M. Fuchs *et al.*,(1972) *Israel J. agric. Res.* 22(2):63-75.

DIURNAL VARIATIONS OF THE VISIBLE AND NEAR INFRARED REFLECTANCE OF A WHEAT CROP

By

M. FUCHS, G. STANHILL AND ALIDA G. WAANDERS*

A macroscopic description of the scattering of the direct incoming solar radiation by the vegetation canopy and by the soil, is used to predict the diurnal variation of the reflectance of the vegetation stand (including vegetation and soil). The probability that direct solar radiation will encounter plant material determines the relation between the stand reflectance and the solar elevation. Hemispherical reflectance measurements in a wheat crop having a cover density of 0.4 suggest that the reflectances below and above 690 nm, considered separately, are related linearly to the probability of wheat plants intercepting direct radiation, which is determined by hemispherical photographs of the sky through the canopy.

The theory predicts that if the soil reflectance is higher than a limit dependent on the density of ground cover and the optical properties of the plant material, the reflectance of the vegetation stand as a whole will decrease with decreasing solar elevation. The opposite pattern of diurnal variation in the visible and infrared reflectance of the wheat crop is used to confirm the existence of such a relationship.

INTRODUCTION

The diurnal variation of the solar reflectance of vegetation stands is widely recognized. Measurements on many types of vegetation indicate that the global solar reflectance is larger near sunrise and sunset than during the midday period (4, 7, 8). Diurnal asymmetry of reflectance changes has also been reported (10) but is less well documented. The variation of reflectance could result from circadien changes of the vegetation, *e.g.* leaf movement (3), but is generally regarded as caused by diurnal changes of the properties of the incident solar radiation. Solar elevation, spectral composition, diffuse-to-direct ratio, and flux density are the main time-dependent solar radiation characteristics which can affect reflectance.

As plant and soil surfaces have no known activation properties, it is well established that the reflected radiation flux density is directly proportional to the incident flux density. The characteristic spectral reflectance of most green plants shows a sharp

Publication of the Agricultural Research Organization. No. 2167-E. Received June 1971; accepted Oct. 1971.

* Div. of Agricultural Meteorology, The Volcani Center, Agricultural Research Organization, Bet Dagan.

increase near the 700 nm wavelength. Consequently, a shift of the spectral composition of incoming solar radiation toward longer wavelengths will result in a corresponding increase of the solar reflectance (2). However, an analysis by Stanhill *et al.* (10) indicates that the diurnal change of solar reflectance of a dense peanut crop was more closely related to the variation of the fraction of diffuse radiation than to the proportion of infrared radiation. This suggests that it is mainly the canopy geometry and the path of the incoming radiation which determine the diurnal variation of the solar reflectance.

The solar radiation reflected by leaves and soil presents a negligibly small specular component which obeys Fresnel's reflection laws. This specular component is further attenuated by the scattering of radiation by the foliage and the uneven soil surface. Measurements (5) and theoretical analysis (6) suggest that the specular component of reflected solar radiation by plant-covered surfaces is too small to account for the observed dependence between reflectance and the angle of incidence of the solar beam. However, the absence of specular reflection does not preclude the dependence of reflectance on the angle of incidence, unless the solar radiation transmitted by the canopy and reaching the soil is completely diffuse. With the exception of very dense canopies for which horizontal leaves are dominant, this is never the case. Measurements by Scott *et al.* (9) provide evidence for the anisotropy of the scattering properties of many canopies. A theoretical analysis by Cowan (1) predicts that in a dense canopy of randomly oriented leaves, the angular anisotropy of the radiation absorption leads to an increase of the reflectance at large angles of incidence.

When the canopy cover is not closed, direct solar radiation reaches the soil. Consequently, the reflectance of the stand will depend on both the reflectance of the soil and the reflectance of the plants. The proportion of incoming radiation which reaches the soil surface directly will depend on the path of the impinging beam and therefore on the angle of incidence. For a given cover density the stand will transmit a larger fraction of direct radiation at normal incidence than at grazing incidence because in the former case the radiation beam encounters fewer vegetal scattering elements.

Measurements of the global solar reflectance of a wheat crop presented in this paper have been analyzed to assess the respective contributions of the soil and the foliage to the angular variation of the stand reflectance in the spectral ranges below and above 690 nm. The division of the solar spectrum at a wavelength where the abrupt change in the spectral reflectance of the leaves is not matched by a corresponding change in the spectral reflectance of the soil, provides an opportunity to verify our interpretation of the angular dependency of the reflection of a vegetation stand.

MATERIALS AND METHODS

Diurnal measurements of the incoming and reflected solar radiation were carried out at two-week intervals throughout the growing season, in an irrigated commercial wheat crop (Miriam 1, a semi-dwarf local variety) growing on a loess-derived soil at the Gilat Regional Experiment Station in the northern Negev (34°40'E, 31°20'N, 150 m. M.S.L.). The ground has a 3% maximum slope descending in the NW direction. The downward and upward global solar radiation were monitored simultaneously for 10 seconds, at a frequency of 16 measurements per hour, with two Kipp solarimeters. At this low sampling frequency significant data can be obtained only when the cloud cover is below 2/8 or above 7/8. The two instruments were mounted at a height of 2.60 m above the ground with the sensing surfaces oriented in the opposite direction on a reversing stand; they were automatically interchanged every 15 minutes so that by geometrically averaging values obtained during successive periods, the reflectance is independent of the calibration factors of the solarimeters.

The global radiation measurements were occasionally supplemented by measurements of the infrared components of the incident and reflected solar radiation using additional Kipp solarimeters with outer glass domes replaced by RG-8 hemispheres characterized by a sharp cutoff centered at 690 nm.

The geometrical properties of the wheat crop were determined by measurements of the crop height and total plant area index (A.I.).

The probability of direct radiation reaching the soil surface for various solar elevations was determined by estimating the relative area of free sky viewed from the soil at

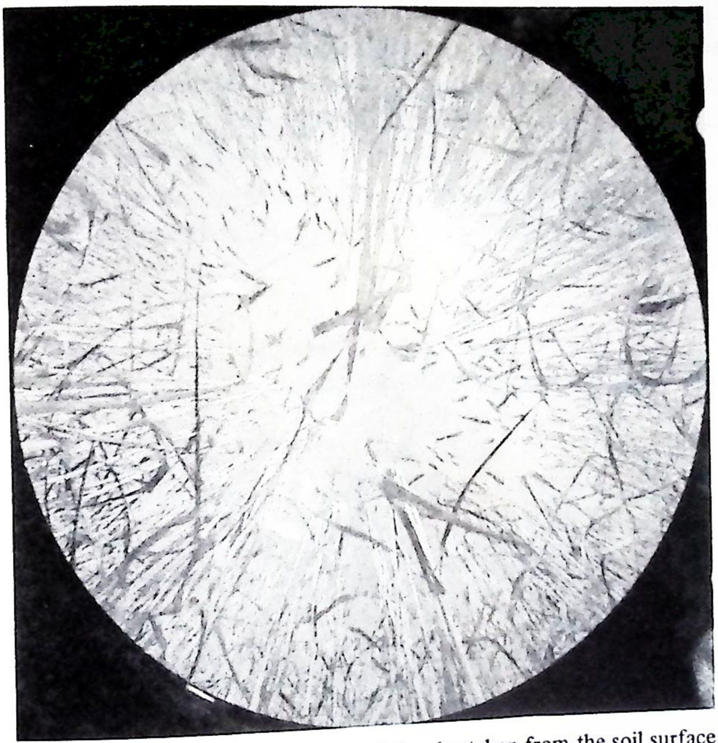

Plate 1. Hemispherical photograph of the sky taken from the soil surface through the canopy of a wheat crop. Early May 1970, Gilat.

various angles of incidence on hemispherical photographs of the sky taken through the canopy from the soil surface (Plate 1). The lens used was a Spiratone 180° fish eye with a focal length of 7 mm. The main advantage of this lens is that it can be used on a reflex camera with the reflex mirror in normal viewing position and therefore does not require a sunshade for protection of the shutter.

RESULTS AND DISCUSSION

The diurnal variations of the solar reflectance from the wheat crop at various stages of its development are shown in Fig. 1, where the time scale has been replaced by the solar elevation. The data indicate clearly that the increase of the plant cover expressed by the height and the total plant area index (A.I.) is associated with an increase of the solar reflectance. A second observation is that the relative increase of reflectance at low solar elevations, which is nonexistent on the bare soil, is more accentuated when the crop cover is still sparse.

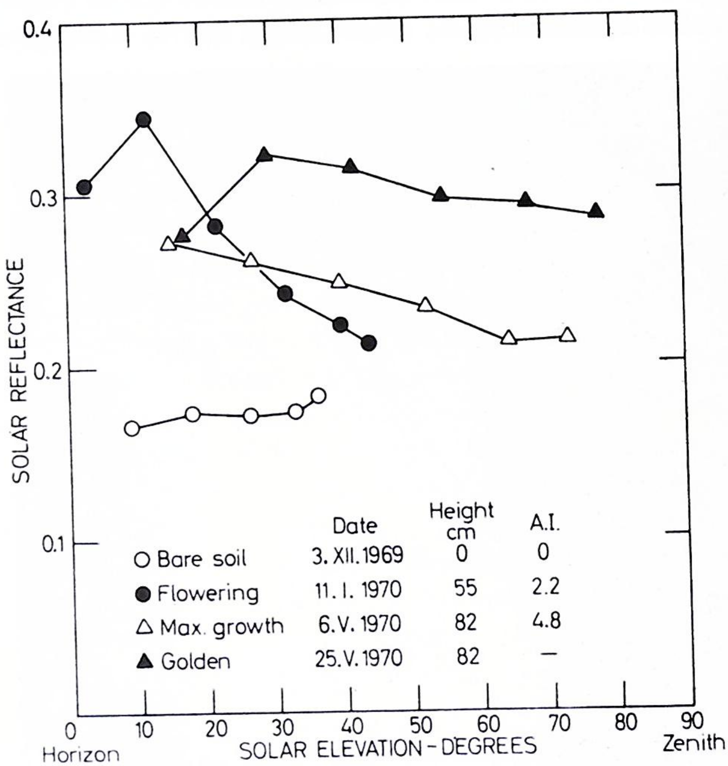

Fig. 1. Variations of the solar reflectance of a wheat crop as a function of solar elevation at various growth stages.

In order to explain these results we will consider successively the possible effects of the variations of the fractional incident diffuse component, of the fractional incident infrared component and the angle of incidence of the solar beam, on the solar reflectance of a vegetation stand.

Diffuse component

The total solar reflectance ρ_T of a surface is given by:

$$\rho_T = (R_2 + R_2')/(R_1 + R_1') \qquad [1]$$

where R_1 is the incident direct radiation, R_2 is the reflected radiation due to the scattering by the surface of the direct incident radiation, R_1' is the diffuse incident flux, and R_2' is the corresponding reflected flux. We can express the direct incident radiation as a fraction of the global radiation

$$R_1 = k(R_1 + R_1'), \qquad 0 \leqslant k \leqslant 1 \qquad [2]$$

The total reflectance is then:

$$\rho_T = k(\rho - \rho') + \rho' \qquad [3]$$

where $\rho = R_2/R_1$ is the reflectance of the direct incident radiation and $\rho' = R_2'/R_1'$ is the reflectance of the diffuse incident radiation. If the diurnal variation of ρ_T is caused by the diurnal change of k only, [3] indicates that a linear relationship between ρ_T and k exists. The set of data presented here does not include measurements of k, but data by Stanhill *et al.* (10) do not confirm this conclusion and suggest that variation of ρ and possibly of ρ' should be considered.

A radiometer measuring reflected radiation cannot differentiate between R_2 and R_2' and therefore experimental data always yield ρ_T, but rewriting [3] in the form

$$\rho_T = k\rho + (1 - k)\rho' \qquad [4]$$

shows that the effect of the properties of ρ on ρ_T is attenuated by the factor k and offset by $(1 - k)\rho'$. However, on clear sunny days k is large and ρ is the main component of ρ_T.

Incident infrared component

Because of the sharp increase of spectral reflectivity of leaves near 700 nm, a shift of the incident radiation toward longer wavelengths should increase the solar reflectance of vegetation. Considering the total reflectance ρ_T as having different visible and infrared components, we can write:

$$\rho_T = (R_{2\,vis} + R_{2\,ir})/(R_{1\,vis} + R_{1\,ir}) \qquad [5]$$

Using the ratio

$$j = R_{1\,ir}/(R_{1\,vis} + R_{1\,ir}) \qquad [6]$$

we obtain

$$\rho_T = j(\rho_{ir} - \rho_{vis}) + \rho_{vis} \quad [7]$$

where $\rho_{vis} = R_{2\,vis}/R_{1\,vis}$, and $\rho_{ir} = R_{2\,ir}/R_{1\,ir}$. If variations of j cause the diurnal changes in ρ_T, the experimental data should confirm the linear relationship claimed by [7]. However, as the diurnal variation of j is small, the relation:

$$(\rho - \bar{\rho}_T)/\bar{\rho}_T = f(j - \bar{j})/\bar{j} \quad [8]$$

where $f = [1 + \rho_{vis}/\bar{j}\,(\rho_{ir} - \rho_{vis})]^{-1}$, and $\bar{\rho}_T$ and $\bar{j}$ represent diurnal averages, was tested in Fig. 2. The correlation coefficient is high, suggesting that the change of the spectral composition of incident solar radiation could affect the measured solar reflectance. However, eq. [8] postulates that the plot of $(\rho_T - \bar{\rho}_T)/\bar{\rho}_T$ against $(j - \bar{j})/\bar{j}$ yields a straight

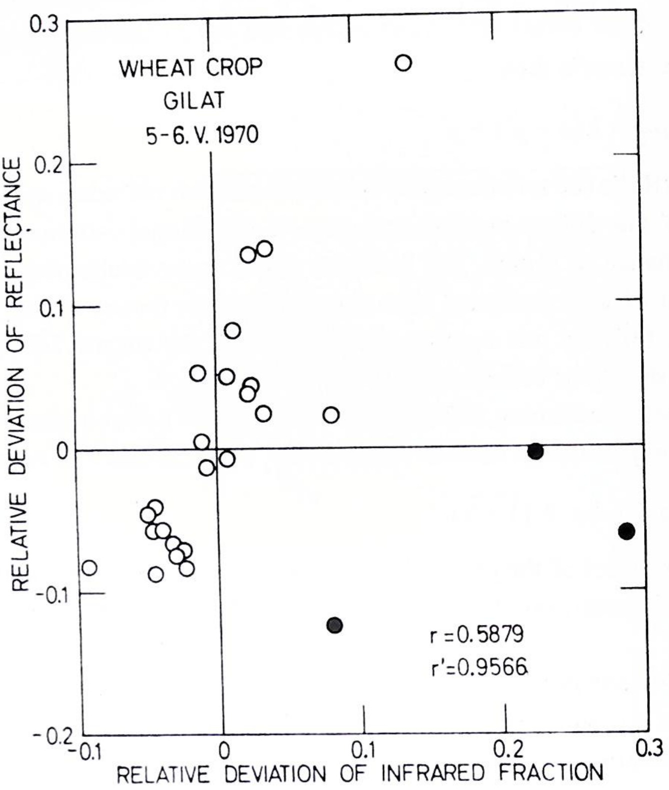

Fig. 2. Variation of the wheat crop reflectance resulting from changes in the ratio of the infrared component of solar radiation. The correlation coefficient r = 0.588 obtains when all the shown points are included and r = 0.957 when the three points corresponding to measurements taken in the half-hour periods immediately following or preceding sunrise and sunset, and marked by black dots, are excluded.

line of slope equal to f. Since for vegetation ρ_{ir} is larger than ρ_{vis}, the value f is always less than unity, and normally between 1/3 and 2/3. The slope of the line which fits the open dots in Fig. 2 exceeds unity, thus indicating that the observed diurnal variation of the solar reflectance is much larger than the variations which could be caused by the measured shift of the spectral composition of incident solar radiation.

Angle of incidence

Direct solar radiation impinging on the surface can be scattered by either the vegetation or the soil. The rate of scattering by the soil will be proportional to ρ_s, the reflectance of the soil, and $(1-a)R_1$, a being the probability for the direct solar radiation to encounter the vegetation.

The portion of direct solar radiation which is scattered by the vegetation has an upward component $\rho_\ell aR_1$, and a downward component $\tau_\ell aR_1$. The coefficients ρ_ℓ and τ_ℓ are, respectively, the reflectance and the transmittance of the vegetation which obtain when $a = 1$ and $\rho_s = 0$. Let R_2 be the upward flux at the upper boundary of the vegetation, R_3 the downward flux at the lower boundary, and R_4 the flux reflected by the soil,

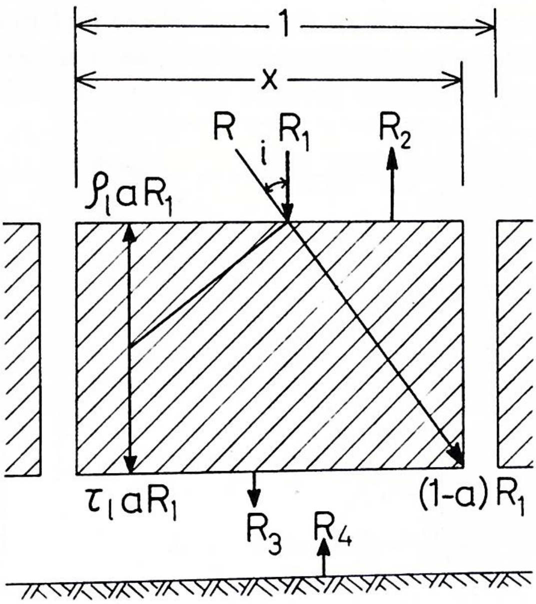

Fig. 3. Macroscopic two-dimensional description of the scattering of direct radiation by a vegetation stand. R = incident beam solar radiation, R_1 = normal incident beam solar radiation, R_2 = upward solar radiation, R_3 = solar radiation transmitted by the canopy, R_4 = solar radiation reflected by the ground, a = probability for a ray to encounter a leaf, i = angle of incidence, x = cover density, τ_ℓ = transmittance of the vegetation, ρ_ℓ = reflectance of the vegetation.

as illustrated in Fig. 3. These three fluxes refer exclusively to transformations of R_1, the direct solar radiation. Note that $R_1 = R \cos i$, where R is the radiant flux density impinging on a receiver normal to the beam, and i is the angle of incidence. The fluxes shown in Fig. 3 as a two-dimensional configuration are measured by hemispherical pyranometers and therefore are reported over 2π steradians. Directional isotropy is implicit.

Assuming that the scattered radiation is completely diffuse, the following relationships between R_1, R_2, R_3 and R_4 obtain:

$$R_2 = \rho_\ell a R_1 + x\tau_\ell R_4 + (1-x)R_4 \quad [9a]$$
$$R_3 = \tau_\ell a R_1 + x\rho_\ell R_4 + (1-a)R_1 \quad [9b]$$
$$R_4 = \rho_s R_3 \quad [9c]$$

The ground cover x is related to a by:

$$x = \int_0^{\pi/2} a \cos i \, di \quad [10]$$

The probability a, measured on four hemispherical photographs taken in the beginning of May 1970, is shown in Fig. 4 as a function of the angle of incidence. The

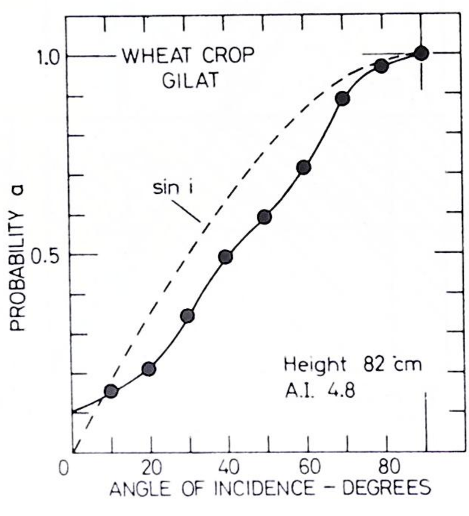

Fig. 4. Relation between the angle of incidence and the probability that direct radiation is intercepted by the vegetation.

data were used to integrate numerically [10]. The resulting value for x is 0.40, indicating that the crop cover was quite open. If a varies as sin i, then the integral in [10] yields x = 0.5. The full cover given by x = 1 corresponds to a = 1. The probability a is a function of both the angle of incidence and the density of the plant stand. When $a = 2i/\pi$, which is the 1:1 line in Fig. 4, x = 0.364. Consequently, when the vegetation is sparse (x < 0.364), the relation between a and i is a concave curve.

The reflectance of direct radiation resulting from [9] is:

$$\rho = R_2/R_1 = a\left[\rho_\ell - \frac{1 - x(1-\tau_\ell)}{1 - x\rho_s\rho_\ell}\,\rho_s\,(1-\tau_\ell)\right] + \frac{1 - x(1-\tau_\ell)}{1 - x\rho_s\rho_\ell}\,\rho_s \qquad [11]$$

Eq. [11] indicates that the reflectance of a vegetation stand is an intricate function of the optical properties of the canopy, the reflectance of the soil, the degree of ground cover, and the probability that the direct radiant beam will be scattered by the canopy rather than the soil. For monochromatic direct radiation, and at a given developmental stage of the crop x, ρ_ℓ, τ_ℓ and ρ_s are assumed constants. Accordingly, the reflectance of the crop is a linear function of a. However, as most field measurements of the solar reflectance include both direct and diffuse radiation, and cover the entire solar spectrum, ρ_ℓ, τ_ℓ and ρ_s may present diurnal variations as shown in [4] and [8], which distort the linear relationship predicted by [11]. As shown in Fig. 2, the division of the solar spectrum at 690 nm should remove the effect of the spectral modification of the incoming radiation on the variations of ρ_s, ρ_ℓ and τ_ℓ. The measured values of the visible and the infrared reflectance measured from sunrise to midday on May 6, 1970 indeed relate linearly to a (Fig. 5). The dispersion of the points becomes large as a approaches 1, and results from the increased diffuse fraction of the incoming radiation at low solar elevation. Linear

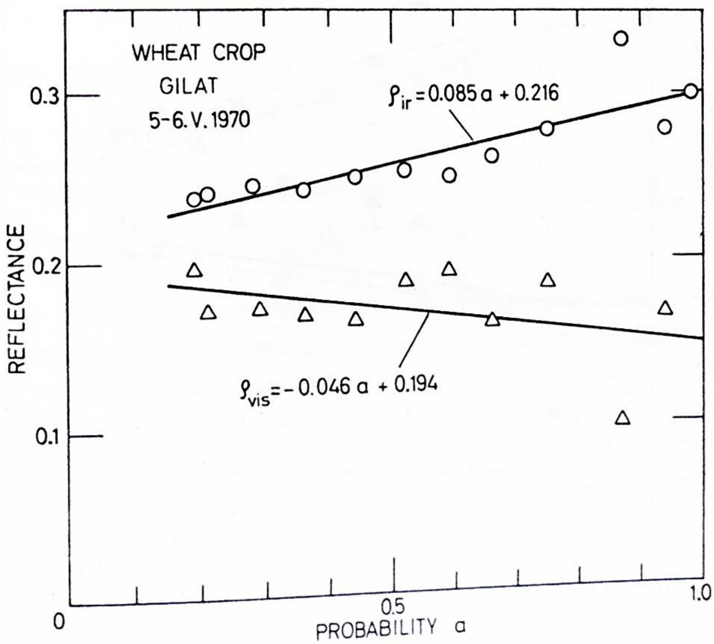

Fig. 5. Visible and infrared reflectance of the wheat crop as a function of the probability that direct radiation is intercepted by the vegetation.

regressions fitted to the data yield the numerical values of the coefficient of a and the independent term in [11].

Considering the relationship between a and i as given in Fig. 4, Eq. [11] can be used to predict the variation of ρ_{vis} and ρ_{ir} as a function of the solar elevation. In Fig. 6 the results of such a prediction are compared with the values of ρ_{vis} and ρ_{ir} measured on May 5 and 6, 1970. Both the theoretical line and the experimental data indicate that the infrared reflectance of the wheat crop increases at low solar elevation, but also that the visible reflectance follows an opposite trend. The theoretical line for the true value of a is in better numerical agreement with the morning data. This is obviously a computational artefact as the coefficients of [11] are based on measurements taken in the morning.

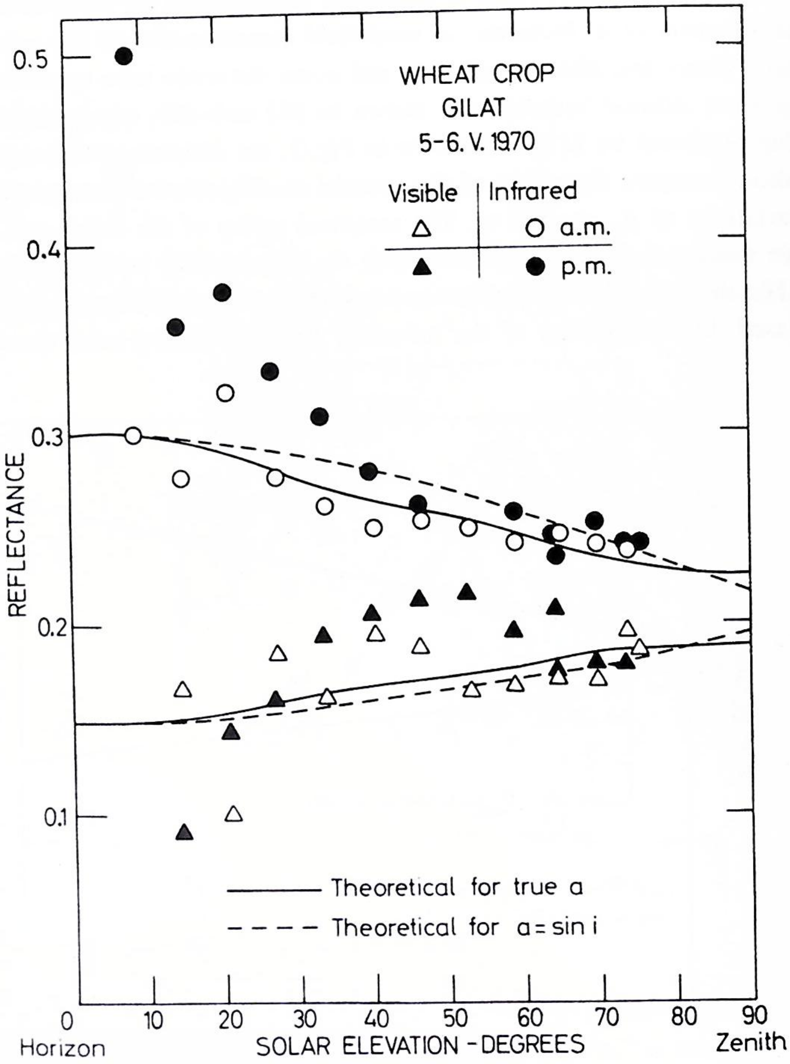

Fig. 6. Variations of visible and infrared reflections of a wheat crop with a cover of density of 0.4, as a function of the solar elevation.

However, it points out that the wheat crop reflectance has a diurnal asymmetry which could be caused by an azimuthal effect on the shape of the relation between a and i. The curve calculated for a = sin i, which yields a ground cover approximately equal to the one truly observed, shows that the prediction of reflectance by [11] is very sensitive to the shape of the relation between a and i. Unfortunately, the hemispherical photographs were not referenced with respect to the row direction of the wheat crop and we are unable to substantiate with data our interpretation of the observed diurnal asymmetry of the reflectance.

When the relation between a and i has a concave curvature which is typical of a sparse vegetation, the diurnal variation of the stand reflectance should be accentuated. The data in Fig. 1 support this conclusion.

The decrease of the reflectance of a vegetation stand at low solar elevation shown in Fig. 6 does not appear to have been reported previously in the literature. Moreover, previous theoretical treatments (1, 6, 11) have predicted that reflectance will either remain constant or increase at low solar elevation. The condition for reflectance to decrease with increasing angle of incidence is:

$$\partial\rho/\partial i = (\partial\rho/\partial a)\ (\partial a/\partial i) < 0 \qquad [12]$$

It is difficult to imagine a crop geometry for which $\partial a/\partial i < 0$ and therefore condition [12] is realized when $\partial\rho/\partial a < 0$, or according to [11] when:

$$\rho_\ell - \frac{1 - x(1 - \tau_\ell)}{1 - x\rho_s\rho_\ell}\ \rho_s\ (1 - \tau_\ell) < 0 \qquad [13]$$

We introduce the assumption suggested by de Wit (11) that

$$\rho_\ell = \tau_\ell = 0.5\sigma \qquad [14]$$

where σ is the scattering coefficient of the plant material. Eq. [13] yields

$$\rho_s > 0.5\sigma/[(1 - x) - 0.5\sigma\,(1 - 2x)] \qquad [15]$$

Accordingly, the reflectance of the wheat field which has a plant cover x = 0.40 should decrease at low solar elevation when $\rho_s > 0.5\sigma/(0.6 - 0.1\sigma)$ and increase for the reverse condition. Assuming a scattering coefficient for visible radiation of 0.15 for the wheat, the visible reflectance of the soil should be larger than 0.12 to account for the trend shown by the data in Fig. 6. On the other hand, a value of 0.6 is a conservatively low estimate of the infrared scattering coefficient of the wheat. The trend of the data in Fig. 6 requires that the infrared reflectance of the soil be lower than 0.56. A spot measurement on a similar soil yielded 0.12 and 0.30 for the visible and infrared reflectance, respectively. These values are within the limits set by [15] to obtain the results of Fig. 6.

When x = 0.5, the condition for decreasing values of the vegetation stand reflectance at low solar elevation is that $\rho_s > 0.5$. The larger the value of x, the density of the plant cover, the larger becomes the soil reflectance for which condition [15] is realized. As most reflectance measurements of vegetation stands have been made on dense cover, the likelihood of fulfilling condition [15] is small, and consequently the increase of reflectance at low solar elevation which obtains (4, 7, 8), is in agreement with the conclusion deduced from [15]. Considering for example a canopy with a scattering coefficient for visible radiation of 0.15 growing on a perfect mirror ($\rho_s = 1$), condition [15] indicates that if the cover is above 0.96 the crop reflectance for visible radiation will increase when the angle of incidence increases.

CONCLUSIONS

When direct solar radiation is dominant, the diurnal variation of the reflectance of a vegetative stand (including canopy and soil) is caused mainly by the increased probability for the direct beam to be scattered by the canopy rather than the soil. Measurements in an open wheat crop suggest that when the solar spectrum is divided at 690 nm, where plant spectral reflectance presents an abrupt increase, there is a linear relationship between the wheat crop reflectance and this probability, indicating that the optical properties of the wheat canopy alone do not vary significantly with solar elevation.

The theory predicts that the vegetation stand reflectance can either increase or decrease with a decrease in solar elevation; the sign of the variation depends upon the density of the ground cover, the soil reflectance and the optical properties of the plant material. Experimental confirmation of these predictions is provided by the opposite diurnal variation patterns for the visible and infrared reflectance measured on the wheat crop.

The magnitude of the diurnal variation is set by the shape of the relation between the angle of incidence and the probability for the radiation beam to impinge on the plant material, and is directly related to the density of the plant cover.

ACKNOWLEDGMENTS

We wish to acknowledge the financial support of the United States Department of Agriculture and the technical assistance of Y. Cohen.

REFERENCES

1. Cowan, I.R. (1968) The interception and absorption of radiation in plant stands. *J. appl. Ecol.* 5 : 367-379.

2. Gates, D.M. (1965) Energy, plants and ecology. *Ecology* **46** : 1-13.

3. Geiger, R. (1965) The Climate Near the Ground. Harvard University Press, Cambridge, Mass.

4. Grulois, J. (1968) La variation annuelle du coéfficient d'albédo des surfaces supérieures du peuplement. *Bull. Soc. R. Bot. Belg.* 101 : 141-153.

5. Howard, J.A. (1966) Spectral energy relations of isobilateral leaves. *Aust. J. biol. Sci.* 19 : 757-766.

6. Isobe, S. (1962) Preliminary studies on physical properties of plant communities. *Bull. natn. Inst. agric. Sci. (Japan)* A9 : 29-67.

7. Kalma, J.D. and Stanhill, G. (1969) The radiation climate of an irrigated orange plantation. *Solar Energy* 12 : 491-508.

8. Monteith, J.L. (1959) The reflection of short-wave radiation by vegetation. *Q. Jl R. met. Soc.* 85 : 386-392 (quoting Berezina, 1957).

9. Scott, D., Menalda, P.H. and Brougham, R.W. (1968) Spectral analysis of radiation transmitted and reflected by different vegetations. *N. Z. Jl Bot.* 6 : 427-449.

10. Stanhill, G., Fuchs, M. and Oguntoyinbo, J.S. (1971) The accuracy of field measurements of solar reflectivity. *Arch. Meteorol. Bioklimatol.* 19 : 113-132.

11. de Wit, C.T. (1965) Photosynthesis of leaf canopies. *Agric. Res. Rep.* 663. Centre for Agricultural Publication and Documentation, Wageningen.