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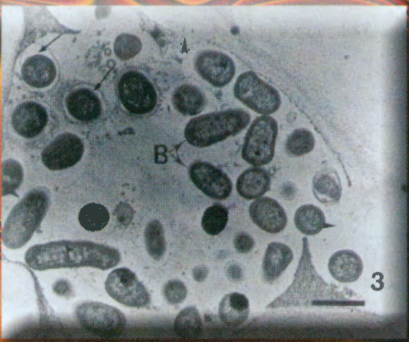

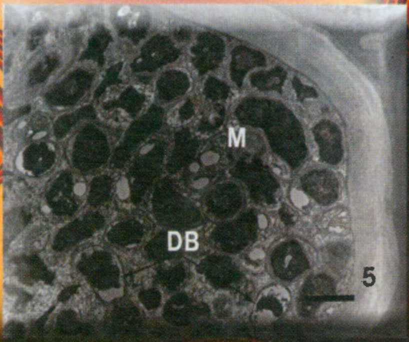

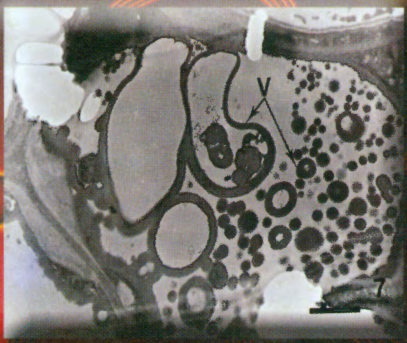

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ARTICLE

Reconstructing The Shape and Area of Simple Leaves

C.B.S. Teh[1], L.P. Simmonds[2] and T.R. Wheeler[3]

[1] *Department of Land Management, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.* [2] *Department of Soil Science, University of Reading, Whiteknights, P.O. Box 233, Reading, RG6 6DW, UK.* [3] *Department of Agriculture, University of Reading, Earley Gate, P.O. Box 236, Reading, RG6 2AT, UK*

INTRODUCTION

Accurate measurement of leaf area is critical for estimating light interception and photosynthesis. Attempts to model leaf area usually involve fitting mathematical functions to the shape of leaves (Daynard, 1971; Dwyer and Stewart, 1986; Keating and Wafula, 1992; Stewart and Dwyer, 1993, 1999). This method has been applied mostly for maize leaves and seldom for other crop leaves. A major disadvantage of using mathematical functions is that it can be difficult to find the appropriate function for a specific leaf shape. Moreover, the accuracy of these mathematical functions is usually dependent on the leaf size and growth stage. In addition, some parameters in these mathematical functions are determined empirically; hence, they may be unstable and specific only to a certain crop variety, crop stage or field condition.

This study introduced a method to "reconstruct" the shape and area of simple leaves without making restrictive assumptions or fitting specific mathematical functions. Reconstruction here meant that based on a few measured points on a leaf, the entire leaf shape and area is reproduced accurately. Our eventual aim was to develop a method to estimate the vertical and horizontal leaf area distributions for use in certain plant radiation models (e.g., Sinoquet and Bonhomme, 1992; Caldwell and Hansen, 1993) that require detailed information on canopy architecture.

MATERIALS AND METHODS

Reconstructing the leaf shape and area

A leaf is assumed to be symmetrical along its midrib so that any measurements on one leaf half applies to the other half as well. If a leaf is obviously not symmetrical, the shape and area of each leaf half are measured separately.

The method to reconstruct the leaf shape and area has three steps, where the first two steps were to reconstruct the leaf shape (curvature), and the third step calculates the leaf area. The *first step* is to choose 3-9 points along the leaf curvature (Fig. 1a). It is important to always choose the two curvature limits (start and end points of curvature) and the point where the curvature is greatest from the midrib. It is also important to choose the points of inflection where the leaf curvature abruptly changes or distorts, if any. The number of points to choose will depend on the uniformity of leaf curvature. Choosing more points will increase reconstruction accuracy, but from our experience, 3-9 points are sufficient. Then, for each chosen point, its vertical distance to the midrib and its horizontal distance to the start of curvature are measured. These measurements correspond to two-dimensional Cartesian coordinates.

The *second step* is to fit a cubic spline curve to the chosen points. The cubic spline fit is a common curve-fitting method because it draws naturally looking smooth curves. This method, described in most numerical methods textbooks (*e.g.*, Mathews, 1987), is essentially a piecewise curve-fitting procedure for each *x*-coordinate interval.

Once the leaf shape is reconstructed by fitting a cubic spline curve, it is possible to determine the partial or total leaf area. Thus, the *third step* is to integrate the fitted curvature within any given limits to determine the area under the curve (Fig. 1b). Numerical methods such as Trapezoidal or Simpson Rule (Mathews, 1987) can be used for integration. When a leaf is assumed to be symmetrical along the midrib, partial leaf area is calculated by multiplying the area obtained by two. When the lower limit is set to zero (start of curvature) and the upper limit set to total leaf length (end of curvature), integrating the reconstructed curvature and multiplying the result by two yields the total area of the leaf.

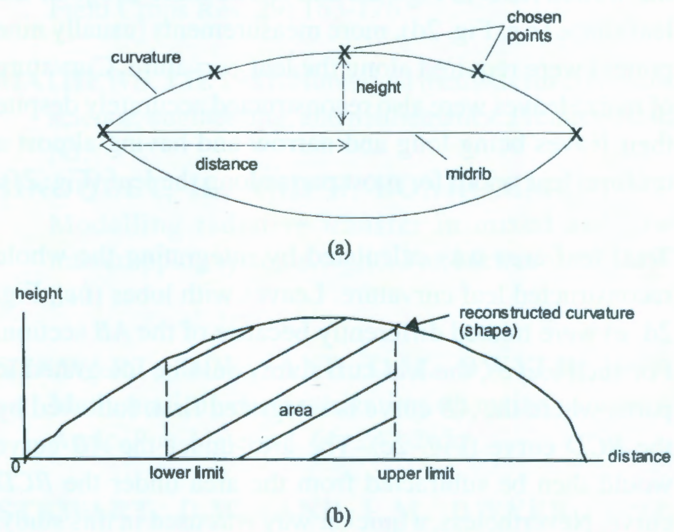

Fig. 1. Reconstruction of the shape and area on one half of a symmetrical leaf

Validation of method

A total of 50 maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) leaves were used to test the accuracy of the method. These leaves were sampled from all heights of the plant, and they were of different sizes (leaf lengths from 50 to 650 mm; leaf widths from 20 to 200 mm) and from different crop stages (from 20 to 50 days after planting). To increase the variety of leaf shapes for testing, a total of ten leaves from various plant and tree sources were also sampled.
Actual leaf shape or curvature was determined by measuring the leaf width from the midrib at every 10 mm along the leaf length. For smaller leaves, leaf widths were measured at smaller intervals of 5 mm. A leaf area machine (Li-Cor Model 3000, LI-COR Inc., Lincoln, NE) was used to measure actual total leaf area. The statistic absolute mean error (AME) was used to compare n pairs of measured (O) and reconstructed (P) parameters:

$$AME = \frac{1}{n}\sum_{i=1}^{n}\left|P_i - O_i\right|.$$

RESULTS AND DISCUSSION

Comparisons between measured and reconstructed parameters

Comparisons between reconstructed and measured leaf curvatures for 6 diverse leaf shapes are shown in Fig. 2. Reconstructed leaf shapes were accurate; the measured points arrayed closely along the reconstructed curves. Figure 2b is an example of a leaf curvature that had an inflection point at location *I*; thus it was important to have this location as one of the chosen points. Reconstruction was also accurate for leaves that had lobes as marked by the section *ABC* in Figs. 2d and e. The more irregular the leaf shape (*e.g.* Fig. 2d), more measurements (usually nine points) were required along the leaf curvature. Curvature of maize leaves were also reconstructed accurately despite their leaves being long and narrow and having almost a uniform leaf width for most parts along the leaf (Fig. 2f).

Total leaf area was calculated by integrating the whole reconstructed leaf curvature. Leaves with lobes (*i.e.*, Fig. 2d, e) were treated differently because of the *AB* section. For such leaves, the leaf curvature could be integrated in parts, where the *AB* curve is integrated first, followed by the *BCD* curve (Fig. 2e). The area under the *AB* curve would then be subtracted from the area under the *BCD* curve. Nevertheless, a quicker way was used in this study. To minimise the error of not including the *AB* section, the point halfway between *BC*, or point *e*, was selected as one of the chosen points (Fig. 2e), and integration was from *eCD*. This method was used for all mature sunflower leaves.

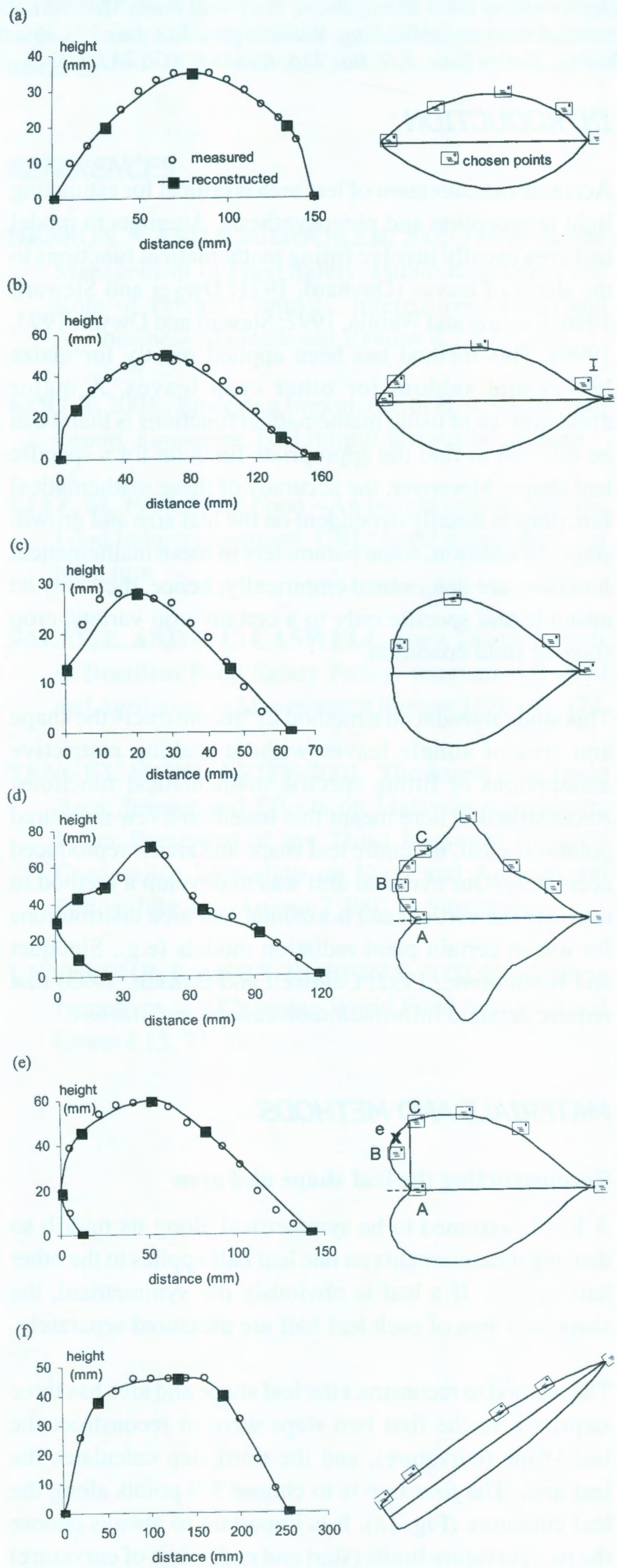

Fig. 2. Comparison between reconstructed and measured leaf curvatures. Sunflower and maize leaves are (e) and (f), respectively. Note: leaves are not drawn to scale.

Total leaf area was estimated accurately for all leaf types. The estimated areas clustered tightly along the 1:1 ratio line (Fig. 3), and the AME calculated between estimated and measured leaf area was 1842 mm^2. This was accurate prediction even for mature sunflower leaves despite using the simplified method described earlier. A mature sunflower plant has an average of 25 leaves and the usual planting density of 6 plants m^{-2}. A mean error of 1842 mm^2 for a single leaf meant that the mean error in estimating LAI (leaf area index) for sunflower would be $0.3m^2\ m^{-2}$ (typical LAI at this planting density is 6 $m^2\ m^{-2}$). As for maize, the mature plant has an average of 12 leaves and the usual planting density of 6 plants m^{-2}. This meant that the mean error in estimating LAI for maize would be $0.12m^2\ m^{-2}$ (typical LAI at this planting density is $3m^2\ m^{-2}$). Thus, for both maize and sunflower, the average error in estimating LAI would be about 5%.

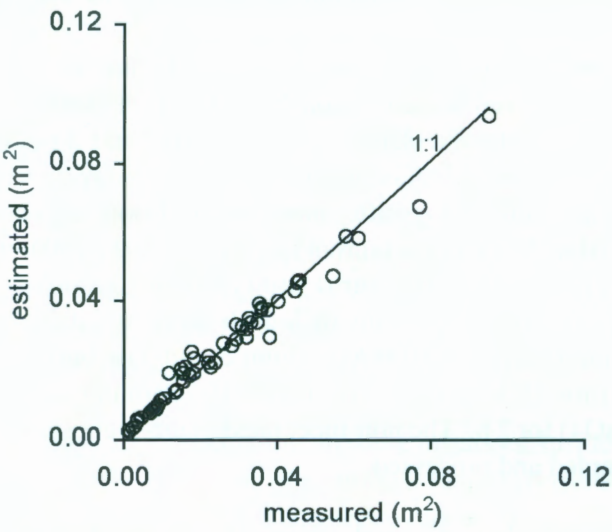

Fig. 3. Comparisons between the estimated and measured area for single leaves

Application in plant radiation models

The proposed method can be used to describe a plant's horizontal and vertical leaf area distributions, which are required in some detailed plant radiation models (e.g., Sinoquet and Bonhomme, 1992; Caldwell and Hansen, 1993). Dividing the canopy space into a set of contiguous rectangular cells, forming a two-dimensional grid network, does this. The aerial space from the soil surface to the canopy top is divided into N_y horizontal layers of thickness E_y, and N_x vertical sections of thickness E_x. If a crop has large or long leaves (like sunflower or maize), a leaf may not lie entirely within a cell; several cells may instead encompass a single leaf. If a single cell encompasses a leaf, then leaf area within that cell is simply the area of the whole leaf. But when a cell encompasses only part of the leaf, the proposed method can be used to simulate the partial leaf area. The vertical borders of a cell (x_i to x_{i+1}; i=0, 1, ..., N_x) can be regarded as the lower and upper integration limits of a curve (*i.e.*, Fig. 1b). A leaf's partial curvature encompassed by these vertical cell boundaries is reconstructed first, then integrating this curve yields the leaf area within the cell. Repeating these steps for each cell in the network eventually produces the horizontal and vertical leaf area distributions required by some plant radiation models.

CONCLUSIONS

The method proposed can be used for reconstructing leaf shapes and areas accurately without using restrictive assumptions or fitting any mathematical functions to leaf shapes. Unlike others, the method in this study was applicable to a greater variety of leaf shapes and sizes. The proposed method is useful for describing the horizontal and vertical leaf area distributions for use in plant radiation models.

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