Stereophotogrammetry of Plant Leaf Angles

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Abstract
Plant canopies have a geometrical structure consisting of several to many layers of leaves placed in a complex spatial pattern and inclined at angles which depend upon the position of the leaf in the canopy and upon solar radiation conditions. Previously, leaf positions and angles have been measured by inclinometer and compass or a three-dimensional digitizer. This paper describes a new method of leaf angle measurement which uses stereo photography and computer analysis of the resulting images.

Introduction
Plant canopies have a geometrical structure consisting of several to many layers of leaves placed in a complex spatial pattern and inclined at angles which depend upon the position of the leaf in the canopy and solar radiation conditions (Horn, 1971). Plant leaves are generally inclined at steep angles with respect to the horizontal when subject to high values of incident light flux (Kuroiwa, 1970; Kuroiwa, 1978; McMillen and McClendon, 1979). Though leaves of some plants are fixed in position and not able to undergo rapid movement during the course of the day, a very large number of plant species are able to rapidly readjust leaf orientation in response to changing magnitude of flux and the direction of the solar beam (heliotropism). The ability to reorient leaves within time periods of several minutes or less is especially common among the plants which comprise common agricultural crops and tropical and sub-tropical forest canopies.

Under conditions of high solar flux, as in the upper portion of a forest or agricultural plant stand canopy near midday, horizontal leaf orientation results in increased thermal damage, inhibition of photosynthesis, and decreased water use efficiency. Thus, a high angle of leaf inclination would be favored if these effects are minimized (Forseth and Teramura, 1986). Similarly, a more horizontal leaf angle would be favored under low light conditions, as in the depths of the plant canopy. Thus, on this basis alone, we predict a vertical gradient of leaf angle in the canopy with more inclined leaves near the top and less inclined leaves near the ground. And, although a more vertical inclination reduces photosynthesis of the top leaf layers in the canopy if photosynthesis is below saturation, increased photosynthesis of the lower layers of leaves more than compensates for the reduced photosynthesis of the upper layers (Herbert, 1989; McMillen and McClendon, 1979). Thus, in addition to the protective benefits of increased leaf inclination, theory predicts that a gradient of decreasing leaf angle from the upper to lower canopy maximizes net canopy photosynthesis.

Given the importance of the measurement of leaf inclination angle for analysis of light interception and canopy photosynthesis, it is surprising that no detailed and comprehensive studies of leaf angle distributions as a function of position in the plant canopy are found. Generally, models of the plant canopy photosynthesis have relied upon broad statistical measures of leaf inclination and position. In part, this has been the result of a lack of easily obtainable and sufficiently detailed knowledge of leaf angle and position. Until recently, sufficient computational power was not readily available to handle detailed models of canopy photosynthesis and productivity which are based upon very large numbers of leaf elements. Because modern computers can handle such complex computational tasks as exact calculation of light interception by large canopies, it is particularly important to develop methods to obtain accurate data on inclination and photosynthetic rate of large numbers of individual leaves in a plant canopy.

Most measurements of inclination angle have been made by manual use of a simple mechanical inclinometer, although Lang (1973) has demonstrated the use of a three-dimensional digitizing apparatus consisting of a stylus attached to a jointed arm. Using this apparatus, the coordinates of the point defined by the tip of the stylus are encoded as the output to a computer and recorded automatically. In spite of the straightforwardness of these methods, both require physical proximity of the apparatus to the object whose coordinates are being recorded, and consume a large amount of experimental time in the field, reducing the usefulness of these techniques for study of rapidly moving leaves or complex systems requiring large numbers of measurements. Remote sensing methods using radar or laser scanning (Vanderbilt, 1985) have resulted in three-dimensional images of plant canopies, but none of these methods have demonstrated sufficient resolution and speed to determine angle and position of large numbers of individual leaves. Use of stereophotogrammetry, as described in this paper, permits accurate measurement of leaf angle and position from a distance of a much as several metres and has sufficient resolution to permit analysis of such complex phenomena as the effect of leaf shape upon interception of light and photosynthesis. Furthermore, because the photographic technique permits recording of a large amount of information rapidly, it is ideally suited for description of the rapid movements of leaves, including heliotropic and wind-induced movement.

Theory
Herbert (1983) has described a system which uses three angles characteristic of leaf orientation: β, the inclination of the leaf or leaflet above the horizontal; τ, the rotation of the leaf surface about the midrib; and α, the compass direction into which the leaf tip points. These angles can be obtained from

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the three-dimensional coordinates of four characteristic points which represent the left and right extent of the leaf or leaflet width, the base of the leaf (pulvinus), and the tip of the leaf (Figure 1). If the two-dimensional coordinates of each of these points are obtained from a stereo pair of photographs, the three-dimensional coordinates of the four characteristic points can be calculated using photogrammetric space intersection (Atkinson and Newton, 1968). A coordinate system is used which has the *x*-axis parallel to the baseline between the two cameras, the *y*-axis directed towards the subject, and the *z*-axis vertical. The three-dimensional coordinates of a point in this system are calculated from the two-dimensional coordinates x_L, z_L of the left stereo pair image and x_R of the right stereo pair images by (Atkinson and Newton, 1968)

$$y = \frac{fb}{(x_L - x_R)} \tag{1}$$

where f is the focal length of the camera lenses and b is the baseline distance between the optical axes of the two lenses. The coordinates x and z are given by

$$x = yx_L/f \tag{2}$$

$$z = yz_L/f \tag{3}$$

The angles of orientation, β and α, can be calculated from the three-dimensional coordinates of the four characteristic points by

$$\beta = \arccos \sqrt{\frac{x_{tp}^2 + y_{tp}^2}{x_{tp}^2 + y_{tp}^2 + z_{tp}^2}} \tag{4}$$

$$\alpha = \arctan \frac{y_{tp}}{x_{tp}} \tag{5}$$

where $x_{tp} = x_{tip} - x_{pulvinus}$, x_{tip} is the x coordinate of the tip of the leaf, and $x_{pulvinus}$ is the x coordinate of the pulvinus. The axial rotation angle, τ, is computed from the elevation, ϕ, of a line which connects the left and right extents of the leaf or leaflet: i.e.,

$$\phi = \arccos \sqrt{\frac{x_{lr}^2 + y_{lr}^2}{x_{lr}^2 + y_{lr}^2 + z_{lr}^2}} \tag{6}$$

where $x_{lr} = x_{left} - x_{right}$, x_{left} is the x coordinate of the left extent, and x_{right} is the x coordinate of the right extent. The angle τ is calculated as (Herbert, 1983)

$$\tau = \arcsin \left(\frac{\sin\phi}{\cos\beta}\right). \tag{7}$$

In principal, the angles β, α, and τ can be obtained from only three of the four characteristic points. For example, τ can be calculated from the coordinates of the left extent, tip, and pulvinus, without use of the coordinates of the right extent of the leaf. This calculation is based upon assumptions that the leaf is flat and symmetric about the midrib, thus permitting calculation of the coordinates of the right extent of the leaf. But, real leaves are often asymmetric about the midrib or curled. In that case, the use of the coordinates of both the left and right extent of the leaf is likely to give a better estimate of the axial rotation angle, τ.

Using propagation of errors, the error $\Delta\beta$ in the measurement of β, as a function of the error in the measurement of film coordinates, is given by

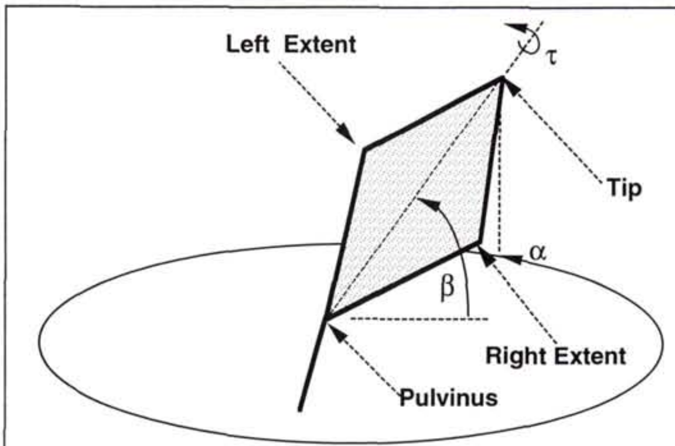

Figure 1. Diagrammatic representation of a plant leaf or leaflet showing the four characteristic points which are digitized and the three angles of orientation of the leaf surface.

$$\Delta\beta = \sqrt{\left(\frac{\partial\beta}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial\beta}{\partial z}\right)^2 (\Delta z)^2 + \left(\frac{\partial\beta}{\partial p}\right)^2 (\Delta p)^2} \tag{8}$$

where Δx and Δz are equal to the error in the measurement of x and z film coordinates and Δp is the error in parallax $p = fb/d$. Generally, we would expect that $\Delta x = \Delta z$. Because the measurement of the coordinate of depth, y, is the essential problem of stereo phototography, errors were calculated for a leaf pointing directly away from the camera. From Equation 8, the error in leaf inclination angle β is given by

$$\Delta\beta = \frac{\sqrt{2}\, d}{f\, l} \sqrt{(\Delta z)^2 \cos^2 \beta + \left(\frac{d}{b}\right)^2 (\Delta p)^2 \sin^2 \beta} \tag{9}$$

where β is the inclination angle above horizontal of a leaf of length l located with its pulvinus a distance d from the baseline connecting the focal planes of the two cameras and with its tip oriented directly away from the baseline. Equation 9 represents the error in leaf inclination as a function of Δz and Δp, assuming no error in the measurement of leaf length, baseline, or focal length, and thus is a good measure of the minimum error in the measurement of β by stereo photogrammetry.

Materials and Methods

A practical demonstration of the three-dimensional digitizing technique and the calculation of leaflet orientation angles was performed using two uncalibrated Nikon F 35-mm cameras with 50-mm, *f*/1.4 Nikkor-S lenses mounted with a baseline distance between optical axes of 338 mm. This system is not very accurate but was successful in achieving the desired results - measurement of angles characteristic of leaf orientation with an accuracy comparable to that of hand measurements with inclinometer and compass. The leaflets photographed were located approximately at a distance of 1.2 m from a line passing through the focal planes of the two cameras. The two cameras were held in place by a machined cradle mounted on an aluminum bar. The cradle was designed to align the camera bodies in parallel orientation by mounting the bodies firmly against a machined aluminum bar. Baseline distance was determined to within ±0.5 mm by measuring the distance between the centers of the two tripod screws with a precision ruler. The use of the tripod screw as a calibration point for baseline distance was checked by mounting the cameras individually on a optical bench and using a micrometer shift stage to measure the distance between a projected image point on a ground glass taped to the film plane of the camera and a machined indentation in the center of the bolt inserted into the camera's tripod screw mount. The focal length of the camera lenses was not calibrated, and its nominal value of 50 mm was used for all calculations. The camera platform was leveled initially with a bubble level, then checked with an inclinometer to ensure that the platform was within ±1° of horizontal. Azimuth was determined with an error less than ±0.5° by a compass mounted to the camera cradle.

A computer program, written in Forth for the Macintosh computer, was developed to encode two-dimensional coordinates of points on a Summagraphics digitizing table. This program has been adapted to perform calculations of three-dimensional coordinates from stereopair images and to obtain angles characterizing leaf orientation from the coordinates of distinctive points on the leaf. This system, which performs calculations as described in the previous section, is very similar to commercially available systems except that those systems do not include provision for the specialized calculations of leaf orientation. With the present system, photographic prints of the full frame right and left photographs are placed on the digitizing tablet and the coordinates of the corners of the frames are digitized as calibration points. This calibration procedure is less accurate than use of more accurately calibrated fiducial marks on the image but does not require specially modified camera bodies. The computer program automatically uses these coordinates to align the digitized points in vertical position and orientation. The baseline, azimuth into which the cameras point, focal length of the lenses, convergence of the camera axes, and inclination of the cameras are entered into the computer program from the keyboard. Then, the coordinates of the four characteristic points on each of the left and right images are digitized, and the program automatically calculates the three-dimensional coordinates of the pulvinus from the equations of Atkinson and Newton (1968) and the three angles characteristic of leaf orientation (β, α, and τ) from Equations 4, 5, and 7, respectively. Statistics of these angles, including the mean, were calculated using circular statistics (Batschelet, 1981).

Measurements of the three angles characterizing leaflet orientation and the coordinates of the pulvinus were made on a single 1-m tall specimen of *Erythrina herbacea* using stereophotogrammetry and with an inclinometer and compass. *Erythrina herbacea* is a leguminous small tree or shrub with a range extending from North Carolina to Florida and has been shown to exhibit daily, solar-tracking, leaf movement (Herbert, 1983). Each leaf of *Erythrina herbacea* consists of three flat leaflets, each of which shows changes in β and τ as the leaflets reorient with respect to the sun during the course of the day. Leaflets ranged in width and length from 4 to 8 cm.

Results

A short program for calculation of the accuracy of determination of leaf orientation angles, based upon Equations 8 and 9, was written to run under the *Mathematica* system on a Macintosh computer. This program calculates the error in the angular measurement of inclination as a function of the error in the measurement of film coordinates and parallax by propagation of errors. Using propagation of errors, confidence levels of the error in the measurement of inclination are the same as confidence limits on the values of film coordinates and parallax. In the present study, we assume that limits in film resolution will limit the accuracy of the measurement of the film coordinates to ±0.02 mm and differences in parallax to ±0.01 mm (Atkinson and Newton, 1968).

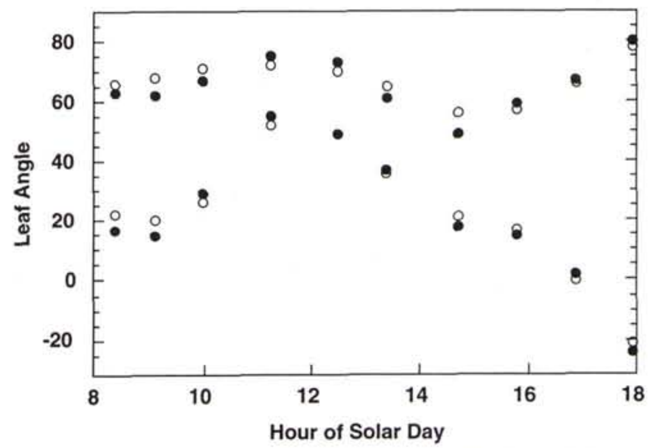

Figure 2. Daily movement of a single leaflet of *Erythrina herbacea* as a function of hour of solar day. The two top curves represent measurements of axial rotation angle, τ and the two lower curves represent measurements of inclination, β. Solid circles represent measurements by inclinometer and compass as described by Herbert (1983); open circles represent values determined by stereophotogrammetry.

Assuming a single *Erythrina* leaflet of length 4 cm pointed directly away from the cameras, an inclination angle of 45°, and no axial rotation, the calculated minimum error in the measurement of inclination angle, β, ±1.98°. For a leaflet of length 8 cm, the error in β is ±0.98°. Calculations of error assume that the optical parameters are baseline = 338 mm, focal length = 50 mm, and subject-to-focal-plane distance = 1.2 m. For these calculations, the overlap of the left and right stereo photographs is 0.60 of the width of the 36-mm frame.

Measurements of β and τ by stereophotogrammetry show good agreement with those determined by measurement with inclinometer and compass (Figure 2). The mean and maximum differences between angular values obtained by photogrammetry and by inclinometer and compass were 2.7° and 5.0°, respectively, for β and 3.5° and 7.0°, respectively, for τ. These differences are significantly larger than the error in measurement predicted by theory. Because measurements of angles by inclinometer are accurate to less than 2°, the remaining error is likely to be attributable to a lack of repeatability in digitization or to a failure of alignment and calibration of the stereo photographic apparatus. To test the repeatability of digitization, coordinates for each of seven leaflets were digitized ten times in the photgrammetric method. Using circular statistics (Batschelet, 1981), 95 percent confidence limits on the mean angle for each leaf ranged from 0.96° to 1.57° for β and 1.21° to 1.92° for τ.

Discussion

Because the repeatability of digitization is good, much of the error in the measurement of leaf inclination angles is attributable to problems in alignment and calibration of the apparatus. Two types of instrumental problems are apparent: Errors could be reduced significantly by the use of properly calibrated photogrammetric camera systems, and coordinates should be digitized directly from the photographic negative.

High accuracy is especially important when leaves or leaflets are small or when the subject to camera distance is large. Calculation of errors in angular determination, when using the *Mathematica* system and the parameters used above, shows that, at a subject-to-camera distance of 1 m, the minimum error in β is $\pm 0.72°$ for a leaf of length 8 cm. But at 4 m, the minimum error is $\pm 9.72°$, and at 10 m, the minimum error is $\pm 60.06°$. Clearly, the maximum theoretical subject-to-camera distance is several metres or less with a stereophotogrammetric system similar to that described in this paper. As the leaf becomes smaller, the error in angular measurement also increases. The accuracy in the determination of the inclination angle is inversely proportional to leaf length. With other parameters remaining the same as described above, the minimum error in determination of β for a leaf of length 1 cm and a subject- to-camera distance of 1 m is $\pm 5.78°$, eight times the error for the same measurement on a leaf of length 8 cm. Reduced error in measurement can be obtained by increasing either the baseline distance between cameras or the focal length of their lenses and by using convergent photography to ensure sufficient overlap between stereopair photographs.

For working distances of approximately one metre or less and a subject consisting of moderate sized leaves or leaflets, the uncalibrated stereophotogrammetric system described in this paper provides adequate results. Leaf angle measurements made with this system have an accuracy comparable to measurements obtained using inclinometer and compass. Additionally, the stereophotogrammetric system is the first system used for leaf angle measurements on individual leaves or leaflets which permits unattended operation and can be operated without physical contact between the leaf and measuring apparatus.

Because stereophotogrammetry offers the advantage of remote, unattended operation, leaf angles can be measured in a forest canopy by suspending a stereo-camera system from a crane or cable system, and daily leaf movement can be observed by taking a series of photographs using clock activated, motorized cameras. For the collection of large amounts of data or for the measurement of rapid, wind induced leaf movement, stereophotogrammetry may be the only practical method available. For truly valid results, one should pay careful attention to calibrating the camera system and making measurements on the original negatives.

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