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The Reflection Characteristics of Healthy Green Leaves*

Zhang Hong Zhu Qijiang
(*Department of Resource & Environment Science, Beijing Normal University, Beijing*, 100875, *China*)

Abstract A remote observation of any plant canopy derives from the collective effect of all the individual component parts including leaves, stems, flowers, and the soil background when the canopy is sparse. Therefore, canopy remote signatures can best understood by characterizing at least the most important components. The most important radiative components in live vegetation are leaves. The partitioning of radiation as reflectance transmitted , or absorbed energy depends on a number of factors including leaf cellar structure, leaf pubescence and roughness, leaf morphology, and leaf surface characteristics[1-4].

Reflectance from leaves can be thought of as having both Lambertian (diffuse) and non-Lambertian (specular) components. The diffuse, Lambertain character of leaf reflectance emanates primarily from the interior of the leaf through multiple scattering. The specular and non-Lambertain character of the leaf reflectance arises at the surface of the leaf[5]. In this paper, we introduce a laboratory goniometer, which was designed and built to measure and model light scattered by individual plant leaves. Goniometric measurements were taken during the summer of 1995 on individual plant leaves of soybean, corn, cotton in Changchun. Source wavebands selected were VIS band (600—690nm) and NIR band (690—760nm), and three illumination angles were used, 20°, 40°, and 60° from the normal on both the adaxial(top) and abaxial(bottom) side of leaves. View zenith angles are also used, 20°, 40°, and 60° for every incident angle. Reflected radiation was measured at 10° increments between 0° and 350° along view zenith angles and illumination angles. The polaroids of 0° and 90° are used to investigate polarized reflectance of leaf in the visible and near infrared wavelength ranges. These results shows the leaf BRDF depends strongly on wavelength, and, has a marked dependence on source incidence angle, view zenith angle and view azimuth angle. The bidirectional reflectance characteristics of individual leaves should be useful in formulating mathematical representations of non-Lambertian leaf properties in radiative transfer models, and this work be continued further to obtain detailed information for s variety of species and leaf conditions.

Key words BRDF, Back reflectance, Face reflectance, Specular reflectance, Diffuse reflectance

1 INTRODUCTION

Leaves in a canopy are oriented at a variety of angles and are subjected to illumination at different source incidence angles. Models of canopy reflectance have generally assumed Lambertian scattering properties for the scattered leaves. Measurements have shown that this is not always a good assumption because the reflectance from individual leaves can have significant specular components[1,5-7] Reflectance from leaves can be thought of as having both Lambertian (diffuse) and non-Lambertian (specular) components.

Radiation incident on a leaf may be transmitted into the leaf ,specularly reflected, or scattered at leaf surface. The optical mechanism and the extent of its effect will depend on the incidence angle and the roughness of surface elements. Leaf surfaces can be considered to be comprised of irregular facets. Each facet may specularly reflect intercepted radiation directly, internally refract and reflect radiation diffusedly, or absorb radiation. The scattered radiation directed back through the first surface of the leaf is measured as reflectance and is considered diffuse. Therefore, The diffusive character of leaf reflectance

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is derived by the multiple scattering of radiation within the leaf structure, and can be calculated with Lambert 's law·

Specularly reflected visible and near-infrared radiation is believed to be a surface phenomenon; i·e·, it is dependent on surface characteristics of the leaf· A number of researchers have exploited the specular nature of radiation reflected by a surface to study leaf reflectance· They found the intensity of reflectance increased with increasing incidence angles· Surface characteristics of the leaf influenced the extent of this increase· And, specularly reflected radiation is polarized· This property has allowed the separation of specularly reflected radiation from multify scattered reflectance and the assessment of the contribution of specularly reflected radiation to overall reflectance· The effect of specular reflectance on leaf optical properties is not negligible at large source incidence angles, especially in wavebands of high absorption·

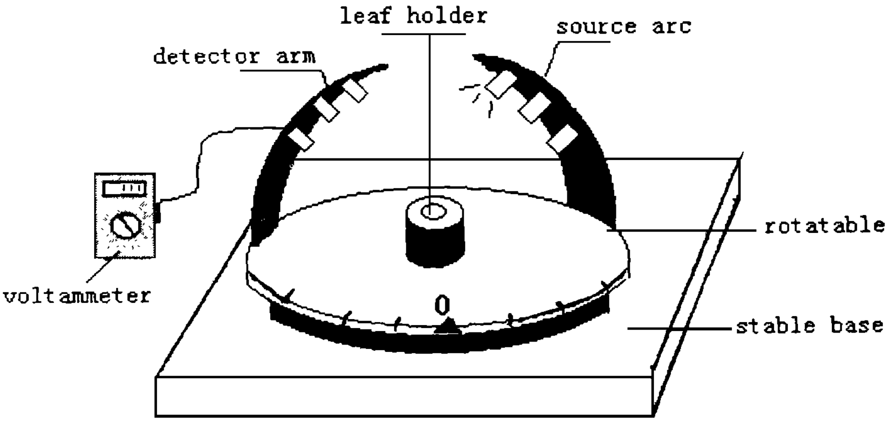
Both diffuse and specular reflectance are dependent on the physical and chemical structure of the leaf , the geometry of the internal structure and of the leaf surface being the primary factor influencing differences in reflectance among leaves· Because leaves are the major contributors to the reflectance from remotely sensed vegetated surfaces, the bi-directional scattering properties of individual leaves should be characterized· Scattering properties of individual leaves at a variety of view zenith and azimuth angles can be used to develop the scattering phase function for leaves used in detailed models of radiate transfer in vegetation·

Therefore, laboratory characterization of the optical properties of leaves is of immediate interest· Typical scattering curves for many species of individual leaf need to be documented to create a reference point for future work· The objectives of this work are to model a simple function to represent the scattering of leaves and apply to canopy radiative transfer models·

2 MATERIALS AND METHODS

2.1 Apparatus Design

Angular distributions of reflectance of healthy individual corn, cotton and soybean leaves were measured in the visible (VIS) and near-infrared (NIR) portions of the electromagnetic spectrum (600—690 nm and 690—760 nm, respectively) with a specially designed goniometer· The goniometer consisted of a stable base, a arc with mounted light source which was fixed on the base, a detector arm which had the same height as the source arc (and there was a angle of 180° between the detector arm and the arc), a rotatable stage, a leaf holder centered on the pivot axis, two polarioids (angle 0° and 90°, respectively) (Fig· 1)· The apparatus could adjust the source incident angle (achieved by altering the source position



Fig· 1 Bidirectional reflectance apparatus with stable base, rotatable stage, light source arc, detector arm, movable light source and detector, leaf holder on the arc), view zenith angles (achieved by altering the detector position on the arm) and view azimuth angles (achieved by rotating the stage)[8,9].

2.2 Procedure

Measurements were taken on intact leaves of corn, cotton, and soybean, which were collected from greenhouse near the laboratory in Chang Chun Optical Fine Mechanical Institute. The leaves used received adequate lighting, were not shaded, and had no disease. As we know, most leaves are different markedly in the structure of their two sides, and show corresponding differences in their reflectance curves. Therefore, Every leaf was measured both the leaf face and the back of the leaf. The terms "face reflectance" will be used here to indicate reflectance with the leaf face (adaxial surface) toward the light source. Similarly "back reflectance"indicates that the light was falling on the abaxial side of the leaf[10].

Leaves were positioned horizontally in the leaf holder at a constant distance from the detector. The illuminated areas of leaves are always constant and less than the platform which loads leaf. No additional precautions were taken to prevent water loss form leaves, because the time of measurement was so short that we thought the water content of leaf is constant during the process of measurement.

Measurements were made in a dark room, in case of stray light. The source wavebands selected were VIS band (600—690 nm) and NIR band (690—760 nm), and three illumination angles were used, 20°, 40° and 60° from the normal on both the adaxial (top) and abaxial (bottom) side of leaf. Reflected radiation were measured at 20° increments between view zenith angle of 20° and 60°. View azimuth angles were taken every 10° from 0° to 350°. At 0° azimuth the light was directed toward the detector so that at a 180° azimuth the detector would be behind the light source, i.e., lying in the principal plane (Fig. 2), where the principal plane is defined by the normal to the leaf and the azimuth of the illumination source.

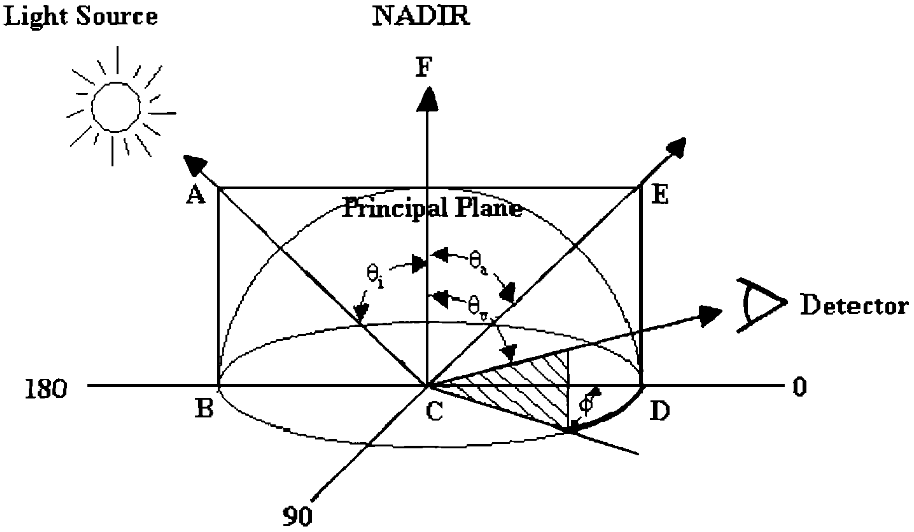


Fig. 2 Coordinate system used in the bidirectional leaf spectral property measurements. Light source is positioned at zenith angle θ_i defined by angle ACF and azimuth 180° and the detector is positioned at view zenith θ_v and azimuth ϕ. ABCD defines the principal plane. FCE defines the specular angle θ_a

The data collection was controlled by hand so that a set of reflectance measurements for one incident angle on a leaf was acquired in 10 minutes. In advance we have assumed that MgO reference panel was non-Lambertian, the radiance of MgO reference panel was measured at the same condition which the observed radiance of leaf was measured (note: the radiance was measured by the output value of voltammeter). The reflectance factor of leaf was calculated by dividing the observed radiance by the radiance from a MgO reference panel at the same illumination and view conditions (Nicodemus *et al*. 1977).

3 RESULTS AND DISCUSSION

3.1 The Characteristic Reflectance Curves Varying with Wavelength

These measurements were made by integrating sphere. The wavelength used ranged from 368.4nm to 1113.7nm. The number of integration times is eight. We measured not only the reflectance of single leaf, but also the reflectance of double leaves. Fig. 3-A shows the radiation curves of single leaf, Fig. 3-B shows the radiation curves of double leaves. Fig. 3-C and Fig. 3-D indicate the reflectance curves of leaf (single leaf, double leaves respectively). Because the output value of source light was very small between 1019.3 nm and 1113.7 nm, these data were useless and should be rejected.

3.2 Visible Region

Fig. 3-C is similar to Fig. 3-D in visible region, they all show that the reflectance is low (approximately 5%-15%)[5] and has a peak at approximately 559 nm in the green region which accounts for the green color of leaf. And, the reflectance of corn leaf is highest than the reflectance of soybean leaf or cotton leaf, and the reflectance of soybean leaf is close to the reflectance of cotton leaf. The reflectance of single leaf is close to reflectance of double leaves in VIS. In this region of the electromagnetic spectrum, chlorophyll and other pigments strongly absorb most of the energy, thus reducing the amount of radiation reflected.

3.3 Near-Infrared Region

The reflectance of leaf suddenly rises between VIS and NIR. In near-infrared region the reflectance of three types of leaf is stable respectively. Fig. 3-C shows that, by contrast with VIS, the reflectance of corn leaf is lowest and the reflectance of soybean comes second. Because the reflectance character of single leaf in NIR is dominated by the internal structure of leaf, pigments contribute little. The difference of three types of leaf is so large that there are markedly differences in their reflectance. In visible region, although there are differences in their reflectance, they are far less than the differences in NIR. Fig. 3-D is very different to Fig. 3-C, Fig. 3-D indicates that the reflectance of three types of leaf is very close. The reflectance of double leaves is higher than the reflectance of single leaf. The reflectance of many leaf layers should be high caused by appended reflectance. Because the radiation enters the first leaf (i.e. the topest leaf), and will be reflected by the second leaf; the reflected radiation by the second will enter the first leaf again, at last strengthening the reflected radiation by the first leaf (Fig. 3-E).

3.4 Dependence on Illumination and View Angles

The following measurements were made by the goniometer, which has been introduced (Fig. 1). The following measurements were made under two circumstances that are 1) the leaf face (adaxial surface) toward the light source; 2) the leaf back (abaxial surface) toward the light source. Based on the definition of BRDF, we studied the reflectance curves varying with illumination and view angles.

3.5 The Reflectance Curve Varying with Incident Angles

Fig. 4, Fig. 5 summarize the reflectance curves of soybean leaf and corn leaf varied with the source zenith angles. From these figures, we can see that the face/back reflectance increased as the source zenith angle increased, although there were some small undulations. For corn leaf, the face reflectance increased faster than the back reflectance when the incident angle increased. But the increments of reflectance in two sides of soybean leaf are same when the source incident angle increased. Although the reflectance in VIS is lower than the reflectance in NIR, The changes of reflectance with changes in the source zenith angle in VIS wavebands is principally identical to the changes in NIR. At greater source incident angles reflectance distributions become more non-Lambertian in character[1,7].

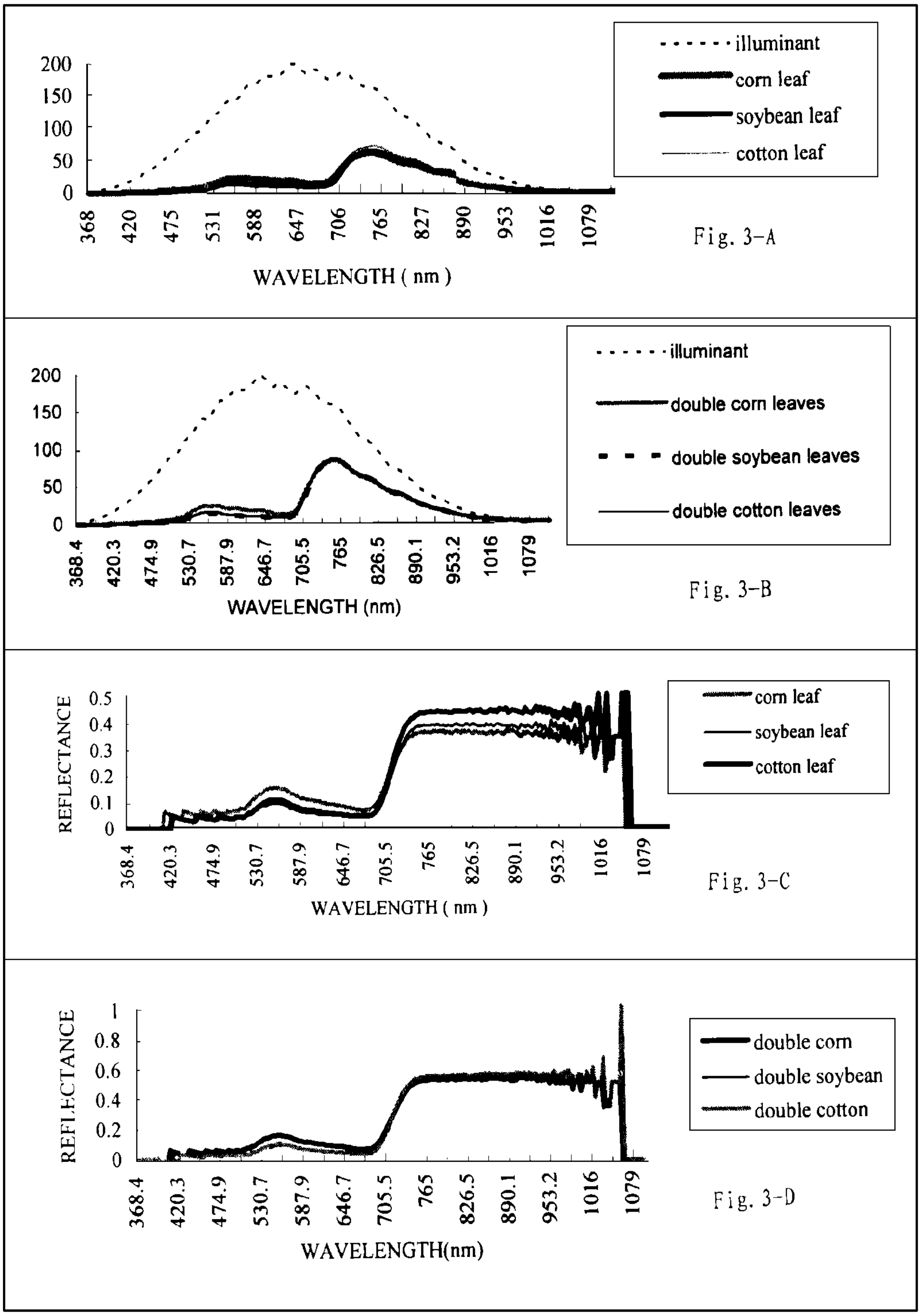


Fig. 3(A—D) The radiation and reflectance curves of leaf (1995.8)

(A) The radiation curves of single leaf ; (B) The radiation curves of double leaves;

(C) The reflectance curves of single leaves ; (D) The reflectance curves of double leaves

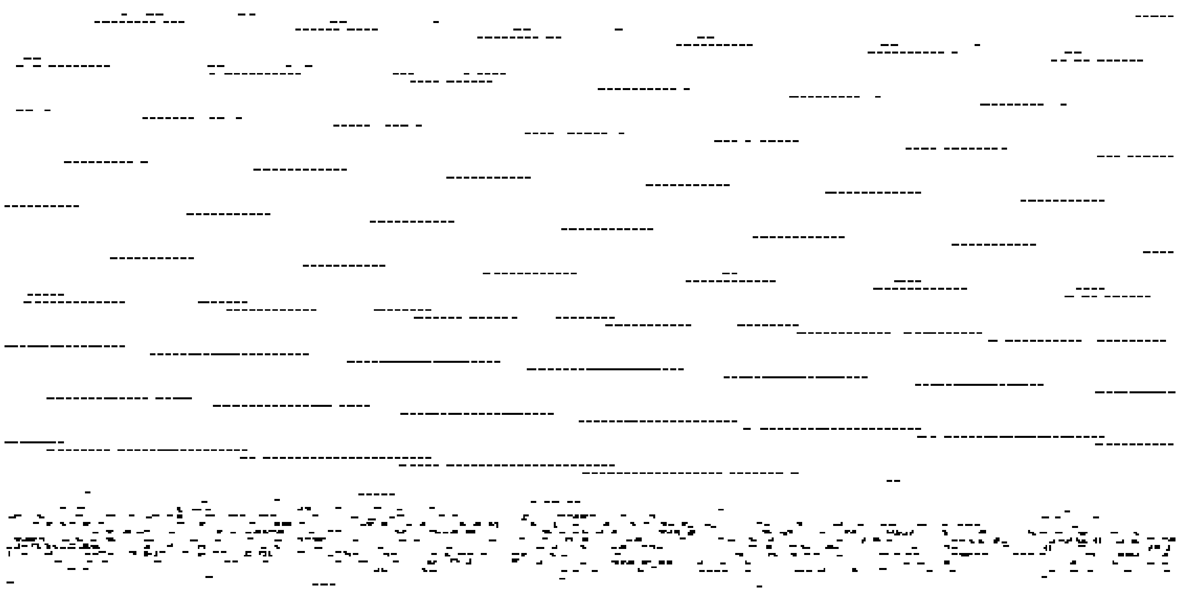


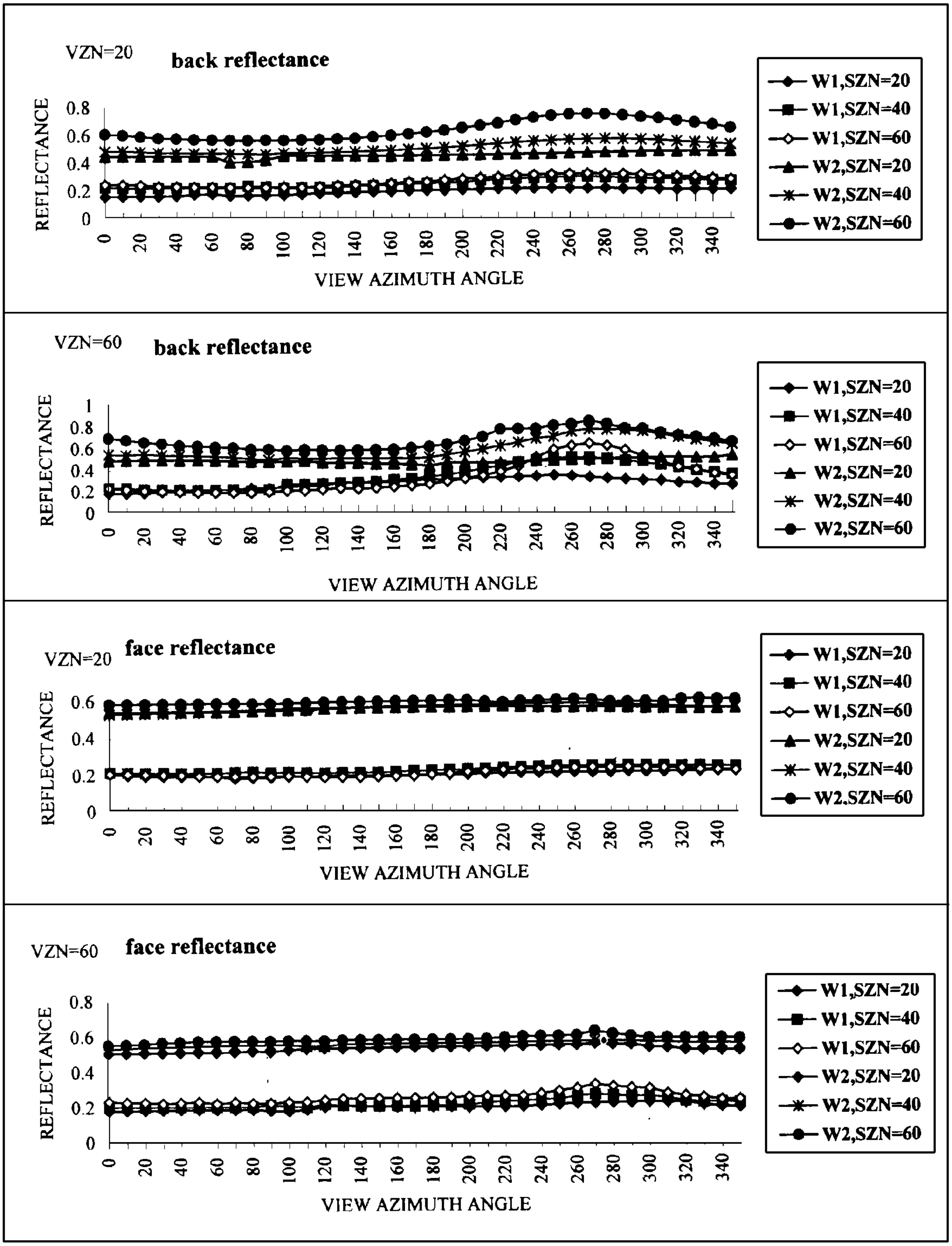
Fig. 3-E The sketch map of the influence of the leaf layers on the leaf reflectance

Soybean leaf was selected to research the changes in the leaf reflectance under the influence of polaroid. The angles of polarization are used, 0°, 90°. The following figures (Table 1 and Table 2) show a comparison of reflectance under three conditions. By contrast, the polaroid affected the reflectance of leaf, and the face reflectance in VIS is affected most by the 90° polaroid, the change of face reflectance with changes in the source zenith angle in VIS wavebands under the 90° polarization smaller than the change under the non-polarization. Among three source incident angles, the leaf reflectance in the source incidence angle of 60° was affected markedly by the polaroid, i.e. the specular reflectance is dominant. The reflectance for near-normal source incidence angle (20°) changed slightly with the change of the polaroid[11-13].

Table 1 Comparison of three average back reflectance

incident angle	view zenith angle	waveband(nm)	R_w	R_0	R_{90}	$\Delta R_0/R$ $=(R_w-R_0)/R_w$	$\Delta R_{90}/R_w$ $=(R_w-R_{90})/R_w$
20°	20°	W1	0.198370	0.195609	0.195121	1.39%	1.63%
20°	60°	W1	0.233964	0.229004	0.227460	2.12%	2.78%
40°	20°	W1	0.265285	0.254965	0.254170	3.89%	4.19%
40°	60°	W1	0.353063	0.335455	0.333221	4.98%	5.62%
60°	20°	W1	0.271475	0.254694	0.251161	6.18%	7.48%
60°	60°	W1	0.323246	0.295041	0.289446	8.73%	10.46%
20°	20°	W2	0.449772	0.443385	0.440867	1.42%	1.98%
20°	60°	W2	0.486902	0.476044	0.472587	2.23%	2.94%
40°	20°	W2	0.524377	0.503768	0.501986	3.93%	4.27%
40°	60°	W2	0.598336	0.567641	0.563094	5.13%	5.98%
60°	20°	W2	0.647653	0.607110	0.598690	6.26%	7.56%
60°	60°	W2	0.751029	0.686365	0.661731	8.61%	11.89%

R_w = average reflectance in non-polarization, R_0 = average reflectance in 0° polarization, R_{90} = average reflectance in 90° polarization.



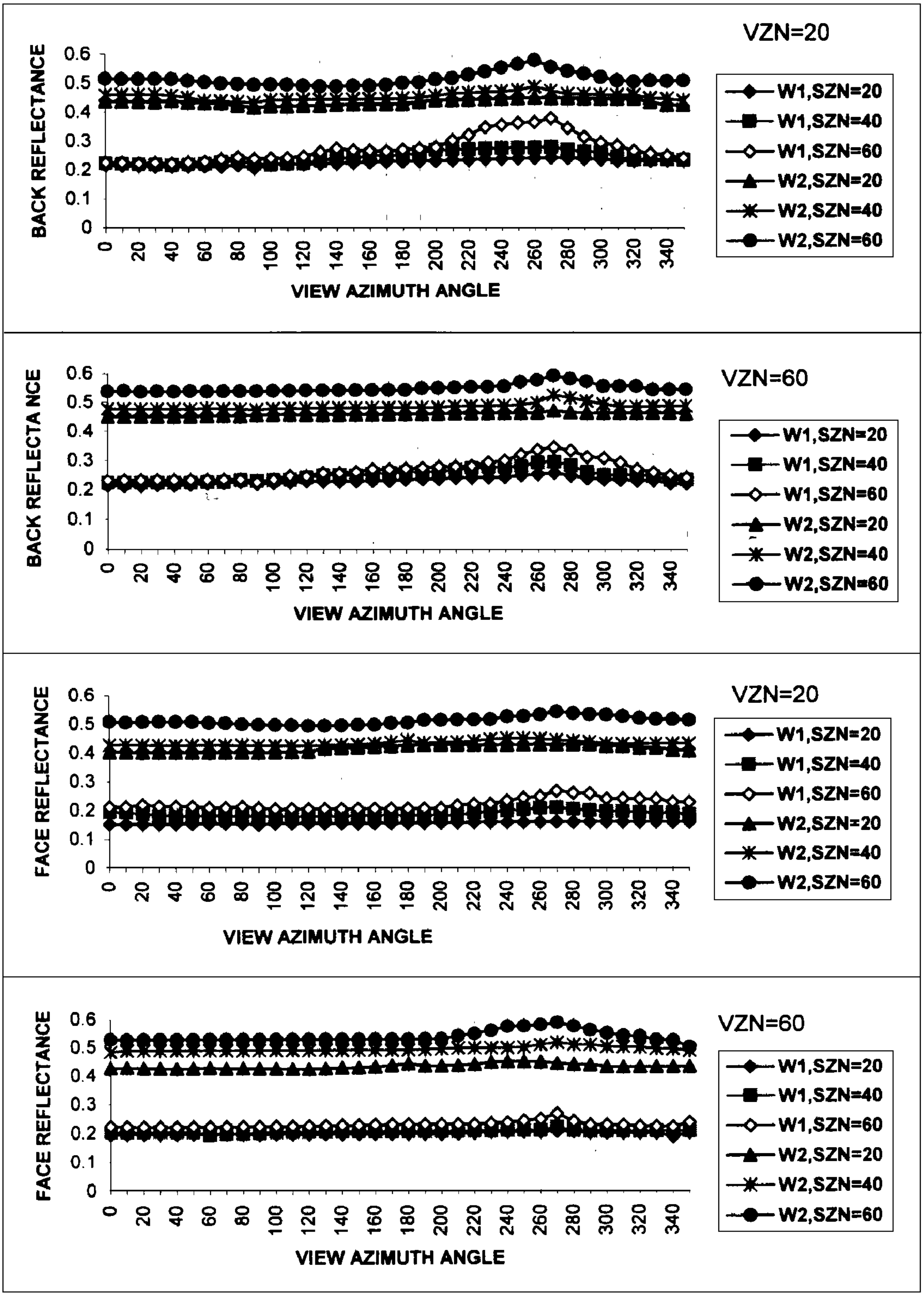
VZN=20 back reflectance

VZN=60 back reflectance

VZN=20 face reflectance

VZN=60 face reflectance

Fig. 4 The reflectance curves of soybean leaf varying with source zenith angle



Fig·5 The reflectance curves of corn leaf varying with source zenith angle

Table 2 Comparison of three average face reflectance

incident angle	view zenith angle	waveband(nm)	R_w	R_0	R_{90}	$\Delta R_0/R = (R_w-R_0)/R_w$	$\Delta R_{90}/R_w = (R_w-R_{90})/R_w$
20°	20°	W1	0.203670	0.202733	0.202183	0.46%	0.73%
20°	60°	W1	0.208646	0.208245	0.204872	1.65%	1.81%
40°	20°	W1	0.208965	0.200669	0.199603	3.97%	4.48%
40°	60°	W1	0.217609	0.206706	0.204378	5.01%	6.08%
60°	20°	W1	0.220904	0.206147	0.204910	6.68%	7.24%
60°	60°	W1	0.224142	0.207488	0.205381	7.43%	8.37%
20°	20°	W2	0.566625	0.562715	0.561752	0.69%	0.86%
20°	60°	W2	0.585779	0.575938	0.573711	1.68%	2.06%
40°	20°	W2	0.604753	0.583344	0.555556	3.54%	4.37%
40°	60°	W2	0.621479	0.590032	0.583320	5.06%	6.14%
60°	20°	W2	0.643664	0.598736	0.596290	6.98%	7.36%
60°	60°	W2	0.650424	0.600927	0.595528	7.61%	8.44%

R_w = average reflectance in non-polarization, R_0 = average reflectance in 0° polarization, R_{90} = average reflectance in 90° polarization.

3.6 The Reflectance Curves Varying with View Zenith Angles

Soybean leaf was studied to illustrate the change in bidirectional reflectance with changing view zenith angle. Fig. 6 shows a comparison of the back/face reflectance at view zenith angles ranging from 20°—60° at 20° intervals in VIS (600—690nm) and NIR (690—760nm) wavebands, As at same source zenith angle (20° or 60°), the reflectance of leaf increased as the view zenith angle increased for most view azimuth angles, and the spectrum band selected affected faintly the magnitude of the change.

In addition ,we can see reflectance distribution in the VIS and NIR at 20° source incident angle varied only slightly in view angle, and the face reflectance in VIS deviated most slightly from that of a Lambertian surface.

By contrast, the changes of reflectance with the changes in view zenith angle are smaller than the changes with the changes in source incidence angle. It comes to the conclusion that the leaf reflectance is more affected by the source incidence angle.

3.7 The Reflectance Curves Varying with View Azimuth Angles

In the front discussion we have demonstrated that the leaf reflectance is related to the source incidence angle and the view zenith angle. On the basis of the definition of BRDF, the relationship between the leaf reflectance and the view azimuth angle should be discussed.

From those curves, it is apparently that the reflectance for a leaf at 270° view azimuth angle is the peak value whatever the source incident angle and the leaf species varies. The peak value increased when the source incident angle or/and the view zenith angle increased. At a near-normal source incident angle of 20°, the reflectance curves varied slightly with changes in the view azimuth angle, by contrast, the reflectance curves varied markedly at 60° source incident angle. The angular dependence of the reflectance maxima in the azimuthal range about 270° indicates specular reflectance[1,7,11]. In particular, Fig. 5 indicate that the reflectance at 270° azimuth angle is affected notablely by the polaroid, the reflectance value at 270° azimuth angle decreased as used a polariod, i.e. the polar portion of reflectance contributed more to total reflectance than the diffuse component at 270° azimuth angle.

4 SUMMARY

These results suggest that the magnitude of the light reflected by the leaf may be significant compared to that scattered by the interior of leaf—and may be an important part of the total light scattered by a canopy.

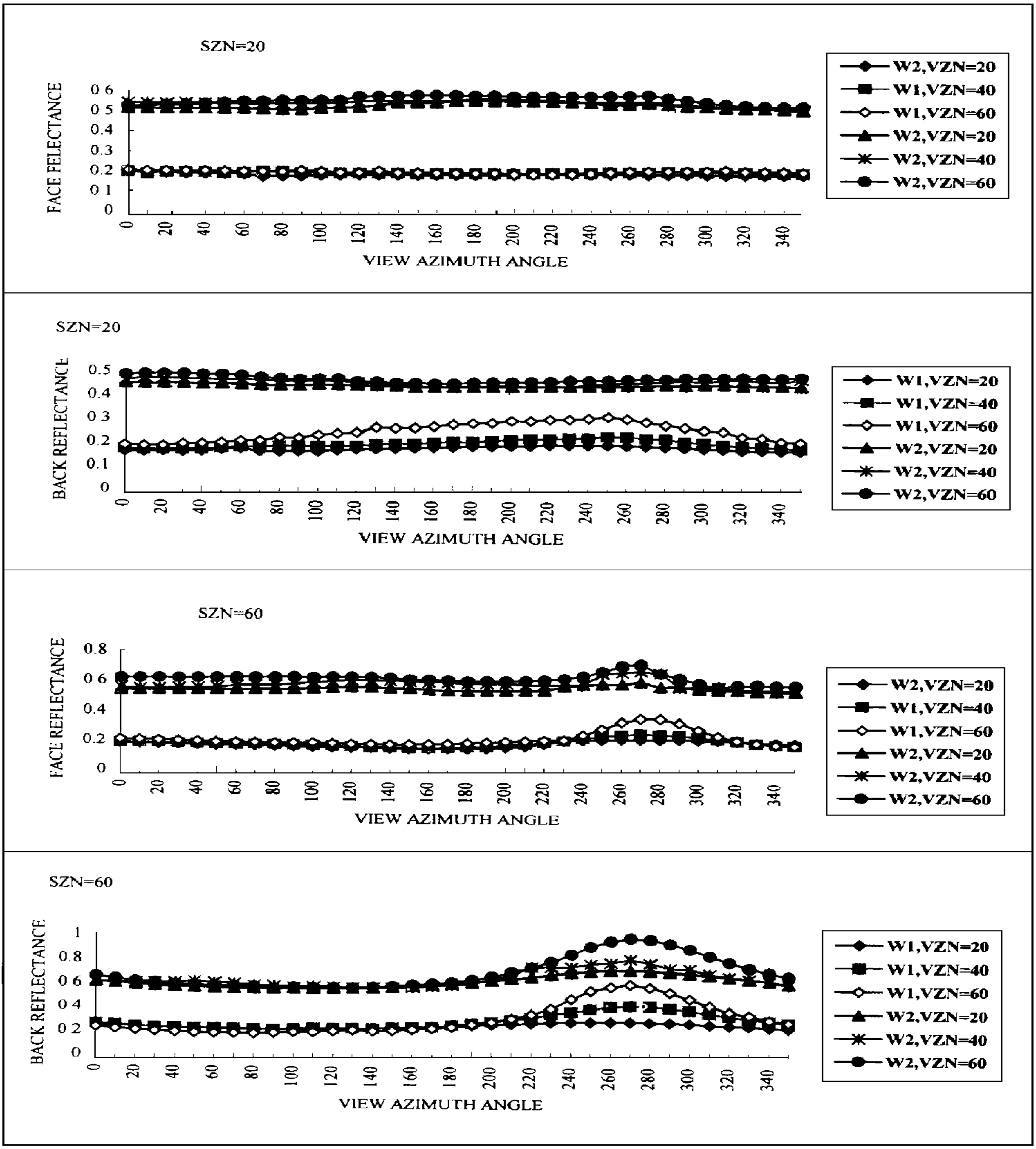


Fig. 6 The reflectance curves of soybean leaf varying with view zenith angle

Bidirectional reflectance factor of individual corn, cotton and soybean leaves were measured as a function of source incidence angle, view zenith angle and view azimuth angle in VIS and NIR portions of the electromagnetic spectrum. The results revealed a great variation in reflectance factor values from leaf surfaces when source incidence and view angles were altered. These measurements indicate the reflectance value in VIS and NIR increased with increasing source incidence angle and/or view zenith angle. The peak value of leaf reflectance is at 270° view azimuth angle, a large part of this scattering can be attributed to specular reflectance, moreover can be tested by the measurements under the polaroid.

The face reflectance is different from the back reflectance that can result in the surface characteristics. And the change of face reflectance varied with source incidence and view angles is also different from the back reflectance.

All these results suggest that the complete reflectance distributions are necessary to define scattering phase functions for leaves to be used in detailed radiative transfer models. This work should be continued for a variety of species and leaf conditions. And, research in separating the specular and diffuse components from total reflectance needs to be continued to the further enhance radiative transfer models.

REFERENCES

[1] Wolley, J. T. Reflectance and transmittance of light by leaves. *Plant Physiol.*, 1971, **47**: 656—662.

[2] Gausman, H. W. Reflectance of leaf components. *Remote Sens. Environ.*, 1977, **6**: 1—9.

[3] Norman, J. M., Welles, J. M., Walter, E. A. Contrasts among bidirectional reflectance of leaves, canopies, and soils. *IEEE Trans. Geo. Remote Sens.*, 1985, **23**(5): 659—667.

[4] Knipling, E. B. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. *Remote Sens. Environ.*, 1970, **1**: 155—159.

[5] Copper, K. D., Smith, J. A., Pitts, D. Reflectance of a vegetation canopy using the adding method. *Appl. Opt.* 1982, **21**: 4, 112—4, 118.

[6] Vanderbilt, V. C., Grant L., Daughtry, C. S. T. Polarization of light scattered by vegetation. Proc. *IEEE*, 1985, **73**: 1,012—1,024.

[7] Breece, H. T., Holmes, R. A. Bidirectional scattering characteristics of healthy green soybean and corn leaves in vivo. *Appl. Opt.*, 1971, **10**: 119—127.

[8] Thomas, W. B., James, A. S., Joann, M. H. Bidirectional scattering of light from tree leaves. *Remote Sens. Environ.* 1989, **29**: 175—183.

[9] Kestner, J. M., Leidecker, H. W., Irons, J. R., Smith, J. A., Brakke, T. W., Horning, N. A. Goniometric observations of light scattered from soils and leaves. *J. Wave-Mater. Interaction*, 1988, **3**(2): 189—198.

[10] Gates, D. M., Keegan, H. J., Schleter, J. C., Weidner, V. R. Spectral properties of plants. *Appl. Opt.*, 1965, **4**: 11—20.

[11] Grant, L., Daughtry, C. S. T., Vanderbilt, V. C. Variations in the polarized leaf reflectance of Sorghum bicolor. *Remote Sens. Environ.*, 1987, **21**: 333—339.

[12] Vanderbilt, V. C., de Venecia, K. J. Specular, diffuse and polarized imagery of an oat canopy. *IEEE Trans. Geo. Remote Sens.*, 1988, **26**(4): 451—462.

[13] Juhan Ross, Aleksandr Marshak. The influence of leaf orientation and the specular component of leaf reflectance on the canopy bidirectional reflectance. *Remote Sens. Environ.*, 1989, **27**: 251—260.

AUTHOR

Zhang Hong was born in Anhui province on May 25, 1972. She received the B.S. degree in theoretical physics from Beijing Normal University in 1994. She is currently graduate student of the Department of Resource and Environment at Beijing Normal University. Her interests are in cartography and remote sensing. Now her primary research is in the reflection and transmission of single leaf.

单叶的反射特性

张　红　朱启疆
(北京师范大学资源环境系，北京，100875，中国)

摘　要　任何植物冠层的遥感信息都是包含叶、茎、花、周围的土壤（当冠层较稀疏时）信息的信息集合体。因此，要研究植物冠层的特性需首先研究其最重要的组成成分。正如我们所知，通过植物冠层的能量变化主要是通过叶片的反射、透射、吸收来实现的，因此叶片的光学特性必须经过适当的定量化、特征化，以发展复杂的、具有可靠预测性的冠层辐射传输模型。

植物冠层叶片有不同的角度，受不同入射方向的太阳光照射。一般地，冠层反射模型都假定叶片为一个漫反射体。但 Rvachev 和 Guminetskii 等多人的实验表明叶片的反射在某些情况下反映出较强的镜面反射。因此叶片的反射特性可以为既有漫反射性（朗伯性）又有镜面反射性（非朗伯性）。

叶片反射的朗伯性主要是由叶内部结构的多次散射引起的，并且可用朗伯定律来计算。当入射光线仅被考虑为法线或近法线方向时，镜面反射对整个反射的贡献很小，镜面反射的情况可被忽略。许多研究表明当增大入射角时，镜面反射明显，叶片反射率增大，且增加程度随叶表面特征变化而变化，这就说明镜面反射是一个叶表面现象。并且镜面反射光是极化光，这个特性使得分离镜面反射和朗伯反射成为可能。

在研究植被反射时，叶片是最重要的因子，因此单叶反射特性的定性、定量研究是极其必要的。多物种的单叶反射特征曲线和数据是冠层反射模型的基础，因此自1994年起，我们连续3年对单叶的反射特性进行了极其细致的研究。我们采用特制的光学测角仪在室内对玉米、大豆、棉花的叶片进行测量。测量时间均选在夏季，植物长势良好，无任何病虫害。选取的波段为可见（600—690nm）和近红外（690—760nm）。照射的入射角分别为20°，40°，60°，对应每一个入射角，选取的探测高度角为20°，40°，60°，方位角在0°到350°之间变化，间隔为10°。对于每一个叶片，我们都测量了其正、反面的反射特性，以区别叶片正、反面的光学特性。同时，为了研究叶片的镜面反射特性，我们使用了两个偏振片0°和90°，以研究在偏振片的影响下的叶片反射性质的变化。

通过对实验数据的分析我们发现不同物种的叶片反射曲线大致相同，但也存在着一些变化。当增大照射角或观测高度角时，在可见和近红外两个波段范围的反射值均增大。无论照射角和探测高度角如何变化，在270°方位角时反射率值均有一个峰值，这个峰值的形式主要是由镜面反射引起的，并且偏振片的实验可证实。叶片的正向反射率不同于背向反射率，这主要是由于正面、背面不同的表面特征。并且正向反射率随照射角和探测角变化的情况也不同于背向反射率。

所有这些结论表明，为了建立更详细而又准确的冠层辐射传输模型，必须研究单叶的反射角分布情况。并且对于单叶的反射角分布研究，必须针对不同的物种和叶状态，建立相应的反射角分布函数。对于镜面反射和漫反射的生物物理机理有待更进一步深入探讨，并能建立各自的特征函数。对于叶片的水含量分析、季节分析也需要进行进一步的研究。总之，单叶的反射特性研究是冠层反射研究的基础，必须足够重视，才能推动冠层反射模型的进一步发展。

关键词　二向性反射分布函数，后向反射，前向反射，镜面反射，漫反射