Plant Prod. Sci. 12(1) : 58—62 (2009)

A Method for Estimating Sago Palm (*Metroxylon sagu* Rottb.) Leaf Area after Trunk Formation

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Abstract : It is important to measure the individual leaf area and leaf area index (LAI) of sago palm (*Metroxylon sagu* Rottb.) to determine the appropriate planting density and maintain populations that are highly productive with regard to starch production. However, the accurate estimation of sago leaf area from the entire leaf profile or the projecting area of the plant is not possible. Thus, we developed a method for estimating leaf area of sago palm after trunk formation by integrating the leaflet areas. All leaflets were diagrammatically converted to rectangles, each having the same area as that of the corresponding leaflet, and these rectangles were arranged on the rachis to initiate the shape of a leaf without overlapping leaflets and gaps between their bases and between their tips. The leaf shape thus produced by the arrangement of these rectangles was represented as ellipsoidal in the apical half and as trapezoidal in the basal half. The ratios of the estimated to the actually measured area of the apical and the basal half of the leaf were 99–107% and 94–108%, respectively. The ratio of the estimated area of the whole leaf to the measured area was 98–104%. From these results, the method for estimating the whole leaf area by converting the leaflets diagrammatically to rectangles, and calculating the area as the sum of the ellipsoidal apical half and trapezoidal basal half, is considered to be accurate and simple.

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

To determine the appropriate planting density and maintain high productivity of cultivated sago palm (*Metroxylon sagu* Rottb.) populations with regard to starch production, it is important to assess the leaf area and leaf area index (LAI) of individual plants. However, a theoretical method for leaf area estimation that ensures high accuracy has not been established thus far. Therefore, it is essential to develop a simple method that is highly accurate. Studies conducted thus far by using methods based on the entire leaf profile or the projecting area of the plant have yielded insufficiently accurate results (Nakamura et al., 2004). We therefore considered that the estimation of leaf area by integrating the leaflet areas is suitable for investigation, and proposed a method for estimating individual leaflet areas in a previous report (Nakamura et al., 2005). The current report describes a method for estimating the whole leaf area after trunk formation based on the estimated leaflet areas.

Materials and Methods

The same non-spiny plants as those used in a previous study (Nakamura et al., 2004; 2005) that were grown on a sago palm plantation (shallow peat soil) in Sarawak, Malaysia, were used in the present investigation. A large plant immediately after trunk formation (Plant 1; with 9 fresh leaves) and a plant approximately 2 years after trunk formation (Plant 2; with 11 fresh leaves) were investigated in detail. The most recently emerged leaves, spear or needle-like leaves, were designated as ebL1; and the lower leaves were sequentially designated as ebL2, ebL3, and so on. Viewing the leaf from the adaxial surface with its tip pointing upward, the leaflets on the left side of the rachis were designated as L and the right, as R. With regard to the leaflet position, the lowest left and right leaflets were designated as L1 and R1, respectively, and counted toward the leaf tip. The leaflet area was estimated by the method used in the previous study for estimating the leaflet area that was then used for computation of the whole leaf area: 0.785×leaflet length×leaflet width (maximum) (Nakamura et al., 2005). The rachis length was defined as the distance from the position of the lowest leaflet to that of the topmost leaflet.

Results and Discussion

Fig. 1a schematically shows leaflets attached to the rachis. Sago palm has large and pinnate compound leaves; the leaflets overlap each other, with gaps

Received 16 January 2008. Accepted 3 July 2008. Corresponding author: S. Nakamura (nakamurs@myu.ac.jp, fax +81-22-245-1278).
Abbreviations : ebLn, the n^{th} (counted basipetally from the tip) emerged leaf; LAI, leaf area index; SLA, specific leaf area; R (L), the right (left) side of the rachis viewed from the adaxial surface of the leaf with the tip pointing upward; Rn (Ln), the n^{th} leaflet (counted acropetally from the base) on the right (left) side of the leaf.

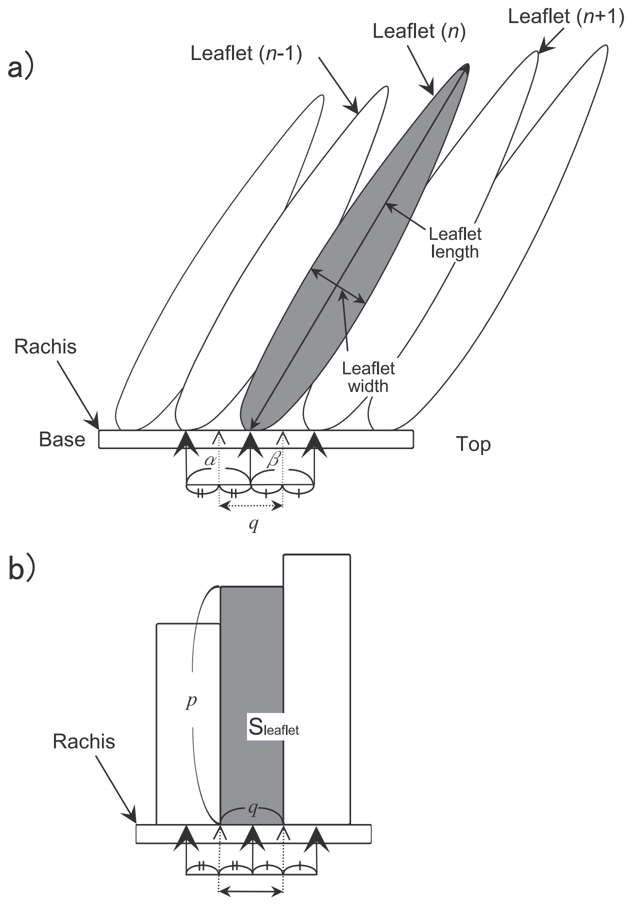

Fig. 1. A schematic diagram of leaflets attached to the rachis (a) and a rectangle having the same area as that of the corresponding leaflet (b). α, β indicate the distance between the position of attachment of the leaflet (n) on the rachis and that of the immediately basipetal leaflet ($n-1$), and acropetal leaflet ($n+1$), respectively. $S_{leaflet}$ indicates the area of the leaflet (n). q denotes half the sum of α and β, and p denotes the height (major side) of the rectangle calculated by dividing $S_{leaflet}$ by the width (minor side) of the rectangle (q).

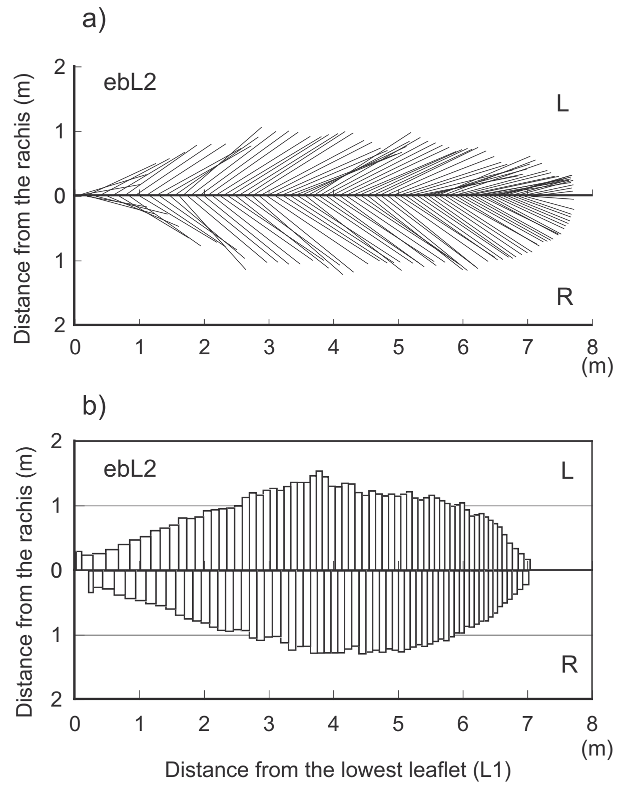

Fig. 2. A schematic diagram of leaf ebL2: (a) the leaflets are expressed as lines; (b) profile of a leaf with rectangles each converted from corresponding leaflets. L denotes the left side of the leaf; R denotes the right side of the leaf.

between their bases and between their tips. Owing to this arrangement of the leaflets, it is difficult to estimate the leaf area from the shapes of the leaves drawn by connecting the tips of the leaflets. Thus, we attempted to estimate the leaf area by converting each leaflet diagrammatically to a rectangle having the same area as that of the leaflet. Then excluding the gaps and overlapping of leaflets, leaves were diagrammatically arranged on the rachis (Fig. 1b), and their profiles were analyzed. This conversion method allows treatment of the leaflets as a single leaf to estimate the whole leaf area. The method for converting the leaflet profiles into rectangles was as follows: For a certain leaflet (n), the distance from the position of attachment of the leaflet to the immediately basipetal leaflet (n–1) as α; and that to the immediately acropetal leaflet (n+1) as β; half the sum of α and β was considered to be the small side (or width) (q) of the rectangle (Fig. 1b).

$$q = (\alpha + \beta)/2 \quad [1]$$

The height (large side) (p) of the rectangle was calculated by dividing the area ($S_{leaflet}$) of the leaflet (n) by the length of the rectangle (q).

$$p = S_{leaflet}/q \quad [2]$$

All the leaflets were converted to rectangles as described above. Subsequently, these rectangles were arranged on the rachis to produce a leaf profile without any gaps and overlapping leaflets.

Fig. 2a schemataically shows the leaf ebL2 of Plant 1, based on the leaflet length and the angle and position of its attachment on the rachis. The leaflet was expressed as a line. In Fig. 2b, the rectangles converted from the leaflets as mentioned above were arranged on the rachis without any space between them. Analysis of this configuration revealed that the leaf area increased linearly from the base to the central part, and then decreased gradually toward the leaf tip followed by a rapid decrease at the tip. A similar configuration was observed in the other leaves.

To establish a simple and accurate method for estimating the area of this leaf profile, we considered the whole leaf as an ellipsoid.

In Fig. 3, the rachis length was represented by the major axis (a), and the sum of the heights of rectangles converted from the leaflets on both sides at the central part of the rachis was represented by the minor axis (b) (Fig. 3). The area of the apical half (T) and the basal half (B) of the ellipsoid were compared with those of the corresponding measured leaf areas. The ratios of the estimated areas to the measured area were 99–107% for T, 124–145% for B, and 111–119% for the whole leaf (T+B) (Table 1). These results demonstrated that the apical half of the laef area toward the tip (T) can be approximated as that of an ellipsoid. However, the basal half of the leaf area (B) was larger than the measured area by over 20% for every leaf. Therefore, we estimated the area of the basal half as a trapezoid.

Fig. 4 shows a leaf profile in which the apical half of the leaf (T) is represented as half an ellipsoid and the basal half (B) is represented as a trapezoid. The area toward the leaf tip (S_T) was estimated to be half of the ellipsoid.

$$S_T = ab\pi/8 \quad [3]$$

Accurate estimation of the basal half of leaf area (S_B) by using the length and width of the leaflets at the leaf base was not possible because these leaflets were extremely narrow and their profiles differed from those of the other leaflets (Nakamura et al., 2005). Therefore, the length (c), corresponding to a half of the sum of small and large base of the trapezoid, was obtained from the sum of the heights of the rectangles converted from the leaflets on both sides at a/4 from the rachis base.

$$S_B = (a/2) \times c = ac/2 \quad [4]$$

In the basal part of the leaf (B), the ratio of the estimated area to the measured area was 94–108%, which was more accurate than that estimated by regarding the basal half of the leaf as ellipsoidal (Table 2). For the whole leaf area (S_{leaf}), which is the sum of T and B, the ratio of the estimated value to the measured area was 98–104%. Thus, this estimation method is more accurate than the method in which the whole leaf is regarded as an ellipsoid.

Flach and Schuiling (1989) estimated the leaf area (S) using the following equation.

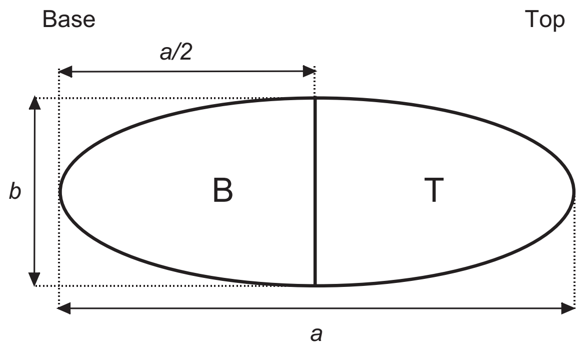

Fig. 3. A schematic diagram of a leaf represented as an ellipsoid, where a represents the rachis length, b denotes the sum of the heights of the rectangles representing the leaflets on both sides at the center of the rachis. T indicates the apical half of the ellipsoid; B indicates the basal half of the ellipsoid.

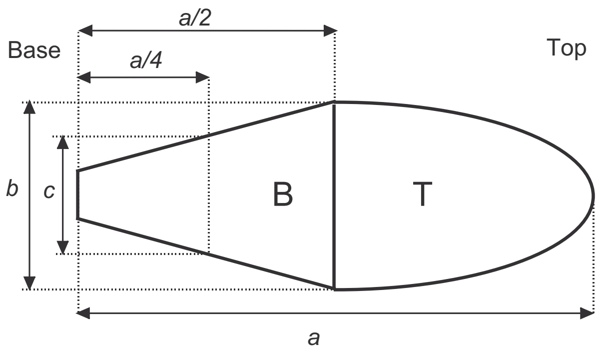

Fig. 4. A schematic diagram of the leaf represented as ellipsoidal in the apical half and trapezoidal in the basal half. T is the same as in Fig.3, B indicates the trapezoid in the basal half. a and b are the same as in Fig.3, and c denotes the sum of the heights of the rectangles converted from the leaflets on both sides at $a/4$ from the rachis base.

Table 1. The estimated values of the apical half (T), the basal half (B) and whole leaf (T+B) as an ellipsoid, and ratio (%) of the estimated values to the measured values.

Part		Plant 1	Plant 2						
			Leaf position						
		ebL2	ebL3	ebL4	ebL5	ebL6	ebL7	ebL8	ebL9
T	estimated value (m^2)	6.99	4.89	4.77	4.95	4.45	4.67	4.57	4.77
	%	100	107	99	105	99	102	100	100
B	estimated value (m^2)	6.82	4.89	4.77	4.95	4.45	4.67	4.57	4.77
	%	124	126	138	134	127	135	138	145
Total (T+B)	estimated value (m^2)	13.81	9.77	9.53	9.90	8.89	9.34	9.14	9.54
	%	111	115	115	118	111	116	116	119

Table 2. The estimated values of the ellipsoidal apical half (T), the trapezoidal basal half (B) and whole leaf (T+B), and ratio (%) of the estimated values to the measured values.

Part		Plant 1	Plant 2						
		Leaf position							
		ebL2	ebL3	ebL4	ebL5	ebL6	ebL7	ebL8	ebL9
T	estimated value (m^2)	6.99	4.89	4.77	4.95	4.45	4.67	4.57	4.77
	%	100	107	99	105	99	102	100	100
B	estimated value (m^2)	5.93	3.93	3.63	3.63	3.38	3.42	3.13	3.16
	%	108	101	105	98	96	99	94	96
Total (T+B)	estimated value (m^2)	12.92	8.81	8.40	8.58	7.83	8.09	7.70	7.93
	%	104	104	101	102	98	100	98	99

$$S = 2 \times a \times b \times c \times \text{(a correction factor)} \quad [5]$$

In this equation, a denotes the number of leaflets on one side of the leaf; b, the length of the longest leaflet; and c, the maximum width of the longest leaflet. Although the "correction factor" of 0.5 was believed to be adequate for this equation, it has not been established definitively. Furthermore, this equation merely shows that the leaf area is proportional to the area of the longest leaflet and the number of leaflets.

In addition, the longest leaflet should be selected through precise measurements. As an example, the lengths, widths, and areas of leaflets at positions 20–50 in ebL3 are shown in Fig. 5. In ebL3, there were 72 leaflets on the left (L) of the leaf and 69 on the right (R); the range of lengths of these 31 central leaflets was 0.131–0.153 m for L and 0.133–0.151 m for R. Particularly long leaflets in L were L34, L35 (0.153 m), L30, L31, L33, and L36 (0.152 m); the exceptionally long leaflets in R were R24, R26, R27, R28 (0.151 m), and R25 (0.150 m). The widths of the leaflets varied. In L, the minimum width was 7.3 cm (L30) and the maximum, 8.0 cm (L36); in R, the minimum width was 7.2 cm (R24, R25) and the maximum, 7.6 cm (R27, R28). In the method of Flach and Schuiling (1989), it should be kept in mind that the number of leaflets differs between the R and L, and the widths of these leaflets differed even if their lengths are equal. Thus, selection of the longest leaflet in the field seems to be extremely difficult. The estimated leaf area greatly differs depending on the leaflet selected.

Specific leaf area (SLA), which is the ratio of leaf area to leaf dry mass, is also useful for estimating the leaf area if SLA has a constant value; however, it appears to be an inadequate parameter for estimating the whole leaf area because SLA of sago palm varies depending on the leaf position, plant age, and variety (Omori et al., 2000; Yamamoto et al., 2002). In addition, the estimation of the entire leaf area is quite laborious, i.e., all leaflets of the leaf should be removed from its rachis and should be dried in a drying oven.

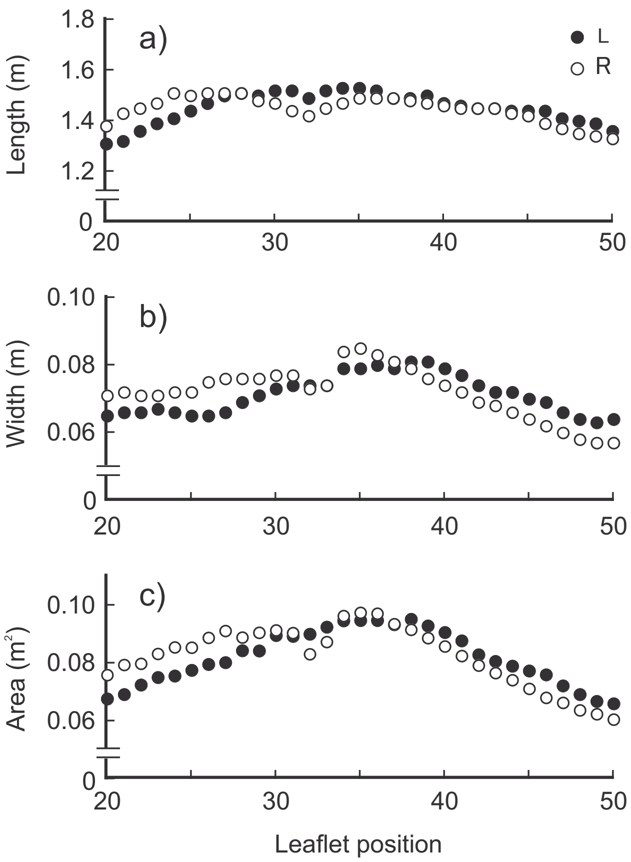

Fig. 5. Length (a), width (b), and area (c) of each leaflet in ebL3 plotted against the leaflet position from 20 to 50. L and R are the same as in Fig. 2.

Fig. 6 shows the procedure necessary to estimate the whole leaf area of sago palm by the method presented here. First, the rachis length (a) is measured. The left and right leaflets at $a/2$ from the base (L_{CL}, L_{CR}) and the left and right leaflets at $a/4$ from the base (L_{BL}, L_{BR}) are selected (Fig. 6a). Next, the length

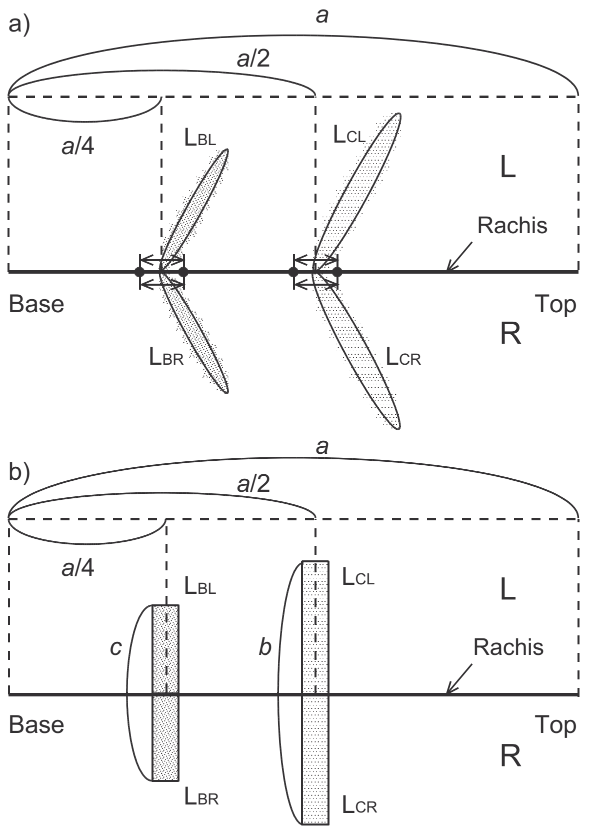

Fig. 6. Procedures and mesurement of sago leaf necessary to estimate the whole leaf area (a). The left and right leaflets (L_{CL} and L_{CR}) at the center of the rachis and the left and right leaflets (L_{BL} and L_{BR}) at a a/4 from the base of rachis are selected. Next, the length and maximum width of these leaflets, and the distance between the adjacent leaflets (indicated by arrows in this figure) are measured (b). These leaflets are converted to rectangles having the same area as that of the leaflet; a represents the rachis length, while b and c denote the sum of the heights of the rectangles converted from the leaflets on both sides at $a/2$ and $a/4$ from the rachis base, respectively.

and maximum width of these leaflets are measured. Then, the leaflet area is calculated using the equation (0.785×leaflet length×maximum leaflet width) following the report of Nakamura et al. (2005). Further, the distance between the attachment points of the adjacent leaflets is measured. The height of the rectangle converted from the leaflet is calculated by using Eq. [1] (Fig. 6b). The leaf area (S_{leaf}) is the sum of S_T and S_B, and the sum of the heights of the rectange converted from L_{CL} and L_{CR} is b and that of the rectangles converted from L_{BL} and L_{BR} is c.

$$S_{leaf} = S_T + S_B = ab\pi/8 + ac/2 \qquad [6]$$

For more stable and accurate estimation, three adjacent leaflets are measured; and the resultant average values are used.

In this study, we developed a method for estimating the leaf area of the sago palm after trunk formation, when the sizes of all leaves were considered to be nearly equal. To determine the LAI in sago palm populations with different ages, we must also investigate the feasibility of this method for the plants before trunk formation, when the leaf sizes are increasing. Furthermore, we should examine the validity of this method for estimating the leaf area of sago with various forms.

Acknowledgments

We are grateful to Mr. Smith and his family in Mukah, Malaysia, for their kind assistance. We also thank the Japan Society for the Promotion of Science for its support in 1999, 2001, and 2003.

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