REFLECTION AND HEATING COEFFICIENTS IN SOUTHERN ONTARIO

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By

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Reflection and heating coefficients were measured during the 3 month summer season at Simcoe, southern Ontario. Contrasting agricultural surfaces and atmospheric conditions were used to analyse their effect on the reflection and heating coefficients. The results confirm the postulate of Montieth (1959a) that α is close to 0.25 for many vegetated surfaces. β values were positive and there was a tendency for β to approximate 0.22 for many of the vegetated surfaces. Finally it was shown that the radiation balance equation for Simcoe can be generalized into a linear function of solar radiation using the same constants that are applicable to many areas in the world.

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CHAPTER I

INTRODUCTION

During the summer of 1967, a programme of micoclimatic research was undertaken at the Simcoe Horticultural Experiment Station in Southern Ontario. This site provided an excellent opportunity to study critical surface parameters concerning the radiation fluxes over a variety of crops (corn, winter wheat, tomato, pepper, tobacco, cucumber, and perennial ryegrass).

Budyko (1958) has stated that "solar radiation is the main source of heat energy for almost all the natural processes developing in the atmosphere, hydrosphere and in the upper layers of the lithosphere". An understanding of the energy transfers from the earth's surface to the atmosphere is basic to all climatic processes. It also has fundamental implications in the growth of natural and cultivated plants. The radiation available at the earth-atmosphere interface supplies the energy to heat the air and soil, evaporate water and carry on photosynthesis. Consequently, any attempts to control or increase agricultural productivity are strengthened by a fuller understanding of the radiation balance.

A radiation balance, or net radiation (Rn), can be defined for any surface as

$$Rn = (1 - \alpha)Q + Ln \qquad (1)$$

where

Q = incident solar radiation
Ln = net long-wave radiation
α = surface reflection coefficient.

Stanhill, Hofstede and Kalma (1966) stated that Rn can be described with the aid of two non-dimensional parameters. These are the reflection coefficient (α) and the surface heating coefficient (β). Using these, we can write

$$Rn = [(1 - \alpha) / (1 + \beta)] \; Q + a, \qquad (2)$$

where a = regression intercept.

The aim of this study is to evaluate characteristic values of α and β over selected cropped surfaces in southern Ontario. Few measurements of this kind have been carried out in the local area. The exception is the work of Graham and King (1961). The effects of cloud, solar elevation, crop height and ground coverage will be considered as well as typical α regimes throughout the crop season. Heating coefficients are also calculated for different surfaces and cloud conditions in order to assess the variability of β.

Discussion of α and β.

(1) Reflection coefficient (α)

The term reflection coefficient or albedo (α) is defined as the ratio of solar radiation reflected from a surface (Q_o), to the solar radiation incident on that surface (Q_i),

$$\alpha = Q_o / Q_i \, . \qquad (3)$$

It refers only to radiation wavelengths between 0.3 and 3.0 μ.

Since Ångström's pioneering work in 1924 (Ångrström, 1925), many measurements of α have been made for varying surfaces, solar elevations and cloud conditions with a variety of instrumental types and techniques. Some values from the literature are given in Table 1.

One of the features of these values is the considerable variation for a given surface. However, Montieth (1959a) has found that many completely vegetated surfaces have values close to 0.25, irrespective of visual differences. The findings of Fritschen (1967) and Davies (1967a) support this conclusion.

The variation in α values has been attributed to a number of factors. Several of these are outlined below.

(a) Solar elevation

Most workers have noted a typical diurnal cycle of α values. Under clear skies, there is an inverse relationship between solar elevation and α. At low solar elevations, reflection is increased because the sun effectively 'sees' a smoother surface. At higher elevations, the solar beam can penetrate the crop canopy and a larger proportion of the reflected component is trapped within the crop. Diurnal variation has been challenged by several workers (Kung, Bryson and Lenschow, 1964). Fritschen (1967) attributes larger α values in the morning and evening to the inverted solarimeter receiving incident radiation. Hence, we should expect to find this variation for all surfaces. However, Davies (1967b) found greater reflection at low sun angles for vegetated than for non-vegetated surfaces which suggests that the variation is real.

(b) Leaf characteristics

The size, density and geometry of leaves may affect the reflective properties of a vegetated surface. Leaves oriented in a

Table 1. Reflection coefficients for various surfaces

Surface	Reflection coefficient	Worker
wet soil	0.14	Fritschen
dry soil	0.24	"
wet sand	0.09	Ångström
wet sand	0.20-0.30	Sellars
clean snow	0.86-0.95	Kondrat'ev
clean snow	0.60-0.95	Budyko
smooth water	0.06-0.51	Davies
disturbed water	0.02-0.13	Kondrat'ev
green grass	0.26	"
green grass	0.25-0.33	Ångström
green grass	0.24-0.32	Montieth
deciduous forest	0.18	Kondrat'ev
deciduous forest	0.16-0.23	Stanhill
deciduous forest	0.15-0.20	Budyko
coniferous forest	0.12-0.13	Stanhill
coniferous forest	0.10-0.15	Budyko
tundra	0.19-0.21	Davies
tundra	0.15-0.20	Budyko
corn	0.12-0.14	Bryson
corn	0.12-0.19	Graham and King
spring wheat	0.10-0.25	Kondrat'ev
spring wheat	0.14-0.21	Montieth
winter wheat	0.16-0.23	Kondrat'ev
winter wheat	0.20-0.27	Montieth
sugar beet	0.14-0.25	Stanhill
alfalfa	0.20-0.27	Fritschen
potatoes	0.17-0.27	Montieth
potatoes	0.15-0.25	Budyko
barley	0.20-0.26	Fritschen
sugar cane	0.12-0.19	Lin-Sien Chia
sugar cane	0.16	Bryson

horizontal manner present a more uniform surface to the solar beam. Plants with this character tend to have higher α values. Plants with vertically oriented leaves trap light, resulting in lower values. There is a positive correlation between leaf size and α. Also there is less radiation trapped between larger leaves and they present a larger reflecting surface.

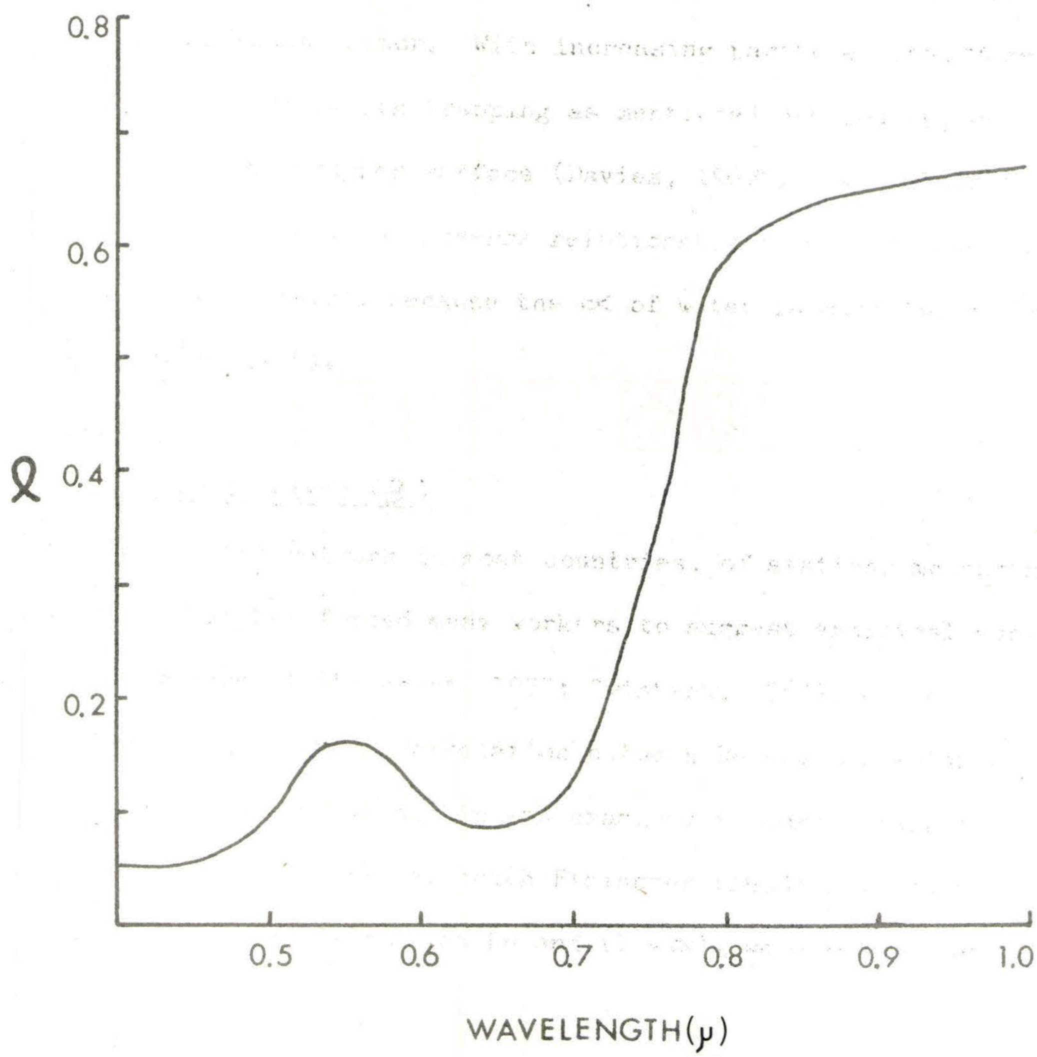
(c) Spectral composition of radiation

The diurnal cycle of α is enhanced by the changing spectral composition of the incident radiation with solar elevation. Incident radiation contains a higher proportion of short-wave radiation as the elevation is increased (Robinson, 1966). When clouds obscure the sun, incident radiation changes in composition. Not only is it completely diffuse but a greater proportion of it has a longer wavelength. This tends to increase α, since the plant's α in the near infrared (0.7-1.0μ) is large. Figure 1 illustrates this change in α for lawn grass.

(d) Height of measurement

When α measurements are taken from an aircraft or balloon, a lower α value may be expected, than if measurements were made closer to the surface. For example, if the sensing level is at 1000 m above the surface, the path of the incident radiation is reduced by 1000 m while the path of the reflected radiation is increased by 1000 m. Consequently absorption and scattering by the atmosphere is lessened for incoming radiation and increased for outgoing radiation. This is equivalent to a lower α value (Krinov, 1947).

Figure 1. Spectral reflectance properties of vegetation (Kondrat'ev, 1954)



(e) Nature of surface

The nature of the surface itself will affect α. Since vegetation and bare ground have different α values, the degree of ground coverage by vegetation has an influence on α. In general, vegetated surfaces have a higher reflectivity than bare soil. Kondrat'ev (1954) has shown that particle size in the soil surface may even be a significant factor. With increasing particle size, α decreases. Greater radiation trapping as mentioned previously, or shadows cast by the rougher surface (Davies, 1967b) may explain this decrease. Also there is an inverse relationship between α and soil moisture. This is mainly because the α of water is much lower than soil (Ångoström, 1925).

(2) Heating coefficient (β)

The present network in most countries, of stations measuring Rn is poor. This has forced many workers to suggest empirical substitutes (Ångström, 1916; Brunt, 1932; Swinbank, 1963), one of which involves the strong linear correlation between Rn and net solar radiation, $(1-\alpha)Q$. This relationship was examined in some detail by Montieth and Szeicz (1961), although Fleischer (1953) had noted it. They showed that for clear skies Rn and $(1-\alpha)Q$ were related as follows:

$$Rn = b(1-\alpha)Q + a \qquad (3)$$

where b = regression coefficient
a = regression intercept.

A heating coefficient (β) is defined as the increase of net long-wave loss per unit increase of net radiation income, -dLn/dRn (Montieth and Szeicz, 1961). β was derived by Montieth and Szeicz (1961) as follows: They found that incoming long-wave radiation was virtually constant during a clear day and that a change in net long-wave radiation was controlled mainly by a change in the outgoing long-wave radiation from the surface. Since surface heating is governed by the Stefan-Boltzman law,

$$Lu = \epsilon \sigma T^4 \qquad (4)$$

where
- Lu = outgoing long-wave radiation
- ϵ = infrared emissivity of the surface
- σ = Stefan-Boltzman constant
- T = surface temperature in degrees Kelvin,

the rate of change of Ln through the day is associated with the active surface.

β can be defined by a simultaneous solution of equations 2 and 3.

Multiplying equation 2 by b,

$$bRn = b(1 - \alpha)Q + bLn. \qquad (5)$$

Subtracting equation 5 from equation 3,

$$Rn\ (1 - b) = a - bLn. \qquad (6)$$

Therefore,

$$Ln = a / b - Rn(1 - b/b), \qquad (7)$$

or

$$Ln = a / b - \beta\ Rn. \qquad (8)$$

Hence

$$\beta = -dLn / dRn. \qquad (9)$$

Since

$$\beta = (1 - b/b),$$

$$b = 1 / (1 + \beta). \qquad (10)$$

The slope of the line relating Rn to $(1 - \alpha)Q$ depends on surface heating. Using β , equation 3 becomes

$$Rn = \left[(1 - \alpha) / (1 + \beta)\right] Q + a. \qquad (11)$$

Reported values of β (Stanhill et al, 1966; Ekern, 1964; Montieth and Szeicz, 1961 and Berger-Landefeldt, 1964) vary considerably and some are even negative. Some of these values are summarized in Table 2. The high correlation coefficients (0.94 to 0.99) demonstrates the closeness of the linear relationship.

There is a need for observations which permit the calculation of further β values. In North America no values have been reported. Values are therefore needed, for comparison with other areas of the world. Also there is uncertainty concerning negative values of β and, again, more data are needed.

(3) <u>Interrelationships between α and β .</u>

Montieth (1959a) suggests an α near 0.25 for green vegetated surfaces while Stanhill <u>et</u> <u>al</u> (1966) found little variation in their β values. These findings indicate the possibility of an unique form of equation 11 for a climatic region such as southern Ontario.

Adem (1967) and Davies (1967a) suggest an inverse relationship between α and β . Using data from contrasting surfaces which ranged from arctic Canada to tropical Africa, Davies (1967a) found that all data followed the line,

$$Rn = 0.617Q - 24 \text{ gcal cm}^{-2}\text{day}^{-1}, \qquad (12)$$

with a correlation coefficient of 0.99. It was argued that if Rn is a constant proportion of Q for widely different surfaces, then α and β must compensate for each other. This means that a lower α value

Table 2. Heating coefficients for various surfaces

Surface	β	Correlation coefficient	Number of observations	Place and/or Author
pine forest	0.013	0.98	165	Stanhill et al (1966)
open oak forest	0.039	0.97	115	" "
evergreen shrub	0.002	0.96	121	" "
semi-steppe hillside	-0.041	0.99	108	" "
mediterranean batha	0.021	0.98	159	" "
desert-wadi veg.	-0.035	0.98	139	" "
dwarf desert shrub	0.014	0.98	182	" "
orange orchard	-0.069	0.99	335	" "
fish pond	-0.015	0.98	85	" "
spring wheat	0.15	0.98		Montieth & Szeicz (1961)
sugar beet	0.21	0.94		" "
bare soil	0.41	0.94		" "
fresh green veg.	0.08			" "
bare soil	0.03			Ekern (1965)
pineapple	0.03			" "
lava	0.03			" "
grass	-0.023			Shaw, 1956
"	-0.012			Scholte-Ubing, 1959
"	-0.08			de Boer, 1959
"	0.177			Rider, 1951
"	0.230	0.97		Montieth & Szeicz, 1961
"	0.08			" " 1962
"	-0.02			Oaki, 20°N. lat.
"	0.15			Ekern, 1965
"	0.25			U. of Wisconsin, 1953
"	0.26			John Hopkins U.
"	0.289			Toronto, Cdn.
gravel and rock	0.338			Resolute, N.W.T., Cdn.
" " "	0.355			Goose Bay Labrdr. Cdn.
grass	0.22			Berger-Landefeldt, 1964
"	0.22			" "
"	0.16			" "
oats	0.01			" "
sugar beets	0.11			" "
spring wheat	0.15			" "
sugar beets	0.21			" "
hay	0.22			" "
bare ground	0.35			" "
" "	0.39			" "
" "	0.41			" "
" "	0.37			" "

will cause greater surface heating and consequently, a larger β . Davies (1967a) concludes that β , which was derived for cloudless skies only, now seems appropriate for average conditions as well.

CHAPTER II

INSTRUMENTATION AND THE EXPERIMENTAL SURFACES

Field work was carried out between May and September 1967. Figure 2 shows the layout of the 420 hectare farm which is situated 8 km. north of Lake Erie and 80 km. south of Hamilton. The predominant soil type is Fox sandy loam which drains relatively quickly and therefore the surface remains quite dry even after irrigation. Most fields are arranged in strips 19 m. by 150 m. Between each of these strips a 2.5 m. strip of grass or bare ground allowed access to each field. For corn, tomato and wheat, the instruments were located where two strips of the same crop occurred together. For tobacco and perennial ryegrass, the fields measured over 100 m. square. With 17 m. of cable from the instruments, the minimum fetch in most cases was 16 m. Peppers and cucumbers had smaller fetches of 10 m. and 8.5 m. respectively.

Four 'Rothamsted'-type solarimeters (Montieth, 1959b) were used. Two of these were purchased (Lintronic, London, England) while the others were made available on loan from King's College, London, England.[1] A Thornthwaite net radiometer was used on selected days. The outputs from the solarimeters and the net radiometer were measured as instantaneous readings on two potentiometers (Doran, Stroud, England and Thermoelectric of Canada).

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[1]The writer wishes to express his gratitude to Mr. John Hay of King's College, London, England for his consideration in lending three 'Rothamsted'-type solarimeters for this project.

The 'Rothamsted'-type solarimeter was developed in 1959 (Montieth, 1959b) as a light inexpensive instrument to measure short-wave radiation over and within crop canopies. It consists of a circular thermopile constructed from 42 gauge copper-plated constantan wire wound toroidally on a perspex former (G in Figure 3). Two sets of thermo-junctions (T1 and T2) result. The former is glued to a paxolin disc (A), the top surface of which is painted with a 1 square cm. circle of optical black paint centred over the T1 thermocouples (hot junctions). A matt white paint covers the rest of the disc including the T2 thermocouples (cold junctions). A few grains of silica gel are inserted within the dome to prevent condensation. Weatherproofing is achieved by sealing all joints with cement.

Montieth (1959b) conducted several laboratory experiments to compare the performance of this solarimeter with that of a Moll-Gorcznski (Kipp) solarimeter. He found that over the range 0.0 to 1.0 cal. $cm.^{-2}$ $min.^{-1}$ the deviation from a linear response between the two instruments was only $\pm 2.5\%$. Deviation from a perfect cosine response was $\pm 6.0\%$ between 15° and 90° elevation. In the field, maximum divergence between the readings of the two instruments was ± 0.002 cal. $cm.^{-2} min.^{-1}$. Because of this good performance, portability and light weight, the 'Rothamsted'-type solarimeter was considered very suitable for the study at Simcoe.

The miniature net radiometer (Thornthwaite Associates, New Jersey, U.S.A.) is based on the design of Fritschen (1963). This is a shielded radiometer of smaller size (5 cm. diameter) which again allows great versatility over and within crop canopies. Hanson (1963) and Fritschen (1963) have evaluated the accuracy of this instrument. Both found it

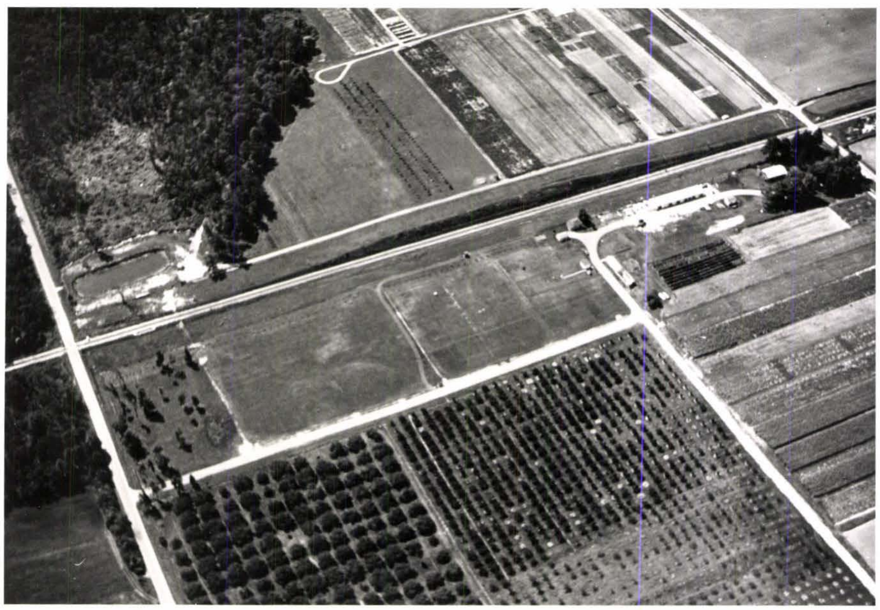
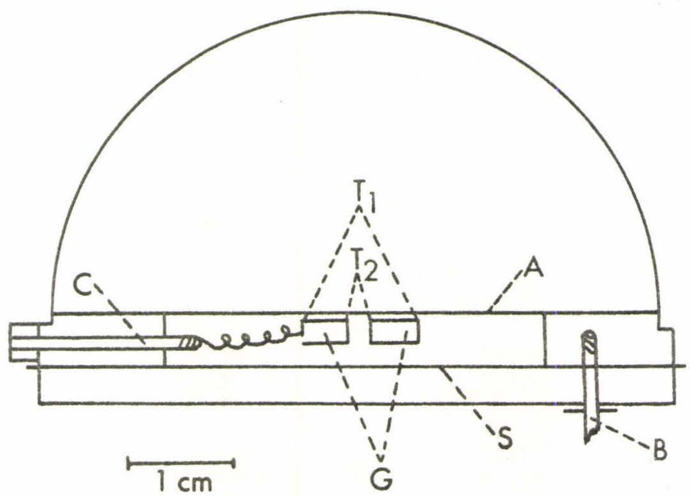


Figure 2. Areal photo of experimental farm at Simcoe

Figure 3. Cross section of Rothamsted-type solarimeter



A = paxolin disc
B = holding bolts
C = bolts for conductor cable connections
G = perspex former
S = aluminium plate
T_1 = hot junctions
T_2 = cold junctions

less sensitive to long-wave radiation than to short-wave radiation by as much as 10%. This is due to the matt black paint used (Glidden #1208). Although this error was overcome by painting 10% of the sensor area with white paint, this adjustment has not been made on the commercial design. Because it is shielded with polythene hemispheres of 2 mil. thickness, the sensor was unaffected by wind speed or direction. Over the range of 20° to 60°C., the ambient air temperature had no effect on the instrument's sensitivity. Therefore, measurement of the sensor's temperature is not required. The characteristics of both radiation instruments are summarized in Table 3.

Since measurements were made at different locations each day, the instrumentation had to be portable. At each site, a 3.75 cm. diameter wooden mast, painted matt black to minimize reflection was mounted permanently for the entire field season. The mast was supported with three guy-wires. A 1 m. horizontal boom was attached to the mast at

Table 3. Accuracy of the radiation instruments

Response	Rothamsted solarimeter	Fritschen net radiometer
Sensitivity	10 $mV/cal/cm^2/min$	0.306 $mV/cal/cm^2/min$
Response time	20 sec for 34% 3 min for 99%	2 sec for 80% 5 min for 100%
Cosine error	2% for 0-60° incidence 5% for 60-90° "	2% in terms of rad'n for a 12 hr, day
Azimuth error	2% at 30° incidence 4% at 60° "	not known
Wind	no effect	no effect
Dew	not known	very little effect

any desired height using 2 U-bolts. At the end of the boom an adjustable ball-and-socket assembly from a camera tripod, allowed two way levelling of the sensor platform which was made from a 14 cm. piece of flat iron containing a circular level. Suitable brackets were placed on the bottom of the solarimeters so they could slide onto this base. The net radiometer was attached to the boom 30 cm. away from the solarimeters (Figure 4).

Sensors were linked to a central box at the edge of the field using standard copper cable. This box housed the potentiometers and a 12-point selector switch (Thermoelectric of Canada). Figure 4 and 5 show the basic instrumentation. This equipment proved quite satisfactory since it could be carried to the field and mounted by one person.

The instruments were consistently placed 1 m. above the average crop height while the boom always faced south away from the mast. For adequate sampling of row crops the instruments were positioned on the border between a crop row and the centre of the intervening bare ground strip. This may have been unnecessary since Stanhill et al (1966) found no significant difference in results regardless of whether the instruments were placed over a row or between rows. Using this system the surface was never significantly shaded by the solarimeters, even at solar noon. Neither did the mast and boom provide significant obstruction to the instrument's view. The percentage of the surface which is effectively viewed by the instrument can be computed (Slatyer and McIlroy, 1961) from

$$A = 1 - (h^2/h^2 + d^2) \qquad (13)$$

where

A = amount of instrument's output originated from the surface beneath
h = height of instrument above the surface
d = diameter of the surface being measured.

Figure 4. Radiation instruments

Figure 5. Field instrumentation

When h = 1 m. and d = 17 m., 99.6% of the reflection that is received is from the surface below.

Spot readings at 5 to 20 minute intervals were taken for either a half or a complete daytime period. The net radiometer was attached to the potentiometer with the greater sensitivity (Doran) since its output was very small ($0.306 mV/cal/cm^2/min$). The reading procedure was as follows. The net radiation and incoming solar radiation readings were first taken simultaneously on the two potentiometers. If these were stable, the inverted solarimeter readings were taken. These four readings could be completed within a period of 15 seconds. The upfacing solarimeter reading was again taken. If it had altered, the whole set of readings were rejected and the procedure repeated. Using this procedure, a reasonably stable set of readings could be obtained in most conditions. Cloudy-bright days presented a major problem since fluctuating sensor outputs made it difficult to balance the potentiometer.

At the end of August when all the crops had reached maturity leaf α values were taken for tobacco, corn, peppers, tomatoes and cucumber. Figure 6 illustrates the procedure. Readings were taken on two separate clear days at solar noon in the middle of a large field of bare ground. A 1 m. square board, painted with Parson's optical black paint provided a base for the leaves. The board was levelled on the ground and the solarimeter was mounted at a height of 20 cm. above the centre of the board. This was the minimum height at which shading was not a problem. Leaves were picked and immediately placed flat so that the board was completely covered. The optical black paint prevented any reflection of radiation transmitted through the leaves.

Readings began within 5 minutes of picking the leaves and were repeated at intervals of one minute for 15-20 minutes or until the leaves became noticably wilted. From equation 13, 96% of the solarimeter's output was assumed to originate from the leaves (Slatyer and McIlroy, 1961). Figure 7 gives some indication of the extent of one of the bare ground surfaces used.

The results of the study depend on the accuracy of the sensor calibration to a considerable extent. Two methods of calibration were used.

(1) The factory calibration for the net radiometer was accepted. A field comparison with a shielded net radiometer (Funk, 1959) justified this acceptance. The 3 King's College solarimeters were calibrated by the Meteorological Branch of the Department of Transport prior to the field season. It was found that one of these instruments was temperature dependent: hence it was rejected for field use. The Lintronic solarimeters arrived too late for similar calibration. However, coefficients were obtained by comparison with those that had been calibrated. After the field season, all instruments were sent for recalibration. Unfortunately the results were not available at the time of writing.

(2) To check changes in calibration during the field season, the relative sensitivities of all short-wave radiation sensors were evaluated from information collected on seven clear days between May and September. All instruments were put in an upfacing position and spot readings were made every 15 minutes throughout the day. Then,

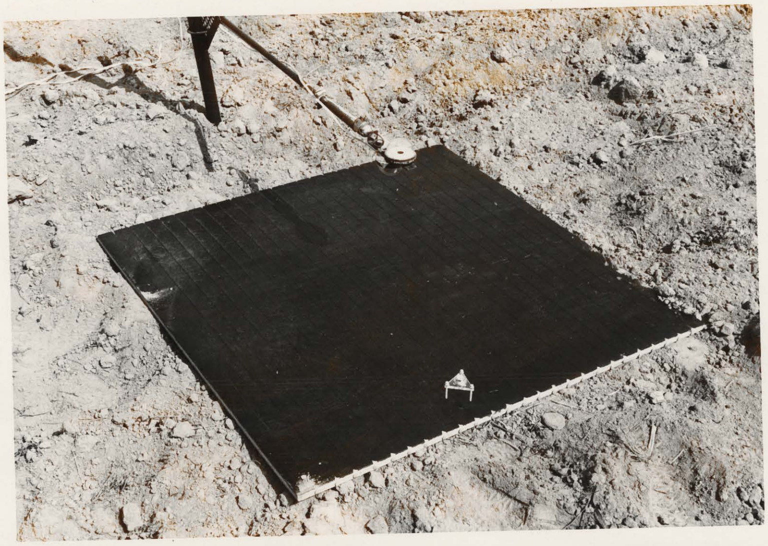


Figure 6. Board used for calculating leaf α.

Figure 7. A bare ground field used for leaf α measurements

each possible pair of instruments were compared and the average daily ratio of their outputs was computed. From the field measurements, α was found by 2 different methods. Since the difference in α between these 2 methods was usually less than 0.01, the average of these 2 α values for each spot reading was used.

The calibration coefficients were analyzed to determine possible instrumental errors due to solar elevation and azimuth variation. Figure 8 shows the seasonal change in the ratios for the sensor pairs that were most frequently used. Maximum variation for the crop season ranged between 4.5 and 8.4% from the mean. Figure 9 shows the variation in ratio values with solar elevation. The average maximum departure from the mean was 8% for the different combinations used. However, if the 0°-10° and 70°-80° solar elevation categories are disregarded, maximum variation is reduced to an average of 3%. This is a more realistic value since very few readings occurred in these categories. The data from the 0°-10° category are of dubious value because of poor instrumental response at low sun angles and the possible receipt of incident radiation by the downfacing sensor. The pairs 1 and 3, and 2 and 3 were the most frequently used combinations. Notice in Figure 8 that these two combinations vary in a similar manner. Therefore, measurements from these two combinations should be comparable.

For the best calibration day of the season, September 6, linear regression and partial correlation[1] coefficients were calculated to examine the relationship between ratio values and solar elevation and

[1]Partial correlation is a statistical technique that allows regression of 2 variables to be carried out while one or more other variables are statistically held constant. Thus the effects of solar azimuth and solar elevation which vary together in nature, can be separated.

Figure 8. Seasonal changes in solarimeter ratios

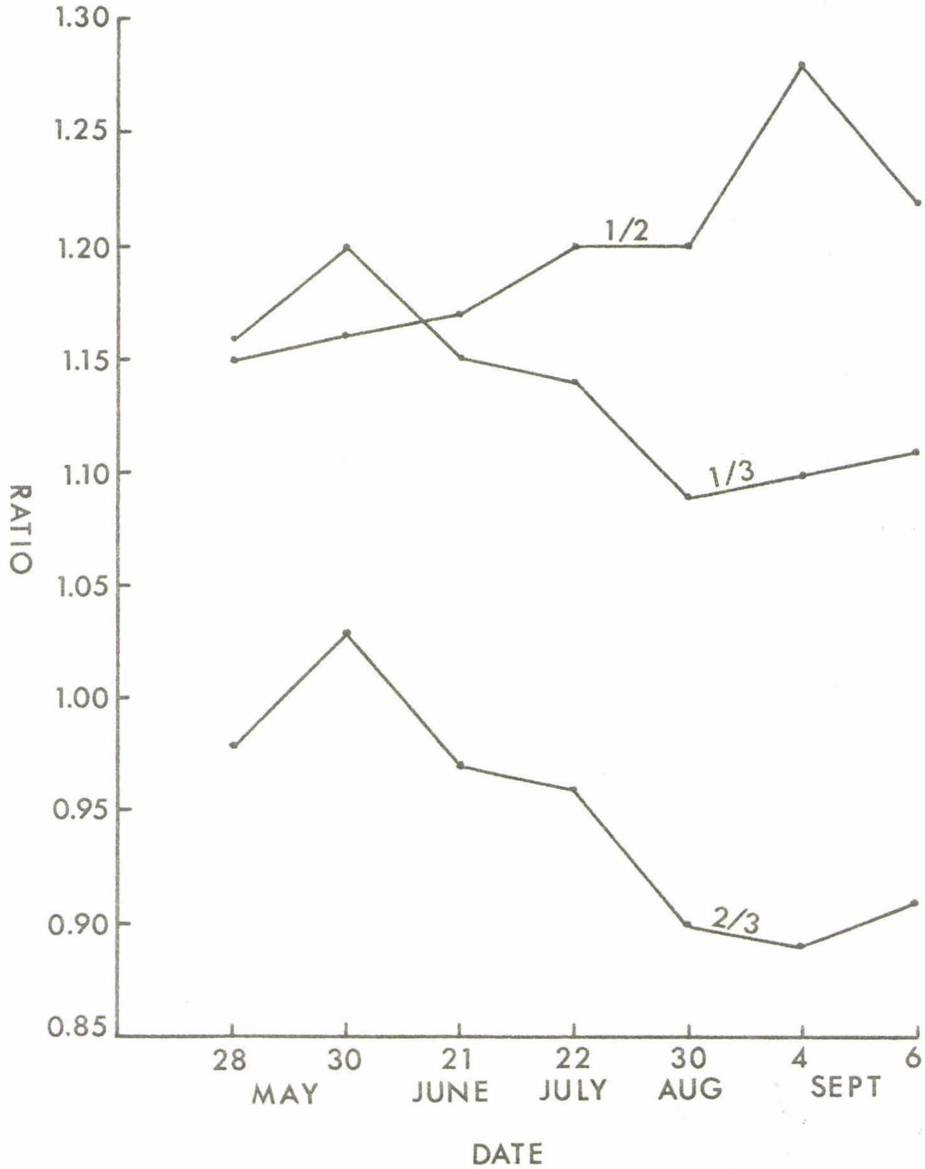
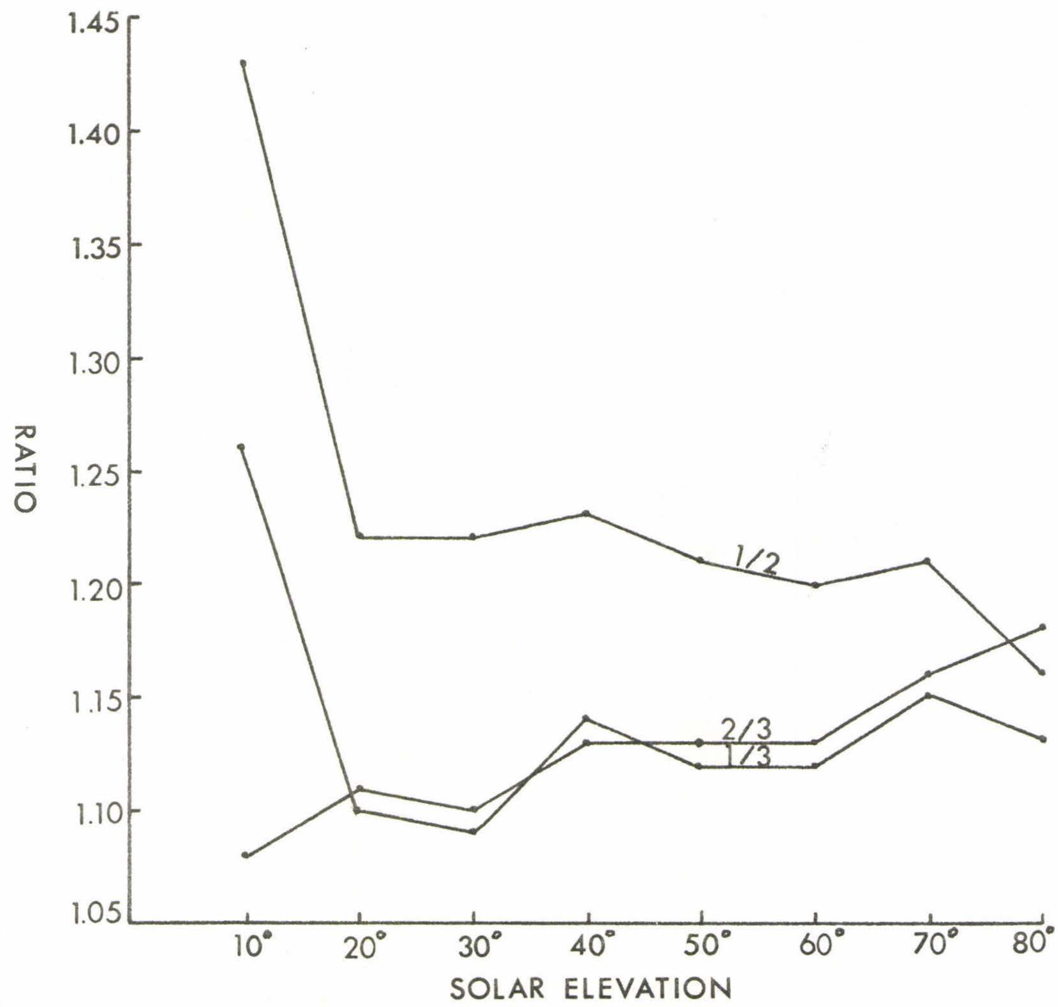


Figure 9. Changes in ratio value with solar elevation



and solar azimuth. The results are given in Table 4. When N = 61, a correlation coefficient of r = 0.25 is needed for a relationship to be significant at the 5% probability level. Besides the expected high correlation between solar elevation and solar azimuth, none of the coefficients were statistically significant. Thus there is no significant changes in solarimeter sensitivity with variation in either solar elevation or solar azimuth.

Table 4. Regression and partial correlation coefficients for ratio value, solar elevation and solar azimuth.

Linear Regression	Ratio 1/2	Ratio 1/3	Ratio 2/3
correlation coefficient of ratio value against solar elevation	-0.155	-0.203	-0.023
correlation coefficient of ratio value against solar azimuth	0.137	0.230	0.055
correlation coefficient of solar elevation against solar azimuth	-0.958	-0.958	-0.958
Partial Correlation			
correlation coefficient of ratio value against solar elevation with solar azimuth held constant	-0.084	0.062	0.104
correlation coefficient of ratio value against solar azimuth with solar elevation held constant	-0.041	0.127	0.115

Stanhill et al (1966) used a white disc to protect the cold junctions in their inverted solarimeter and therefore maintain the cold junction temperature close to the ambient air temperature. This method was tried during one clear day at Simcoe. A piece of polystyrene plastic foam (5 cm. by 7.5 cm. by 1.2 cm.) was placed against the back of the inverted solarimeter (see Figure 10). This lowered the output of the instrument by 6-12%. Since incident radiation was constant and the output of the solarimeter is proportional to the temperature difference between the hot and cold junctions, a lower output must be the result of a higher temperature at the cold junction. Therefore, the addition of the polystyrene sheet did not cool the cold junctions but caused it to warm up. It is likely that heat loss by long-wave radiation and convection was prevented by this insulating material. Consequently, this method was not used during field measurements. However, further work is needed to determine a method whereby the cold junction temperature is kept as close as possible to ambient air temperature.

Fritschen (1967) has recommended that an 18 cm. diameter disc should be placed over the inverted solarimeter to prevent incident solar radiation from directly hitting the inverted dome. Figure 11 indicates that this occurs mainly at low sun angles under conditions of direct radiation. It was calculated at Simcoe, that the absence of such a disc increased the output from 5-10% with a solar elevation of 5°. However, this represents a small absolute change in output since this effect occurs only near sunrise and sunset when radiation intensity is low. It was found (Figure 12) that incident solar radiation reaching the side of the inverted dome was refracted upwards onto the sensor surface and increased the sensor's output. Such a shield was not used at Simcoe. Although this omission may have introduced a small error at low sun angles, the writer feels it prevented other possible errors. A shield could interfere with the heat exchange between the cold junctions and the atmosphere as indicated previously and could also

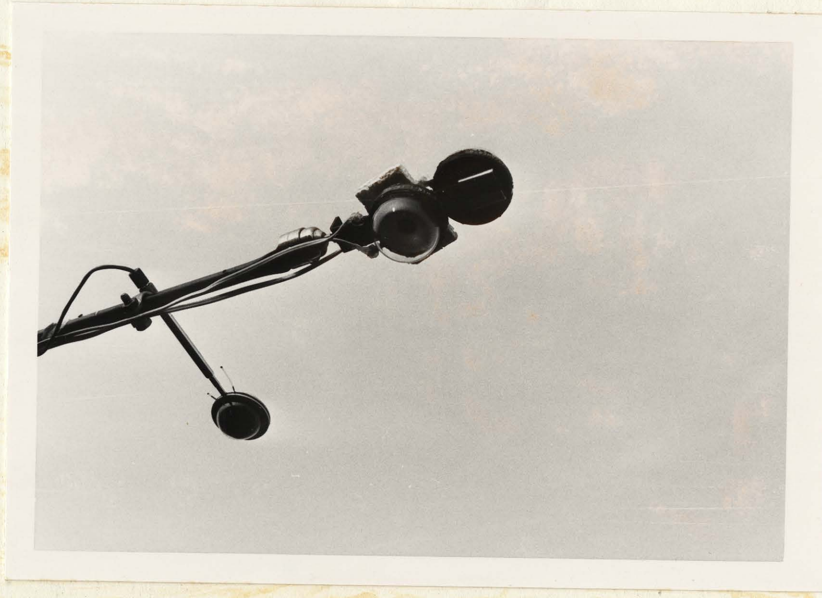


Figure 10. Polystyrene foam backing the inverted solarimeter

Figure 11. Inverted solarimeter receiving incident solar radiation

cast a larger shadow on the sampling surface.

(3) Other Variables

Along with α and Rn values, several other variables were recorded.

(a) Soil Moisture was taken once during the day. Since only the soil moisture at the surface of the ground is pertinent to α, samples were taken from the top 1 cm. of the soil. Soil was scraped from the top surface with a knife at a minimum of 15 sites in the field to ensure a representative spatial average. Because of the sandy nature of the soil, the top 1 cm. was usually quite dry and the moisture content was almost a constant during the summer. The overall seasonal average was 2.14% soil moisture by weight with a standard deviation of $\pm$2.2%. Even when the surface was noticeably wet in the early morning, it was dry by solar noon. Consequently this variable was not significant in the analysis. Perhaps in a soil with better moisture holding ability, such measurements would have been more fruitful. For sandy soil, a suitable tone chart may give a more meaningful description of the soil in terms of α.

(b) Crop height and percentage ground cover were taken for each day. Measurements of plant diameters and width of bare ground spaces between rows were used to calculate ground cover. However the variability across a field meant that any such calculation was partly subjective. Unfortunately vertical photographs could not be taken for the calculation.

(c) Cloud cover and cloud type were recorded for each spot reading.

The presence or absence of direct solar radiation was also observed.

(4) Crop Descriptions

Although 8 different surfaces were used in this study, only 6 of these were given extensive consideration. The crops were chosen to obtain contrasts in height, roughness, leaf size and leaf orientation. All crops except for cucumber and one field of peppers (used twice), had rows oriented in an east-west direction: the possible affect of row orientation was not considered. Measurements were made over the 6 major crop surfaces on an average of once a week.

(a) Corn

Measurements over corn started when the plants were 10 cm. high with 75 cm. of bare ground between the rows. This gave an approximate ground coverage of 5%. After several weeks of moderate growth, the crop developed remarkably fast to a height of 245 cm. and a ground coverage of 85%. The large long leaves hung down between the rows and established emphemeral sun flecks on the ground beneath. The largest leaves occurred 150 cm. to 180 cm. above the ground with smaller leaves above. Lighter coloured tassles extended 30 cm. above the top leaves. Although these large smooth leaves oriented in a horizontal or convex manner should promote reflection, the tassles and great height of the crop provides a rough crop surface and therefore less reflection. Slightly higher soil moisture was found in this field which was situated in a slight depression. The greater ground coverage would also help moisture retention.

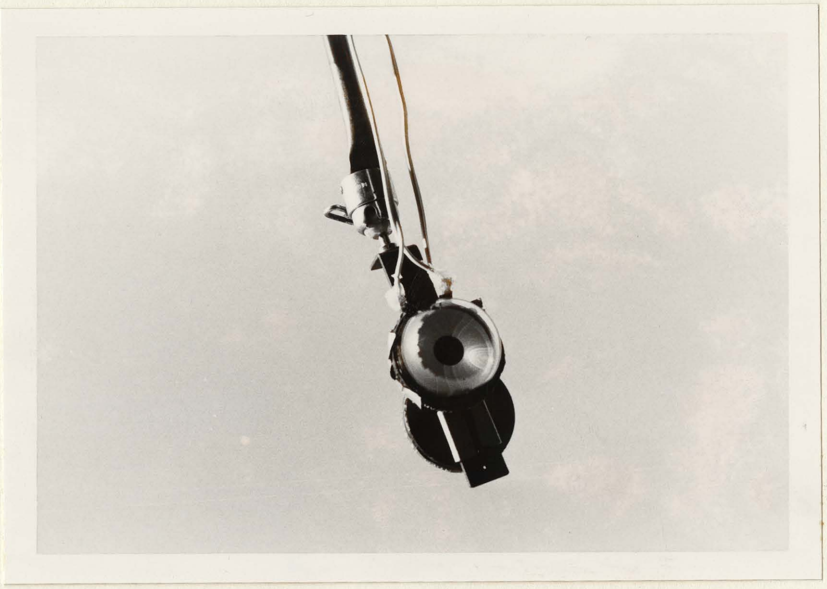


Figure 12. Refracted solar radiation on inverted solarimeter

Figure 13. Soil moisture variation in tobacco field

(b) Tobacco

A very extensive field of tobacco was used. Its slightly concave shape caused soil moisture to vary across the field, as indicated in Figure 13. The transplanted plants had an average height of 10 cm. and a ground coverage of 5% initially. By August 1st, they had attained their maximum height of 125 cm. and a ground coverage of 70%. There was great height variation across the field which reflected the soil moisture differences. The leaves continued to mature and give a maximum ground coverage of 80% after which it declined to 60% by the last day of measuring. This decline was due to the gradual harvesting of the leaves. Many leaves measured 20 cm. by 58 cm. and curved downwards from the horizontal to an angle of 45°. Although the leaves should be good reflectors, the bare ground between the rows was never covered entirely. Thus, the surface roughness factor would be large.

(c) Tomato

At the time of the first measurements, the plants had a height of 20 cm. and a ground coverage of 10%. Until August, the plants developed in a rounded shape with approximately equal height and diameter. Leaves were small but their great numbers gave a dense coverage. Leaf orientation did not seem to predominate in any particular direction. At maturity the leaves were lighter in colour and the plants had a much greater diameter to height ratio. Bare spots occurred randomly over the field where plants had died earlier, or where weeds had not colonized spaces between rows. The red fruit did not take up a significant enough portion of the surface to be a factor.

(d) Pepper

Peppers grew very slowly from a height of 13 cm. and a diameter of 37 cm. to an average height of 35 cm. and a diameter of 37 cm. Consequently ground coverage rose from 5% to only 45%. The leaves drooped at an angle of 45° or greater below the horizontal. They were noticeably a darker green than any of the other crops. During the last several weeks, lack of cultivation allowed weeds to cover some of the ground surface between rows. The low crop height and thick leaf coverage on the plants produced a low surface roughness factor.

(e) Cucumbers

Cucumbers were used only on two days. On the first day, the crop was 25 cm. high with 35% ground cover. The leaves were about 10 cm. in diameter and oriented mostly in the horizontal. On the other day, ground coverage was virtually 100% and leaf orientation as well as height were unchanged. The light green leaves had a covering of fine hairs which one might expect to increase the reflectance (Gates, 1965; Billings and Morris, 1951).

(f) Winter Wheat

The winter wheat had reached its maximum coverage, virtually 100%, by the time of the first measurements on June 14. The leaves were a moist green and were inclined downwards in a convex manner. From thereafter only the tassles grew another 12 cm. above the leaves to give an overall height of 113 cm. By July 15, the leaves turned a light greenish colour and withered, thereby significantly changing the crop structure. Coverage was down to 80% or less and the solar beam could easily reach the floor near solar noon. Consequently the effective roughness of the surface was greater. The wheat was harvested on August 3, leaving a 30 cm. high stubble. Two more days of readings were made over this stubble. The stubble left a lower ground coverage but the soil was partly covered by wheat chaff.

(g) Perennial Ryegrass

The perennial ryegrass, planted early that spring, was maintained at a constant height of 8 cm. for the entire field season. The constant cutting prevented the grass from seeding or turning brown. Although this field was irrigated once a week, ground coverage never exceeded 85%.

(h) Bare Ground

The bare ground surface consisted of Fox sandy loam as described previously. These several fields were ploughed and levelled to give a uniform appearance. Soil moisture was always very small at the surface (1% or less). The ploughing left small clods of earth which gave the surface some roughness. Kondrat'ev (1954) concluded that even the roughness created by these clods could effect the α values.

CHAPTER III

REFLECTION COEFFICIENTS

(1) The Data

Radiation measurements were made over 7 crops during 38 days between June and September. Table 5 shows the surfaces over which measurements were made on each day and the average α values computed by 3 methods. In column 3, a daily mean value is given which was calculated from all the data on a given day. This gives equal weighting to all α values irrespective of the radiation level and is therefore affected by the high values at low sun angles. These α values at low sun angles were more prominent towards evening than in the early morning for two reasons. Firstly, the ground surface of the farm slopes about 5° towards the west and many fields had trees or buildings on the east side, but not on the west. Hence, the sun was at a greater solar elevation when it appeared above the local horizon in the morning than when it was about to set in the west. Sun angles, therefore, caused less α variation in the morning. Secondly, the prevalence of dew on plant surfaces in the morning could lower α because of the lower reflecting power of water. This situation was found at Rothamsted (Montieth and Szeicz, 1961).

Column 4 lists an adjusted daily average α value. The high values over 0.33, which occurred at low sun angles, were excluded in this calculation. The writer feels that this is a more realistic mean value for the day.

Table 5. Surfaces and α values for each day at Simcoe

Date	Surface	Means	Adjusted means	Stanhill mean	Difference
June 13	bare ground	0.210	0.210	0.204	0.006
June 14	corn	0.210	0.210	0.187	0.023
" "	tomato	0.248	0.239	0.218	0.021
" "	wheat	0.326	0.304	0.290	0.014
" "	pepper	0.231	0.231	0.213	0.018
June 22	grass	0.232	0.232	0.234	-0.002
June 23	tobacco	0.208	0.208	0.251	-0.043
June 26	corn	0.196	0.196	0.194	0.002
" "	tomato	0.206	0.206	0.189	0.017
June 27	wheat	0.275	0.259	0.216	0.043
" "	pepper	0.243	0.243	0.249	-0.006
July 5	grass	0.256	0.256	0.248	0.008
July 6	corn	0.274	0.234	0.119	0.035
" "	tomato	0.274	0.247	0.213	0.034
July 7	wheat	0.298	0.294	0.302	-0.008
" "	pepper	0.198	0.198	0.207	-0.009
July 8	tobacco	0.241	0.241	0.209	0.032
July 13	corn	0.227	0.227	0.210	0.017
" "	tomato	0.245	0.245	0.214	0.031
July 17	tobacco	0.233	0.233	0.220	0.013
July 18	grass	0.237	0.234	0.197	0.037
July 19	wheat	0.241	0.238	0.197	0.041
" "	pepper	0.283	0.271	0.254	0.017
July 20	corn	0.287	0.282	0.256	0.026
July 21	pepper	0.238	0.238	0.234	0.004
" "	cucumber	0.260	0.260	0.265	-0.005
July 25	grass	0.292	0.267	0.240	0.027
July 26	tobacco	0.252	0.252	0.236	0.016
July 27	wheat	0.210	0.210	0.168	0.042
" "	pepper	0.262	0.262	0.216	0.046
July 29	wheat	0.212	0.212	0.143	0.069
" "	pepper	0.270	0.263	0.219	0.044
July 30	grass	0.233	0.233	0.218	0.015
Aug. 1	tobacco	0.263	0.253	0.237	0.016
Aug. 3	wheat	0.221	0.221	0.188	0.033
" "	pepper	0.240	0.240	0.225	0.015
" "	corn	0.268	0.265	0.237	0.028
" "	tomato	0.250	0.250	0.219	0.031
Aug. 4	pepper	0.235	0.235	0.214	0.021
" "	cucumber	0.317	0.294	0.258	0.046
Aug. 8	grass	0.224	0.224	0.204	0.020
Aug. 9	pepper	0.214	0.214	0.210	0.004
Aug. 10	corn	0.286	0.281	0.259	0.023
" "	tomato	0.249	0.249	0.237	0.012
Aug. 11	tobacco	0.286	0.275	0.274	0.001
Aug. 15	wheat	0.291	0.261	0.228	0.033
" "	pepper	0.251	0.245	0.232	0.013

Table 5 - continued

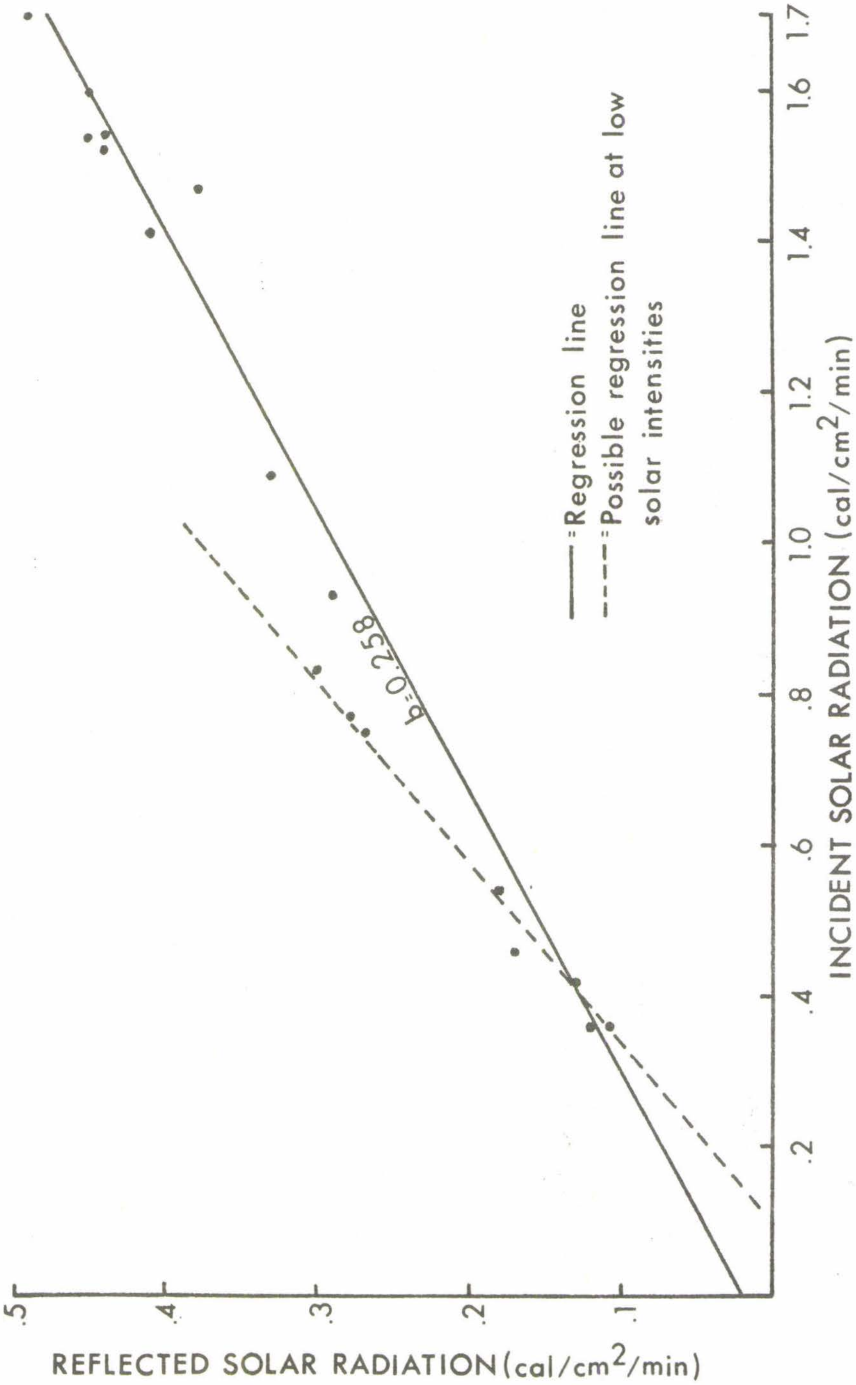
Date	Surface	Means	Adjusted mean	Stanhill mean	Difference
Aug. 16	corn	0.274	0.267	0.231	0.036
" "	tomato	0.258	0.256	0.227	0.029
Aug. 22	wheat	0.283	0.238	0.204	0.034
" "	pepper	0.245	0.228	0.209	0.019
Aug. 23	tobacco	0.266	0.253	0.231	0.022
Aug. 24	corn	0.222	0.222	0.220	0.002
" "	tomato	0.300	0.288	0.281	0.007
Aug. 28	grass	0.241	0.241	0.238	0.003
Aug. 29	bare ground	0.191	0.188	0.208	-0.020
Sept. 3	corn	0.283	0.267	0.233	0.034
" "	tomato	0.247	0.242	0.228	0.014
Sept. 5	tobacco	0.277	0.252	0.229	0.023
Sept. 7	pepper	0.292	0.254	0.226	0.028
		Total combined means			
			0.245	0.225	
		Overall standard deviation			
			0.025	0.028	

Column 5 gives the mean daily α value using a method recommended by Stanhill et al (1966). This value gives weight to the radiation intensity. It is attained by regressing spot values of reflected against incident radiation. The slope of the regression line then becomes the average α value. In most cases, the regression lines had a correlation coefficient greater than 0.99 and a standard error of the estimate less than 0.01 cal. $cm.^{-2} min.^{-1}$. Stanhill et al (1966) considered that this gave a truer value.

Column 6 shows the differences between the adjusted mean and the Stanhill mean. The difference between the overall average of these means is 0.02. Using the standard error of the difference (0.0048), the two methods do give a significantly different value. In most cases, the Stanhill average was 0.02 lower than the adjusted mean.

The regression line and spot values for calculating the Stanhill average are illustrated in Figure 14 for August 4 over cucumber. On this day the difference between the Stanhill and adjusted means was

Figure 14. Stanhill mean α for cucumber, August 4



0.036. The high values at low solar intensities are given less weight by the regression line.

(2) Crop α values in relation to Montieth's postulate

Montieth (1959a) established that many surfaces where the ground is completely covered with vegetation have a uniform reflectivity close to 0.25. Only a few daily average α values in Table 5 do equal 0.25 even near the end of the season when there was maximum vegetative cover. Although great daily and seasonal variation exists in all these cropped surfaces, if the seasonal average, in the form of the modal value of all spot readings is considered, there is excellent agreement with Montieth's postulate. Figures 15 and 16 show the frequency distributions for each crop, together with mean and modal values. All crops, except cucumbers, had a mean and modal value between 0.24 and 0.26. Since this modal value considers all spot readings for the season and not daily average values, it is weighted by mid-day values where a greater number of spot readings were taken. Consequently, the diagrams give a much clearer picture of the range of α values for a crop than averages alone. Since α values range widely for a single surface type, for many reasons, the mode may be a more representative figure to use.

Cucumbers and bare ground are special cases. Only 2 days of readings were completed for each. In each case, when the histogram for each day is superimposed, the trend becomes evident.

Bare ground has a mode of 0.22 for June 13 and 0.18 for August 29. These values are within Fritschen's (1967) range (0.14-0.24) for bare ground and agrees well with Montieth's (1959a) values of 0.18

Figure 15. Frequency distributions of α

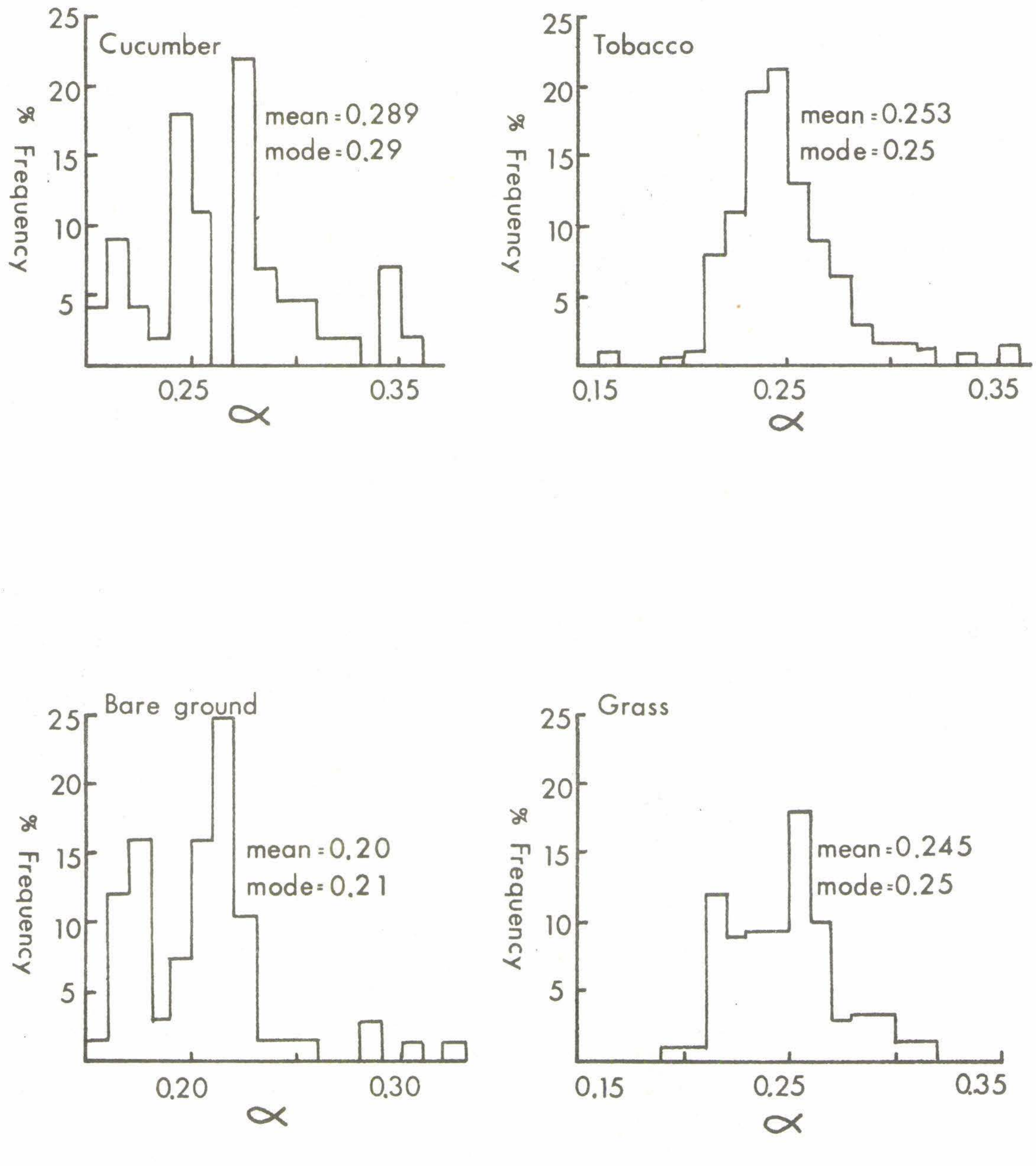
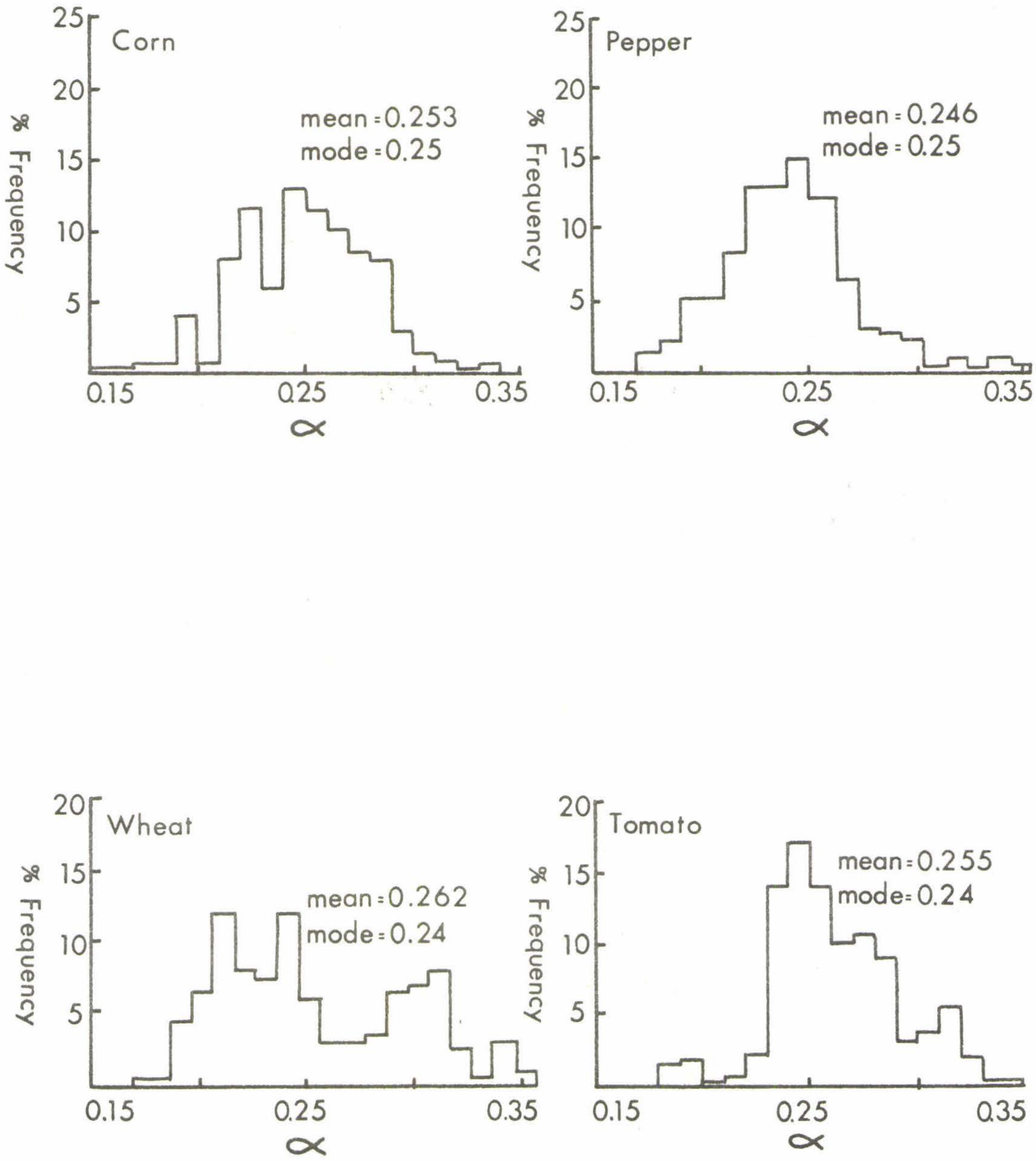


Figure 16. Frequency distributions of α



for dry soil. The difference between these 2 days of equal soil moisture (1% by weight) and similar weather may be due to greater shading between earth clods caused by a lower maximum sun elevation in August.

The α value for cucumbers increased from 0.26 on July 21 to a mode of 0.29 on August 4. This may be attributed to the increase in ground cover from 35% to 100% during this period. The low surface roughness and large, horizontally oriented leaves would also partially explain the larger α values. Unfortunately, no values for cucumber are reported in the literature.

In the majority of cases, therefore, seasonal averages support Montieth's hypothesis. Graham and King (1961), working at Guelph, obtained much lower values for corn (0.19). However, their measurements were made over an irrigated field and the moist soil, visible through the crop, would lower the reflection. Ekern (1965) and Chia (1966) obtained low values for grass (0.15 and 0.19 respectively) working in tropical environments. The effects of higher solar angles might be responsible. Since values less than 0.25 were reported by Stanhill et al (1966) in Israel, it is not safe to conclude that departures from the 0.25 value are due entirely to greater solar elevations. This study has confirmed Montieth's postulate but there is a need to extend such measurements over different soil and moisture conditions.

(3) Reflection coefficients and solar elevation

Of the 7 variables recorded throughout the summer, solar elevation had the most pronounced effect upon α . Figure 17 shows the relationship between α and solar elevation using averaged data for the 6 major cropped surfaces. The curves have basically the same shape and the difference between them is small. The difference is largest for the 0-10° and the 70-80° solar elevation categories where sample sizes are smaller than for other elevation categories. Visual interpretation indicates these lines form a sigmoid shape similar to those plotted by Montieth (1959a). The scatter of actual values about these curves is considerable due to variation in cloud cover, ground cover and crop height. Figure 18 shows the standard deviation for tobacco. All surfaces tended to have a lower standard deviation as solar elevation increased. Scatter for the other surfaces (except for cucumber and bare ground) are given in Appendix (A).

Again cucumber and bare ground can be treated separately because of the small number of days that are involved. The α-solar elevation relationship for bare ground is shown in Figure 19. The curve for June 13, which was a very clear day, flattens out very quickly at values beyond 0-10° and does not show the same amount of variation as for cropped surfaces. Davies (1967b) also found that increased reflection with decreasing solar elevation is more marked for vegetated than for non-vegetated surfaces in a desert area. The curve for August 29 is different from any other. When solar elevation increased beyond 40°, α values rose sharply. No explanation can be suggested for this increase. However, it was associated with a rapid increase in cloud cover (from 1/10 to 7/10's). Since the composition of the radiation would change towards a higher diffuse component, a dependence of α on the spectral character of the radiation might be indicated.

Figure 17. Variation of α with solar elevation for vegetated surfaces

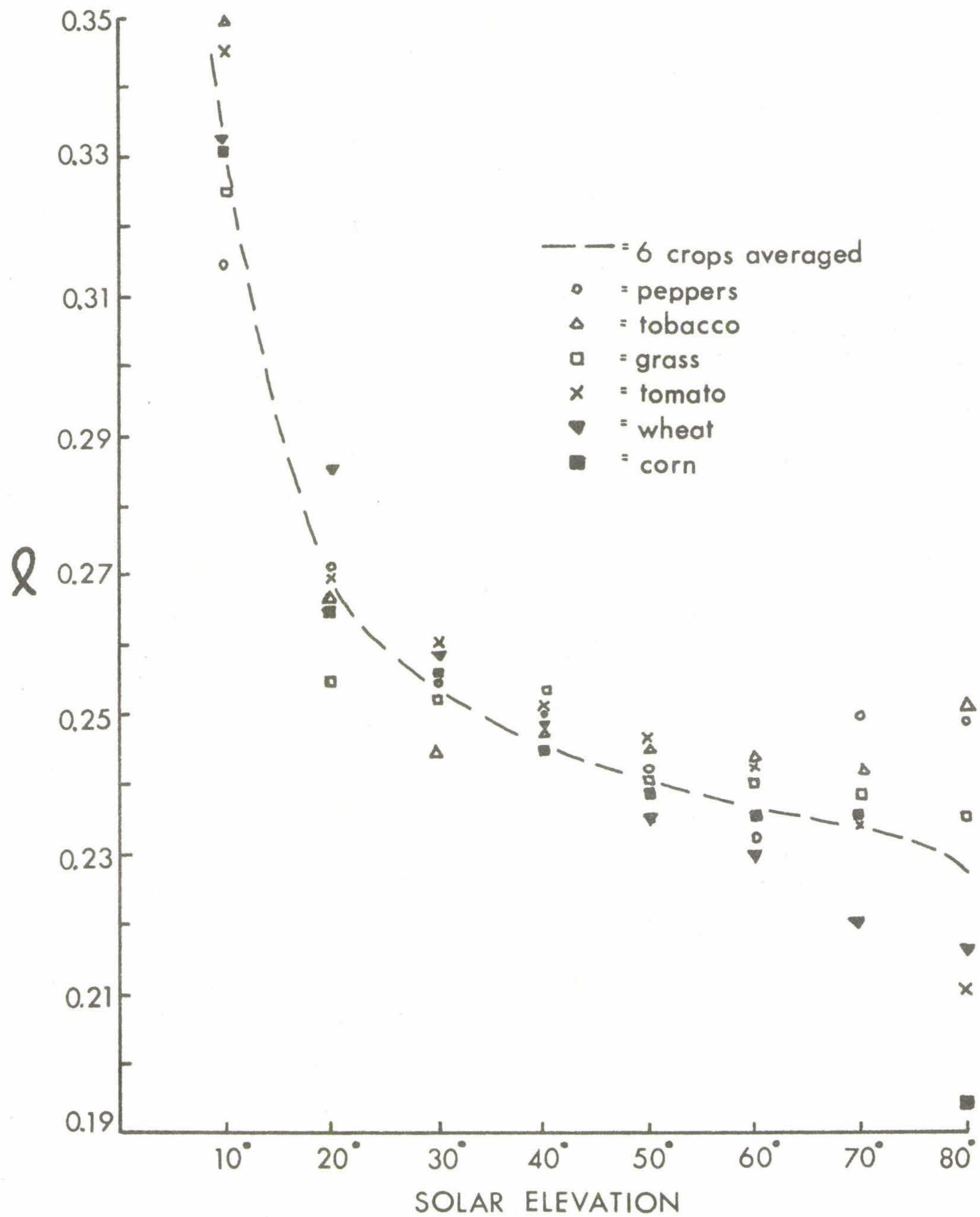


Figure 18. Variation of α with solar elevation for tobacco

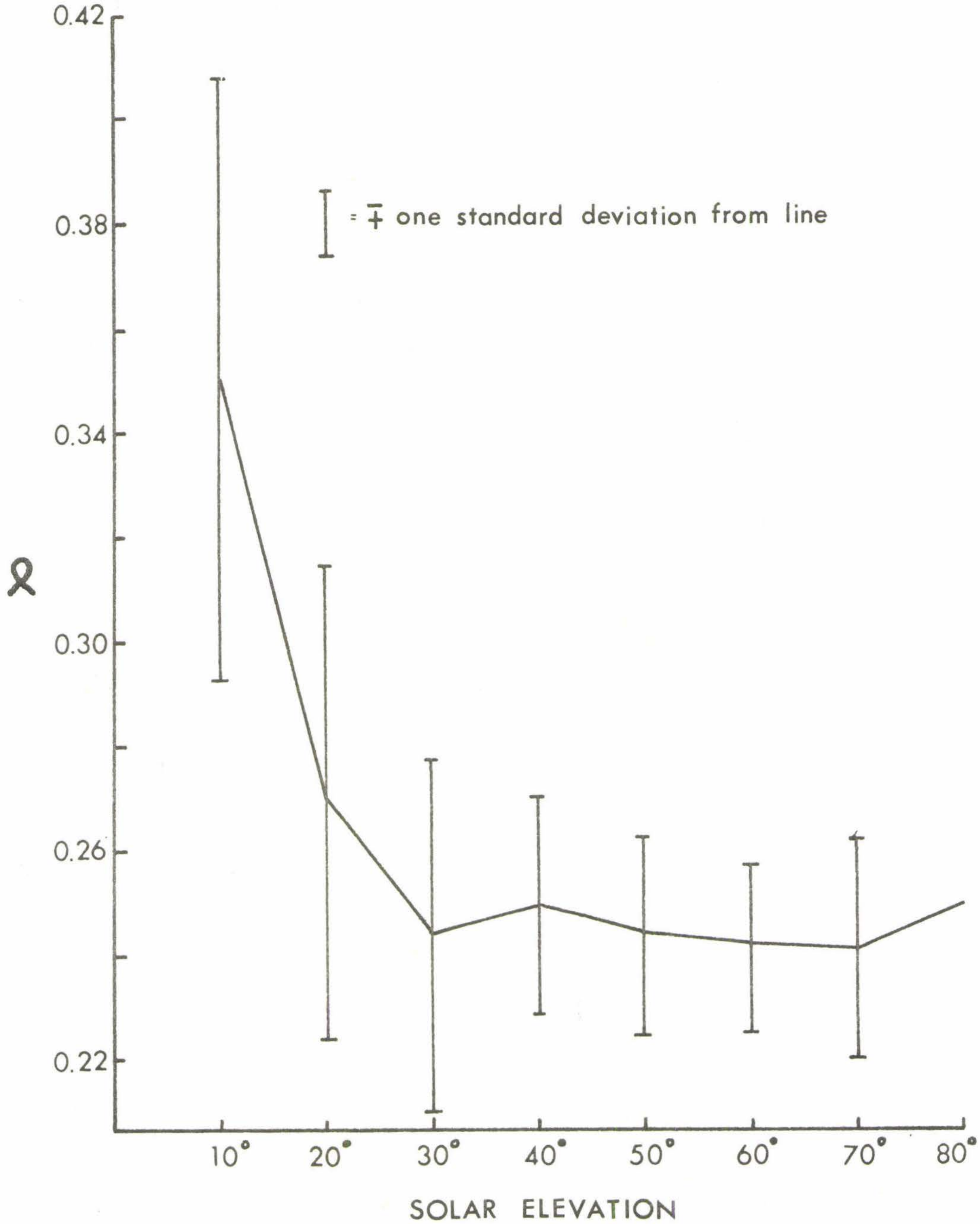
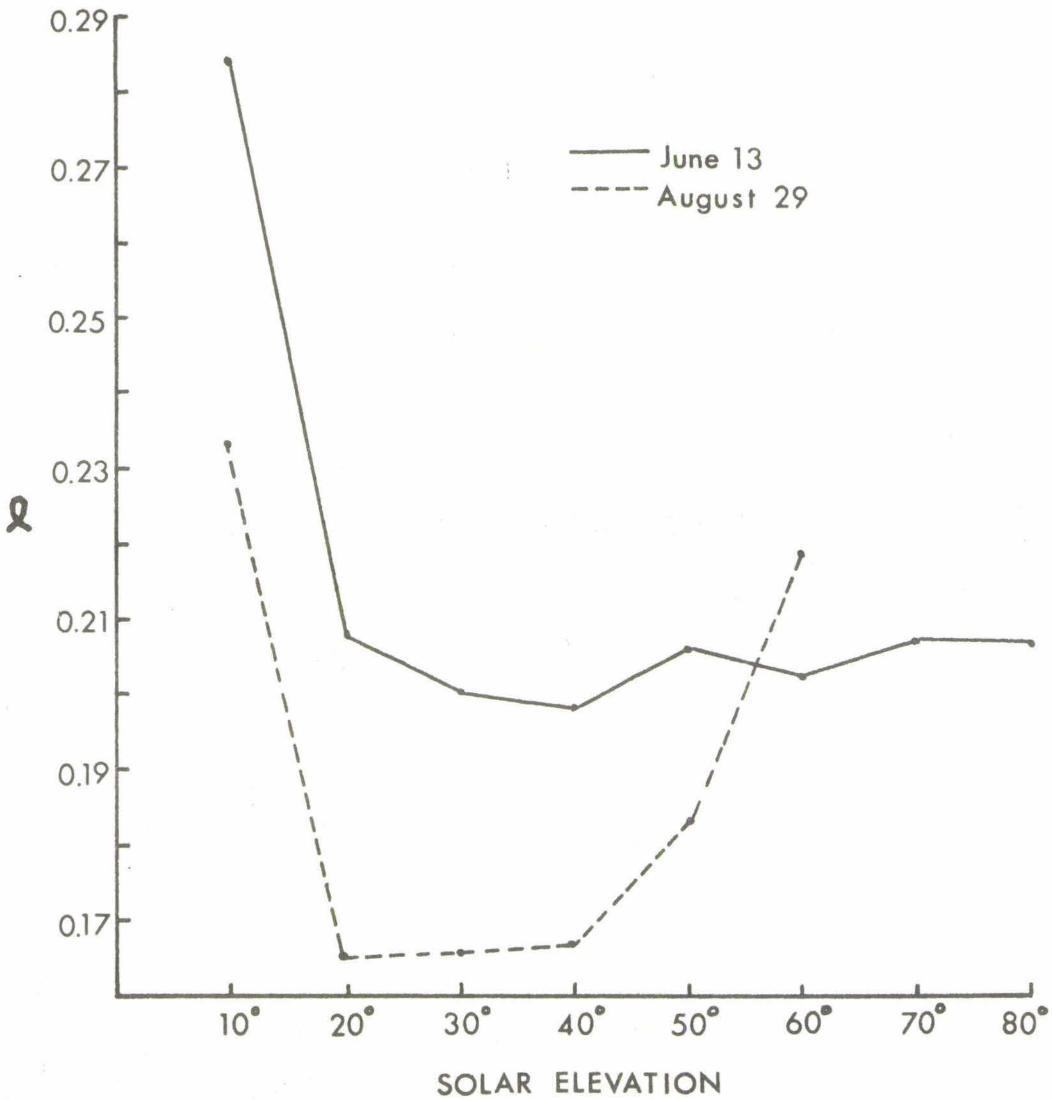


Figure 19. Variation of α with solar elevation for bare ground



The 2 curves for cucumber (Figure 20) illustrates an important feature of solar elevation. Solar elevation is only important in controlling α under direct beam radiation conditions. When the sun is obscured by cloud, the composition of incident radiation changes from predominantly direct to predominantly diffuse. The curve for August 4 represents clear sky conditions where the direct component is predominant while the curve for July 21, which is quite flat and shows no decrease in reflection with increasing solar elevation, represents a cloudy day where radiation was largely diffuse.

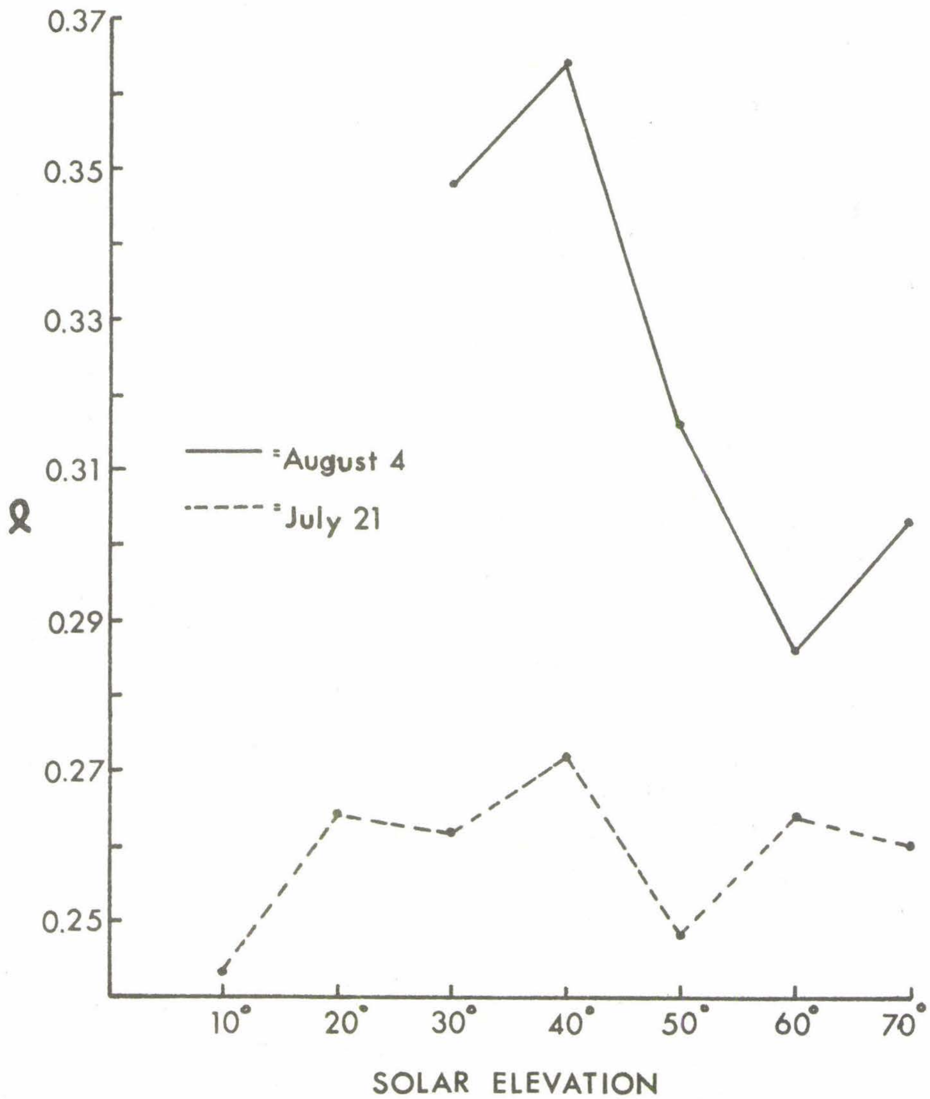
In order to evaluate the effect of solar elevation on α, linear correlation coefficients were calculated for each crop and for the total combined data (Table 6).

Table 6. Correlation coefficients for α against solar elevation

Crop	Sample Size	Correlation Coefficient
corn	270	-0.42
pepper	279	-0.52
tomato	269	-0.51
tobacco	259	-0.53
grass	312	-0.39
wheat	173	-0.53
Total data	1682	-0.42

All coefficients are significant even at the 1% probability level. Solar elevation accounted for 16-28% of the variation in α values. The use of sine and logarithmic transformations of solar elevations made little difference. Thus, it is evident that solar

Figure 20. Variation of α with solar elevation for cucumber



elevation is significant in explaining some of the variation in α . However, the exact causal relationship here is not so straightforward. Part of the effect of solar elevation is due to the presence and type of vegetation cover. Part of this effect has been attributed to changing spectral composition of the incident radiation as solar elevation increases (Kondrat'ev, 1954). As the sun reaches its zenith, the incident radiation contains a larger short-wave component. In addition, instrumental error is also a possible source of variation. In Chapter II, it was shown how incident radiation may be received by the inverted sensor at low sun angles causing a higher α . The relative importance of these different sources of error could not be determined in this study.

(4) Reflection coefficients and other variables

Besides solar elevation, several other variables were recorded throughout the field season. These were crop height, soil moisture, ground cover, cloud type, cloud amount and illumination type. It was hypothesized at the start of this study that these variables may be related to α . Both linear and multiple regression techniques were used to suggest possible relationships. Correlation coefficients are given in Tables 7 and 8.

Table 7. Multiple correlation coefficients for α.

Surface	Multiple correlation coefficient	Variables in order of importance
Tomato	0.556	solar alt., crop height, cloud type
corn	0.64	solar alt., ground cover, cloud amount, crop height
wheat	0.64	solar alt., cloud type, crop height, ground cover
cucumbers	0.906	crop height, cloud amount cloud type
bare ground	0.367	illumination type, cloud type, solar altitude
tobacco	0.67	solar alt., crop height, soil moisture, cloud amount
grass	0.43	solar alt., crop height, ground cover
peppers	0.61	solar alt., cloud amount, cloud type
total combined data	0.523	solar alt., ground cover, cloud type, crop height

Table 8. Linear correlation coefficients for α.

		Correlation coefficients with				
Surface	Sample size	Cloud type	Cloud amount	Crop height	Ground cover	Soil moisture
tobacco	259	-0.04	+0.09	+0.455*	+0.39*	+0.08
tomato	269	+0.03	+0.07	+0.20*	+0.20*	-0.04
grass	312	-0.045	+0.01	-0.06	+0.02	0.00
corn	270	+0.11	-0.21*	+0.28*	+0.36*	-0.09
pepper	279	-0.06	-0.41*	+0.11	+0.13	+0.03
wheat	173	-0.01	-0.12	-0.23*	-0.165	+0.08
total combined data	1682	-0.04	-0.06	+0.19*	+0.25*	+0.08

*Figure shows significant relationship at 1% probability level

Illumination type is a dichotomous variable. It was recorded to tell whether the sun was visible or whether it was obscured by clouds at the time of the spot reading. Because of its dichotomous nature, linear regression could not be successfully employed. Consequently, a significance test using the standard error of the difference for the total combined data was employed. For all α spot values, regardless of surface type, the average α value under conditions of sun was 0.256 while an average of 0.249 was found when the sun was obscured by clouds. With a sample size of 1682, the standard error of the difference was 0.0066. Thus, these two α values are significantly different at the 5% probability level and just short of being significantly different at the 1% level. Although this agrees with Fritschen (1967) who found lower α values on several days due to partly cloudy skies, it disagrees with many workers. Davies (1963) found higher values when radiation was diffuse for surfaces in Labrador-Ungava. Robinson (1966) also indicates that α values will rise as the long-wave component of the radiation rises. However this trend was not found at Simcoe for either the total combined data or individual days.

Kondrat'ev (1954) gave evidence on the relation between soil moisture and α. He found that α decreases with increasing soil moisture as explained in Chapter II. The predominantly dry soil surface conditions at Simcoe has reduced the effect of soil moisture. Table 8 shows that all correlation coefficients for soil moisture are quite low and none are statistically significant. Table 7 also shows that soil moisture is only of minor importance in a few cases.

Crop height and ground coverage will be discussed together.

Tables 7 and 8 indicate that there is some interrelationship between these 2 variables. For many crops, ground cover closely follows crop height. A few low crops such as grass and peppers would be exceptions to this trend. Neglecting these two crops, and also wheat, crops in Table 8 which show a significant correlation coefficient (r) between α and crop height also have a significant correlation with ground cover. The r values for grass and peppers which are low crops are not significant at the 1% probability level. Wheat is an exception here since its maximum ground coverage was reached before the field season started and it decreased during the summer. In Table 7, it is evident that crop height and ground cover usually explain 3-21% of the variation in α where a relationship can be shown. This means they are second only to solar elevation in their effect on α .

This high degree of inter-dependence between crop height and ground coverage indicates the problem in isolating the effects of any variable. Although these 2 variables are inter-related, the hypothesized effect that they have on α are not the same. As a crop becomes taller, the amount of multiple reflection within the crop canopy tends to lower α (Stanhill <u>et al</u>,1966; Montieth, 1959a). Davies (1967b) also found lower α values with taller vegetation. He attributes part of this phenomenon to shading between plants. However, if ground cover is positively correlated with crop height, there is also the opposite tendency for α to increase with crop height. Since the α of soil is generally lower than that for vegetation, there will be an increase in α as crop coverage increases. This may be the reason why Fritschen (1967) found a tendency for taller crops to have higher α values. At Simcoe, a significant positive relationship was found between crop height and ground coverage, and α. Such a relationship suggests that the effect of increasing vegetation cover is greater than the effects of multiple reflection and shading. As crops such as corn and tobacco become taller, the space between crop rows is filled. This would tend to lower the surface roughness factor and therefore decrease both radiation trapping by the crop canopy and visible shading. Perhaps a roughness factor of the magnitude found in orchards (Stanhill et al, 1966) and forests (Miller, 1959) is required for shading and multiple reflection to become dominant.

Cloud amount and cloud type were recorded with each spot reading during the summer. Their correlation with α are shown in Table 8. With most crops cloud type proved to be a statistically insignificant variable for α. Cloud amount was not a powerful variable either. However it was significant for the data gathered over corn and peppers. In both these samples as well as for the total combined data, the r value was negative. This means that there was a trend towards lower α values with more extensive cloud cover. This conclusion is compatable with the lower α values found under diffuse sky conditions. It also agrees with Fritschen's (1967) data where values found under partly cloudy conditions were lower than those under clear sky conditions. As the amount of cloud cover increases, there is a greater possibility for the sun to be obscured by cloud. When clouds are present, the incident and reflected radiation which they intercept is modified such that the fraction of near infrared radiation is increased. Consequently there is some inter-relationship between cloud coverage and illumination type mentioned previously.

(5) Reflection coefficients of leaves

On two clear days, August 29 and September 7, 5 types of leaves were placed on a board painted with Parson's optical black and their reflectivities were determined. The procedure was outlined in Chapter II. The mean value and standard deviation for each leaf surface as well as for the plants in situ are listed in Table 9. From

Table 9. The α of leaves on a board

Crop	Mean α (board)	Standard deviation	Sample size	Mean α in situ	Standard deviation in situ
corn	0.284	0.91	10	0.259	4.9
cucumber	0.322	0.35	15	0.283	3.8
peppers	0.304	0.66	16	0.251	4.14
tobacco	0.286	0.31	9	0.260	4.04
tomato	0.283	0.48	14	0.259	3.7

the board measurements, leaves have an average α value between 0.03 and 0.05 greater than crop α values. The higher value is probably due to a lower surface roughness factor and to a greater coverage. The plants rarely reached a ground coverage of 100% in the field and thus, they were affected to some degree by the lower α of the visible soil surface.

The values for leaves on a board are somewhat higher than the 0.22 to 0.27 range which Kondrat'ev (1954) found. Since these measurements were taken over a short period of time, solar elevation, cloud amount, soil moisture, ground coverage and illumination type were all constant. Consequently the standard deviations are 5 to 12 times less than that for the crop's seasonal average.

Montieth (1959a) has suggested that most leaves have a similar α regardless of their colour. To test this hypothesis, analysis of variance was used on four combinations of these 5 leaf samples. The resulting F values are listed in Table 10. Corn, tobacco and tomato leaves show a strong statistical similarity to one another. However, pepper leaves have an average α value that is significantly higher.

Table 10. F values for the α of leaves on a board

Crops	F value	F value needed to be significant at the 1% level
corn and tomato	0.065	7.88
corn, tomato, tobacco	0.619	5.34
corn, tomato, tobacco, pepper	33.913	4.22
corn, tomato, tobacco, pepper, cucumber	109.82	3.65

Cucumber leaves are significantly higher than any of the other four. The hair cover on cucumber leaves is similar to some desert plants. Billing and Morris (1951) found that such a cover will increase α . Consequently, the Simcoe results show that all leaves do not have similar α values. In the field, cucumber also had an α value that was noticeably higher than 0.25 which was typical for the other crops. In part this is due to the higher reflectivity of the plant. However the high ground coverage (100%) and the horizontal leaf orientation is also influential. Peppers had an α similar to that for other plants. The maximum ground coverage that peppers reached was only 45%. Consequently the lower α of the bare ground decreased the α to a value similar to corn, tobacco and tomato.

The variation of leaf α with time is shown in Figure 21. Except for tobacco, values tended to rise over the 9 to 16 minute period. Ångström (1925) found a similar phenomenon. He attributed the rise to water loss from the leaf as it wilts. This loss of water from wilting was noticed in all leaves used at Simcoe.

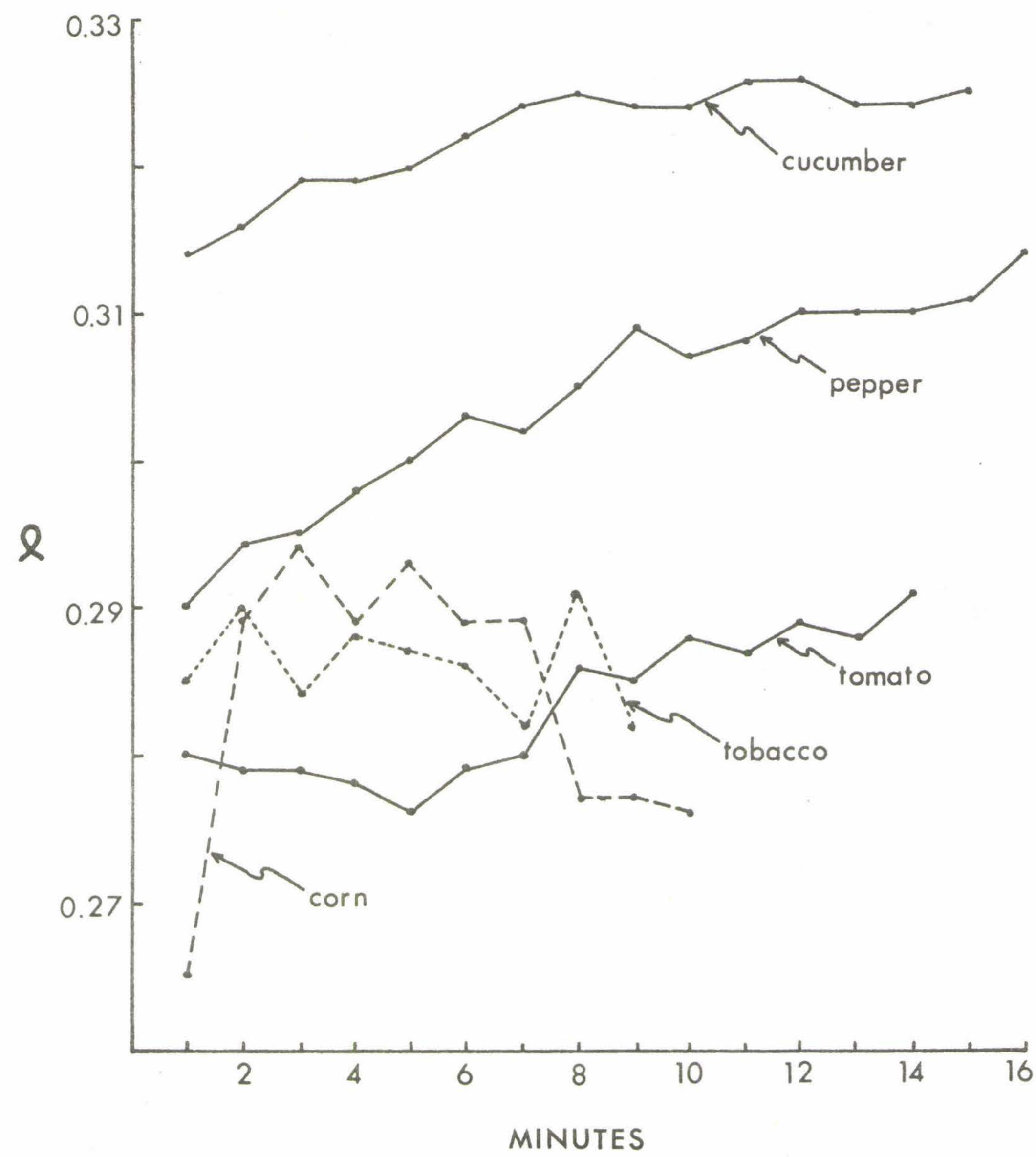
(6) Reflection coefficient change through the season

Since most plant characteristics change through the crop season, corresponding changes in α should be expected. The seasonal trends in daily average α values are given in Figures 23, 24, and 25. For all crop surfaces, the standard deviations were close to ± 0.024. With the possibility of such a large error, care must be taken when attempting to establish a meaningful trend from a small number of values.

The 8 surfaces can be divided into 3 groups. Firstly, corn, tomato, pepper, tobacco and cucumber all increased in ground coverage, height and leaf size during the summer. Secondly, winter wheat shows a decline in ground coverage during the season. Thirdly, perennial ryegrass and bare ground constitute a group whose characteristics remain relatively unchanged through the summer season.

Figure 22 shows the monthly mean α values for the first group. Cucumbers have been omitted since measurements were not taken during all these 4 months. From June to September there is a consistent rise in the mean values. The greatest increase occurs from June to July which is the time of greatest crop development. During August and September crop growth declines as maturity is reached. This is reflected in a more gentle slope of the mean α line.

Figure 21. Time change in leaf α



This same trend is seen in the individual mean α lines (Figures 23, 24, and 25). Corn displays a sharp increase after July 16 which corresponds to its period of rapid growth. The α of tobacco also rises consistently until late August. At this time the loss of leaves from harvesting lowered the α values by 0.022. The considerable change in α for corn and tobacco is undoubtedly related to their large size, high ground coverage and large leaf size. The rise in mean values of α were less for tomatoes and least for peppers. This correlated with their respective increases in ground coverage of 10-85% and 5-45%. All crop surfaces experienced fluctuations in their mean daily α, which were not related to the seasonal trend but indicates the influence exerted by other climatic variables and random error.

In contrast to these other crops, winter wheat indicates an opposite seasonal trend (see Figure 24). The highest mean α occurred in June and early July when ground coverage and leaf area index are highest. During July, its crop structure alters dramatically. The stalks become dry and change to a yellow-green colour while the leaves withered away. This change in crop structure is reflected in a significant drop in α from 0.294 to 0.210 within 13 days. This lower value was maintained until the crop was harvested. Slight increases in α during this ripening stage agree with Montieth's (1959a) findings for winter wheat. He attributes this to the growth of weeds. The mean α over the stubble (30 cm. high) was consistently higher than over the ripened wheat (113 cm. high). Although the stubble provided a lower ground coverage which should give a lower α, the 0.029 increase

Figure 22. Combined monthly mean α

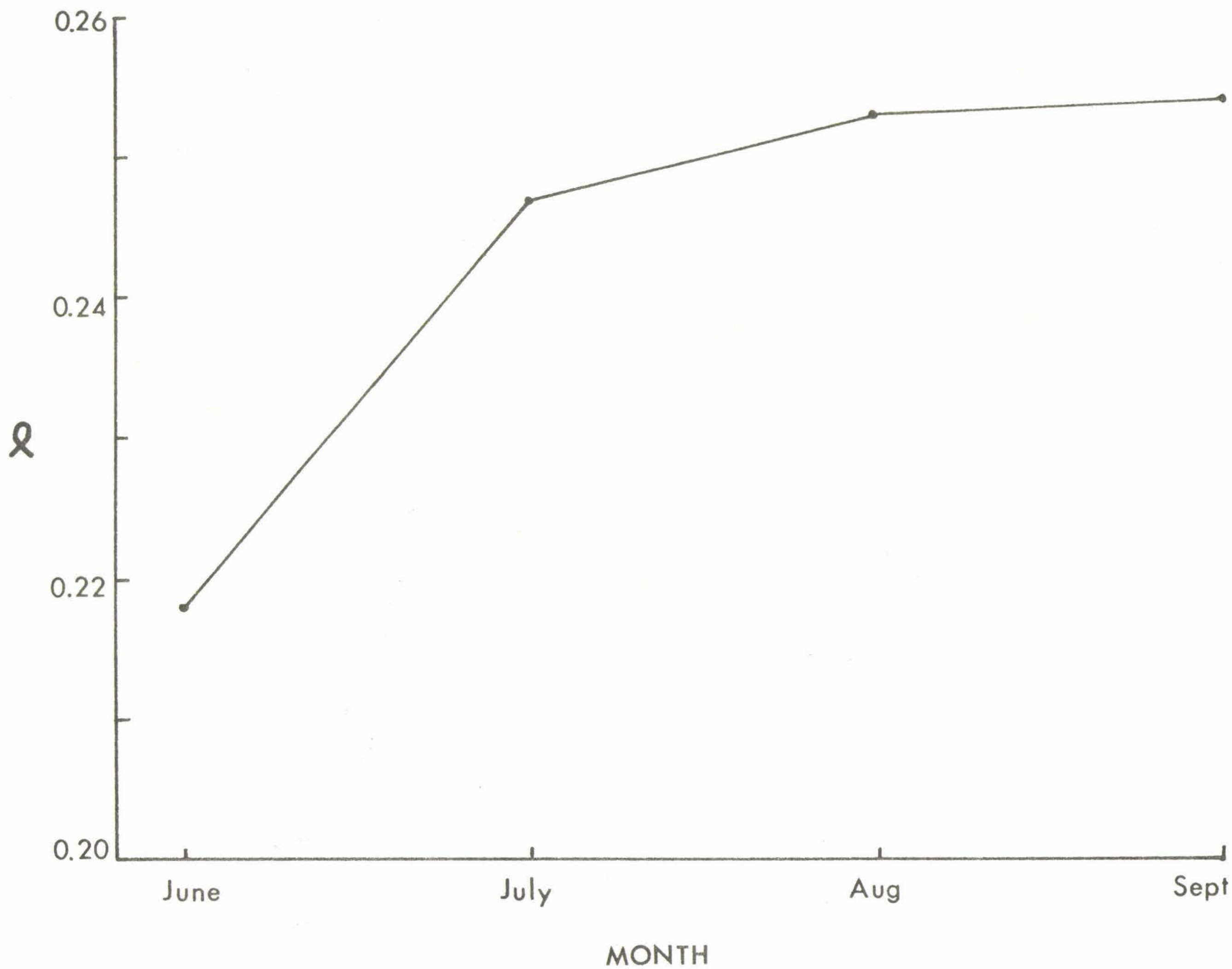


Figure 23. Mean daily adjusted α

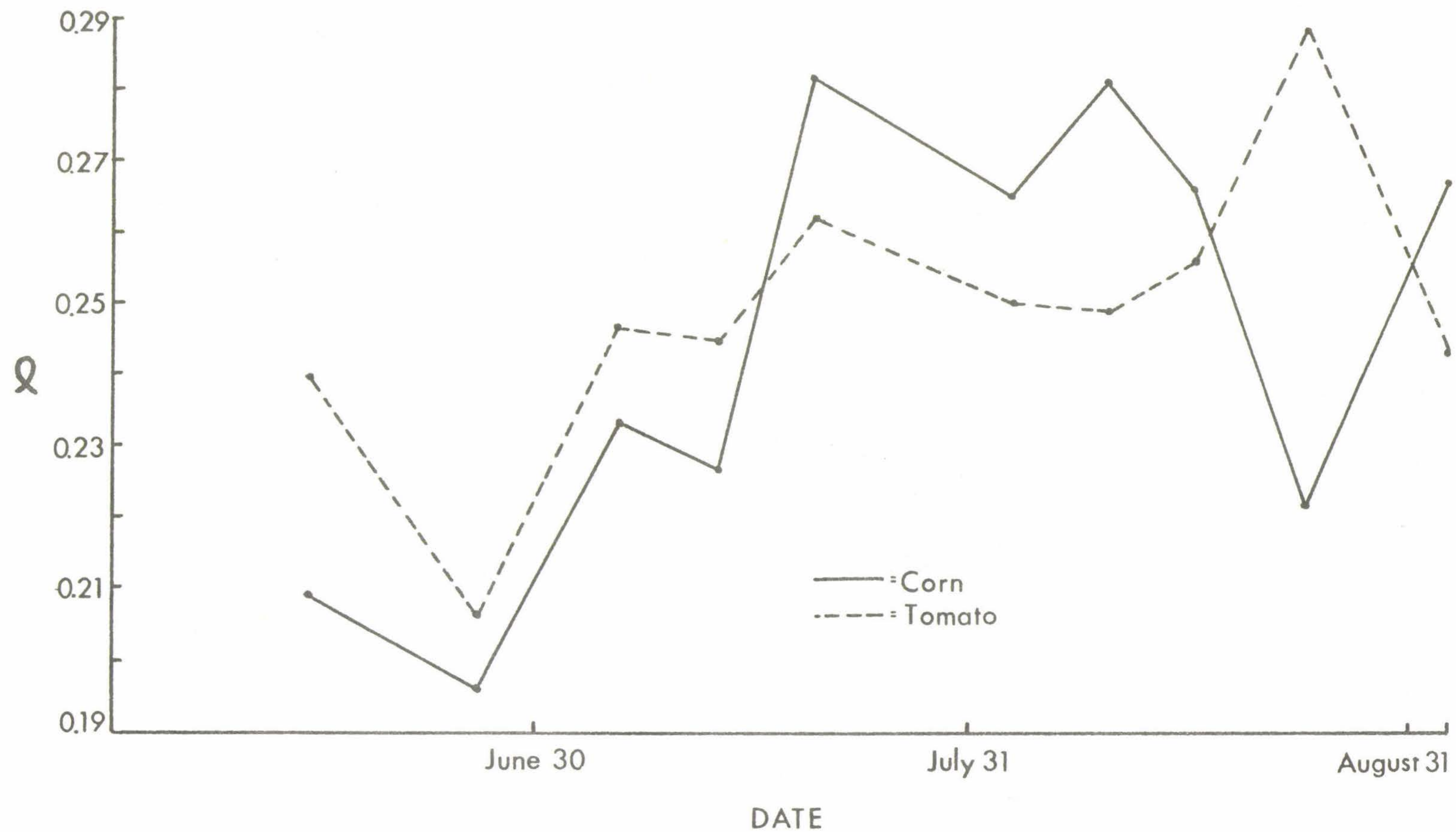
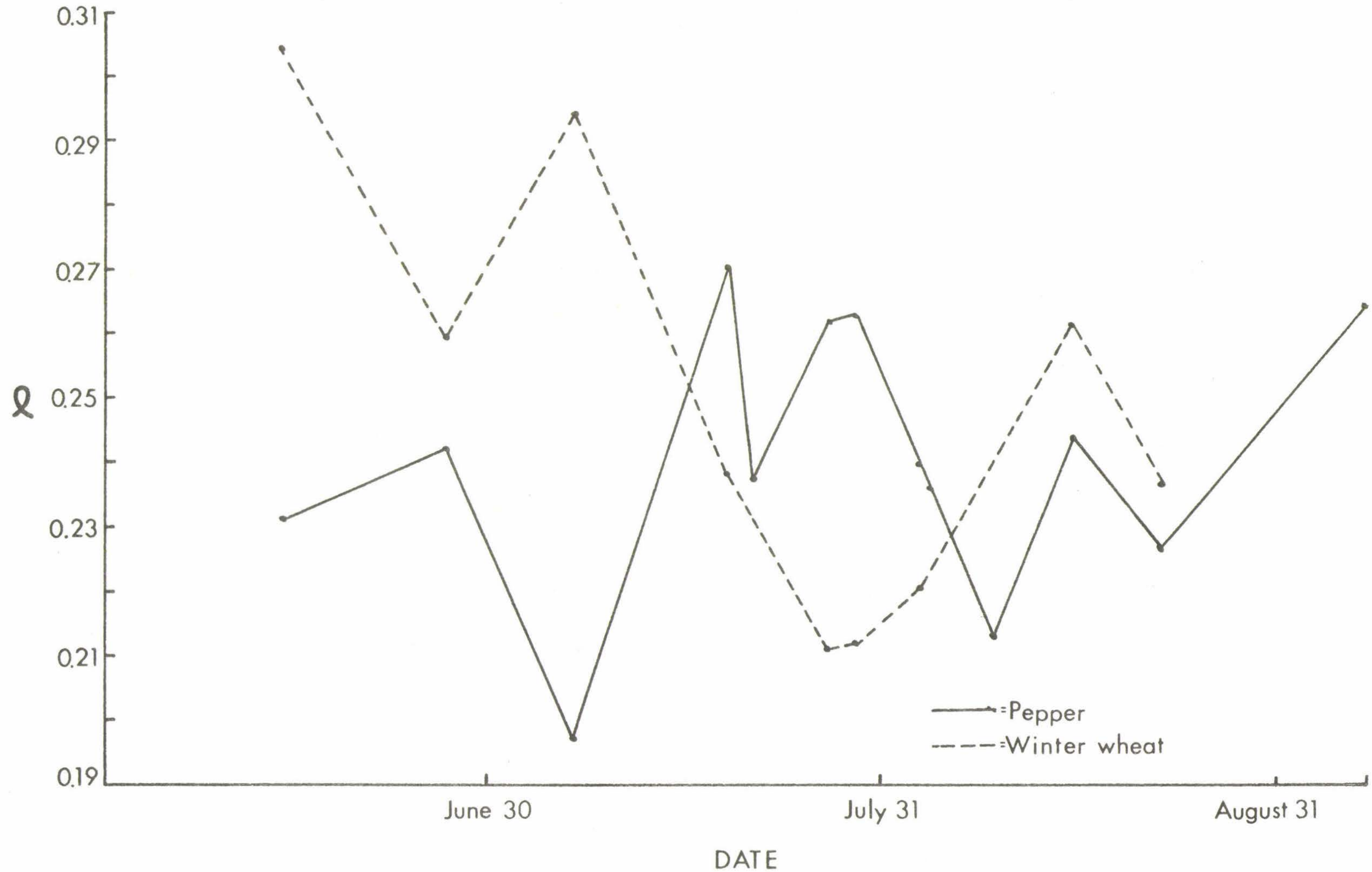


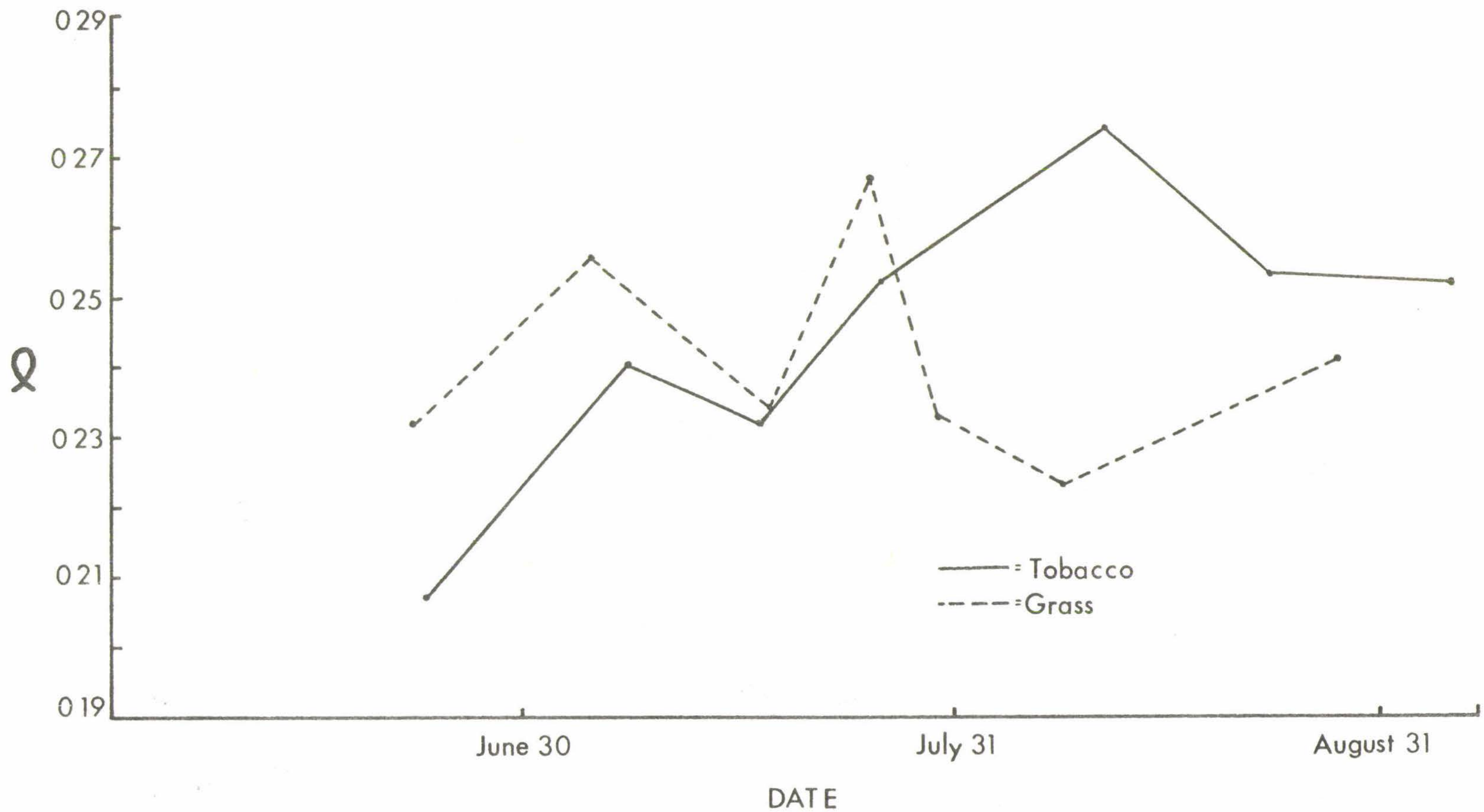
Figure 24. Mean daily adjusted α



in α was probably produced by a decrease in the amount of radiation trapped within the crop canopy.

The perennial ryegrass surface was maintained at a height of 8 cm. for another experiment and a ground coverage of about 85% existed for the entire field season. Disregarding periodic α fluctuations, no seasonal increase or decrease is apparent (Figure 25). Maximum fluctuation over the summer season in α was 0.033. This and the seasonal trend of the curve compares favourably with Montieth's (1959a) findings.

Figure 25. Mean daily adjusted α



CHAPTER IV

HEATING COEFFICIENTS

Between July and September, net radiation was recorded on 22 selected days, over different surfaces under varying cloud cover conditions. Figure 26 illustrates the good relationship between Rn and $(1 - \alpha)Q$ on both clear and partly cloudy days for corn. These data enabled daily β values to be calculated. These are listed in Table 11 together with corresponding values of ground cover, shade value, regression intercept, mean α and weighted daily α . The frequency distribution of these β values is given in Figure 27. The variation of β between and within crop categories is large due to variations in the crop parameters. β ranged between 0.17 and 1.93.

Table 2 lists many of the recent β values in the literature. Variation is present in these values for similar surfaces. When days of maximum sunshine and crop cover are considered in the Simcoe data, there is a trend for β to approach 0.22. This value was found by Montieth and Sceicz (1961) at Rothamsted and Kew and by Berger-Landefeldt (1964) at Berlin. Both studies refer to grass. In addition, β was calculated from radiation measurements over grass at the Department of Transport station at Toronto Scarborough. These values which refer to clear sky conditions only, are listed in Table 12. The average summer value for these data is 0.22. This supports the postulate of Montieth and Szeicz (1961) that β is the same for all freely transpiring vegetated surfaces exposed to the same weather. However,

Table 11. Simcoe β values and measured parameters

Crop % Date	β	Shade Value (%)	Ground Cover (%)	Regression Intercept	Wind Speed m.p.h.	Mean α	Stanhill α
GRASS							
July 5	0.47	87	85	0.018	6.3	0.256	0.248
" 18	0.51	22	85	0.047	9.2	0.234	0.197
" 25	0.22	13	85	-0.074	12.5	0.267	0.240
Aug. 8	0.30	21	85	-0.166	7.8	0.224	0.204
". 28	0.43	65	85	-0.027	10.0	0.241	0.238
TOMATO							
July 13	0.29	13	35	-0.046	7.1	0.245	0.214
Aug. 10	0.24	95	80	-0.045	10.7	0.249	0.237
Sept. 3	0.22	0	85	-0.112	8.6	0.242	0.226
TOBACCO							
July 17	0.46	28	40	-0.004	6.9	0.233	0.220
" 26	0.46	13	60	-0.051	10.2	0.252	0.236
Aug. 1	0.44	24	70	-0.049	7.5	0.253	0.237
" 11	0.17	11	75	-0.143	5.0	0.275	0.274
" 23	0.22	8	80	-0.116	7.5	0.253	0.231
WHEAT							
July 19	0.72	53	90	0.153	6.1	0.238	0.197
Aug. 3	1.93	14	80	0.049	8.7	0.221	0.188
CORN							
July 20	0.35	0	80	-0.026	4.7	0.282	0.256
Aug. 16	0.17	0	90	-0.108	8.4	0.267	0.231
" 24	0.29	60	90	-0.053	2.2	0.222	0.220
PEPPER							
July 21	0.53	49	30	0.032	3.9	0.238	0.234
Aug. 15	0.27	13	45	-0.117	8.6	0.245	0.232
CUCUMBER							
Aug. 4	0.45	17	100	-0.024	9.5	0.294	0.258
BARE GROUND							
Aug. 29	0.32	9	0	-0.122	9.7	0.188	0.208

Figure 26. The linear relationship between Rn and $(1-\alpha)Q$

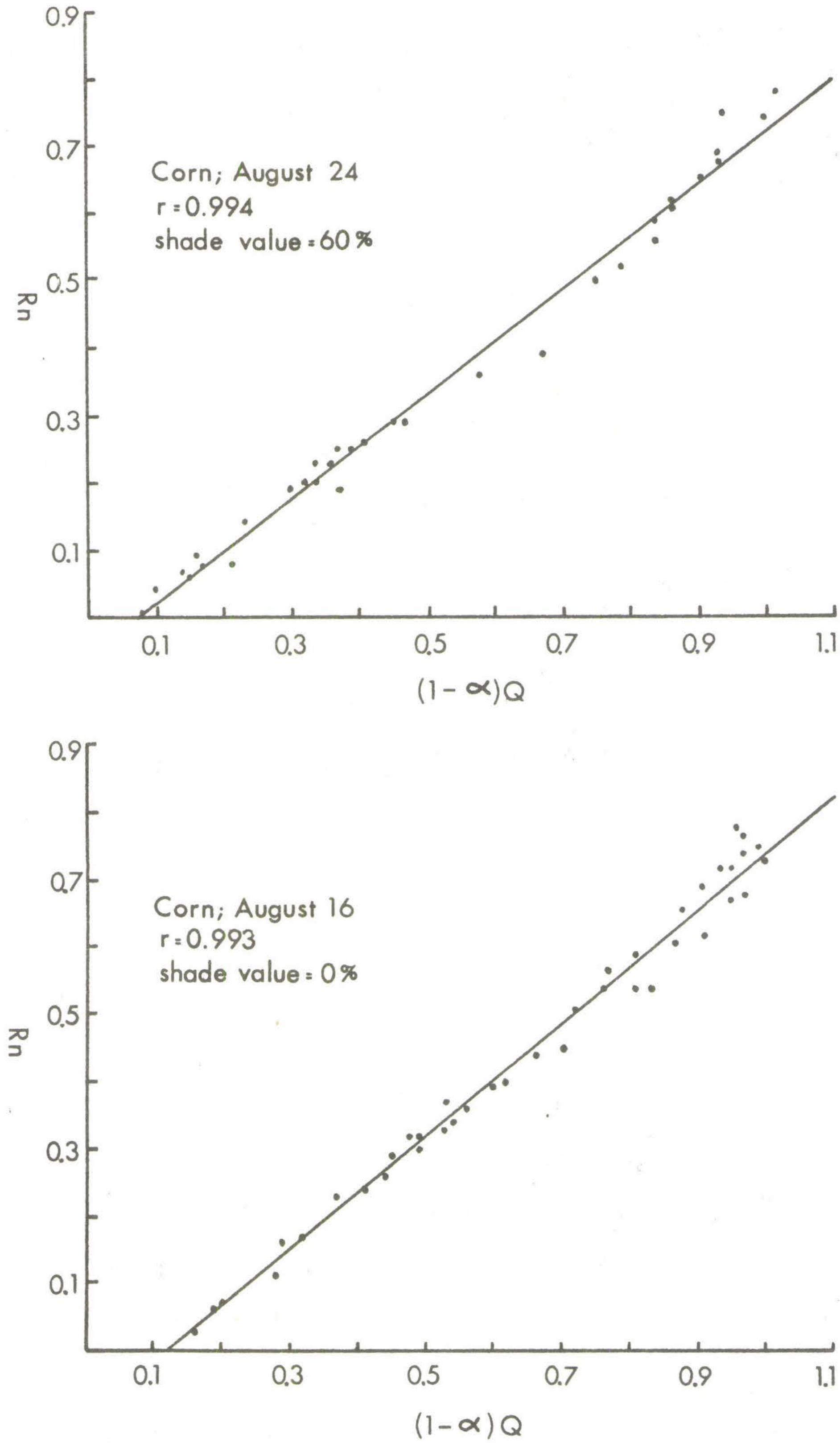
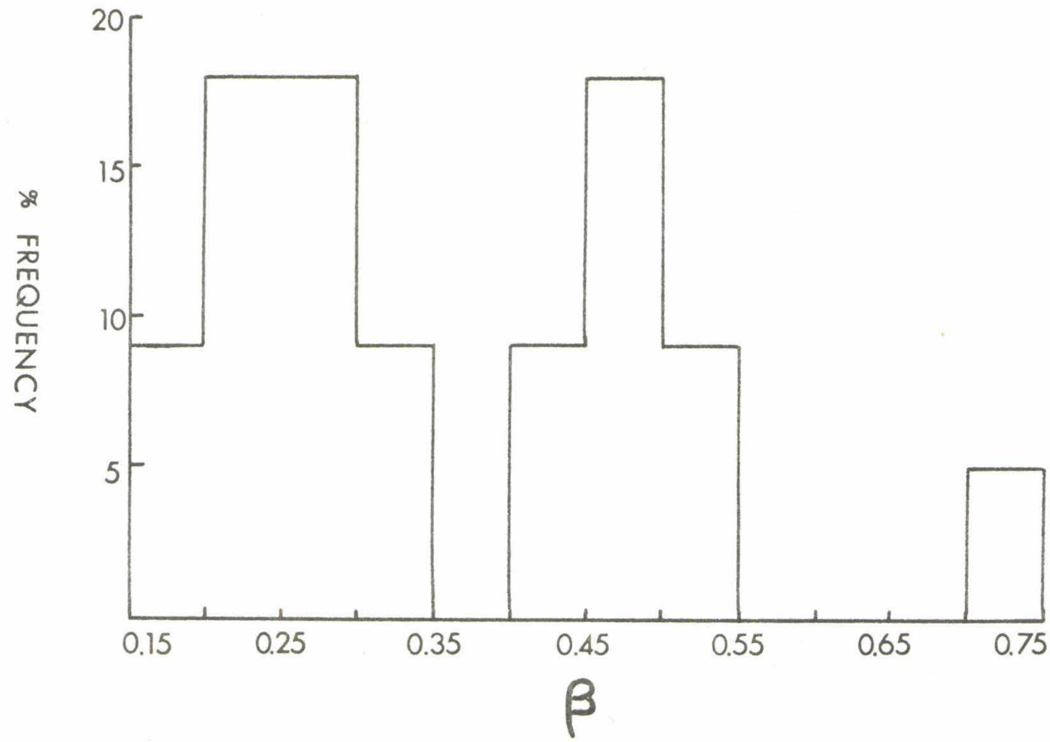


Figure 27. Frequency distribution of β values



these values are far larger than those found by Ekern (1965) and Shaw (1956) and also by Montieth and Szeicz (1962) in a later study (see Table 2).

In order to analyze this variation in β , both linear regression and partial correlation methods were used. The resulting coefficients are listed in Tables 13 and 14.

Table 12. Summer β values for clear skies at Toronto over grass

Month	β	r	Sample size	Monthly mean
June	0.159	0.999	16	0.204
	0.218	0.997	16	
	0.209	0.998	16	
	0.230	0.995	16	
July	0.181	0.999	16	0.210
	0.192	0.997	16	
	0.257	0.997	16	
August	0.265	0.999	14	0.225
	0.229	0.999	14	
	0.187	0.996	14	
	0.220	0.999	14	
September	0.334	0.998	14	0.236
	0.264	0.998	14	
	0.137	0.987	14	
	0.202	0.997	14	
	0.241	0.996	14	
				Summer mean = 0.219

(1) Wind speed and β

The daily average wind speed was calculated for the 22 days. Data from the Simcoe meteorological station located on the experimental farm were used. Montieth and Szeicz (1961) suggested that wind may be a relevant factor in determining β through its affect upon surface temperature. However, linear regression revealed no significant relationship

Table 13. Linear regression coefficients for β

Variable	Mean	Standard deviation	Correlation coefficient
shade value	27.95	27.09	0.03
ground cover	70.45	24.26	0.06
regression intercept	-0.045	0.07	0.57
mean α	0.246	2.25	-0.27
weighted α	0.229	2.08	-0.50

between wind speed and β. This does not eliminate the effect of wind since crop structure and surface roughness may well have to be considered. The more open structure of winter wheat should allow air to penetrate the crop canopy more easily than the dense cover of tomatoes. These effects could not be considered at Simcoe.

Table 14. Partial correlation coefficients for β

Variable	Partial correlation coefficient
β and shade value keeping ground cover statistically constant	0.020
β and ground cover keeping shade value statistically constant	0.056

(2) Ground cover and β

Some workers (Montieth and Szeicz, 1961; Berger-Landefeldt, 1964) have found a higher β value for bare ground than for vegetation. This is consistent with the larger diurnal variations in surface temperatures found for bare soil. Although some relationship between β and ground cover should exist, none was found at Simcoe.

(3) Shade value and β

In order to assess the influence of cloud cover on values, a shade index was used. This index consisted of a ratio between the number of spot readings during the day when clouds obscured the sun to the total number of readings for the day, expressed as a percentage. The term surface heating coefficient was developed for clear skies only since it assumes that incoming long-wave radiation from the atmosphere is constant during the day. However the presence of cloud will increase the amount of incoming long-wave radiation. Hence, during partly cloudy days, the incoming long-wave component of the radiation balance will not be constant. This has lead Stanhill et al (1966) to conclude that "the heating coefficient should not be considered a characteristic exclusively of the surface, but rather of the surface and atmosphere". However linear regression revealed no relationship between β and shade values. This index is coarse and probably a more refined number which considers both amount and density of clouds may be required before the relationship can be defined.

Because of the small sample size, the influence of one variable was difficult to isolate. Consequently partial correlation coefficients were calculated for shade value and ground cover. However no relationship between β and the postulated factors, ground cover and shade value, was found.

(4) Regression intercept and β

From the data at Simcoe, a significant relationship existed between β and its regression intercept (a). Stanhill et al (1966) found a dubious relationship between these two variables in the form of a seasonal trend. The a value tended to increase from mid-winter to mid-summer. However this relationship at Simcoe is more probably a statistical phenomenon with no physical meaning. Since this relationship is positive, it means, in fact, the regression line tends to pivot. Hence, as the slope of the line lessens, it tends to intercept the ordinate at a higher value.

(5) Reflection coefficients and β

The weighted mean α was regressed against β. The correlation coefficient is -0.50 and is highly significant at the 5% probability level. This supports the postulate of Davies (1967b) and Adem (1967) that there is an inverse relationship between α and β. If the ordinary mean α is used there is no significant relationship.

The results from Simcoe indicate recurring values of α and β for contrasting cropped surfaces. Under clear skies α approaches 0.25 while β is close to 0.22. Using these values, the radiation balance can be written as,

$$Rn = (0.75/1.22)Q + a \quad (14)$$

$$= 0.615\ Q - a\ \text{cal. cm.}^{-2}\text{day}^{-1}. \quad (15)$$

This equation agrees favourably with

$$Rn = 0.617\ Q - 24\ \text{cal. cm.}^{-2}\text{day}^{-1} \quad (16)$$

calculated by Davies (1967b). The constant (a) should depend on the time period of integration (Davies, 1967b). The average value for a at Simcoe was -0.045 cal. cm.$^{-2}$min.$^{-1}$. Since equation 15 refers to the period of positive Rn, 0.045 has to be multiplied by 60 times N where N is the duration, in hours, of positive Rn. During the field season N ranged between 8.0 and 12.0. Therefore a should range between 22 and 33 which is fairly similar to the value of 24 in equation 16. Consequently, the work at Simcoe supports Davies' suggestion that there is a general radiation balance equation which is a linear function of solar radiation and which applies to summer conditions in temperate regions.

CHAPTER V

CONCLUSIONS

The results from the Simcoe data show,

1. that α is close to 0.25 for cropped surfaces
2. that α varies with solar elevation
3. that β has positive values between 0.17 and 0.53 (if wheat is excluded). These values support the findings of Montieth (1959a) and Montieth and Szeicz (1961, 1962).

Several improvements are suggested. Continual measurement of α, using an albedometer[1], is desirable. This would give direct readings of α in the field and free the observer from manual balancing of potentiometers. Then it would be possible to study short-run variations in α, such as the change in α as a cloud approaches and obscures the sun.

More accurate and rugged instruments are needed for field measurement of solar radiation. The instruments used in this study were small and light-weight which made them versatile in the field. However, problems were encountered because the solarimeters were not air-tight. Furthermore, such instruments should be constructed with proper mounting devices, a circular level and an easier system for connecting the conductor cable.

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[1]An Albedometer utilises an electric circuit that combines the outputs of the upfacing and downfacing solarimeters as a ratio. This ratio has to be corrected by a factor which allows for the different calibration coefficients of the 2 solarimeters.

Because of the large diurnal variation of α , a more effective value than the arithmetic mean is needed to represent the daily average. Since α is important because of its role in the radiation balance, this value should be weighted according to the solar intensity. This study has presented some evidence that the weighted mean proposed by Stanhill et al (1966) may help this need.

Although values of β are positive and of similar size to those obtained by Montieth and Szeicz (1961), the understanding of β has not been furthered. There is clearly a need for a careful study with accurate instruments to determine the individual fluxes of the radiation balance over different surfaces and surface temperature changes before the physical meaning of β will become apparent.

An important finding in this work is that the radiation balance equation can be generalized for Simcoe into a linear function of solar radiation using the same constants that are applicable to many areas in the world. A general radiation balance equation for large areas is of importance since Rn is not widely measured. It should be of great use in other studies, such as in estimating potential evapotranspiration spatially, where Rn is not available.

APPENDIX A

The variation of α with solar elevation for cropped surfaces at Simcoe

I = $\pm$one standard deviation from line

Figure 28. Variation of α with solar elevation for winter wheat

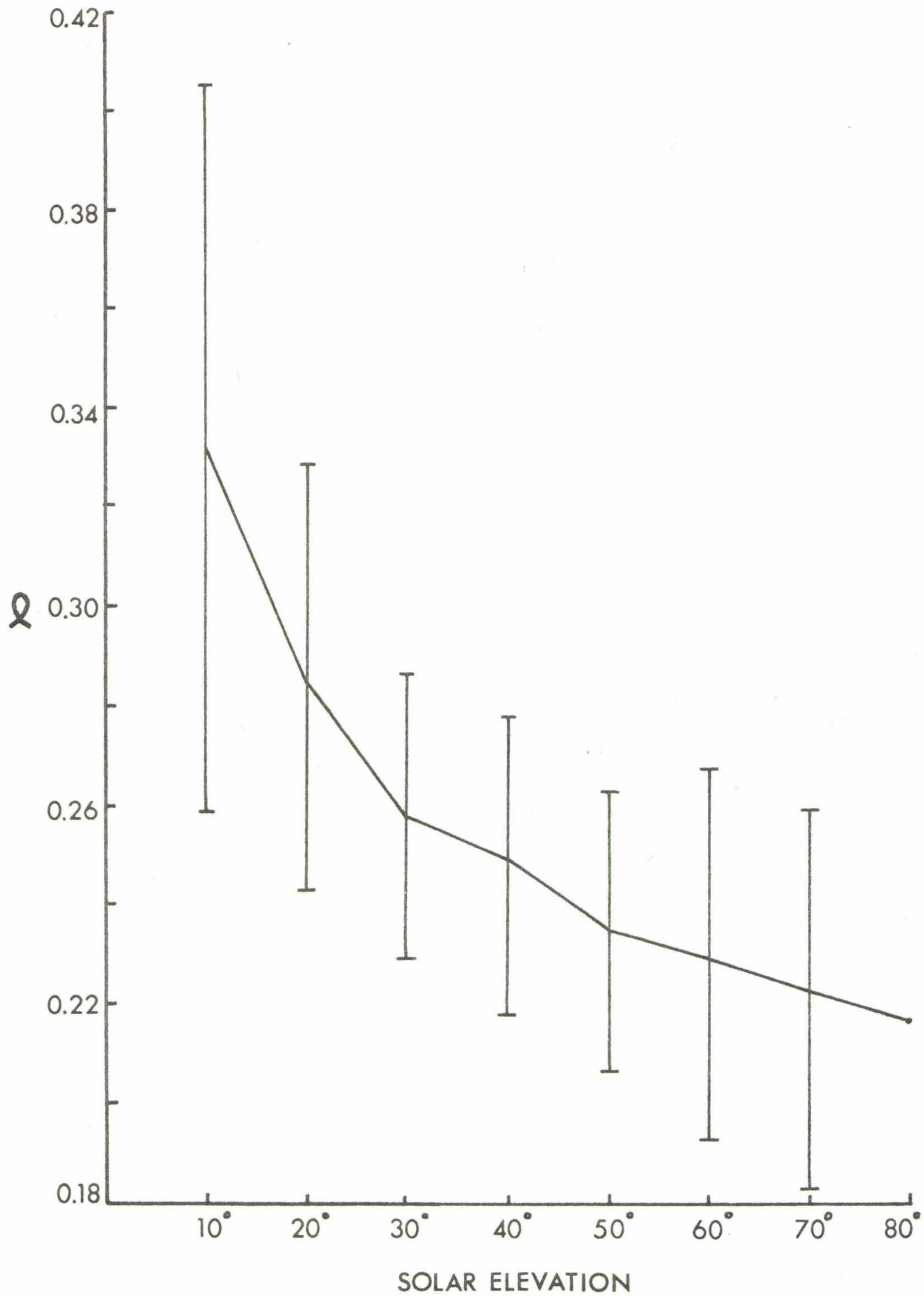


Figure 29. Variation of α with solar elevation for corn

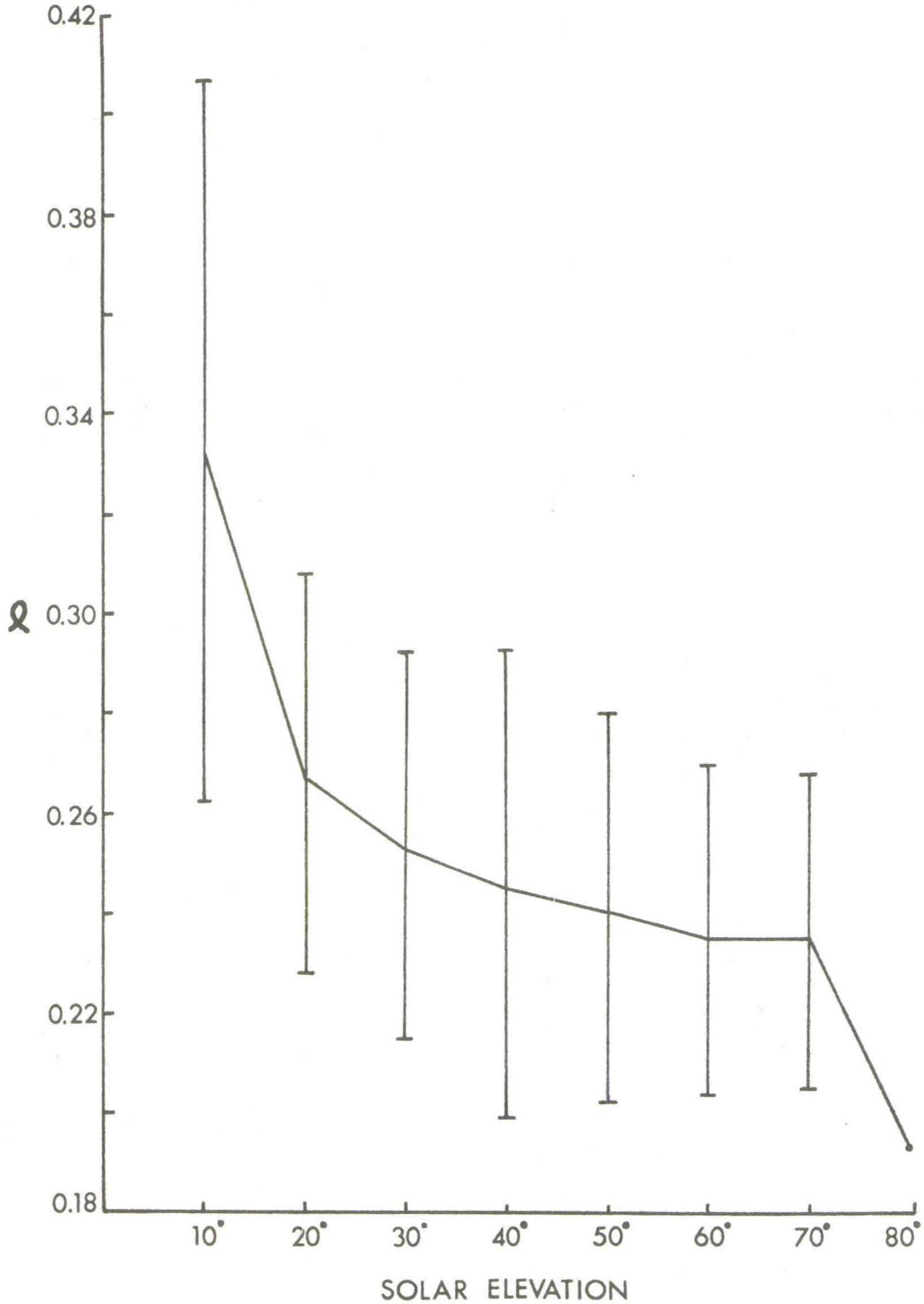


Figure 30. Variation of α with solar elevation for tomato

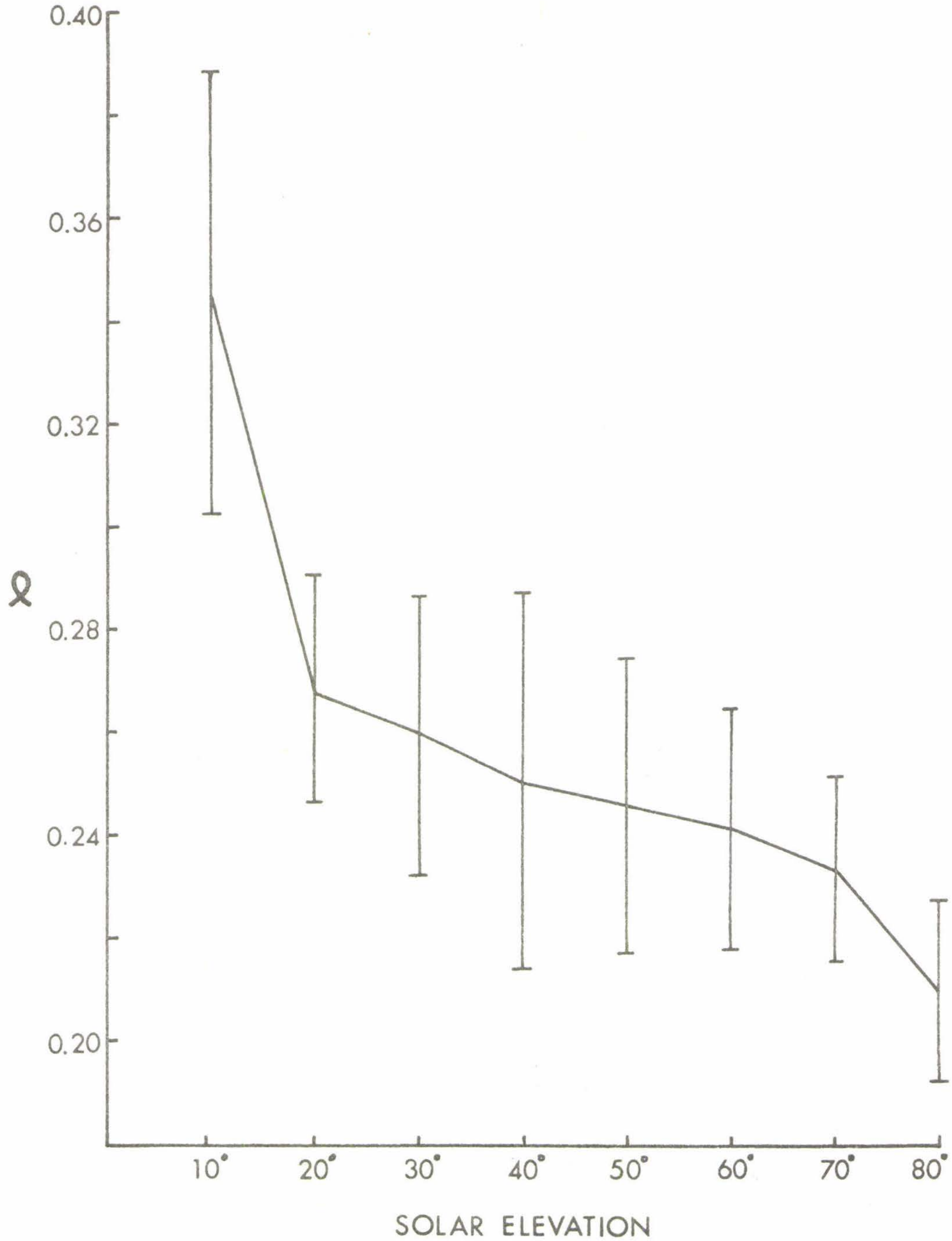
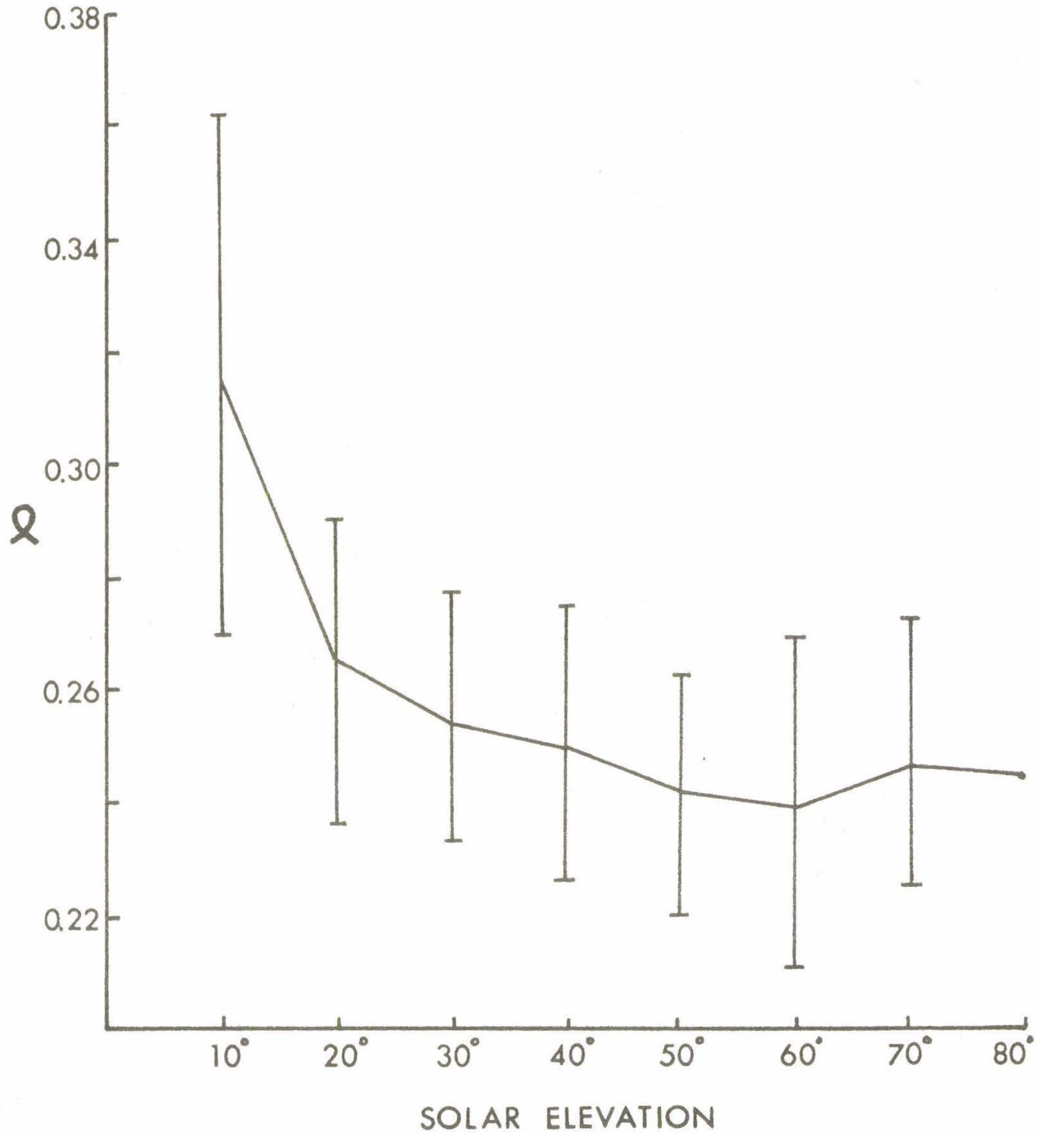


Figure 31. Variation of α with solar elevation for pepper



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