MODELING PLANT CANOPY REFLECTANCE USING COMMERCIAL RAY TRACING SOFTWARE

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Abstract

A study was conducted to investigate the feasibility of using a commercial ray tracing software package (Ray Dream Designer) to model the reflectance of a cotton canopy. Results of this study indicate that, while use of ray tracing software may not precisely duplicate all the optical interactions between light and the plant canopy, this approach may be useful in getting an approximate visualization of the effects of certain stresses in the plant canopy, and thus provide useful information on our ability to detect these stresses through remote sensing.

Introduction

Aircraft and satellite remote sensing in the visible and near-infrared wavelengths of light has shown considerable promise in detecting the presence and areal extent of stress factors, such as water and nutrient deficiencies, that affect the growth of agricultural crops. In these cases, detection of the stress is achieved as a result of differences in the reflectance of the affected plant canopy as compared to the reflectance of a healthy plant canopy. These differences may involve reductions in plant canopy biomass, changes in plant canopy architecture, or alterations in the reflectance of individuals leaves in the canopy.

Most of the information regarding the remotely sensed detection of crop stress has been obtained through observations made in the field on research plots. Typically, treatments involving one or more stress factors are set up, along with nonstressed controls, to illicit differences in plant canopy reflectance detectable through remote sensing. While much has been learned through this approach, there are a number of difficulties with the use of field plots in remote sensing studies. The natural variability in plant growth resulting from the influence of uncontrolled environmental factors can confound interpretation of the relationship between crop growth and remotely sensed canopy reflectance. Episodic stress factors involving biological organisms (weeds, insect pests, and diseases) may not become adequately established in research plots to facilitate developing methods for their detection through remote sensing. The early stages of some stresses may be masked in field plots by random variations in plant growth.

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For these reasons, remote sensing researchers seek new tools for assessing our ability to detect stress in agricultural crops. One area of research that has received increased attention has been the use of radiative transfer models (RTMs), such as SAIL (Verhoef, 1984) and Cupid (Goel and Norman, 1992). These models contain systems of equations for computing the interaction of a plant canopy with the electromagnetic radiation flux, producing estimates of the reflection, transmission, and absorption of light by the canopy. The mathematics of RTMs are by necessity rather complex, and thus it is often necessary to represent the structure of the plant canopy in a simplified form to achieve a model solution. The vertical structure of the plant canopy is handled in RTMs like SAIL and Cupid by partitioning the total leaf area index (LAI) among one or more layers. The distribution of plant material within each layer, however, is assumed to be uniform. This simplification makes it difficult for RTMs to explicitly simulate reflectance from spatially heterogeneous plant canopies such as crops grown in rows. Thus, RTMs have typically been applied to investigations involving quasi-uniform vegetation canopies (such as forests and grasslands) or row crops following canopy closure.

An approach that can accomodate spatial heterogeneity in computing scene optical characteristics is the use of visualization techniques such as ray tracing. In its basic form, ray tracing follows the path of light rays through an environment and determes the interaction of the rays with objects in the environment (Watt and Watt, 1992). The user must construct a detailed three-dimensional digital model of the objects within the environment, including information on the surface characteristics of each object. The user must also specify the types and locations of the sources of illumination, along with the location of the viewer. With this information, the procedure computes ("renders") an image of the scene from the viewpoint of the viewer. While ray tracing has been used by optical scientists since the 17th Century (Descarte used ray tracing to explain the formation of the rainbow), its application to computer imaging began around 1980. In recent years, ray tracing and allied rendering techniques have been extensively applied to commercial advertising and motion pictures to produce computer-generated images that are extremely realistic in appearance.

A number of computer image visualization software packages that include ray tracing are commercially available for use on desktop workstations or personal computers (PCs). These include RenderMan (Pixar, Inc., Redmond, WA), 3D Studio MAX (Autodesk, Inc., San Rafael, CA), LightWave 3D (NewTek, Inc., San Antonio, TX), Softimage 3D (Softimage, Inc., Redmond, WA), and Ray Dream Designer (Ray Dream, Inc., Mountain View, CA).

The objective of this presentation is to describe preliminary results of an effort to apply ray tracing techniques to model the reflectance of cotton (Gossypium spp.) canopies and, in

particular, to visualize differences between healthy and stressed plant canopies that could be detected through remote sensing. The commercial software package Ray Dream Designer was used in this application. This presentation describes the initial methods used to model the plant canopy and some advantages and drawbacks associated with this approach. An example is presented of simulating cotton canopy reflectance characteristics associated with an infestation of aphids.

Materials and Methods

Software

Ray Dream Designer Version 3 for Microsoft Windows was used in this study. It was run on an IBM-compatible PC with an Intel 66-MHz 486 CPU and 64 MBytes of RAM.

The visualization of a scene using this software is achieved through a sequence of steps (Ray Dream, 1993). The user must first build a three- dimensional (3-D) digital model of the objects within the scene using software tools that allow the size, shape, orientation, and position of each object within the modeling environment to be specified. Next, the user must specify the surface characteristics of each modeled object in a process termed "shading". Through shading, the user assigns surface properties that control the color, brightness, and finish of each object, and control optical properties such as reflectance, transmittance, and refractance. Once the 3-D model has been specified, the user must select the number, type, intensity, color, and position of each light source that will illuminate the objects in the scene. The software can simulate both direct beam light (like from a lightbulb or the sun's disk) and diffuse light (like from the sky). The user must also specify the position of the viewer relative to the objects in the scene. When these steps are completed, the user instructs the software to render an image of the modeled scene from the point of view of the viewer. Ray Dream Designer contains a computational engine called the RDI Ray Tracer that traces the paths of light rays within the scene and determines their interactions with the modeled objects. Depending on the detail and complexity of the modeled scence, this process may take from a few minutes to a few hours. The result of the rendering is a two-dimensional image of the scene analogous to a photograph obtained by a camera at the position of the viewer.

The Ray Dream Designer software contains a wide variety of features that allow the user to visualize a diversity of objects and scenes. The method by which the software features were used in this study to visualize the cotton canopy is described in the following section.

3-D Canopy Model

The structure of the cotton canopy was modeled in Ray Dream Designer by specifying the size, orientation, and location of each leaf. Several simplifying assumptions, based on general observations of actual cotton plants in the field, were used in this initial attempt to visualize the cotton canopy. All leaves were represented as squares with a surface area of 100 cm2. Since the optical characteristics of the modeled leaves were determined by their assigned surface characteristics, their thickness was assumed to be negligible. In this initial study, all leaves were assumed to be oriented horizontally in a heliotropic response to a high sun angle.

Figure 1 shows overhead and oblique views of the arrangement of modeled leaves within the software environment to form a medium-size cotton plant. Due to their relatively small surface area, stalks and lateral stems were not considered in this simulation. Flowers, squares, and bolls were also not considered in this initial study. Dimensions of the modeled plants (height, width, number of nodes) were based on unpublished field observations. The arrangement of modeled leaves into branches was based on an idealized pattern derived from field observations.

Figure 2 shows overhead and oblique views of the arrangement of 17 cotton plants of the form shown in Figure 1 into a row. Modeled plants were spaced 20 cm apart within the row, and each plant was rotated 60° about the vertical axis relative to the plant immediately adjacent to it in the row. This rotation provided a degree of variability in the orientation of plants within a row. Rows of plants formed in this manner could be placed parallel to each other separated by an appropriate spacing to form a modeled cotton canopy.

Ray Dream Designer keeps track of each object (in this case, each leaf) in the modeled scene. Thus, it was possible to assign unique surface characteristics to each leaf in the simulation. Two situations were investigated in this study--one in which the surface characteristics of all leaves were the same, and one in which the surface characteristics of some leaves in the modeled canopy were different due to the effects of insect (aphid) attack.

Ray Dream Designer allows seven optical characteristics to be specified for an object's surface, of which color, reflection, and transmission were most important in this study. In nature, cotton leaves exhibit two reflectance qualities. The first is a quasi-isotropic reflectance originating from backscattering of light by cellular structures within the body of the leaf. The second is a directional specular reflectance of light from the leaf's outer surface. The transmittance of cotton leaves is also quasiisotropic, originating from the forward scattering of light by cellular structures within the leaf. The ray tracer in Ray Dream Designer can simulate directional reflection from the surface of an object, but cannot directly simulate isotropic reflection associated with backscattering within the body of an object. While the ray tracer can simulate direct-beam transmission of light through an object, including refraction, it cannot directly simulate diffuse transmission of light through an object.

The following strategy was used in this study in a n attempt to overcome these limitations. The quasi-isotropic reflectance of the modeled cotton leaf was accounted for through the assigning of the "color" of the leaf surface. Using the red-green-blue (RGB) color model in the software, an intensity value of 0 to 255 could be assigned for each of the three color channels. By assigning the same intensity value to all three channels, a grayscale color could be produced that was proportional to the quasiisotropic reflectance of the leaf. The appropriate intensity value was computed as 256 times the quasi-isotropic (non-specular) reflectance of the leaf surface. Using this approach, an image of the modeled cotton canopy could be rendered for any given waveband of light from the average known value of non-specular leaf reflectance for that waveband. Specular reflectance from the modeled leaf surface could be simulated using the Ray Dream Designer ray tracer. Specular reflectance from a cotton leaf is panchromatic in the visible and near-infrared wavelengths (unpublished data), so a single value (approximately 10 percent) was used for the surface reflectance setting for all wavebands. Maas (1997) showed that cotton canopy reflectance was dominated by reflectance from the outer layer of leaves in the plant canopy. Observed canopy reflectance showed little or no dependence on canopy density, indicating that the light level within the plant canopy was relatively low and that the upward transmission of light through leaves was relatively small. Thus, it was felt that the inability of the Ray Dream Designer ray tracer to simulate diffuse transmission of light through an object would not lead to serious errors in rendering external views of the cotton canopy. Therefor, diffuse transmission of light through modeled leaves was ignored in this initial study.

Figure 3 shows measurements of non-specular leaf reflectance obtained for cotton leaves at Shafter, CA, using an LI-1800 field spectroradiometer (LI- COR, Inc., Lincoln, NE). The effects of aphid feeding within the plant canopy is apparent in the reduction of leaf reflectance at all observed wavelengths. Feeding aphids excrete honeydew which collects on leaf surfaces, particularly those lower in the plant canopy. This sugary substance supports the growth of sooty mold on the leaf surface, the presence of which markedly descreases the non-specular reflectance of the leaf. The spectra in Figure 3 were used to calculate average values of non-specular reflectance in various wavebands for use in establishing sets of surface characteristics (called "shaders" in Ray Dream Designer) for modeled cotton leaves that were unaffected, moderately affected, and heavily affected as a result of aphid feeding.

In addition to modeled plants, an object representing the soil surface was included in the modeled scene. For this initial study, this modeled soil surface consisted of a horizontal flat plane located below the modeled plants. The shader for this object had a grayscale color derived from field observations of soil reflectance. The modeled soil was assumed to be opaque and have no specular reflectance.

Under sunlit conditions, the cotton canopy is illuminated by both directbeam solar and diffuse sky irradiance. These conditions could be approximated for the modeled cotton canopy using the lighting options in Ray Dream Designer. Diffuse sky irradiance was simulated using the "ambient light" setting in the software, which produces a uniform level of illumination throughout the scene without shadows. Direct beam solar irradiance was simulated using the "distant light" setting in the software, which provides a virtual source of light with rays that are parallel throughout the modeled scene. The location of this modeled "sun" relative to the other objects in the scene could be established by the user. Intensities of the two light sources were adjusted to give a reasonable ratio of direct and diffuse illumination as observed in the field (approximately 30 percent of the above-canopy irradiance being diffuse).

The software allows the user to view and render an image of the modeled scene from any location inside or outside the scene. For this study, images were rendered for a viewer directly over the canopy looking down, as in the case of aircraft observations of a field.

Results and Discussion

Figure 4 shows the overhead near-infrared image of the cotton canopy and soil surface obtained by modeling three rows of plants. The component of the sun angle perpendicular to the rows was approximately 25o, resulting in shadows being cast on the soil surface and on lower canopy leaves between the rows. As in nature, the "sunlit" plant canopy is brighter than the soil in this near-infrared view, while the shadows are darker than the soil. The influence of shadows is further illustrated in Figure 5, which shows a reflectance transect across the rows constructed from reflectance values at 2.5-cm (1-in) intervals. This transect is qualitatively similar to actual cotton canopy transects reported by Maas (1997). Shaded leaves and soil make up a significant portion of the scene, and thus would have a marked effect on the overall scene reflectance.

Expansion of this simulation to the field level is presented in Figure 6a, which shows a portion (10 m wide by 20 m long) of a modeled cotton field spanning 10 rows viewed from above in the near-infrared. Figures 6c, 6e, and 6g show resampled versions equivalent to Figure 6a viewed with minimum resolutions of 2, 4, and 10 m, respectively. Figures 6b, 6d, 6f, and 6h are computer enhanced versions of figures 6a, 6c, 6e, and 6g, respectively, in which the histograms of the brightness levels have been stretched to emphasize features in the image. As indicated in Figure 6b, a small portion of the modeled plant canopy has a different reflectance, the result of simulating the effects of aphid damage on individual leaf reflectance as described in the previous section of this article. As in nature, only the reflectance of the lower leaves in the modeled cotton canopy were affected by the hypothetical aphid infestation.

Nonetheless, the portion of the field affected by the infestation was made visible in Figure 6b through image enhancement. The subtlety of the effects on canopy reflectance, however, make the infestation extremely difficult to detect in the unenhanced version of the image (Figure 6a).

The other versions of the image in Figure 6 show the effects of reduced spatial resolution on the ability to detect the hypothetical aphid infestation. Enhanced versions (Figures 6d and 6f) show that the differences in overall canopy reflectance resulting from the infestation are still detectable with 2- and 4-m resolution. However, at 10-m resolution (Figure 6h), the difference in overall canopy reflectance for the pixel containing the infestation as compared to the rest of the field has dropped to below one digital count, preventing detection of the infestation despite any amount of image enhancement. As in Figure 6a, detection of the infestation in the unenhanced versions of the image (Figures 6c, 6e, and 6g) is extremely difficult.

Conclusions

Ray tracing procedures were used to produce simulated images of cotton canopies and fields that were qualitatively similar to actual imagery. Ray tracing is particularly capable of modeling the effects of shadows cast by rows of plants, a feature ignored in radiative transfer simulations of plant canopies that assume spatial homogeneity. The inability of ray tracing procedures to explicitly simulate diffuse reflectance and transmittance of light may limit the absolute accuracy of this technique. However, it may find use in visualizing features of canopy reflectance, like the example involving insect infestations presented above. Combination of ray tracing and radiative transfer techniques may provide a more comprehensive description of scene reflectance for spatially nonhomogenous plant canopies.

Disclaimer

Mention of trade names in this manuscript does not imply endorsement by the United States Department of Agriculture.

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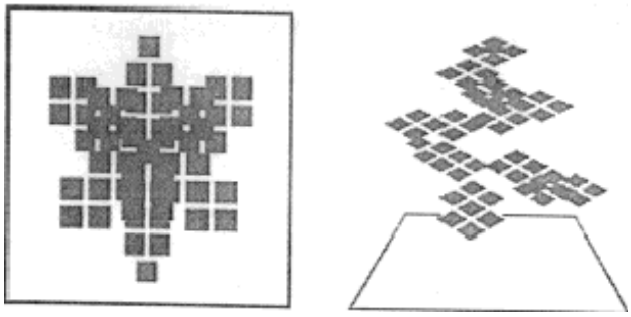

Figure 1. Overhead and oblique views of a modeled cotton plant consisting of 59 leaves. The modeled plant is 100 cm tall with 11 branches (including the terminal).

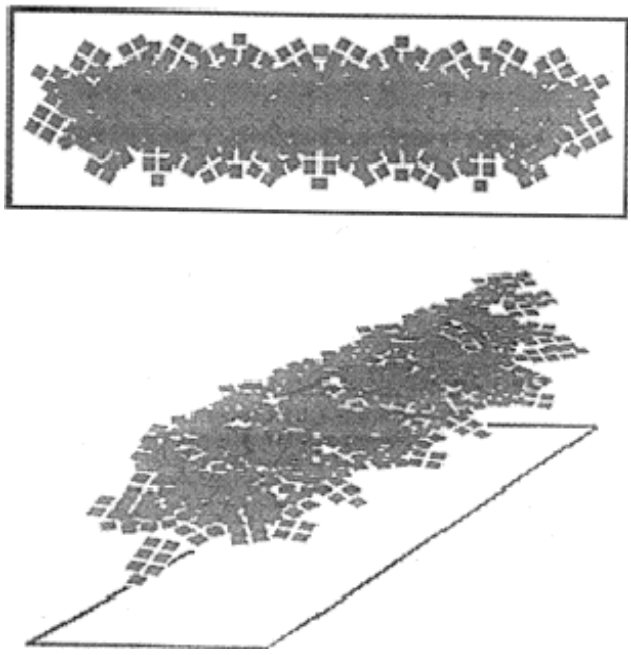

Figure 2. Overhead and oblique views of a modeled cotton row consisting of 13 plants.

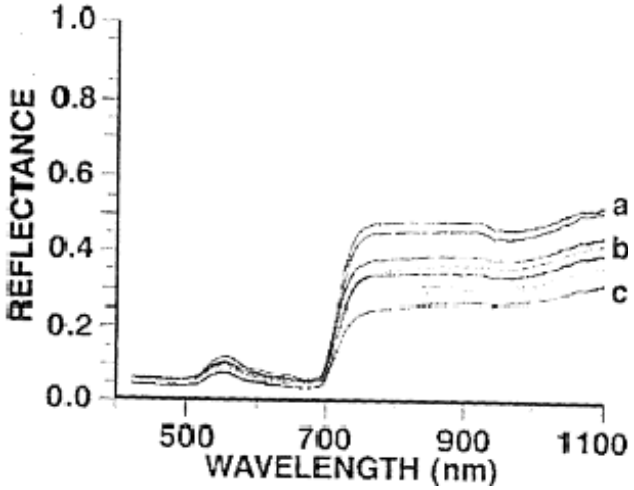

Figure 3. Observed cotton leaf spectra, for leaves (a) unaffected, (b) moderately affected, and (c) heavily affected by sooty mold associated with feeding by aphids.

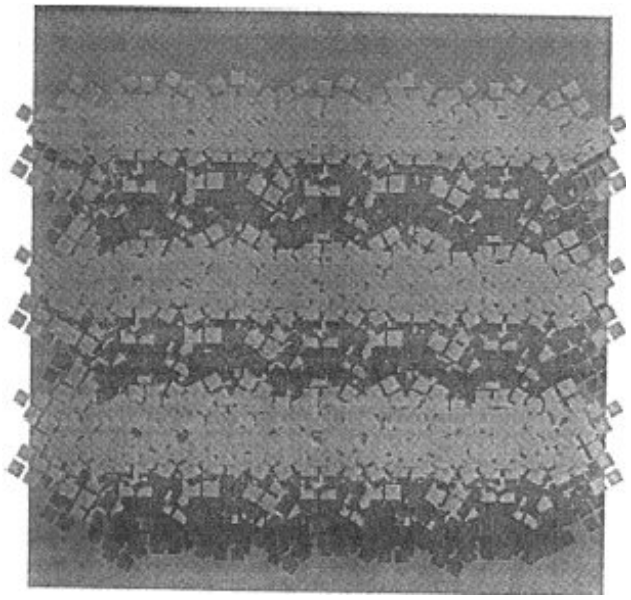

Figure 4. Overhead view of the modeled cotton canopy and soil in the near-infrared.

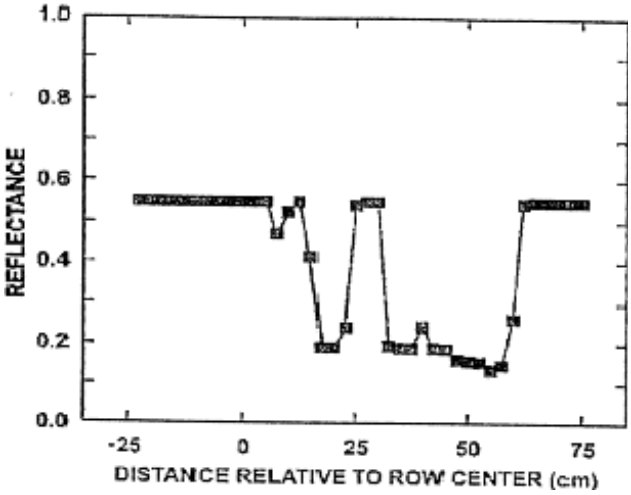

Figure 5. Reflectance transect across a row in Figure 4 in the near-infrared.

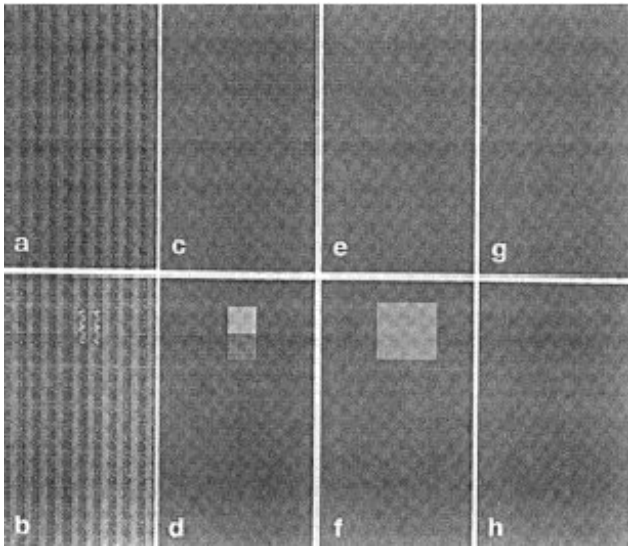

Figure 6. Overhead view of a modeled cotton field in the near-infrared. Normal views are shows at (a) high resolution, (c) 2-m resolution, (3) 4-m resolution, and (g) 10-m resolution. Computer-enhanced views are shown at (b) high resolution, (d) 2-m resolution, (f) 4-m resolution, and (h) 10-m resolution.