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BIDIRECTIONAL REFLECTANCE MODELING OF NON-HOMOGENEOUS PLANT CANOPIES

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Objective

The objective of this research is to develop a 3-dimensional radiative transfer model for predicting the bidirectional reflectance distribution function (BRDF) for heterogeneous vegetation canopies. The model (named BIGAR) considers the angular distribution of leaves, leaf area index, the location and size of individual subcanopies such as widely spaced rows or trees, spectral and directional properties of leaves, multiple scattering, solar position and sky condition, and characteristics of the soil. The model relates canopy biophysical attributes to down-looking radiation measurements for nadir and off-nadir viewing angles. Therefore inversion of this model, which is difficult but practical, should provide surface biophysical properties from radiation measurements for nearly any kind of vegetation pattern; a fundamental goal of remote sensing. Such a model also will help to evaluate atmospheric limitations to satellite remote sensing by providing a good surface boundary condition for many different kinds of canopies. Further this model can relate estimates of nadir reflectance, which is approximated by most satellites, to hemispherical reflectance, which is necessary in the energy budget of vegetated surfaces.

Technical Approach

The approach to this research requires development of the mathematical equations and computer coding of the heterogeneous-canopy model, better characterization of leaf and soil properties which are a serious limitation at the present time, and finally comparison of model predictions with field measurements that are obtained from other investigators. The Bidirectional General Array Model (BIGAR) is based on the concept that heterogeneous canopies can be described by a combination of many subcanopies, which contain all the foliage, and these subcanopy envelopes can be characterized by ellipsoids of various sizes and shapes. The foliage within an ellipsoid may be randomly positioned or non-randomly positioned. Estimates of multiple scattering are obtained by transforming each point of interest in a particular ellipsoidal canopy to an equivalent one-dimensional canopy and solving the radiative transfer equations for this simple case. The BRDF for individual leaves has been measured so that appropriate leaf properties can be used in the model. The BRDF for several soils has been measured and modeled with a simple block-modeling approach to provide a reasonable lower boundary condition for the canopy model. Field measurements of corn and soybean canopy BRDFs are compared with model predictions.

Research Results

The results of this study are three fold: 1) A simple soil BRDF model tested with measurements, 2) laboratory measurements of leaf BRDFs for live corn and soybean plants grown in the greenhouse and the field, and 3) the development and validation of a 3-dimensional canopy BRDF model of heterogeneous vegetation that combines soil, leaf, and canopy-architectural information.

The simple soil BRDF model approximates a soil aggregate by a single rectangular block placed on a fixed lot area with a fixed orientation relative to the sun azimuth. The relative reflectance factor in any view direction is computed from projections of block faces and the shadow of the block on the horizontal. Fig. 1 contains a comparison of model results with measurements in the solar waveband over a rough surface that was recently plowed from sod with furrows approximately 15 cm deep. The RMS difference between the surfaces is 2.2% in reflectance. The simple-black-model predictions fit measurements from smooth (0.5-1 cm gravel) and medium rough (2 to 5 cm clods from multiple tillages) even better with 1% RMS differences in reflectance.

Leaf BRDF measurements were made at 3 source incidence angles (20, 45, 70) and about 50 view angles for intact corn and soybean leaves attached to their respective plants. The distribution visible and near-infrared, reflectance and transmittance factors is shown in Fig. 2 for a 45 degree source incidence angle. The leaf hemispherical reflectance, which is essential to all models of vegetation radiation exchange, was calculated from the integral of the BRDF (Table 1). Clearly normal incidence valves which currently are being used in other models may not be appropriate since mean leaf-sun angles for most canopies are between 45 and 60 degrees and not near normal incidence.

The 3-dimensional bidirectional reflectance general array model (BIGAR) predictions have been compared to measurements on corn and soybeans that were obtained from the Laboratory for Applications to Remote Sensing (LARS), Purdue, University, West Lafayette, Indiana as part of the AGRISTARS program. An example of how ellipsoids are used to represent a young corn canopy is shown in Fig 3 and a comparison of measured and modeled results is in Fig. 4. In general the model predictions agree very well with measurements considering that soil BRDF measurements cannot be made for the same site as the vegetation BRDF measurements.

A simple 3-term empirical equation has been derived to fit measured and modeled, soil and canopy BRDFs over a wide range of wavelengths. The RMS reflectance difference between the 3-term empirical equation and modeled or measured distributions (including view zenith angles from 0 to 60 degrees) is about 0.2% in the visible and 2% in the near infrared for soybeans and several soils; a remarkably good fit.

Significance of Results

Significant research results from this study impact on vegetation remote sensing in three ways: 1) relation of soil BRDF to roughness and sun angle, 2) interactions between soil BRDF and canopy reflectance properties that lead to confounding the discrimination of sparse vegetation using angle-of-view observations, and 3) interpretation of leaf BRDF measurements to provide more suitable leaf spectral properties for models of vegetation radiative transfer.

The very simple block model, which has beem verified with field measurements, relates the soil BRDF to roughness. Unfortunately the roughness is a relative roughness and thus not the same kind of "roughness" used by soil physicists, Thus a disked field and a gravel lot can have similar relative roughnesses (ratio of size to spacing) and BRDFs but represent very different roughnesses to the soil physicist.

The BRDF of sparse vegetation is not as different from soil as is desirable for discrimination based on view angle observations. However the structure of sparse canopies may be distinguishable from each other or soil backgrounds with zenith view angels of 60°. Unfortunately this is not possible from satellites. In addition we now understand how a BRDF is different for a soil below a canopy than a soil in the open even though their physical characteristics are identical. The 3-term empirical equation fits soil and vegetation BRDFs so well that it may greatly simplify extraction of canopy properties from off-nadir observations for natural surfaces so that use of such data may become practical. Perhaps it may even reduce the number of off-nadir angles needed for obtaining canopy properties from satellite observations.

During this study we have measured leaf BRDFs for corn and soybean; a rather formidable task that few have attempted. From this work we have learned that models based on normal-incidence integrating sphere leaf spectral properties, and to date nearly all leaf spectral property data is for normal incidence, are using underestimates of leaf reflectance and overestimates of transmittance. Using the more appropriate leaf spectral properties may change canopy reflectance by 5 to 15% of the reflectance value. The improved estimates of leaf spectral properties will also improve estimates of canopy water use and photosynthesis. In fact the reduced water use of an isogenic line of dense pubescence (dense hairs) soybeans could only be explained by the leaf BRDF and not normal incidence integrating sphere measurements.

Future Work

Future research should emphasize the inversion of 3-dimensional vegetation-soil bidirectional reflectance factor models and develop simpler inversion algorithms from exercising these complex models. Both angular (view direction) and wavelength information should be combined in the inversion process to extract the maximum amount of information; perhaps inverting the distribution of normalized-difference with view angle may hold promise. The logical extension of this 3-D model is to include more complex canopoy architecture such as conifer trees, and also extend the wavelength band to the thermal.

Table 1. Hemispherical reflectance and transmittance of corn and soybean calculated by integrating the results of leaf BRDF measurements.

Crop	Incidence Angle	Visible Refl (%)	Visible Trans (%)	NIR Refl (%)	NIR Trans (%)
Corn	0	7.7	3.9	-	-
	20	9.1	4.2	34.6	39.3
	45	9.3	3.4	33.0	35.4
	70	14.2	3.9	45.2	45.0
Soybean	0	8.3	4.9	-	-
	20	9.3	4.3	41.7	30.9
	45	9.6	3.7	44.9	33.2
	70	15.3	3.1	51.6	32.0

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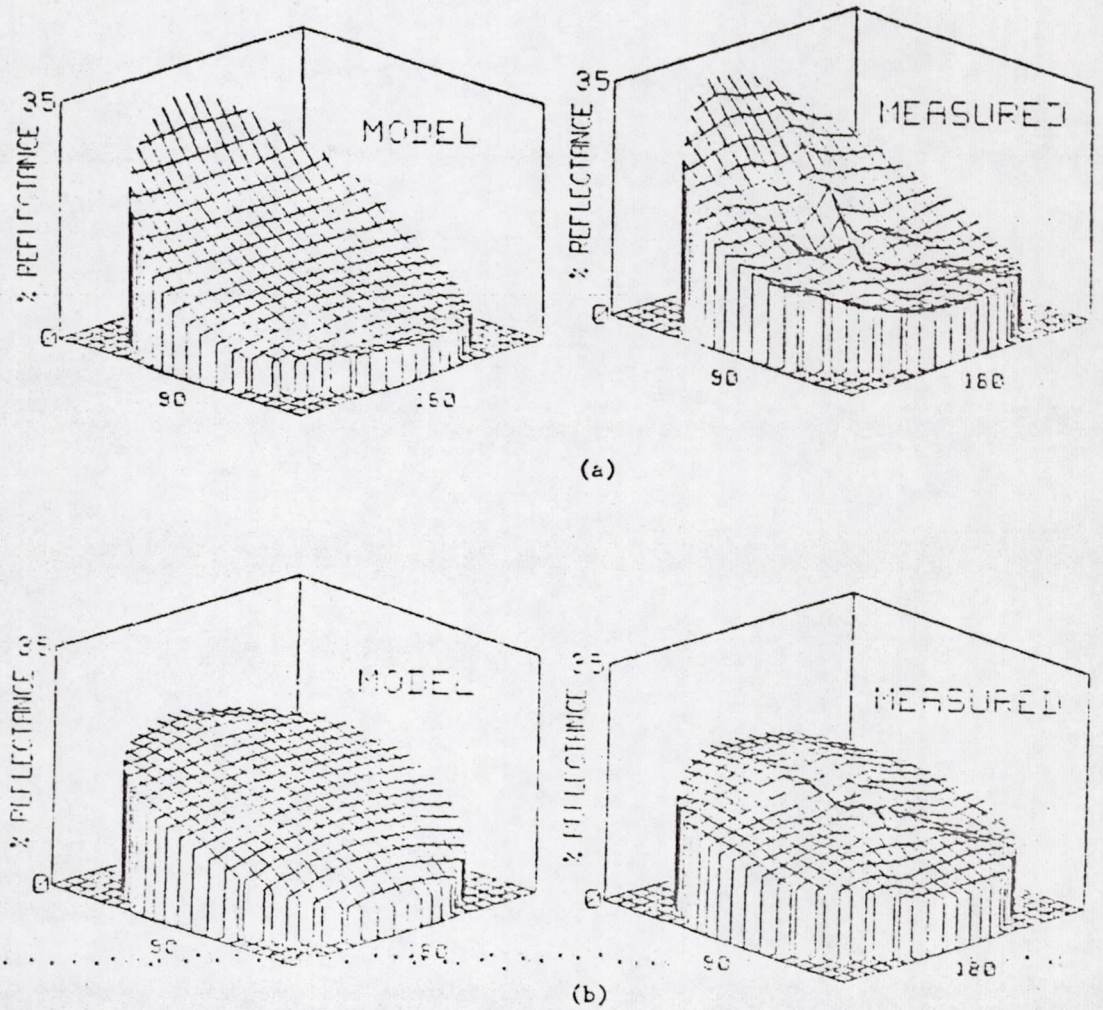

Fig. 1. Soil BRDF predicted from simple model (H=0.4, L=0.85 W=0.1, =0.67) and measured for a rough plowed soil with 15 cm furrows and clods for a solar zenith angle of (a) 63° and (b) 28°. The RMS difference between measured and modeled for (a) is 2.2% and for (b) is 1.1% in reflectance units. Maximum zenith view angle is 60° (outer rim), center is nadir and sun azimuth is 0°.

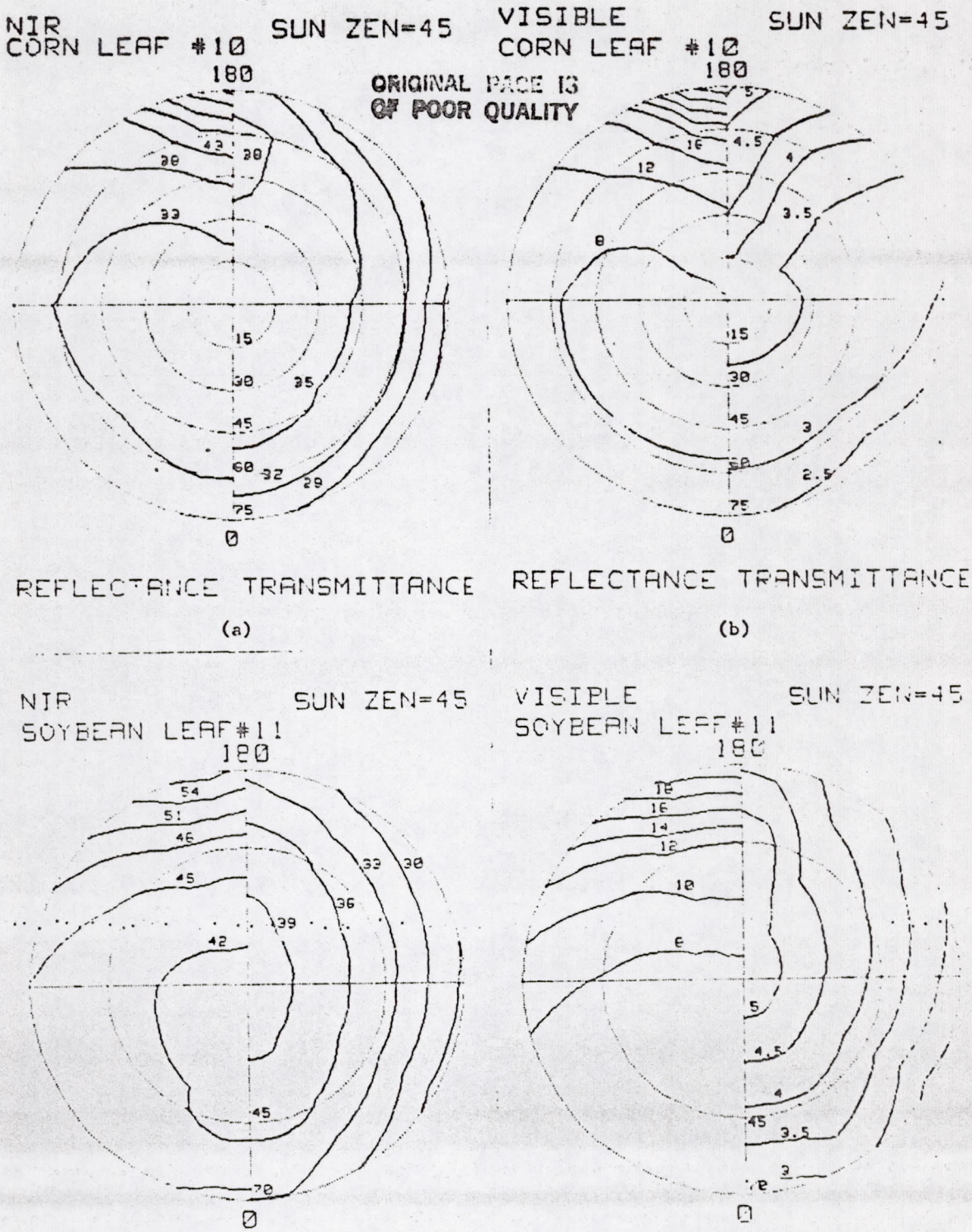

Fig. 2. Leaf BRDF and bidirectional transmittance distribution function at a source incidence angle of 45° and azimuth of 0° for (a) corn at near infrared wavelengths, (b) corn at visible wavelengths, (c) soybean at near infrared wavelengths, and (d) soybean at visible wavelengths.

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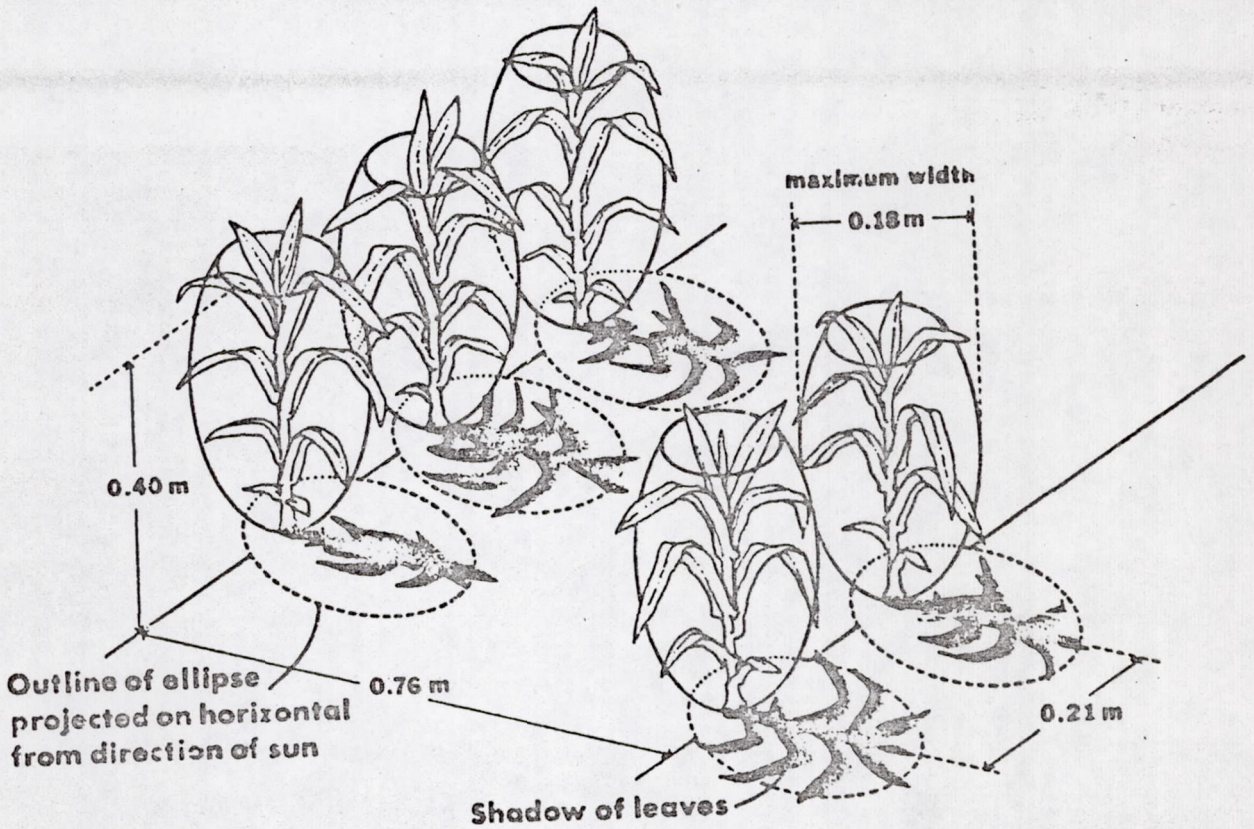

Fig. 3. Sketch of a corn canopy with LAI= 0.4 including the ellipsoids used to approximate the canopy envelope.

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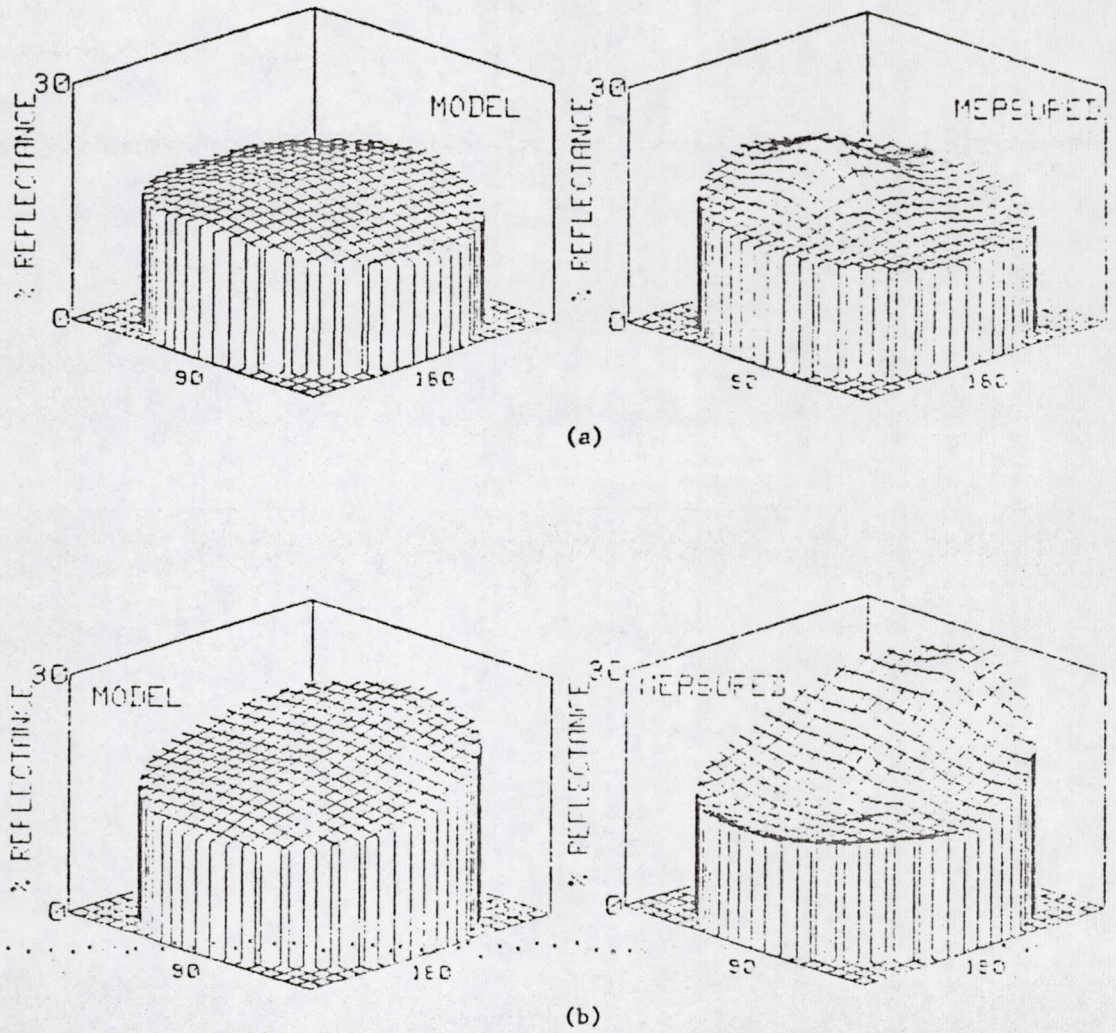

Fig. 4. Comparison of measurements and model predictions for a corn canopy of LAI = 0.4 having north-south rows. (a) solar azimuth = 7°, solar zenith = 18°, (b) solar azimuth= 276°, solar zenith = 47°. South is 0°. Maximum view zenith angle is 60° (outer rim) and nadir view is at the center.