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Linear Polarization of Light by Two Wheat Canopies Measured at Many View Angles

by V. C. Vanderbilt, L. L. Biehl, B. F. Robinson, M. E. Bauer and A. S. Vanderbilt

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16. Abstract

This paper reports research to understand how visible light is linearly polarized and reflected by wheat as a function of sun-view directions, crop development stage, and wavelength. The analysis is based on 200 spectra taken continuously in wavelength from 0.45 to 0.72 μm in 33 view directions using an Exotech model 20C spectroradiometer six meters above two wheat canopies in the boot and fully headed maturity stages. The analysis results show that the amount of linearly polarized light from the wheat canopies is greatest in the blue spectral region and decreases gradually with increasing wavelength. The results show that the linearly polarized light from the canopies is generally greatest in the azimuth direction of the sun and tends toward zero as the view direction tends toward the direction of the hot spot or anti-solar point. The results demonstrate that the single angle, angle of incidence of sunlight on the leaf, explains almost all of the variation of the amount of polarized light with sun-view direction.

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LINEAR POLARIZATION OF LIGHT BY TWO WHEAT CANOPIES MEASURED AT MANY VIEW ANGLES

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Summary

This paper reports research to understand how visible light is linearly polarized and reflected by wheat as a function of sun-view directions, crop development stage, and wavelength. The analysis is based on 200 spectra taken continuously in wavelength from 0.45 to 0.72 um in 33 view directions using an Exotech model 20C spectroradiomter six meters above two wheat canopies in the boot and fully headed maturity stages. The analysis results show that the amount of linearly polarized light from the wheat canopies is greatest in the blue spectral region and decreases gradually with increasing wavelength. The results show that the linearly polarized light from the canopies is generally greatest in the azimuth direction of the sun and tends toward zero as the view direction tends toward the direction of the hot spot or anti-solar point. The results demonstrate that the single angle, angle of incidence of sunlight on the leaf, explains almost all of the variation of the amount of polarized light with sun-view direction.

1. INTRODUCTION

Remote sensing is potentially capable of providing information to aid in predicting the global production of key, economically important crops. The LACIE project, while demonstrating this potential for wheat, showed that better approaches to crop discrimination and to assessing the condition of crops are also needed (1). Current approaches to solve these problems involve satellite data from the visible and near infrared spectral regions. It is possible that more information, information in data from other spectral regions (e.g. middle infrared, thermal infrared, and microwave) and in polarization data from all spectral regions, may be needed if we are to better discriminate crops and assess their condition with remotely sensed data. This paper reports research to understand how visible light is linearly polarized and reflected by wheat as a function of sun-view directions, crop development stage, and wavelength.

2. LITERATURE

Using data obtained in the laboratory and with an aircraft, Egan, Egan and Hallock, and Egan, et al. found evidence that the degree of linear polarization of the response of a scene provides additional discriminatory information with which to classify the scene(2,3,4,5). Egan reached a potentially important conclusion that drying of leaves generally increases their depolarizing properties(5). Curran used a photographic measurement technique to relate soil surface moisture to the proportion of polarized light in the scene response(6,7). In an appendix Curran presented data showing a possible link between the percent linear polarization of a canopy and its roughness(6).

3. MATERIALS AND METHODS

Data were acquired on wheat (Triticum aestivum L.) on 19 June and 17 July during 1976 at Williston, North Dakota, USA (Lat. 48 8', Long. 103 44') in support of the Large Area Crop Inventory Experiment (LACIE).(8) On each date agronomic measurements were made to characterize the condition of the wheat canopy (Table I). Meteorologic data (Table I) were acquired at the North Dakota Agricultural Experiment Station at Williston, located near the test sites.

More than 200 spectra (visible wavelengths, 0.46 to 0.72 um) were acquired using an Exotech model 20C spectroradiometer. (Exotech, Inc., Gaithersburg, Maryland) positioned 6 m above the soil(9). Spectral data and a photograph of the instrument field of view were taken in each of 33 view directions, eight azimuths (the eight points of the compass) at four zenith angles (15 , 30 , 45 and 60) plus nadir. A polarization analyzer, a sheet of polarizing film mounted in a rotateable bracket, was attached to the spectroradiometer at the entrance port. In each view direction, two spectra were acquired, one with the polarization analyzer oriented for maximum detector signal amplitude and the other with the analyzer oriented for minimum signal. On 19 june data were acquired from -2h to +2h from solar noon. On 17 July data were acquired from -2h to -0.3h before solar noon and from +1hto +2h after solar noon.

Analysis of the polarizing properties of the canopy was performed on data at 13 wavelenths selected at 0.02 um intervals from 0.48 to 0.72 um. At a particular wavelength the spectral resolution of the data is better than 1.0% of that wavelength. At each wavelength selected for analysis, linear polarization was computed as illustrated in Figure 1. For a view direction the two reflectance factors representing the maximum and minimum amount of light transmitted by the polarization analyzer, R_{MAX} and R_{MIN} (Figure 1a), were combined to obtain the following: $R_I = (R_{MAX} + R_{MIN})/2.0$; $R_Q = (R_{MAX} - R_{MIN})/2.0$; Linear polarization = 100% R_Q/R_I The term R_I, measured in a particular view direction, equals the reflectance factor of the canopy measured in the same view direction but without the polarization analyzer. The term R_Q, measured in a particular view direction, is the ratio (percent) of the linearly polarized radiance of the canopy divided by the radiance of a perfectly white, perfectly diffuse calibration panel. The linear polarization, measured in a particular view direction, is the ratio (percent) of the linearly polarized radiance of the canopy divided by the radiance of the canopy.

4. RESULTS

The linear polarization of wheat was plotted as a function of wavelength and view direction for two crop development stages. The analysis assumes there are no atmospheric effects. The R_{MAX}, R_{MIN}, R_I, R_Q , and linear polarization are plotted (Figure 1) as a function of wavelength for the wheat canopy measured 19 June 1976, 19 minutes before solar noon for sun-view afternoon for sun-view directions of (31, 134; 60, 135). Figures 1a and 1b show that R_{MAX} and R_{MIN} and their average, R_I, all have a wavelength dependence typical of a green vegetation curve. They have local minima in the blue ($\lambda, R_{MAX}, R_{MIN}, R_I$) = (0.48 um, 3.5%, 2.0%, 2.8%) and red (0.66 um, 3.8%, 2.6%, 3.2%) and local maxima in the green (0.56 um, 7.6%, 6.2% 6.9%) and infrared (0.72 um, > 10%, > 10%, > 10%)

spectral regions. The amount of linearly polarized light, R_Q (Figure 1b), the difference of two curves (Figure 1a) divided by two, decreases essentially monotonically with increasing wavelength and does not have a wavelength dependence typical of green vegetation. In the blue spectral region, 0.48 um, the value of R_Q indicates that the linearly polarized flux from the canopy equals 0.76% of the flux from the calibration panel whereas in the infrared at 0.72 um, the value is 0.44%.

The percent linear polarization (Figure 1c) of the flux scattered toward the spectroradiometer by the canopy, the ratio of the two curves (Figure 1b) times 100%, has local maxima (0.48 um, 0.66 um) where the typical green vegetation reflectance curve has local minima and local minima (0.56 um, 0.72 um) where the typical green vegetation reflectance curve has local maxima. The percent of the linearly polarized light from the canopy for the particular view/illumination angles is generally greater than 10% in the visible spectral region; at 0.48 um 28% of the light scattered by the canopy to the radiometer is linearly polarized. The curve shows a large decrease from 16% at 0.68 um to 2.4% at 0.72 um.

The R_Q is plotted as a function of wavelength for both dates for zenith view angles oriented toward and away from the sun azimuth direction. The value of R_Q, as shown in Figure 2, increases with increasing zenith view angle and is larger for view azimuth directions toward as opposed to away from the sun azimuth direction. The value of R_Q generally increases with decreasing wavelength for the 19 June data (Figure 2a); such a pattern is not evident in the 17 July data.

The linear polarization at 0.62 um (Figure 3) is plotted for both dates, four view zenith directions, and view azimuth directions relative to the sun azimuth; 0 degrees azimuth in Figure 3 represents a view azimuth equal to the sun azimuth and positive angles represent clockwise rotation. The linear polarization data are approximately, not perfectly, symmetric about the 0 degrees azimuth view direction on both dates; there is slight skewness as for each date the maximum value of linear polarization for each zenith view angle occurs always at positive azimuth view angles. The results show that on both dates linear polarization generally increases with increasing view zenith angle; it generally decreases with increasing angular distance from the solar azimuth direction. For example, near 0 to 60 degrees (at 0.62 um) view azimuth and 60 degrees zenith, the linear polarization on 19 June is approximately 14-15 percent (that is, 14-15 percent of the light at 0.62

um reflected by the wheat in this particular view direction is polarized.) Only about 3-4 percent of that light is polarized at the same view zenith but + 180 view azimuth. The data values for preheaded wheat, Figure 3a (Waldron cultivar), are significantly less than the data values for headed wheat, Figure 3b (Ellar cultivar), at large view zenith and small view azimuth angles.

The linear polarization at a wavelength of 0.62 um is plotted for data from 19 June (Figure 4a) and 17 July (Figure 4b) as a function of the angular view directions indicated (Figure 4c). As in Figure 3, 0 degrees azimuth indicates a view direction toward the sun. In each plot the linear polarization in a particular view direction is indicated by topographic notation with contour lines at intervals of 2%. The two plots were prepared using linear interpolation to estimate the positions of the contour lines. A dotted line segment signifies insufficient data were available to position the contour line with assurance. On both dates the linear polarization increases generally with increasing angular distance from the anti-solar point, the canopy hot spot, and is maximum for large view zenith angles about 60 degrees to the right of the sun azimuth direction. For example, on 19 June (Figure 4a) the linear polarization at 0.62 um varied from more than 14 percent at (zenith, azimuth) = (60, 60) view angles to approximately zero at the anti-solar point. Similarly, on 17 July (Figure 4b) the linear polarization varied from about 8 percent at (60,60) to approximately zero at the anti-solar point.

The linear polarization (Figure 5) at a wavelength of 0.62 um is plotted for 19 June (Figure 5a) and 17 July (Figure 5b) for four view zenith angles and angle of incidence, gama, given by 0.5 arccos ($\sin\theta_V \cos(\phi_S - \phi_V) \sin\theta_S + \cos\theta_S \cos\theta_V$) where the angles θ_S, ϕ_S, θ_V, ϕ_V are the zenith and azimuth, sun and view directions. Azimuth angles are measured from north. The equation provides the angle of incidence for any combination of view/illumination angles. Gama is the angle of incidence of a light ray upon a small leaf area correctly oriented to specularly reflect the ray to the spectroradiometer provided the leaf is a specular reflector. Figure 5 shows that most of the variation in linear polarization (Figures 3 and 4) as function of the two variables, view zenith and view azimuth angles, is explained by the single variable, angle of incidence.

5. DISCUSSION

The results, Figures 1 and 2, demonstrate that the light polarizing processes in the two wheat canopies are not wavelength dependent in the manner of green vegetation spectra. The amount of incident flux polarized by the canopy, Figure 1b bottom, monotonically decreases with wavelength, revealing no maximum in the green nor mimima in the blue and green, characteristics typical of green vegetation spectra. The linear polarization, Figure 1c, computed as a ratio, does have significant wavelength dependence. However, the dependence is due to the green vegetation characteristics of the canopy reflectance factor, the denominator of the ratio. From these results, Figure 1 and 2, there appears no need for the spectral polarization of the reflectance factor of the two wheat canopies to be measured with high wavelength resolution in the visible spectral region; a polarization sensor covering the entire visible wavelength region or a large portion of it would suffice. These results support the predictions of a model for linear polarization of light from plant canopies (10).

The results, Figures 3-5, demonstrate that the single variable, angle of incidence of specularly reflected sunlight, explains almost all of the variation of the amount of linear polarization with the two angles view zenith and view azimuth. The angle of incidence is computed knowing that a small area of shiny leaf must be uniquely directioned to specularly reflect sunlight to an observer. These results, Figures 3-5, support the polarization model (10) which predicts that the single variable, angle of incidence, explains much of the variation of the amount of linear polarized light with not only view angles but also sun angles.

Visual observations with polarizing sun glasses suggest the amount of polarized light from a wheat canopy decreases significantly with the advent of the heading development stage. These results, Figure 5, support but do not prove the visual observations. The amount of linearly polarized light is significantly less from the headed canopy, Figure 5b, compared to the preheaded canopy, Figure 5a. However, the data are from two different fields of wheat representing two cultivars and the 7-17 data set was not acquired sufficiently timely to heading to be certain that factors other than heading did not affect the data.

6. ACKNOWLEDGEMENT

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Table I. Ancillary meteorologic and agronomic data.

	Date	
Variable	19 June 76	17 July 76
wind direction	southwest	southeast
wind speed (km/hr)	18	10
cultivar	Waldron	Ellar
maturity stage	boot	milk
rowdirection	east-west	north-south
leaf area index	1.85	0.81

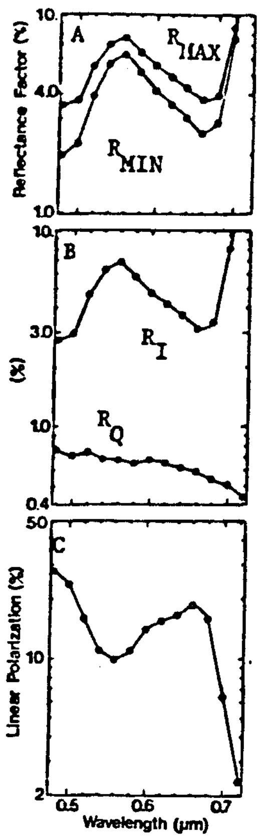


Fig. 1 (above). Calculation of polarization. View direction is toward sun azimuth and at 60° zenith.

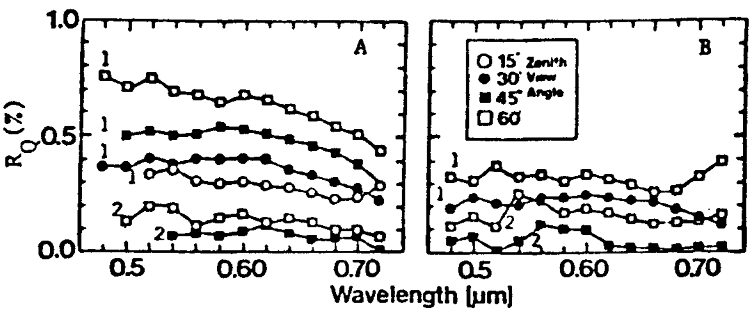


Fig. 2. R_Q for view zenith directions toward (1) and away (2) from sun azimuth direction for wheat on 19 June 1976 (A) and 17 July 1976 (B).

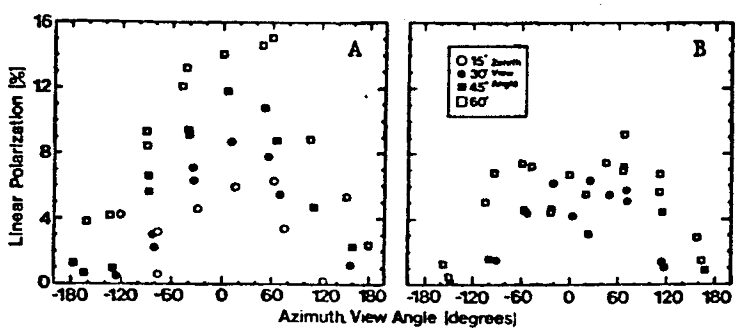
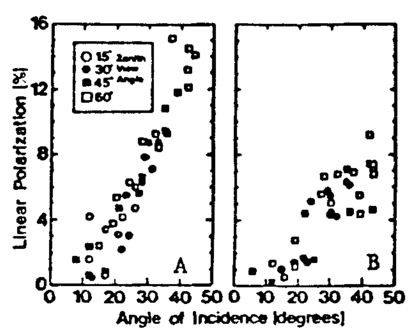


Fig. 3. Linear polarization (%) for view directions of wheat on 19 June 1976 (A) and 17 July 1976 (B). 0° azimuth is toward sun azimuth.

Fig. 5 (right). Linear polarization for angles of incidence of sunlight on wheat on 19 June 1976 (A) and 17 July 1976 (B).



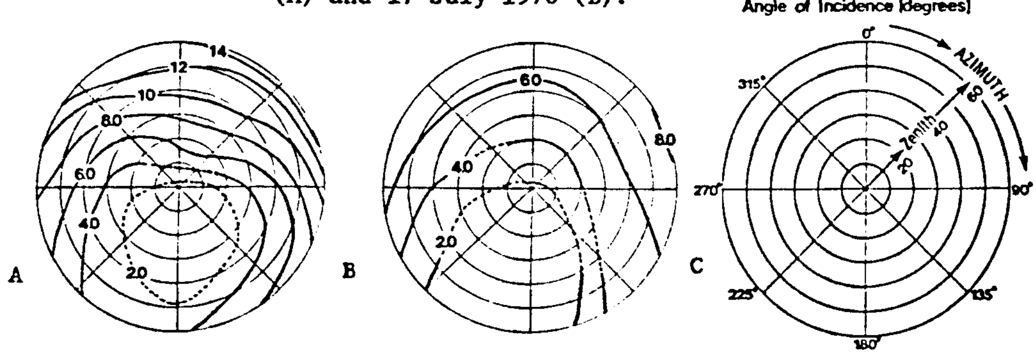


Fig. 4. Linear polarization (%) for view direction (C) of wheat on 19 June 1976 (A) and 17 July 1976 (B). 0° azimuth is toward sun azimuth.