−35.0
2	Deli	35	2.64	2.70	2.4	3.30	25.2	1.87	−29.1
2	Compact	114	1.97	1.99	1.2	2.51	27.4	1.45	−26.2
Mean				–	−0.7	–	21.3	–	−28.6

Table 5. True leaf areas versus those estimated from the equation of Hardon *et al.* (1969), Henson and Dolmat (2003) and of our study (leaf area = −0.245 + 0.455 *nlw*), together with the percentage difference with true area, for 18-year-old *tenera* palms derived from *pisifera* of AVROS and Ekona origins of Experiment 3

				Estimated leaf area (m^2) based on several equations					
Palm age (years after planting)	Origin	Number of leaves	True leaf area (m^2)	Present equation	% difference	Hardon *et al.* (1969)	% difference	Henson and Dolmat (2003)	% difference
18	AVROS	26	11.93	11.63	−2.5	14.88	24.7	14.36	20.3
18	Ekona	17	11.66	11.18	−4.1	14.31	22.8	13.81	18.4
Mean				–	−3.3	–	23.7	–	19.4

of Henson and Dolmat (2003), on the other hand, *underestimates* the area of young *dura* palms (−28.6%) and, as shown in Table 5, *overestimates* the areas of old *tenera* palms (+19.4 %).

We conclude that, compared with the regression equations on oil palm in previous studies, our revision results in a clearly more accurate estimate of leaf area for *dura* and *tenera* palms of several ages and various origins.

Discussion

Leaf area estimates

The present revision is based on the standard method for estimating true leaf area in oil palm as developed by Hardon *et al.* (1969), which was also applied by Henson (1993). A comparison of measurements of true areas with the estimated areas showed that the equation of Hardon *et al.* (1969) considerably overestimates the leaf area of *dura* and *tenera* palms of all ages up to 18 years after planting. On the other hand, the replication of Henson and Dolmat (2003), in which the data of Henson (1993) were re-analyzed, revealed an underestimation of true area for young palms and overestimation for older ones.

Regression coefficients for several palm ages and pisifera origins

Contrary to the methods for estimating leaf area of both Hardon *et al.* (1969) and Henson and Dolmat (2003), our study showed no trend in regression coefficients with palm age. Moreover, there was virtually no difference between *pisifera* origins, as found by Mendham (1971). The absence of the effect of palm age or palm origin on the regression coefficient is confirmed by the test of accuracy of estimating true areas, based on the common regression equation of our study, for palms of a broad range of origins as well as for a large variation in palm age. Our data pattern consistently revealed that our equation very accurately estimates true area of young palms (1 to 4 years) and advanced age (18 years) of *tenera* origins as well as young *dura* palms of three distinct origins.

As shown in Figure 1, the regression coefficients of the regression lines for individual years are all smaller than those of the common regression equation based on data of 4 years. The reason, as explained for AVROS (*cf.* Table 1), is the wider range of data (*nlw* and true leaf area) for fitting the regression lines.

Possible causes of the discrepancy with previous equations

It seems puzzling to observe a strong contrast between the estimate of true leaf areas of the present study and that of previous studies. The discrepancy is likely not due to the use of a single *pisifera* origin, provided that data over several years are taken, as in our study (see Supplementary Material Table S1).

Actual testing of the equation on palms of several origins and ages, as in our investigation (Tables 3–5), may have pointed to the lack of accuracy in estimating true area by previous methods.

The equation of Hardon et al. *(1969)*

The slight increase in the regression equation with age, from 0.51 to 0.57, as provided in the formula of Hardon *et al.* (1969), exerts a minor effect on the accuracy of estimating true leaf area. For most purposes, a regression coefficient of 0.55 is applied anyway for all palm ages (*cf.* Corley and Tinker, 2016). Ignoring the regression coefficient (0.838) for estimating *leaflet* area may be a possible cause of deviation, as Henson (1993) suggested. Indeed, including the latter factor would result in a regression coefficient of 0.46, which is identical to our value. However, his assumption is not supported by the remark as given in Hardon *et al.* (1969). They evidently wrote that the regression coefficient is applied for *measuring* instead of *estimating* true leaf area in the regression equation.

It should be noted that, as usual with plant growth, the first part of leaf development generates a convex curve, which gradually becomes by and large linear. Our interest is solely to estimate the area of fully-grown leaves. A regression line through the origin (*cf.* Hardon *et al.*, 1969) versus a regression function with a constant value, as in our study (*cf.* Figure 2), may therefore partly explain the discrepancy between both studies in estimating true leaf area.

The equation of Henson and Dolmat (2003)

In their equation, an age-specific factor is introduced. Although no details are given about how this factor is obtained, the authors may have involved the palm age (years after planting) in the regression equation for the age groups as presented by Henson (1993). The authors could possibly have obtained an accurate linear regression equation based on all of their individual measurements for several age groups (see Supplementary Material Table S1).

Consequence of applying the standard formula

So far, most investigations are based on leaf area as estimated by the standard equation of Hardon *et al.* (1969). Their method is of course still valid when *comparing* progeny differences in breeding trials. An accurate estimate of leaf area becomes crucial, however, when the effect of leaf area on light interception is studied, as Squire (1983), for example, applied by analyzing the results of fertilizer experiments.

Furthermore, an overestimation of leaf area may have consequences for the values of physiological parameters related to absorbed radiation. Breure and Siregar (2020) showed already that Breure's 1988 estimate of 5.6 for leaf area index that gives the highest bunch yield per ha becomes 4.5 by using the equation of the present study. Revising other parameters depending on leaf area, such as canopy extinction coefficient and radiation conversion efficiency, will be addressed in the following study (Breure and Siregar, in prep.)

Other methods of determining leaf area

Since our adapted equation appears to accurately estimate leaf area, it could be used as a quick method to verify the validity of other methods. An example is the CIRAD method, as developed by Tailliez and Ballo Koffi (1992). With their more laborious method, leaf area is assessed on the basis of the number of leaflets and the size of one leaflet taken from 10 equal sections of the rachis, but without calibrating the outcome with true (measured) leaf area.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479720000332

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