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Modeling cotton (*Gossypium* spp.) leaves and canopy using computer aided geometric design (CAGD)☆

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A B S T R A C T

The research presented here develops a geometrically accurate model of cotton crop canopies that can be used to explore changes in canopy microenvironment and physiological function with leaf structure. We develop an accurate representation of the leaves, including changes in three-dimensional folding and orientation with age and cultivar. Photogrammetrical analysis of leaf surfaces is used to generate measured points at known positions. Interpolation of points located on the surface of the cotton leaves is then performed with a tensor product interpolants model that generates a generic leaf shape. Dynamic changes in leaf shape and canopy position over the growing season are based on measurements of cotton canopies in the field, and are used to modulate the generic leaf shape. The simulated leaves populate a canopy element based on statistical distributions from measured crop canopies. The simulation is found to give a good representation of cotton canopy leaves, adequately capturing the three-dimensional structure of the leaves and changes in leaf shape and size over the growing season. The simulated canopy accurately estimates leaf area index, except for the earliest measurement period prior to canopy closure. The application of the CAGD algorithm for representing cotton leaf and canopy geometry, and the technique for changing the leaves' spatial position, size and shape through time of four representative cotton canopies is found to be a useful tool for developing a realistic crop canopy. We use leaf area index (LAI) as a measure of the accuracy of model-predicted LAI values in comparison to LAI in crop canopies in situ, obtaining r^2 values ranging from 0.82 to 0.92. The level of detail captured in the model could contribute greatly to future studies of physiological function and biophysical dynamics within a crop canopy.

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1. Introduction

Representations of crop canopies in models allow study of biophysical and physiological processes within the canopy. Improved accuracy of canopy geometry in these models enhances the detail of interaction between factors that impact crop performance. The photon flux distribution across leaf surfaces and throughout a crop canopy is dependent on leaf and canopy structure (Sassenrath-Cole, 1995), and impacts total canopy productivity (Sassenrath-Cole et al., 1996). Accurate simulations of leaf and canopy structure allow us to predict physiological function based on a variety of biotic and environmental conditions. It can also be related to remote imagery of the crop (Espana et al., 1999). Insects have also been shown to distribute within a crop canopy based on microenvironmental conditions (Sudbrink et al., 2003; Willers et al., 2005). Accurate knowledge of crop canopy structure, and the changes in canopy microenvironment within that structure, could assist in the development of better targeted and more efficient insect control efforts.

Many modeling studies have explored physiological functions using a representation of the crop canopy rather than a detailed geometric model. Vegetation canopy models linking terrestrial biosphere to atmosphere are categorized as either multilayer (models that integrate the fluxes from each layer to give the total flux) or big-leaf models (those that map properties of the whole canopy onto a single leaf to calculate fluxes) (Dai et al., 2004). Ko (2004) developed a cotton crop model able to use remote sensing data as input for estimation of leaf area index (LAI), boll number, and other agriculturally important parameters using a simplified spatially aggregated representation of the vegetation canopy. Other models introduce a more detailed description of canopy architecture. For example, Zhao et al. (2001) used dual-scale automation to simulate cotton plants' growth by generating a virtual plant with flat leaves. Honghao and Fanlun (2005) proposed an object oriented automation model for virtual plant growth based on the dual-scale automation principle. This model can simulate not only the process

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of plant growth but also the appearance of the plant in different layers. Leaves, however, are modeled using simple geometrical shapes represented by flat leaves. In Ma et al. (2009), single-lobe Nephthytis plants were modeled. The planes representing the geometry of the leaves consisted of 36 triangular elements per leaf. These planes were then deformed by an optimization process that produced an effect of realism in the simulated leaves, though it was not supported by measurements. Drouet and Kiniry (2008) investigated the effect of maize row spacing on Total Photosynthetically Active Radiation and extinction coefficients using the MODICA model and the light model RIRI (Sinoquet and Bonhomme, 1992) to investigate development stage and time integration effects. Each plant was geometrically represented by a set of about 1000 triangles.

Several other modeling efforts have been carried out in this context (e.g., Chelle and Andrieu, 2007; Koetz et al., 2005; Birch et al., 2003; Weiss et al., 2001). The representation of the leaf geometry in these research projects was also simplified by assuming flat surfaces or other simple geometrical shapes. The reason for the limited representation of leaf geometry is the degree of difficulty that is entailed in developing an exact mathematical representation of the leaf surface. While these studies have contributed to our understanding of crop performance mostly in terms of sunlight distribution or interception within the crop canopy, the details of canopy function and the dynamic environment within the crop canopy would be better understood by using a more detailed geometric representation of the vegetation canopy. For example, to model how transport phenomena occur within the foliage, a good representation of leaves, stems, etc., is necessary for generating a computational grid. In current finite-elements or finite-differences fluid dynamic models, the representation of the geometry of the surfaces or bodies that are in contact with the fluid is one of the most important steps in the process of modeling the phenomena. Tannehill et al. (1997) consider that a well-constructed computational grid greatly improves the quality of the solution of the conservation equations usually solved in transport processes models. Moreover, these researchers state that poorly constructed grids are major contributors to poor results.

Recent advances in computational methodologies allow us to simulate accurate depictions of the crop canopy, which will allow us to more accurately explore biophysical changes within the canopy. Undertaking the construction of a geometrically accurate crop model presents several challenges, however, including: (1) representing the actual leaf shapes, (2) positioning those leaves within a realistic canopy, and (3) adding the temporal dynamics to this representation (leaves and canopy change over time). To test the accuracy of the simulated canopy, the model should be used in an actual engineering application that would demonstrate its use and applicability to represent natural phenomena by comparing the model output to measured data.

Computer aided geometrical design (CAGD) is a methodology that uses mathematical techniques to analyze and manage geometric data in a computer. The applications of CAGD in engineering are very diverse, and have been used in large dataset representation; visualization; design of pipe systems; modeling surfaces in the construction of cars, ships and airplanes; planning and controlling in surgery; and computer graphics (Hoschek et al., 1993). CAGD has also been applied to plants to improve the descriptive detail for modeling studies (Loch et al., 2003).

Cotton leaf shape is complex, including lobes of different lengths and various curvatures and folding. Therefore a technique that could handle higher degree curves in two directions is necessary to accurately model this shape. Interpolating leaf surfaces from a discrete set of measured coordinates over the surface of a leaf can be done using several surface-generating techniques of CAGD. In many situations such as surface reengineering and facial movement animation, a designer specifies a set of data points that describes a shape, and seeks a surface that contains the data points (Fisher et al., 2004). The basic approach to the design of curves and surfaces consists of using control points which define control polygons or control polyhedrons, together with a smoothing scheme that draws a smooth curve out of a control polygon, or a smooth surface out of a control polyhedron (Dyn et al., 1990). Tensor product interpolants (Farin and Hansford, 2000; Farin, 1999) allows such free-form design and interpolation (i.e., building a surface backwards, from measured points over the surface).

Here, we present a computer aided geometric model of cotton leaves and canopies. The tensor-product-interpolants algorithm was used to mathematically represent several types of individual cotton leaves by creating surfaces from measured point locations on cotton leaves. These individual leaves are then positioned within a three-dimensional virtual cotton canopy populated according to statistical distributions of leaf position and inclination (Alarcon, 2000). Here we focus on the application of the CAGD algorithm and the technique for changing the leaves' size and shape through time. To better explore intra-canopy parameters, the model simulates a crop canopy element of 1 m × 1 m rather than an individual plant. A crop canopy can then be generated by replicating canopy elements, each of which will be unique because of the dynamic aspects of the model. Four representative cotton canopies were generated corresponding to different cotton cultivars. The geometrical models of the cotton canopies were then used to estimate LAI values and those estimations were compared to measured LAI values.

2. Materials and methods

2.1. Plant growth

Four cotton cultivars varying in leaf shape and canopy structure were planted on the North Farm at Mississippi State University, Mississippi State, MS or the USDA Agricultural Research Station in Stoneville, MS during the growing seasons of 1997, 1998 and 1999. These included two commercially available cotton cultivars, *Gossypium hirsutum*, cv. Deltapine-50 (DP-50) and *Gossypium barbadense*, Pima S-6 (PS-6), and two experimental cultivars: *G. hirsutum* sub-okra (Sub-Okra), and *G. barbadense* lanceolate (Plan). The lanceolate and sub-okra leaf shapes have more deeply divided leaf lobes, lower individual leaf area and lower canopy LAI than the conventional leaf shapes (Percy, 2001). Seeds were planted in the field in 1 m rows in rectangular plots of 14 rows by 210 m row length. Three replications of each plot were planted for each cultivar. Standard agricultural practices for insect, weed, irrigation and fertilization were followed to maintain optimal crop growth.

2.2. Leaf and canopy structure measurements

Leaf and canopy structural characteristics were measured using close-range photogrammetrical techniques (Baker, 1960; Ghosh, 1988). The canopy or row-crop element was defined as a regular parallelepiped of 1 m × 1 m × canopy height (Fig. 1). Row crop orientation was essentially North-South, with the transverse to the row essentially East-West (designated the East-West Transverse). It was anticipated that the distribution of leaves within the canopy element would be heterogeneous along the row orientation (East-West transverse), but reasonably homogeneous along the North-South transverse assuming even planting density.

2.2.1. Photogrammetric measurements of canopy structure

A row-crop element, or canopy element, was photographed along a 1 m section parallel to the row direction. The 1-m canopy element was subdivided into approximately 30-cm height blocks, and leaf position within each block determined. Each leaf position

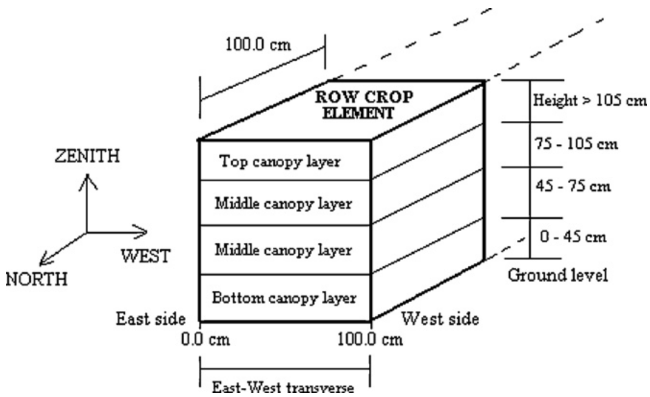

Fig. 1. Diagrametric representation of a row crop canopy element. The cotton rows were oriented from South to North. The East West transverse is defined as a line perpendicular to the cotton row orientation.

was determined from the photographs along the East-West Transverse using photogrammetrical algorithms (Alarcon, 2000; Ghosh, 1988; Baker, 1960). To locate each leaf, two points were defined over the surface of the leaf: the point of intersection of the surface of the leaf with its leafstalk called "leaf origin" or simply "leaf position" (Fig. 2), and the tip of the central lobe (i.e., the outermost point of the leaf, with respect to its origin) called "central-lobe-tip".

Instead of using stereo pairs, an inversion geometrical process as described in Ghosh (1988), and Baker (1960) was used. Using at least three points of known positions, defined as the "benchmark points", completely located within the picture, it is possible to know the location of the camera with respect to the center of the picture. "Benchmark points" are defined as points for which the spatial locations (in terms of three-dimensional coordinates) are completely known. Once the position of the camera is known, geometrical interpolation of other points in the picture is possible (Turek et al., 1989).

The desired benchmark points were fabricated using five graduated sticks, vertically planted within the area of the canopy to be photographed (Fig. 3). The horizontal relative position of each stick, with respect to each other, was measured using a standard 1-m ruler. Each graduated rod was leveled with respect to the central rod. This provided at least five benchmark points along the rod's height. Once the sticks were set up, vertical photographs of the crop canopy were taken from above using a 35-mm camera (Nikon CoolPix 990, Nikon, Inc., NY) mounted on a tripod. After the entire canopy test area was photographed, the canopy of the area was cut until reaching a horizontal plane 30 cm below the previous level. Leaves were collected from each layer for determination of leaf structure as described below. The process was repeated along the canopy height until the soil surface was reached. After photogrammetrical analysis, the pictures corresponding to each horizontal plane along the canopy height provided a set of interpolated points corresponding to the position of the leaf origin and central-lobe tip orientation and inclination for each of the leaves entirely contained within the picture. These values were used to estimate statistical distributions of leaf position (position of leaf origin), and central-lobe tip position with respect to the leaf origin that defined orientation and leaf inclination. For each of the cultivars used in this study, one canopy element was harvested at each time point in canopy development.

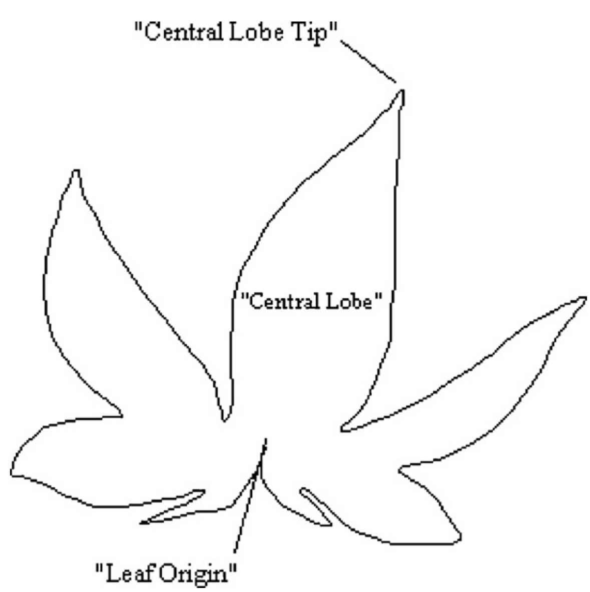

Fig. 2. Particular points defined over the cotton leaf surface. The leaf position was estimated as the position of the leaf origin. The angle of inclination of the leaf and its orientation is defined as the position of the central lobe tip.

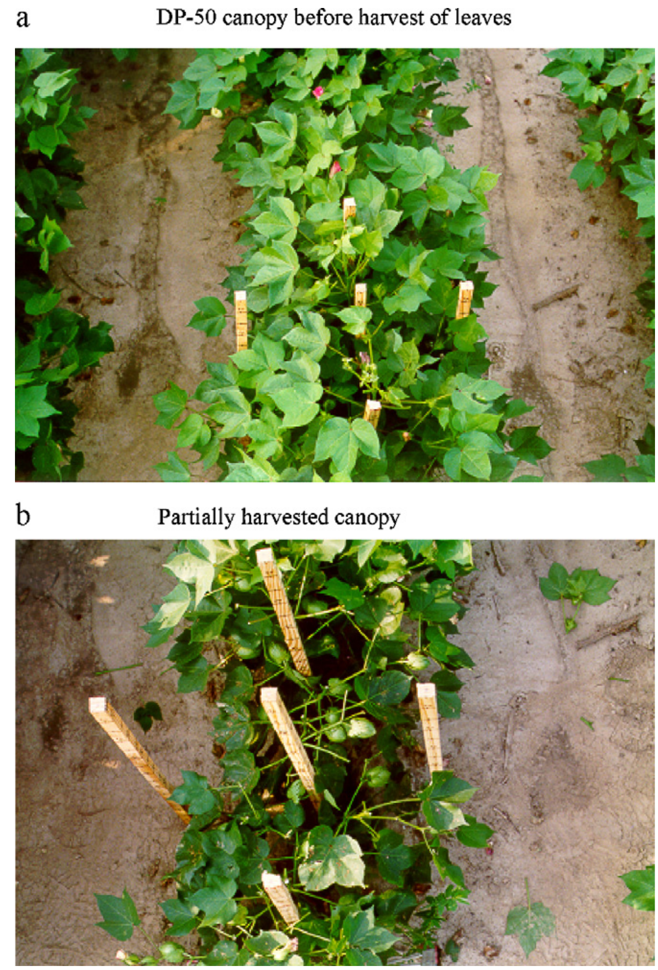

Fig. 3. Benchmark points for photogrammetrical analysis. Benchmark points were fabricated using five graduated sticks vertically planted within the cotton crop rows. The pictures corresponding to each horizontal plane along the canopy height provided a set of interpolated points corresponding to the position, orientation and inclination of the each of the leaves entirely contained within the picture.

2.2.2. Measurements of leaf structure

After being photographed in situ, the leaves were collected and measured in the laboratory for shape and area. Leaf area was measured with a leaf area meter (Delta T Devices, Cambridge, England). In addition to the photographs of the cotton canopy in situ, leaves

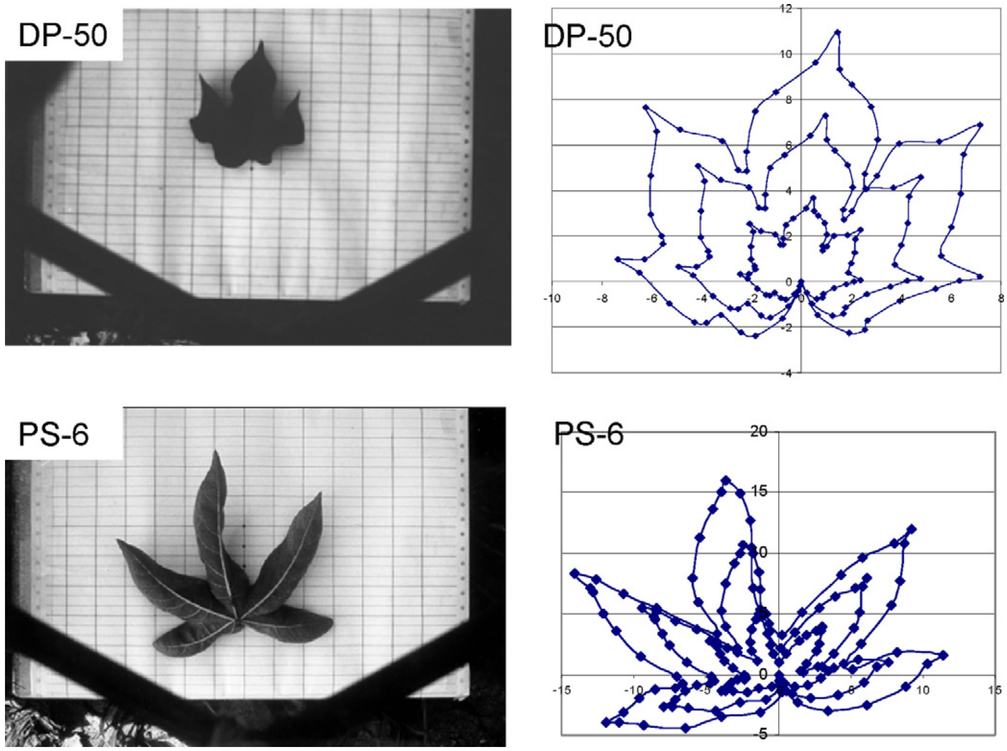

Fig. 4. Individual leaves were photographed over a gridded plate to obtain detailed information on individual leaf geometry. Close-range photogrammetry techniques were used for estimating (X, Y, Z) coordinates of several points over the surface of the leaves (benchmark points). Those coordinates were used for interpolating individual leaf surfaces (through CAGD) for each of the cotton cultivars included in this study.

were photographed over a gridded plate to obtain detailed information of individual leaf structure. Selected photographs were scanned (Fig. 4) and the resulting image files were analyzed using image analysis software (ArcView v. 3.0, ESRI, Redlands, CA). Positions of several selected points in each photograph were obtained in the form of (X, Y) pairs in the plane of the photograph that were used for further calculations.

Non-destructive leaf area indices were measured in each of the canopies using a LiCor LAI 2000 plant canopy analyzer (LiCor, Inc., Lincoln, NE). Multiple readings were taken at several consecutive heights within the canopy (15 cm interval). The reliability of this instrument has been reported when the calibration process (gap test) and sky conditions (no direct sun beam to the sensor) are satisfied (Welles and Norman, 1991). Care was taken to record non-destructive leaf area index measurements only under reliable conditions.

2.3. Model development

In this section, a detailed description of the application of the tensor product interpolants technique for generating a geometrical model of the different cotton canopies is presented. The measured positions of points over the surface of the leaves and individual leaf locations within a simulated canopy were obtained from the photogrammetrical analysis described above. These measured points were then used in the tensor product interpolants to generate the geometrical model.

2.3.1. Computer aided geometrical design of cotton leaf surfaces

Given a convex grid defined by coordinates (I, J), if a discrete set of $m \times n$ control points, P_{ij}, $i = 0, 1, 2, \ldots, m$; $j = 0, 1, 2, \ldots, n$, corresponding to a surface S, are known (Fig. 5), it is possible to mathematically generate points belonging to the surface S, with any level of resolution, using the tensor product of two Bezier curves. One of the curves draws the longitudinal shape and the other draws a curve transverse to the initial curve. In Fig. 5, the longitudinal curve, in direction I, corresponding to $J = j_0$ (J-direction) can be described by:

$$b^m(u) = \sum_{i=0}^{m} B_i^m(u),$$

given $u \in [0,1]$ a parameter that draws the curve and:

$$B_i^m(u) = \frac{m!}{i!(m-i)!}(1-u)^m u^i, \quad \text{a Bernstein polynomial.}$$

If the transverse curves (j-direction) are considered to also be Bezier curves, then:

$$b_i(v) = \sum_{j=0}^{n} P_{ij} B_j^n(v),\ v \in [0, 1].$$

Combining both equations, the tensor product expression becomes:

$$S(u, v) = \sum_{i=0}^{m} B_i^m(u) \left[\sum_{j=0}^{n} P_{ij} B_j^n(v) \right]. \tag{1}$$

The surface is drawn by the two parameters u, v, i.e., fixing the value of the parameter $v = v_0$. A Bezier curve is drawn in direction I, calculating the curve $S_0(u,v_0)$, for $u \in [0,1]$. Once S_0 is drawn, the process is repeated for other values of v. The step with which the real interval [0,1] is mapped (by v and u) depends on the desired resolution.

In the case of cotton leaf surface generation, the tensor product approach (Eq. (1)) has one problem: the control points that may generate the surface are not known. To solve this problem, a reversed calculation of the control points was done as follows.

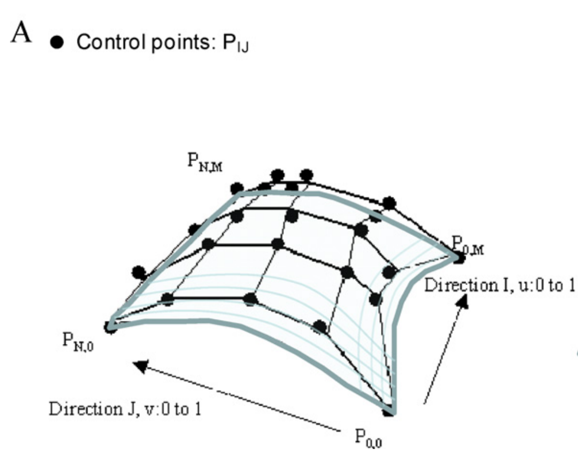

Fig. 5. The tensor product surfaces technique. Using $m \times n$ control points (A) it is possible to generate points belonging to the surface S using the tensor product of two Bezier curves. Parameters u,v draw curves in I and J directions when varying from 0 to 1. One of the curves draws the longitudinal shape and the other draws a curve transverse to the initial curve. The intersection of the curves generates a grid of quadrilateral elements (B). Each of the quadrilateral pieces is associated to a normal vector Ω_{Li} and an elementary area A_i.

The photogrammetrical analysis provides a number of points (X_{ij}) over the surface of the leaf. Since those points are on the leaf surface, they must comply with:

$$X_{ij} = \sum_{i=0}^{m} B_i^m(u) \left[\sum_{j=0}^{n} P_{ij} B_j^n(v) \right].$$

This equation can also be written in matrix notation as:

$$X = A\,\mathbf{C}\,B,$$

where $A = B_i^m(u)$, $C = P_{ij}$, $B = B_j^n(v)$, and $X = X_{ij}$.

Then, matrix C can be calculated with:

$$C^T = (B^T)^{-1} X^T (A^T)^{-1}. \tag{2}$$

Therefore, given that $C = P_{ij}$ is fully known through Eq. (2), P_{ij} can be replaced in Eq. (1) and the surface of the leaf $S(u,v)$ can be calculated at any desired level of detail. The combination of both algorithms is more commonly known as the tensor product interpolants technique (Farin, 1992).

The model developed in this research applies the above-described numerical technique (Eqs. (1) and (2)) to sets of 20 ($m = 5$, $n = 4$) data points, i.e., interpolates a quartic polynomial in the i-direction and a cubic polynomial in the j-direction, using consecutive sets of 20 points over the surface of the leaf. The resolution of the interpolation can be a maximum of 20×20 per set. In this research, a resolution of 225 points per set was used since it provided a good representation of the leaf surface with reasonable computer processing time. Depending on the complexity of the leaf,

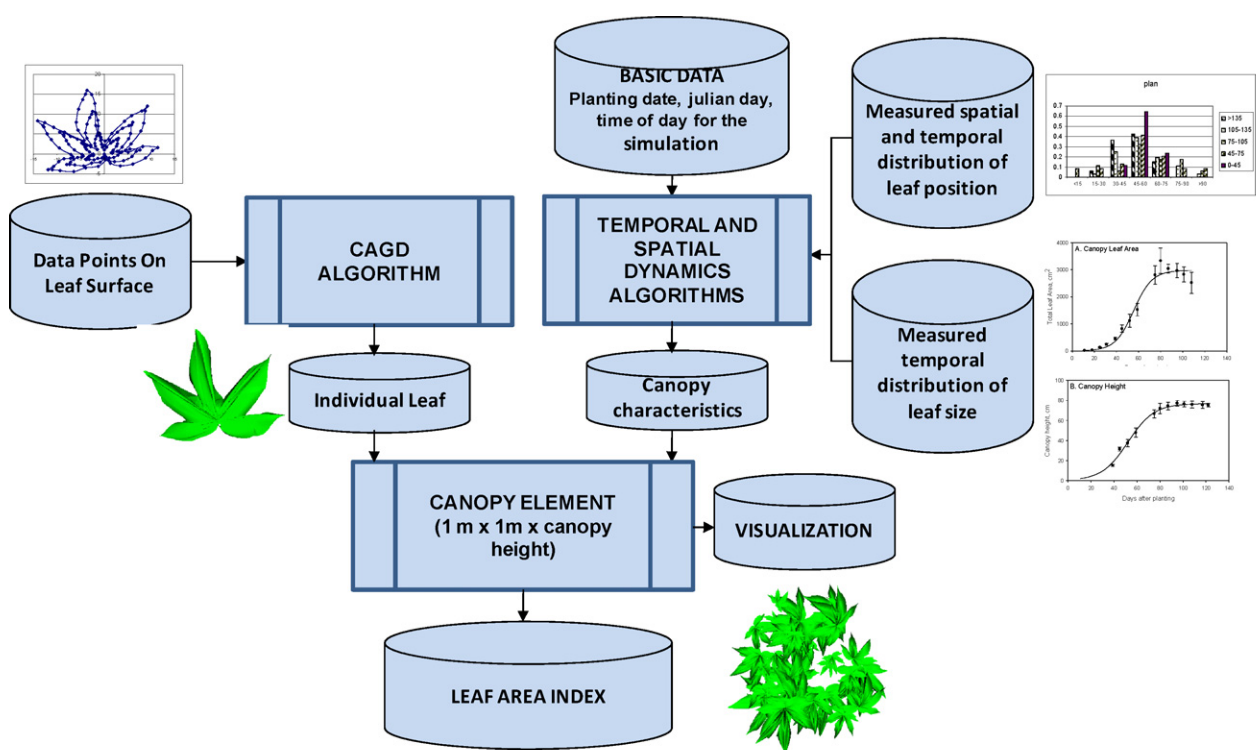

Fig. 6. Flow chart of model development. Points measured on the leaf surface are used to generate a geometrical model of an individual leaf through the CAGD algorithm. Measured temporal and spatial algorithms of leaf position and size are used to place the individual leaves into a canopy element of 1 m × 1 m × canopy-height.

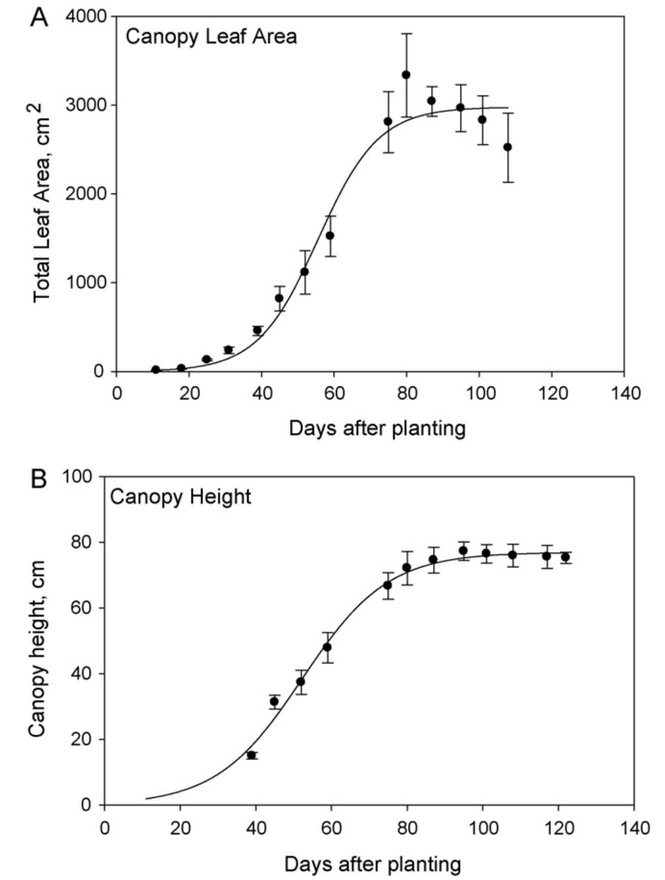

Fig. 7. Change in total canopy leaf area and canopy height during the growing season for DP-50. The measured values are fit with a sigmoid function ($r^2 > 0.98$) to develop a model for the simulation. (A) Total canopy leaf area (cm^2). (B) Canopy height (cm).

Table 1

Maximum values of leaf sizes. Values shown include leaf sizes measured from incomplete or damaged leaves. Damaged leaves presented the maximum values of leaf area.

Cultivar	Height (cm)	Area of leaves (cm^2) *MAX_SIZE*
DP-50	>90	182
	45–90	186
	0–45	161
Sub-Okra	>90	208
	45–90	229
	0–45	187
PS-6	>90	280
	45–90	320
	0–45	290
Plan	>90	286
	45–90	320
	0–45	268

the number of sets, per leaf, varies from 12 for DP-50 and Sub-Okra to 16 for Plan. The actual resolution varied between 2700 and 3600 calculated points per leaf (Fig. 10). Each of these points is associated with a small irregular quadrilateral element as shown in Fig. 5. The number of quadrilateral elements per leaf ranged from 2314 to 3086, depending on the cultivar.

2.3.2. Design of the crop canopy

To explore the utility and accuracy of the model, four types of cotton leaves (DP-50, Sub-Okra, PS-6 and Plan) were generated using the above-described algorithm (Eqs. (1) and (2)). A general description of how these simulated leaves were located in a representative volume of canopy is shown in Fig. 6. The leaves generated by the geometrical model were placed by layers in a canopy element of size 1 m × 1 m × 1.5 m height as defined by statistical distributions of leaf position and functional relationships describing changes in leaf size through time (Eqs. (3) and (5)). The combination of individual geometrical leaf features, and changes in leaf and canopy characteristics through time and space provided a flexible methodology that allows improving the representativeness

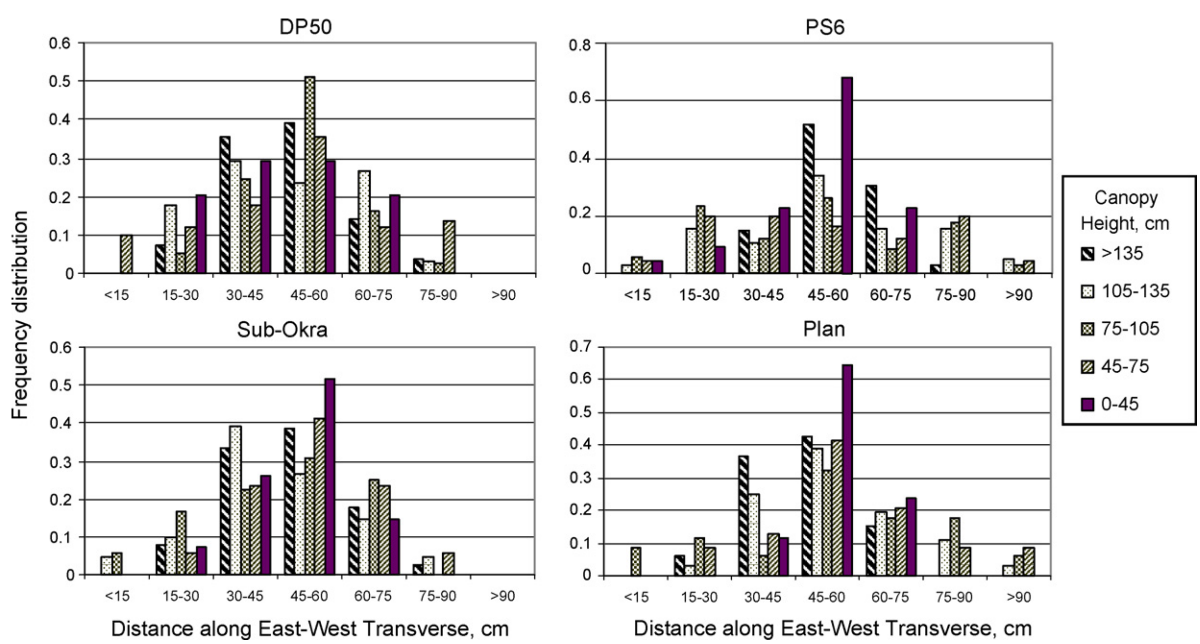

Fig. 8. Measured frequency distribution of leaves along East-West transverses for the four cotton cultivars included in the study. Transverse distance from East in centimeters (from the East) is shown in the horizontal axis. Labels detail the cotton plant height at which the east-west leaf position was measured. The figure shows measurements at 102 days after planting.

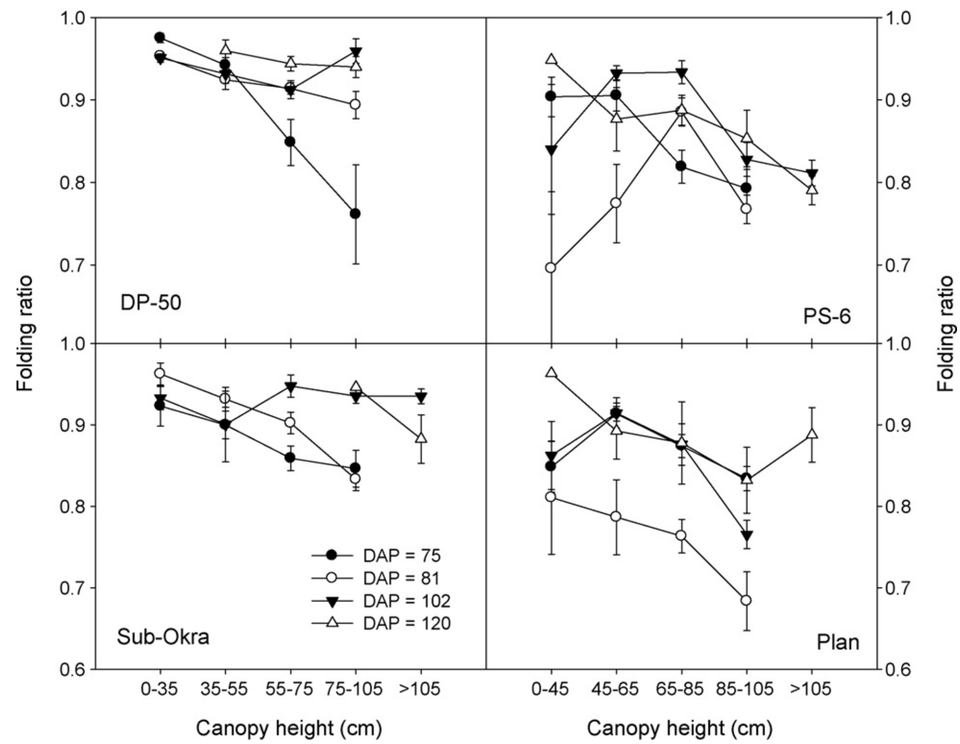

Fig. 9. Changes in the folding index (ratio of leaf area in situ to the flattened leaf area) of leaves over time. Leaves were harvested at different heights within the canopy for several time periods after planting. The innate leaf area was measured with a Delta T Devices leaf area meter by placing the leaf on the surface. The total flattened leaf area was measured with the same device by flattening the leaf under a plexiglass cover. All leaves from each canopy height were measured. Results presented are averages of all measurements for each cultivar, ±s.e.

of the simulated canopy element if new leaf/canopy information and/or data are acquired. The simulated canopy can then be used for estimating crop indicators (such as LAI), and exploration through visualization software. The next sections provide more details on the process steps shown in Fig. 6.

We chose to represent the canopy as an element on a land-area basis rather than simulating individual plants, as this is a more realistic way that cotton plants grow in a production setting. Several plants overlap within a given canopy element, contributing to the changes in canopy microenvironment and photon flux distribution.

2.4. Modeling dynamic changes of leaf and canopy structure

The model introduces temporal changes in total leaf area and height through sigmoid functions. These functions were developed from standard plant growth data from previous studies on cotton growth and development (Sassenrath-Cole and Thomson, 2001; Sassenrath-Cole et al., 2002). The sigmoid-shaped temporal changes in total canopy leaf area and canopy height were corrected for measured values for the cultivars used in this study (Fig. 7), and incorporated into the model (Fig. 6). The spatial distribution of leaf positions is given in Fig. 8. In addition to statistical distributions of leaf position, the model also uses measured statistical distributions of leaf angles and central-lobe-tip orientation (data not shown).

2.4.1. Temporal dynamics during the growing season

Changes of leaf size through time were introduced to the model in the form of a size coefficient, which multiplies each individual leaf according to its vertical position (z-coordinate) inside the canopy. Depending on the cultivar, leaves at mid-canopy heights are affected by a bigger size coefficient. Measurements of maximum individual leaf area through time were used to develop a theoretical function describing the temporal trend of leaf size change based on the measured maximum individual leaf areas for each. A heuristic process led to the development of the following equation to model leaf changes with time:

$$SIZE(t) = \frac{1}{1+e^{-3*DAPS}} * MAX\_SIZE. \tag{3}$$

Here, $SIZE(t)$ is the maximum leaf area in cm^2 through time (t is counted in days after planting, DAP). MAX_SIZE is the highest value of maximum leaf area for a particular cultivar. The range of variation of the MAX_SIZE coefficient is extracted from measured values of leaf size, summarized in Table 1. $DAPS$ are standardized DAP values, such that:

$$DAPS = \begin{cases} -1, & \text{when } DAP = 0 \\ +1, & \text{when } DAP = 150 \end{cases}. \tag{4}$$

Leaf shape and size is modified by the model according to the calculated area $SIZE(t)$ from Eq. (3) for each cultivar and canopy layer.

The changes in leaf size through time are combined with changes in the number of leaves through time for each cultivar (example for DP-50 given in Fig. 7). In general, the measured values of number of leaves increase with canopy age for all cultivars. Plan and PS-6 cultivars have lower number of leaves at all times, although they seem to have a slightly higher number of leaves at the top canopy layers. Sub-Okra has a similar tendency in the way it distributes more leaves to higher positions in the canopy. DP-50 shows the most variability in leaf distribution within the canopy. This cultivar concentrates more leaves at lower canopy layers. Despite its relatively low plant height, DP-50 has consistently more leaves, in total, than any of the other cultivars. The sigmoid function, modified for cultivar-specific changes in leaf size and number of leaves

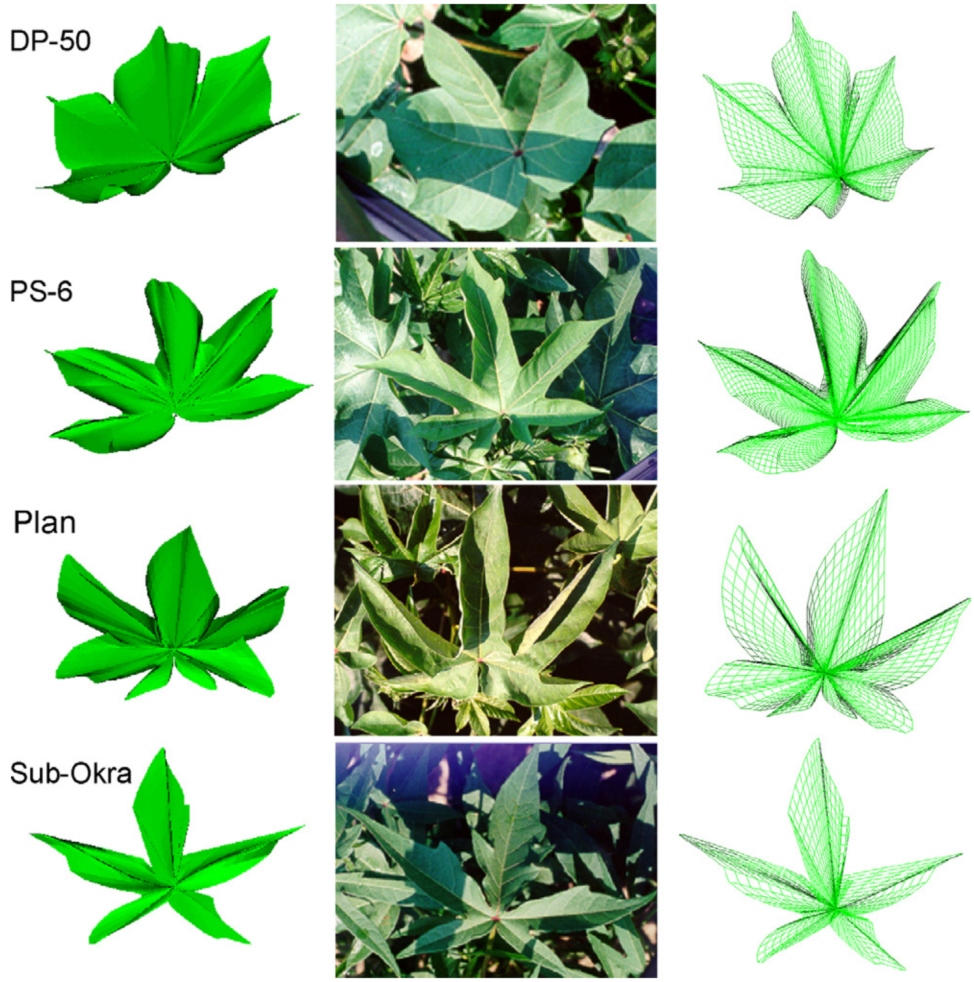

Fig. 10. Cotton leaves generated using computer aided geometrical design for the four cultivars used in this study. Geometrical grids for the four types of cotton leaves are shown as well as simulated surfaces and photos of the corresponding leaves. Resolutions of 2700 points per leaf for DP-50, 2925 for PS-6 and Sub-Okra, and 3600 points for PLAN were used to produce the grids and surfaces.

with time, was used for modeling the variation of the number of leaves during the growing season. The general form of the function is:

$$NUMBER = \frac{1}{1 + e^{-COEF*DAPS}} * MAX\_NUMB. \quad (5)$$

where *NUMBER* is the number of leaves at a particular days after planting (*DAP*), *COEF* is a fitting coefficient that varies according to the cultivar and the canopy layer for which the number of leaves is calculated, and *MAX_NUMB* is the maximum number of leaves (from destructive harvest) for that particular cultivar and canopy layer. *DAPS* values are standardized *DAP* values as defined in Eq. (4).

Folding ratios, the ratio of the normal leaf area in situ to the area of the flattened leaf, are shown in Fig. 9. There is a slight tendency for the leaves at upper canopy heights to have lower folding-ratio values, indicating that upper-canopy leaves are more folded than leaves lower in the canopy. As leaves age, however, folding ratios for all cultivars decrease, indicating that leaves become flatter with time. Sub-Okra leaves are flatter than other cultivar's leaves, followed by DP-50. Plan seems to be the most folded leaf with folding ratios ranging between 0.65 and 0.95. PS-6 presents a similar folding ratio range but, from mid-canopy to the top, the range is 0.75–0.95, compared to 0.65–0.95 for Plan leaves.

Folding is simulated by incrementing the tortuosity of peripheral points in the simulated leaf (i.e., the points located in the periphery or outer boundary of each simulated leaf, see Figs. 2 and 4). Since those points command the interpolation of the whole leaf, the folding effect is propagated through the leaf surface. The increment in tortuosity is forced by increasing the z-distance between consecutive points along the leaf perimeter. The changes in tortuosity were implemented as random values that would produce the folding ratios shown in Fig. 9.

2.4.2. Spatial dynamics

Individual leaves generated by the methodology detailed in Section 2.3 were placed in a canopy element of 1 m per 1 m per canopy height, following measured statistical distributions of leaf position specific to each cultivar. The rationale for modeling a canopy element instead of an individual plant comes from the need to include the effect of neighbor plants (Kimes, 1995; Myneni, 1991). In a crop canopy, neighboring plants within the same row result in overlap of leaves and affects shading. As the canopy grows, plants from adjacent rows contribute to overlap and shading. This structure is not adequately accounted for in models of individual plants. By modeling a canopy element instead, the structure of the canopy can be better represented. Using the method presented in this research, a "full" canopy can be simulated by replicating the canopy elements to a larger area (Sassenrath et al., 2003). Because of the temporal and spatial dynamic components included in the model, the nat-

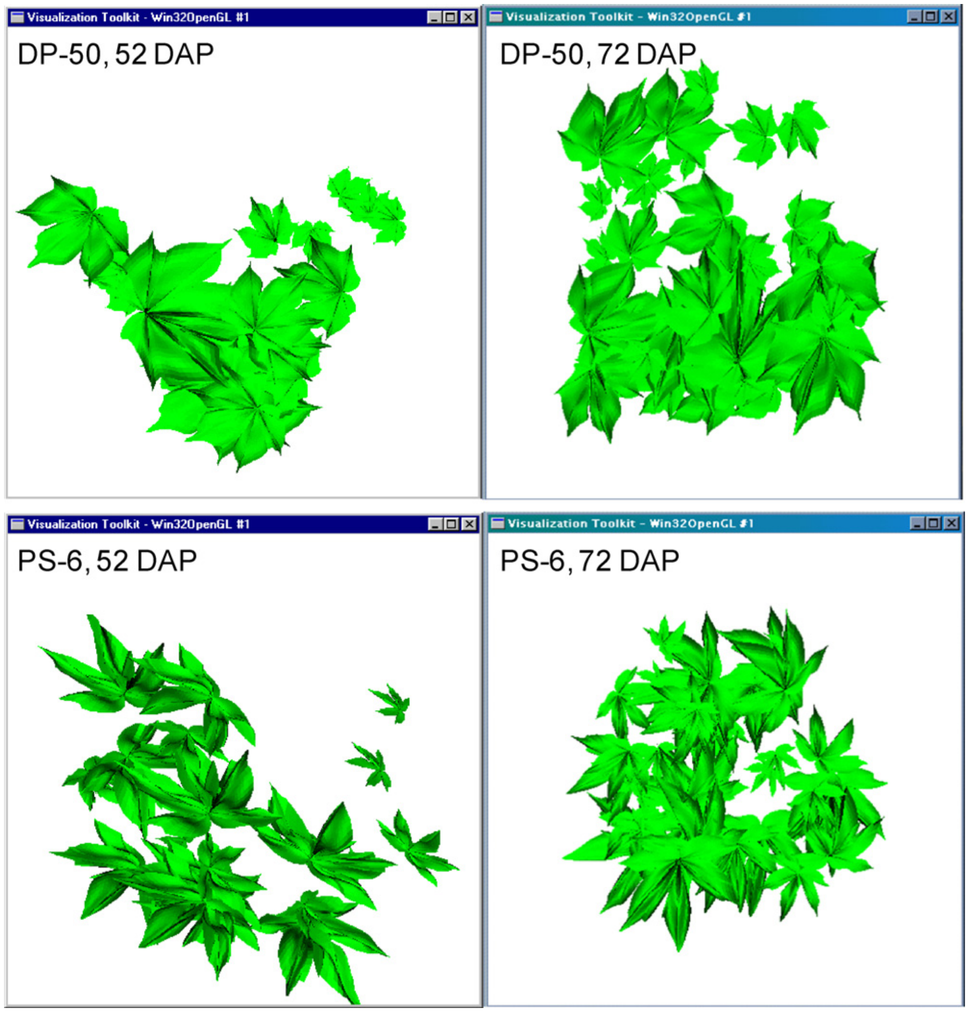

Fig. 11. Visualization of the CAGD 3D model simulation results for two cotton cultivars: DP-50 (top) and PS-6 (bottom) at 52 and 72 DAP.

ural variation within a canopy will be captured (i.e., each canopy element will not be identical).

2.5. Implementation and visualization of leaves and canopy

2.5.1. Computer program

The tensor product interpolants algorithm (Eqs. (1) and (2)), the temporal dynamics method (Figs. 7–9, and Eqs. (3) and (5)), and the three-dimensional spatial distribution of leaves after statistical distributions were coded in a C program. After initialization, the program prompts the user to input planting date, date for which simulation is desired, and time of day for the simulation. The program calculates and displays the solar position (azimuth and elevation). The basic geometry of the cotton leaf, as defined by the X_{ij} coordinate points, is input as a source file. The program calculates a number of control points $C = P_{ij}$ (Eq. (2)) that govern the whole geometry of the leaf (192 points for DP-50, 208 points for PS-6 and Sub-Okra, and 256 points for Plan). These points are then used in sets of 20 to generate the leaf surface points $S(u,v)$ (Eq. (1)) with a resolution of 225 points for each set (resulting on 2700 points-per-leaf for DP-50, 2925 points per leaf for PS-6 and Sub-Okra, and 3600 points per leaf for Plan). Fig. 10 shows the simulated surface and corresponding CAGD grids as calculated by the model. As each leaf is generated, it is positioned into the virtual canopy. The number of leaves is determined by the temporal and spatial dynamics algorithms specific to the cultivar being simulated. The coordinates for each set of points representing the leaves are used to calculate the leaf area per leaf and the total leaf area per canopy element (leaf area index). Normal vectors to the surface for each of those points are calculated by subtracting points in both directions, e.g., for a particular point $S(u,v)$, a tangent vector in i-direction will be:

$$v1 = S(u + \Delta u, v) - S(u, v);$$

similarly, a tangent vector in the j-direction is:

$$v2 = S(u, v + \Delta v) - S(u, v).$$

Then, the normal vector to the leaf surface at that point will be: $\Omega_{Li} = v1 \times v2$, and the corresponding leaf area for that small piece of leaf will be: $A_i = |\Omega_{Li}|$ (Fig. 5). The leaf area index will be the cumulative sum of all individual leaf areas for the simulated canopy element. The calculated coordinates are also written to a text file for visualization of the leaves and canopy as detailed in Fig. 6.

In addition to outputting LAI and the geometry of individual leaves and canopy, the model also calculates extinction coefficients for any point within the canopy as follows. For Ω_P a vector that points to the position of the sun, it can be demonstrated (Alarcon, 2000) that the extinction coefficient k_e for an individual quadrilateral piece of leaf is $k_e = |\Omega_P \cdot \Omega_{Li}| \times A_i$. Here, A_i is the area of the individual quadrilateral.

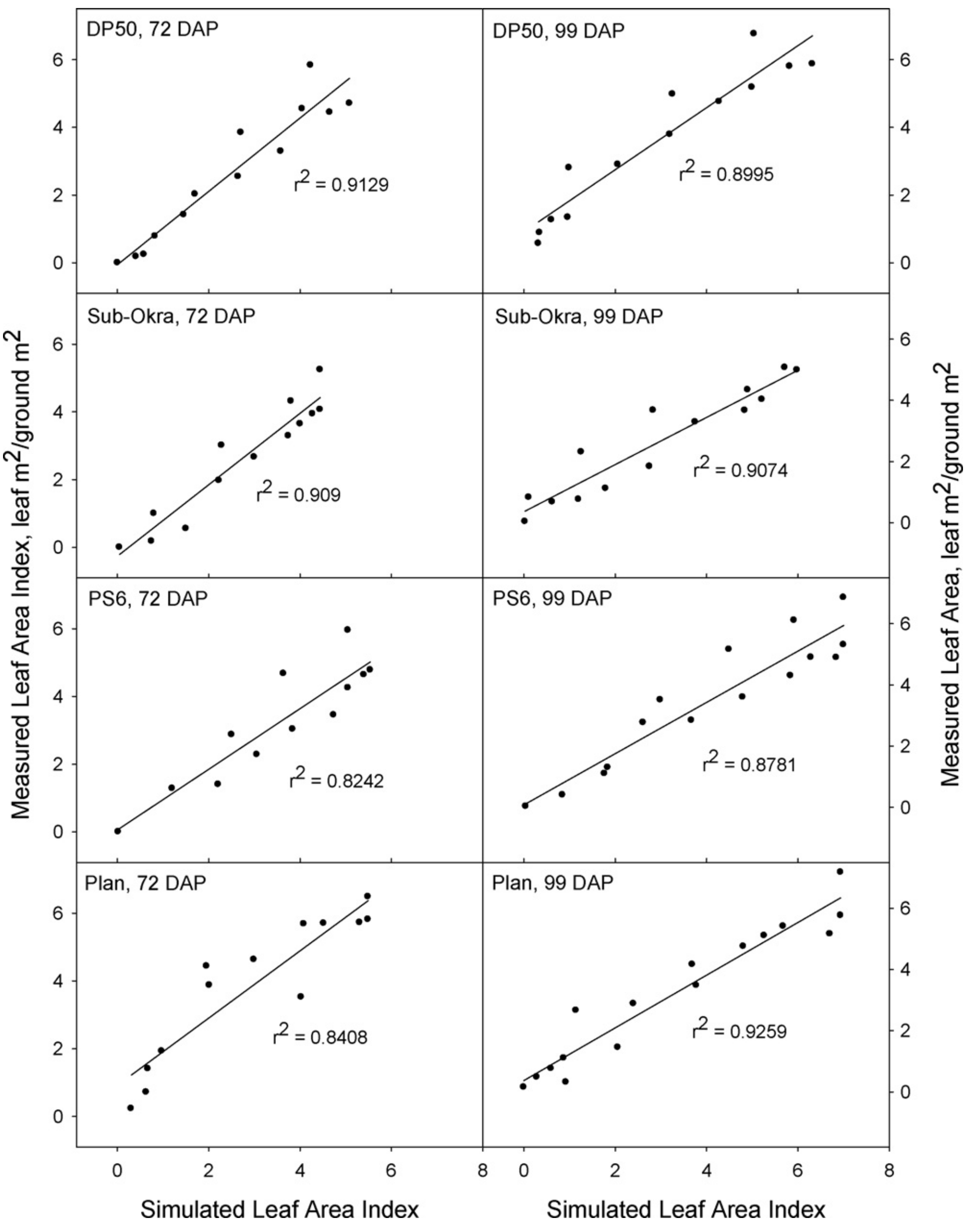

Fig. 12. Comparison of LAI for simulated canopies at 72 and 99 DAP simulations with measured LAI values of cotton canopies in situ, with coefficient of determination (r^2) values calculated from regression fit.

2.5.2. Visualization

The Visualization Toolkit (VTK) was used for rendering the virtual leaves and canopy output by the program. The Visualization Toolkit (Schroeder et al., 1996) is an open-source, freely available software system for 3D computer graphics, image processing and visualization. VTK consists of a C++ class library and several interpreted interface layers including Tcl/Tk, Java, and Python. Specific Tcl/Tk scripts were developed for visualizing either individual leaves or cotton canopies in this research. The (X, Y, Z) data points were read as 4-point polygons (quadrangles) using the vtkPolyReader VTK library. The polygons were mapped to graphics primitives using vtkPolyMapper and subsequently rendered. The Visualization Toolkit allowed rendering of the interpolated leaf surfaces and resulting canopy from any angle through mouse interaction. This capability allowed fast exploration of the smoothness of the surfaces and additional checking of the correctness of the numerical CAGD and temporal dynamics algorithms.

3. Results

3.1. CAGD model of cotton leaves and canopy

Three-dimensional simulated leaves are shown in Fig. 10 for the four cotton cultivars in this study. The differences in leaf shapes between the cultivars are adequately captured with the CAGD. Notably, the twisting of the leaves, at times resulting in illumination of abaxial leaf surfaces (Wise et al., 2000), is accurately represented by the simulation. VTK allows the simulated surface to be rotated for viewing from different angles.

The individual leaves shown in Fig. 10 were placed into a unit volume of cotton canopy of dimensions 1 m × 1 m × 1.5 m height using a statistical distribution. Fig. 11 shows CAGD-modeled cotton canopies for DP-50 and PS-6 cultivars at two stages of plant development (52 and 72 DAP). The canopy is visualized vertically

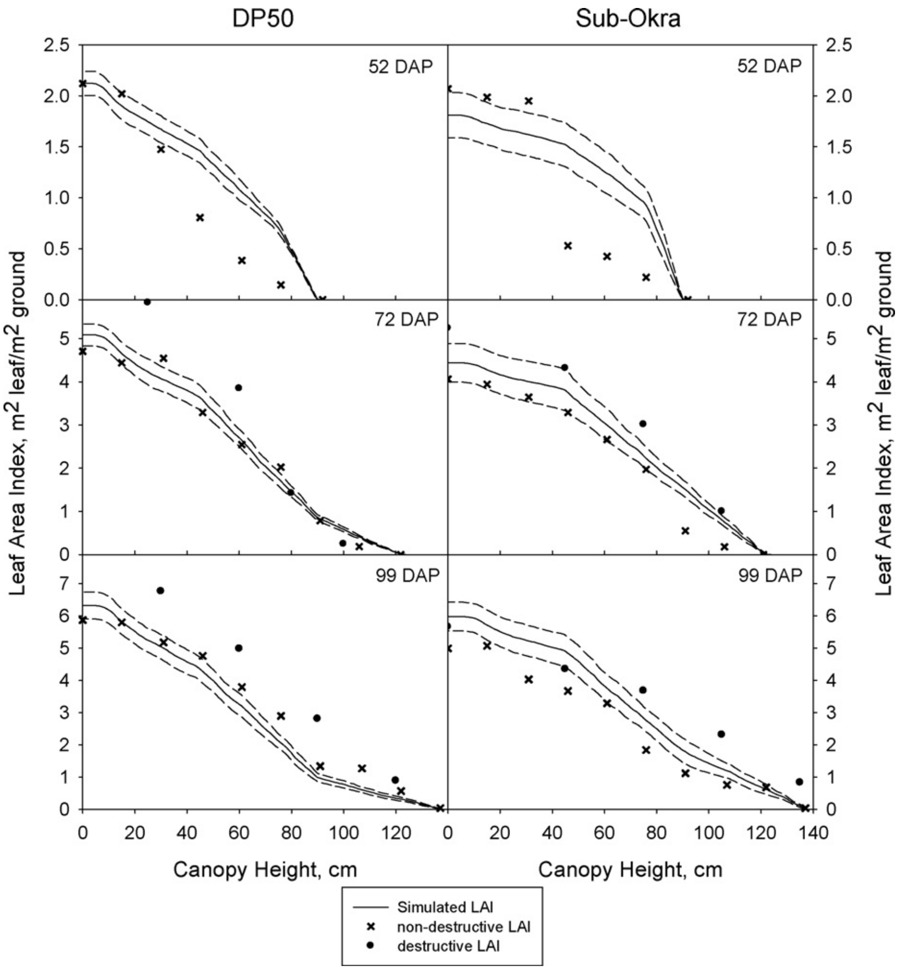

Fig. 13. Measured and simulated leaf area index (LAI) for *G. hirsutum* cotton cultivars (DP-50 and Sub-Okra) at different stages through the growing season. The dotted line represents the 90% confidence interval, calculated as $\mu \pm 1.645\sigma/\sqrt{n}$ from several LAI simulations.

from above but the visualization engine (VTK) makes it possible to rotate, zoom, and pan at will. The initial orientation of the canopy element is along the cotton rows. Approximately 9 individual plants would be positioned within the 1 m × 1 m of canopy element shown in the simulation. The reader is encouraged to visit http://www.msstate.edu/∼vja1/CAGD/CAGD.htm to explore animations of the cotton leaves and canopies produced by the CAGD model presented in this paper.

3.2. Leaf area index

Leaf area index was calculated for the simulated canopies and compared to measured LAI determined in crop canopies in the field. The development of the CAGD model of the cotton canopy was performed primarily from destructive harvest data (individual leaf area and leaf number distribution per layer), and close-range photogrammetry (leaf shape and horizontal distribution of leaves). In order to validate the model, the CAGD cotton canopy model output for leaf area index was compared to in situ measured LAI values and also LAI values from destructive harvest of leaves. Fig. 12 shows scatter plots and coefficient of determination (r^2) values, produced through the validation process for 72 and 99 DAP. The r^2 values ranged from 0.82 to 0.92.

Fig. 13 shows model-simulated LAI values for the *G. hirsutum* cultivars DP-50 and Sub-Okra compared to measured LAI distributed at different heights within the canopy. A similar comparison for the *G. barbadense* cultivars PS-6 and Plan is shown in Fig. 14. Although the model can generate LAI throughout the growing cycle, calculated LAI for the following days after planting (DAP) are shown for brevity: 52 DAP (square to first bloom), 72 DAP (first bloom to peak bloom), and 99 DAP (bloom to open boll). All LAI values generated with the model are shown with 90% confidence intervals (shown in dotted lines along the average LAI value). Confidence intervals were calculated by generating LAI simulations for several times. With these values, the standard 90% confidence interval is calculated as $\mu \pm 1.645\sigma/\sqrt{n}$.

For all cultivars, the simulated canopies fail to fit measured values of LAI at 52 DAP in the upper canopy. Actual upper canopy LAI is less than that calculated in the simulation, except for PS-6 (Figs. 13 and 14). This may result from differences in leaf folding, indicating a need for further adjustment to the folding index (Fig. 9). Alternatively, the error in simulating early canopy LAI may arise because of the incomplete canopy at this stage of growth (Sassenrath-Cole, 1995), with concentration of leaf area around the main stem. Lower canopy LAI was adequately simulated at this early growth stage. Since destructive harvest of leaves was not performed for earlier stages of growth, there is no way of estimating the actual error of the model-calculated LAI values. Simulated canopy LAI was greatly improved at 72 and 99 DAP for all cultivars and at all heights within the canopy.

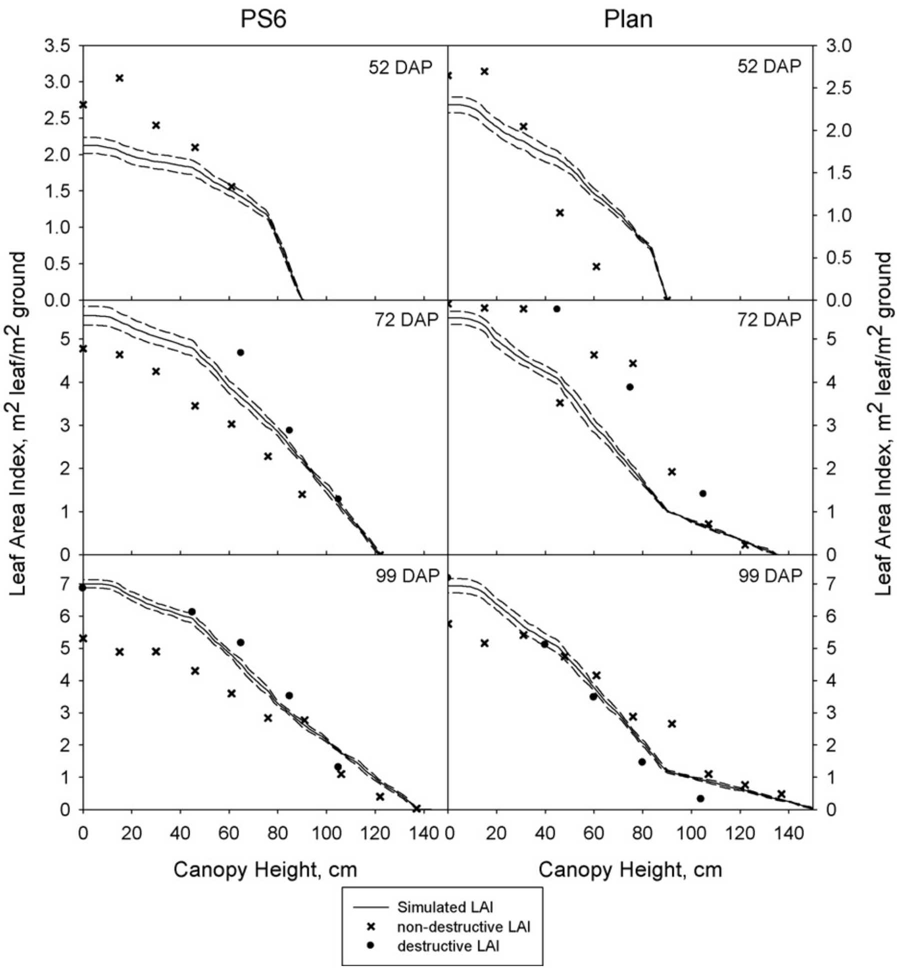

Fig. 14. Measured and simulated LAI for *G. barbadense* cotton cultivars (PS-6 and Plan) at different stages through the growing season. The dotted line represents the 90% confidence interval, calculated as $\mu \pm 1.645\sigma/\sqrt{n}$ from several LAI simulations.

4. Discussion

The use of the tensor-product-interpolants technique is shown to be very applicable to the interpolation of cotton leaf surfaces. Polynomials of third and fourth degree were found to be adequate for capturing the geometrical characteristics of several different cotton leaf shapes. The reviewed literature showed that geometrical representation of leaves and plants in similar studies used between 36 triangular elements per leaf, up to 1000 triangular elements per plant. The model presented here provides a much finer representation of leaf shape by capturing leaf geometry using 2700 points per leaf for DP-50, 2925 for PS-6 and Sub-Okra, and 3600 points for Plan, corresponding to 2314, 2506 and 3086 quadrilateral elements, per leaf, respectively. The use of irregular quadrilateral elements provides a realistic representation of the leaves and also a straightforward way of calculating the area of those individual quadrilaterals that is used for calculating total areas of leaf foliage and leaf area indices.

The computer program developed for this research also calculates perpendicular vectors associated with the quadrilaterals that, in turn, are used for estimating and outputting extinction coefficients at any position within the canopy. LAI and extinction coefficients generated by the model can be used in radiative-transport models for estimation of photosynthetically active radiation within the cotton canopies. The output of the model presented in this paper can be linked to transport models of mass, energy, or momentum that would require a detailed representation of vegetation canopies. The improved detail of leaf and canopy structure throughout the growing season will enhance simulation of transport within the canopy. This detailed representation of the canopy can also be used for estimating the distribution of insects, and insecticides or pesticides during and after application if it is linked to a model representing the trajectory of the chemicals.

Statistical distributions of leaf position in a representative canopy element of $1\,\text{m} \times 1\,\text{m} \times$ canopy height provided a good approximation to the spatial distribution of leaves. Geometric resolutions of individual leaves and statistical placement of the individual leaves in the canopy provide an approximation of canopy structure as reflected by estimations of leaf area index values. Improvement to the model may be possible with a statistical study of the variation of the number of leaves through time that would enhance the theoretical approximation presented in Eq. (5). Additional improvements in the canopy detail may result from information on the statistical distributions of leaf folding, enhancing the random increments of tortuosity implemented here to represent the spatial changes in leaf folding (Fig. 9).

Model-generated leaf area index (LAI) profiles were successfully compared to measured LAI values (destructive and non-destructive measurements). Coefficient of determination values higher than 0.82 were calculated for older canopies. The model fails to estimate acceptable LAI values for canopies at 52 days after planting. This can be improved by the introduction of better measurements of canopy structure at early stages of growth. The model code calculates dynamic canopy structural changes in space and time as statistical distributions resulting from field measurements. Future field measurements could be performed to enrich the statistical distributions currently implemented for the model to better represent young cotton canopies.

The Tcl/Tk scripts developed for visualization of the interpolated leaf surfaces and resulting virtual canopies are shown to be very useful and efficient in determining reasonableness of leaf shape and canopy structure. The mapping of the individual (*X*, *Y*, *Z*) points to graphics primitives in the form of quadrangles using vtkPolyMapper and subsequent rendering results in virtual cotton canopies that are very realistic.

Given the robustness of the simulated canopies, their use should improve the accuracy of simulations of other canopy functions. While similar models have concentrated in understanding crop performance mostly in terms of sunlight distribution or interception within the crop canopy, or only in the visualization of "realistic" canopies, the model developed in this research could be more efficiently connected to transport processes models, due to its more detailed capture of the leaves' and canopy geometry. Also, a better representation of leaf and canopy could also be applied to investigate the insect distribution, and the spreading of insecticides or pesticides within the canopy. These will be the focus of future studies.

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