Analysis of Leaflet Shape and Area for Improvement of Leaf Area Estimation Method for Sago Palm (*Metroxylon sagu* Rottb.)

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**Abstract**: Leaf area of sago palm (*Metroxylon sagu* Rottb.) can not be estimated accurately from the whole leaf shape, and individual leaflet area must be measured for accurate estimation of leaf area. In this study we examined leaflet characteristics in detail and developed a method of estimating individual leaflet area. Shapes of all leaflets were similar regardless of their sizes. The leaflet width was maximal at the distal position around 30 ~40% from the leaflet base. Products of leaflet lengths and maximum widths (as the X-axis) showed almost a linear relationship with the leaflet areas measured with a leaf area meter (as the Y-axis). Moreover, the Y-intercept of the primary regression equation was very small compared to leaflet area values, and we can regard it as 0. We compared the measured leaflet area with the area of the ellipse with the leaflet length as the major axis and the maximum width as the minor axis. The difference between them was within ±5% except for some leaflets at the base or tip of the leaf. These results suggested that the method of estimating leaflet area from the ellipse area calculated from the leaflet length and the maximum leaflet width as major and minor axes, respectively was simple and accurate. The estimation equation for the leaflet area is \( S(e) = 0.785 L_{\text{leaflet}} \times W_{\text{leaflet}} \), where \( S(e) \) is the estimated leaflet area, \( L_{\text{leaflet}} \) is the leaflet length, and \( W_{\text{leaflet}} \) is the maximum leaflet width.

**Key words**: Leaf area, Leaflet, Leaflet area, Leaflet shape, *Metroxylon sagu* Rottb., Sago palm.

It is important to determine the leaf area index (LAI), which indicates the condition of a sago palm (*Metroxylon sagu* Rottb.) canopy, in order to properly manage large-scale plantations. The accurate determination leaf area using a leaf area meter requires a lot of work because a sago palm has large pinnate compound leaves. The currently used leaf area estimation method (Flach and Schuiling, 1989) that calculates leaf area from the length, width, and number of leaflets on one side of the leaf has a low accuracy and is illogical. Therefore, a simpler and more accurate method of estimating the area of each sago palm leaf is necessary. Previously, we described the leaf characteristics and shape in detail for developing a simpler method of estimating leaf area (Nakamura et al., 2004). The results revealed differences in the overlapping area of leaflets depending on the leaf age and on the angle of the leaflet to the rachis, rendering it impossible to determine the area accurately from the leaf outline or the area of leaf projection diagram. Thus, it seemed feasible to establish a method of estimating leaf area with high accuracy by estimating the leaflet areas and then integrating them. There have been no methods to estimate leaflet area, except for one under study by Oomori et al (2000a, b).

In this study, we examined the characteristics of leaflets in detail and developed a method of estimating the area of each leaflet.

**Materials and Methods**

As in the previous report (Nakamura et al., 2004), we used a large plant just after trunk formation (with nine living leaves: Plant 1) and a plant around two years after trunk formation, which was average on the farm with respect to plant height and trunk girth (with eleven living leaves: Plant 2), in a sago palm farm in Sarawak, Malaysia. The youngest emerged leaf, namely the spear leaf (or needle-like leaf) was named ebL1, and sequentially lower leaves ebL2, ebL3, and so on basipetally. The right (R) and the left side (L) of the leaf were determined viewing the adaxial surface of the leaf with the top upward (Fig. 1). The lowest (basal) leaflets on the left and the right sides were defined as L1 and R1, and the leaflets counted upward as L2, L3 and R2, R3, in successive order. The length, width (maximum width), and area of each leaflet were measured. A leaf area meter (Laser Area Meter CI-203; CID Inc.) was used for measurements of width and
area. In addition, for leaflet shape, we obtained its outline by measuring the distance between the leaflet midrib and the left or right leaf margin at 5~10 cm intervals. The side of a leaflet midrib facing the top of the leaf was defined as the top side, and the other side facing the base of the leaf was defined as the base side (Fig. 1).

1. Leaflet shape

The shape of sago palm leaflets tended to be similar at all leaflet positions. As a representative, the leaflet shape of ebL2 in Plant 1 is shown here. This leaf had 69 leaflets on the left side and 66 on the right side, 135 leaflets in total (Nakamura et al., 2000). Fig. 2 shows the distances from the midrib to margin of the leaflet at every 5~10 cm from the base to the leaflet tip of leaflets R10, R30, and R56 in ebL2 of Plant 1. The top side was wider than the base side at the base of the leaflet, whereas the base side was wider than the top side at the tip of the leaflet. The same tendency was observed in all leaflets on the left side of a leaf, although the difference between the distance at the tip and base sides was quite small: 8 mm at most. Thus, we estimated leaf area considering that leaflets are symmetrical in this study.

Fig. 3 shows the shapes of nine leaflets using the distance from the midrib (X-axis) and that from the base of the leaflet (Y-axis) to the margin of the leaflet. Here, the scale for the distance from the midrib (X-axis) was magnified compared with that from the leaflet base (Y-axis). Shapes of all leaflets were similar regardless of their dimensions.

In most palms the edges of the leaflets turn down and are described as being reduplicate (A in section) (Jones, 1995). The basement of sago palm leaflets attached to the rachis was also A shaped, as shown in Fig. 4.
2. Estimating leaflet area

Fig. 5 shows the correlation of the product of leaflet length and its maximum width with the leaflet area measured with a leaf area meter in ebL3 of Plant 2. Almost an identical linear relationship was found between them for the leaflets on both sides of the leaf. Table 1 shows the slope, the Y-intercept and the coefficient of determination of the primary regression equation for respective leaf positions of Plant 1 and Plant 2 with less damage over a leaf. The coefficient of determination was high for all leaf positions and was in the range of 0.994 to 0.999. The slope of the primary regression equation ranged from 0.79 to 0.82. Moreover, the Y-intercept was within the range of −0.0005 to 0.0034 (m²), which was very small compared to the leaflet area. Therefore, it was considered that an equation to estimate the leaflet area can be made with the Y-intercept fixed at 0, although the relationship between the product of leaflet length and its maximum width and the actual measurement of the leaflet area is in fact shown by a primary regression equation. For this reason, we decided to use a proportional expression with the Y-intercept at 0 as an equation to estimate the leaflet area and examined the slope of a proportional expression.

Many simple estimation methods for the leaf area using the leaf length and width have been reported for some plants with a somewhat simple leaf shape. For a rice leaf that is morphologically similar to the sago palm leaflet, a relationship reportedly exists between the leaf area (Y) and the leaf length (X) that can be shown as a regression equation Y = 0.72X + 1.20 (Mori and Murayama 1978). However, Kawashima and Hirano (1982) proposed the equation Y = 0.736X. In sago palm, Oomori et al. (2000a) used the equation Y = aX where Y was leaflet area and X was leaflet length × width for estimating leaflet area. They called the slope (a) α value, and calculated it for many leaflets. As a result, the α value ranged from 0.561 to 0.996; and in many cases it was around 0.8, suggesting the possibility of leaf area estimation using the α value. Moreover, when the α value was examined in sago palms of various plant ages, in leaflets attached to the middle of leaves on the upper, middle, or lower leaves in a plant, the α value was around 0.82 regardless of plant age, the leaf position, or/and varieties (Oomori et al. 2000b). It is important to determine the slope (a) in Y = aX to estimate the leaflet area. We tried to determine the slope.

To illustrate the leaflet shape graphically, we show in Fig. 6 the shape of each leaflet shown in Fig. 3 in percentage taking the leaflet length and the maximum...
leafl et width as 100. For each leafl et, the width was the maximum at the distal position around 30\textendash}40\% from the leafl et base. Accordingly, in a field survey of the maximum leafl et width, the leafl et should be measured at approximately one-third from the bottom.

The ellipse in Fig. 6 was drawn using the leafl et length as the major axis, and the maximum leafl et width as the minor axis, and it was used as an approximate means for determining the leafl et area. The leafl et area was presumed to be almost equal to the area of the ellipse because the leafl et area was larger than the ellipse area from the base of the leafl et to 40\% of the leafl et length, whereas the area of the ellipse was larger than the leafl et area beyond that point, almost balancing out the area differences between the leafl et and ellipse in total. The area of the ellipse $S(e)$ for estimation of leafl et area can be expressed as:

$$S(e) = \left(\frac{\pi}{4}\right) L_{\text{Leafl et}} \times W_{\text{Leafl et}}$$

where $L_{\text{Leafl et}}$ is the leafl et length and $W_{\text{Leafl et}}$ is the maximum leafl et width. Based on this relationship, it seems appropriate to set $(a)$ in $Y = aX$ as $\pi/4$, or 0.785. This setting was verified as follows.

For all leafl ets measured leafl et area was calculated by using Eq. [1], and the value was plotted on the X-axis against the corresponding measured leafl et area on the Y-axis, as shown in Fig. 7. Their relationship proved to be almost $Y = X$. For closer evaluation, the error of each estimated value $S(e)$ against the measured leafl et area ($A$) was calculated by the equation:

$$\text{Error ratio} \% = \left[\frac{S(e)}{A}\right] \times 100.$$  \[2\]

Fig. 8 shows the relation between the estimated leafl et area and the error ratio (%) for measured leafl et area. The estimated leaf area was plotted on the horizontal axis and the error on the vertical axis. The first through fifth leafl et on each side from the base of the leaf was indicated by $\triangle$, the first through fifth leafl et on each side from the top of the leaf by $\triangledown$, and the other leafl ets, which were about sixty in the middle of the leaf, by $\bullet$. Leflets at the base or
the tip of a leaf, which were smaller in size showed a larger error. In the leaflets at the base of leaf with the estimated area was larger than the measured area. It is conceivable that such a larger error is based on the morphological difference between the leaflets at the base or tip and those leaflets in the middle of a leaf. Most of the leaflets over 20% error were at the lowest and next from at the base of leaf. These leaves had the shape of a long or narrow triangle. However, for most leaflets except those at the base or the tip of the leaf, the error in the estimated leaflet area was within ±5%.

The present results above show that this method of estimating leaflet area from the area of the ellipse using the leaflet length and the maximum leaflet width as axes is simple and accurate. The estimation equation for the leaflet area is

\[ S(e) = 0.785 L_{\text{Leaflet}} \times W_{\text{Leaflet}} \]  

[3]

where \( S(e) \) is the estimated leaflet area, \( L_{\text{Leaflet}} \) is the leaflet length, and \( W_{\text{Leaflet}} \) is the maximum leaflet width. A leaf area estimation method based on integration of the leaflet area is to be reported in the near future.

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