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A Study of the Radiation Quality under Plant Canopies In the Wave Range 0.4 to 2.5 Microns

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A STUDY OF THE RADIATION QUALITY UNDER PLANT CANOPIES

IN THE WAVE RANGE 0.4 TO 2.5 MICRONS

by

Nolasco G. Baldazo

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

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Nolasco G. Baldazo

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ABSTRACT

A Study of the Radiation Quality under Plant Canopies

In the Wave Range 0.4 to 2.5 Microns

by

Nolasco G. Baldazo, Doctor of Philosophy

Major Professor: Dr. Inge Dirmhirn
Department: Soil Science and Biometeorology

The spectral distribution of the global radiation from 0.4 to 2.5 microns penetrating deciduous and coniferous canopies were measured during clear days between 10 a.m. and 2 p.m. using a double-quartz monochromator.

In the visible region (0.4 to 0.7 micron) the average relative spectral transmissions under both canopies are about one percent beginning at 0.4 micron and decreasing to about half a percent at 0.67 micron. There is only a small peak in the green (0.55 micron) transmission under deciduous stands while there is none under coniferous canopies. The slightly higher transmission in the blue (0.4 micron) is attributed to the direct sky radiation penetrating through the gaps in the canopies. There is a steep increase in the transmission at about 0.7 micron. The increase is relatively higher under deciduous stands compared to coniferous stands.

In the infrared region from 0.8 to about 1.4 microns, the average relative spectral transmission under deciduous stands is about 10 percent which is double the transmission under coniferous canopies. The transmission under deciduous stands is about twice that of the coniferous

stands throughout the near infrared with very low transmission in the water absorption band at 1.45 and practically no transmission at all in the 1.90 micron-band.

The absolute spectral transmission exhibit a somewhat different distribution, especially in the visible region. Since the highest intensity of the solar spectrum in the open is located in the 0.5 micron-band, this is also reflected in the absolute values. The small peak in the green under deciduous stands is now indicated as a slight shift of the peak to the 0.55 micron-band. The water absorption bands at the 0.95 and 1.15 microns are also distinct, with hardly no transmission at all beyond 1.7 microns.

The spectral transmittance of forest canopies differ from those reported for single leaves in the proportion of radiation transmitted in the visible and infrared regions. For example, the ratio of the transmission at 0.55 micron to that at 1.10 micron-band is about one to twelve compared to about one to five in single leaves.

A deciduous canopy consisting of several layers of leaves will only allow a very small amount of transmission, mostly in the green portion and somewhat more in the infrared region between 0.72 and 1.40 microns. Under natural conditions in the forest, there exists a very weak "green" shadow and a somewhat stronger "infrared" shadow. The altered spectral composition may influence the understory vegetation as regards photosynthesis, seed germination, and the photoperiodic responses in the forest floor.

(88 pages)

INTRODUCTION

Background and scope of study

Knowledge in the radiation fields influenced by plants is still
very limited. Under the plant canopy the measurements of solar radia-
tion as to its intensity and spectral composition are more complex than
is often realized. Variations may range from a few percent of the value
in the open to about full intensity. And if measurements are made,
satisfactory interpretation is very difficult, if not impossible, due
to a number of reasons. Prominent among these are the failure to give
details of the techniques used and the spectral response of the sensors.
These make some of the previous measurements very limited in value.

This study is mainly concerned with the determination of the
spectral composition of the global radiation penetrating the forest
canopy, specifically coniferous and deciduous canopies. The measure-
ments are made in the wave range 0.4 to 2.5 microns. According to
Thekaekara and Drummond (1971), the 0.3 to 2.2 micron wavelength
interval accounts for nearly 94 percent of the total energy.

Not all portions of the solar spectrum are of equal importance to
the plant for its growth and development. For example, the wave range
0.4 to about 0.73 microns, which is also called the visible region,
appears to be involved in five photochemical reactions--photosynthesis,
chlorophyll synthesis, phototropism, photomorphogenic induction, and
photomorphogenic reversal (Robertson, 1966). According to Monteith
(1965), when a plant receives adequate water and nutrients during the
growing season, dry matter production is governed by the solar energy

available for photosynthesis. In addition, the radiant energy trans-
mitted after its interaction with the plant canopy exerts a controlling
influence on the microclimate of the forest floor. Evapotranspiration
from the understory vegetation mainly depends on the net radiation
absorbed (Reifsnyder, Furnival and Horowitz, 1972). The radiation
intercepted by the crown plays a major role in the energy and water
balance of forest communities (Vezina and Pech, 1964; Cowan, 1968).
The germination and early development of tree seedlings are also
dependent upon the intensity and spectral composition of available
"physiological" radiation as referred to by Shakov, Khasanov and Stanko
(1965).

Another purpose of this study is to assess the possible effect of
the forest canopy in transmitting the global radiation and to evaluate
whether there is a difference between deciduous and coniferous canopies.

Definitions

In the literature, the word "light" has been used to describe
different, although related, physical entities. The failure to define
terms in any particular investigation can bring up difficulties in
comparing or evaluating the results.

Short wave radiation is usually meant to be the wave range interval
0.25 to 3.0 microns. This is about 98 percent of the total emitted
energy from the sun. This is also the range that optical glasses used
as domes on pyranometers allow transmission to the sensor. The parallel
beam of the sun's rays, or direct solar radiation, plus the diffuse
radiation falling from every point of the sky, or sky radiation, is
conveniently termed global radiation.

The aspect of radiation as to quality means the spectral composition of the global radiation whether it be in the open or after it passes through plant canopies. In general terms, it is often more understandable to distinguish between ultraviolet radiation which is roughly 0.28 to 0.38 microns, visible radiation from 0.38 to about 0.72 microns and the near infrared, from 0.72 to about 3.0 microns. Radiation beyond 3.0 microns is termed as the far infrared or the long wave radiation.

The ordered array of all known electromagnetic radiation according to wavelength, frequency, or photon energy extending from an extremely small fraction of a millimeter (cosmic rays) to several kilometers (radio waves) is known as the electromagnetic spectrum.

In a strict sense, "light" refers to the sensation caused on the human eye and brain by electromagnetic radiation. This is also known as the visible radiation which is involved in the photochemical reactions in plant leaves. It is for this reason that biologists often equate this with "photosynthetic" wavelengths (Anderson, 1964; Robertson, 1966) and, in another case, as "physiological" radiation (Shakov, Khasanov and Stanko, 1965).

REVIEW OF LITERATURE

The three aspects of solar radiation are duration, intensity and quality or spectral composition. The spectral composition is the most elusive to measure. Not only does solar radiation vary with the solar angle and atmospheric conditions, but at any given time in a forest stand, the intensity and spectral composition vary in spatial distribution.

The disposition of light striking the vegetation on the surface of the earth has fascinated scientists for over a century. The interaction of global radiation with the plant canopy requires detailed understanding. As soon as the light strikes the leaves, reflectance, absorptance, transmittance, and scattering all influence the disposition of the incident energy. According to Rabinowitch (1951) the proportion of "white" light transmitted by plant leaves was first measured by Sachs (1861). After more than a century, not enough is known about the spectral composition of the global radiation that passes through the woodstand for ecological studies. Researchers are still hindered by the inability to describe the radiation environment adequately. This inability is due, in part, to the lack of suitable radiation measuring instruments, the difficulty of working in the forests, the variety of instruments and techniques used, and the inadaptability of the apparatus for all weather conditions desired in the study. Anderson (1964) stated that all radiation measurements involve some compromise between accuracy and possibility.

In the United States the increased awareness and understanding of the significance of the variation in the duration, intensity, and spectral composition of solar radiation was brought about by the classical report on photoperiodism by Garner and Allard (1920).

Many plant responses related to growth are wavelength dependent. These are discussed by Wassink and Stolwijk (1956). The Dutch Committee on Plant Irradiation (1953) recommended the following divisions of the solar spectrum for considerations:

1st Band: greater than 1 micron. No specific effects are known other than its conversion into heat.

2nd Band: 1.0 to 0.7 micron. Specific elongating effect on plants.

3rd Band: 0.7 to 0.61 micron. Strongest absorption of chlorophyll and photosynthetic activity in the red region. In many cases it also shows the strongest photoperiodic activity.

4th Band: 0.61 to 0.51 micron. Spectral region of low photosynthetic effectiveness in the green and weak formative activity.

5th Band: 0.51 to 0.4 micron. Virtually the region of strong chlorophyll adsorption and absorption by yellow pigments. It is also the region of strong photosynthetic activity in the blue-violet and of strong formative effects.

These differences in the influences of different wavelengths of the solar spectrum on the photochemical processes in plants warrant that a special consideration be given to the spectral composition of radiation as an environmental factor (Robertson, 1966). Monteith (1965) pointed out that a week-to-week relationship between growth and solar radiation

is very difficult to establish because it depends on other parameters, such as leaf area index that changes as the crop matures. Another fact is that photosynthesis in most species is reached at an intensity well below the maximum. Bonner (1962) stated that plants are inefficient at high intensities because they are efficient at low intensities. For these reasons very few plant scientists or ecologists are willing to use even a simple physical model to describe their complex biological behavior. This is why most analysis of the dependence of plant growth and development on the meteorological elements stop at a statistical correlation without any quantitative representation of cause and effect.

Early measurements of the spectral composition in the visible region of the solar spectrum were, according to Federer and Tanner (1966), "inadequate by current standards." However, it is well established in general terms that a leafy canopy of a forest is a highly selective filter of the visible radiation passing through it. Zederbaur (1908) was able to show that the red portion was absorbed the most, and the green the least. Knuckel (1914) was cited by Shirley (1929) and Coombe (1957) to have shown that there was no significant change in the spectral composition of the visible region of the solar spectrum under spruce and fir canopies or other needle-leaved canopies. Knuchel's measurements, which were considered as the most reliable at that time, showed that the canopy of conifers were practically neutral filters over the wavelength 0.44 to 0.65 microns while deciduous canopies showed higher transmission in the yellow-green than in the red and blue regions. Later measurements by Egle (1937) and Atkins, Poole and Stansbury (1937), using narrow-band filters, were in agreement.

Although plant ecologists are aware of these phenomena, Shirley (1935, 1945) stated the common opinion that changes in the spectral composition of the visible radiation resulting from passing through the leafy canopies were of minor ecological significance. Shirley (1945), however, indicated that Seybold and Egle (1937) "evidently believed that leafy canopies did cause changes in light quality of ecological significance." Later it was emphasized by Coombe (1957) that any further discussion of the effects of varying spectral composition on the growth of woodland plants is fruitless unless this variation in the composition of the light in woodlands is firmly established and understood. In an attempt to find out more about the spectral composition under the woodland canopy, Coombe (1957) used a set of 12 combinations of glass color filters which transmitted fairly narrow bands of the spectrum over the range 0.365 to 0.73 microns, a sensitive barrier-layer photoelectric cell, a shunt, and a galvanometer. Coombe agreed with earlier findings that the canopy of a deciduous woodland is a highly selective filter of the visible radiation, and the conifer canopy less so. In addition, Coombe emphasized that it is no always possible to say whether one woodland site is lighter or darker than another without specifying the wavelength.

Akulova et al. (1964) carried out an investigation in three regions of the spectrum: red, green, and blue, using wide-band filters (optical glass). Experimental data are given on the dependence of the spectral distribution and intensity under a forest canopy on the character of the incident radiation and density of the crowns.

Federer (1964) and Federer and Tanner (1966) distinguished four components of radiation within a plant canopy. A spectrophotometer

utilizing a wedge interference filter and a silicon photovoltaic cell as a detector and a high-gain amplifier was used to study the spectral distribution in a wave range 0.4 to 0.74 microns.

Robertson (1966) made measurements with a 5-band spectral light meter in the visible region of the spectral distribution below and within a crop canopy. Robertson indicated that there may be significant differences in the spectral composition with changes in solar elevation or haziness of the atmosphere. The inference was made based on measurements in the open from both clear, cloudy and hazy skies.

Vezina and Boulter (1966) determined the spectral composition of the near ultraviolet and visible radiation under a forest canopy under cloudless, hazy and overcast conditions. The quality of radiation in the wave range studied was changed greater with respect to the open during clear days than during cloudy days. On overcast days and during the leafless period of the deciduous canopy, the transmission of the incident radiation was very high with very slight changes in the spectral composition.

The spectral analysis of radiation under a coniferous forest was made using an ISCO spectrophotometer by Atzet and Waring (1970). It was found that minor changes in the proportion of radiation in one band to that in another occurred throughout the day. However, the 0.4 to 0.7 micron wave range appeared rather uniformly adsorbed by the coniferous canopy. Using the same instrument, Freyman (1968) found that aspen stands showed radiation low in the blue, high in the green, and low in the red and exceptionally rich in the far-red. The lodgepole pine and Douglas fir showed a uniform decline in energy from 0.47 to 0.675 micron wave band without the distinct 0.55 micron (green) peak characteristics of the aspen.

The only investigations of the spectral composition of the solar radiation under plant canopies beyond the visible up to about one micron were those by Scott, Menalda, and Brougham (1968), Shakov, Khasanov, and Stanko (1965), and Yocum, Allen, and Lemon (1964).

Scott, Menalda, and Brougham (1968) concluded that all green vegetation had low reflection and transmission of visible radiation and high reflection and transmission of infrared radiation. In the visible region of the spectrum some vegetation have sharper peaks in their transmission of the green than other vegetation. On the other hand, Shakov, Khasanov, and Stanko (1965), working under forest canopies, found that the intensity beneath crowns was 100 to 1,000 times weaker in the violet portion of the spectrum, 30 times weaker in the green, 100 to 1,000 times weaker in the red-orange, and 3 to 5 times weaker than the open in the infrared portion. Working under a dense stand of corn, Yocum, Allen and Lemon (1964) showed measurements of the transmission of radiation in the wave range 0.3 to 1.0 microns. The results show quite low transmission in the visible spectrum and higher transmission beyond the 0.7 micron wavelength.

Fundamentals of leaf reflectance, transmittance and absorptance

Suits (1960) pointed out that the reflective power is decreased with increasing wavelength until the radiation emitted by the object becomes dominant. The crossover point is approximately at 3.0 microns where the emitted radiation becomes dominant over the reflected radiation.

Hoffer and Johannsen (1969) showed that in the measurements of spectral reflectance of a healthy green leaf, the 0.4 to 2.6 micron

portion of the spectrum can be roughly divided into three areas: the visible region in which plant pigments, especially the chlorophylls, dominate the spectral response of plant leaves; the second is the 0.72 to 1.3 microns where there is less absorption by the leaves which means that the energy impinging upon the leaf must either be transmitted or reflected; the third is the water absorption at the 1.3 to 3.0 micron interval.

Knipling (1969) emphasized that the absorption of the visible radiation by chlorophyll and the infrared radiation by water is a strong evidence for the internal reflectance mechanism since the radiation must enter the leaf before it can be absorbed. Further evidence was given by Gates et al. (1965) when they found a drastic reduction in the infrared reflectance as the leaf is infiltrated with water under vacuum. The water fills the air cavities and a continuous liquid phase medium is formed throughout the leaf. The reflective index difference is eliminated and direct transmittance increases at the expense of multiple scattering according to Knipling (1969).

It has been shown that the infrared reflectance of dehydrating leaves changes very little in the wilting range but increases with severe dehydration especially in the water absorption bands beginning at about 1.3 microns (Allen and Richardson, 1968; Thomas et al., 1966).

Knipling (1969) also cited Keegan et al. (1956) and Knipling (1967) that in some cases the initial stages of disease and leaf senescence are accompanied by an increase in the infrared reflectance. Knipling (1969) also mentioned that there is strong evidence of the reorientation of the cell walls into the same plane as the leaf surfaces and this may increase reflectance.

Effect of pigmentation

It was illustrated by Hoffer and Johannsen (1969) that leaf
pigmentation can cause marked differences in the spectral response of
single leaves. For example, the white Coleus leaf without any apparent
pigmentation shows a high level of reflectance throughout the 0.5 to 0.9
micron wave range while the green leaf shows a relatively low reflectance
at 0.5 micron, a peak in the 0.55 micron (green), and again low reflec-
tance in the 0.65 micron (red) and then increases sharply at about 0.7
micron. On the other hand, the red leaf had a low reflectance throughout
the red and near infrared wavelengths. The reddish-purple leaf had a
relatively low level of reflectance throughout the visible region with a
sharp rise coinciding with the green leaf. There is very little
difference in the reflectance throughout the infrared region in spite of
the marked differences in the visible regions caused by pigmentation for
the four leaves. These findings agree with previous measurements by
Dirmhirn (1964).

Optical properties of single leaves

Studies involving the optical properties of single leaves in the
laboratory are extensive. Most of the work has been concerned with the
visible and the very near infrared portions of the spectrum.

Gates et al. (1965) measured the spectral reflectance and trans-
mittance of plant leaves using a Cary 14 spectrophotometer. The
mechanism by which radiation in the wave range 0.4 to 1.1 microns
interacts with a leaf was discussed, including the presence of pigments.
The effect of chlorophyll pigmentation was indicated by the deepening
of the reflectance band at the 0.68 micron. Desert plants were found

to reflect more radiation at all wavelengths measured than did the meso-
phytic types. Earlier, Billings and Morris (1951) showed that desert
species reflected the greatest amount of visible radiation, followed
by subalpine, west-facing pine forest, north-facing pine forest, and
shaded campus species in that order. In the infrared wave range from
0.78 to 1.10 microns, the difference between groups were not so marked,
but the desert species still had the greatest reflectance.

Carlson, Yarger and Shaw (1971) measured the reflectivity and
transmissivity of leaves from corn, sorghum and soybean in the wave
range 0.7 to 2.6 microns and discussed the leaf structure and water
content as factors affecting the interaction with radiant energy.
Leaf water content accounted for more than 80 percent of the variability
in leaf reflectivity measurements for all species investigated. Specific
leaf density was more highly correlated with leaf transmissivity and
absorptivity than either leaf water content or specific dry weight
density. Pearman (1966), measuring in the 0.32 to 0.62 micron range,
found that a decrease in water content tended to increase reflectances.
Dirmhirn (1964) also observed that surface hairs and surface wax
increased reflection.

Thomas, Wiegand, and Myers (1967) made a study of the effects of
soil salinity, cotton leaf relative turgidity and chlorine content on
reflectance and transmittance of radiation over the wavelength interval
0.4 to 2.5 microns using a Beckman spectrophotometer. Soil salinity
increased the percentage reflectance and decreased the percentage of
the incident radiation on single cotton leaves. A decrease in relative
turgidity or an increase in the chlorine content of the leaf blade
increased reflectance.

Howard (1966) studied reflectance and transmittance of eucalyptus in the spectral range 0.4 to 0.95 micron at varying angles of incidence using a Beckman spectrophotometer. Reflectance and transmittance was observed to be high in the infrared. All leaf surfaces were found to be highly diffusing and not to reflect "white" light in accordance with sine law. Transmittance in the visible spectrum through a single leaf was observed to be insignificant, and reflectivity in the infrared increased but slightly with layers in excess of four leaves.

Gupta and Wolley (1971) used the Beckman spectrophotometer in measuring reflectance and transmittance of three varieties of soybean leaves over the wavelength interval 0.5 to 2.5 microns. Except in the visible the three varieties did not differ very much. Relatively, young leaves reflected more than did the old leaves. This is probably associated with chlorophyll development. The upper surface reflected less than did the lower surface of the same leaves in the visible. This was explained on the basis of internal leaf structure and composition. In a similar study by Gausman et al. (1971), it was shown that leaf age affects the interaction of light with cotton leaves. Earlier, Gates and Tantraporn (1952) made the same conclusions.

Gausman et al. (1969) tried to relate light reflectance to internal structure of cotton leaves of the same chronological age which were subjected to low, medium and high osmotic stress. A slight decrease in reflectance and a greater increase in transmittance caused by high osmotic stress is associated with a more compact cellular organization in the leaf mesophyll. Infiltration of leaves with water increased transmission of radiation.

Gausman et al. (1971a) found that transmittance was lower when radiation was passed from the top through the leaves compared with passing radiation from the bottom through the leaves. They felt that the difference in transmittance was caused by greater light diffusion by the top leaf surfaces.

Howard, Watson and Hessin (1971) compared measurements of the visible and near infrared spectra of foliage taken from *Pinus ponderosa* growing in a copper-rich area and from that growing in a background area of low copper content. There were differences in the reflected energy in the red and far-red regions (0.68 to 0.78 micron) but only in the field not in the laboratory measurements. The differences between the laboratory and field results were attributed to possible needle-density differences. Under similar conditions, Yost and Wenderoth (1971) made simultaneous *in situ* measurements with an ISCO spectrophotometer in the 0.38 to 1.25 micron wave range. The results indicated significant difference in the spectral reflectance between mineralized (copper molybdenum) and non-mineralized red spruce and balsam fir. The difference generally occurred in the 0.55 and 0.70 to 0.90 micron, with both red spruce and balsam fir showing higher reflectance for mineralized conditions.

Doraiswamy (1971) concluded that the energy balance and water use efficiency of plants are characterized by their spectral properties. Doraiswamy followed the theoretical suggestions of Seginer (1969) and the laboratory studies of Aboukhaled (1966) on the use of reflectants (kaolinite) to increase reflectivity of soybean canopies.

Hoffer and Johannsen (1969) believed that laboratory studies are a very necessary step in developing and understanding the radiation

interactions in plant canopies. However, it must be stressed that the capability for differentiating plants on the basis of laboratory spectra does not guarantee the same results in the field. Recent model and field studies by Myers et al. (1966) have shown that spectrophotometer studies of single leaves can be very misleading for predicting reflectance or transmittance from plant canopies. This is because the near infrared radiation when transmitted through the top of the canopy changes in spectral composition within the canopy. There are also multiple internal reflections within the canopy and reinforcement of reflectance from the top of the canopy. Changes in the leaf-water status during measurements can also be an additional source of error (Carlson and Yarger, 1971).

Spectral distribution of solar
radiation in the open

The spectral distribution of the solar spectrum outside the atmosphere (m=0) and at sea level (m=1) recorded with a low resolution spectrometer is redrawn in Figure 1 (Handbook of Geophysics, 1960). The shaded areas represent absorption of ozone, oxygen, water vapor, and carbon dioxide. The difference between the curve at sea level and outside the atmosphere is due to scattering.

The combined effect of the air mass, water vapor content, and all other components, such as dust, is illustrated by Robinson (1966). The measurements for a clear sky and an almost dry atmosphere at high altitudes (i.e., Rayleigh atmosphere) differ from those obtained at sea level (humid and turbid atmosphere) showing the considerable effects of the water content and turbidity on radiation reaching the earth. The strong minima in the humid and turbid atmosphere are due to either water
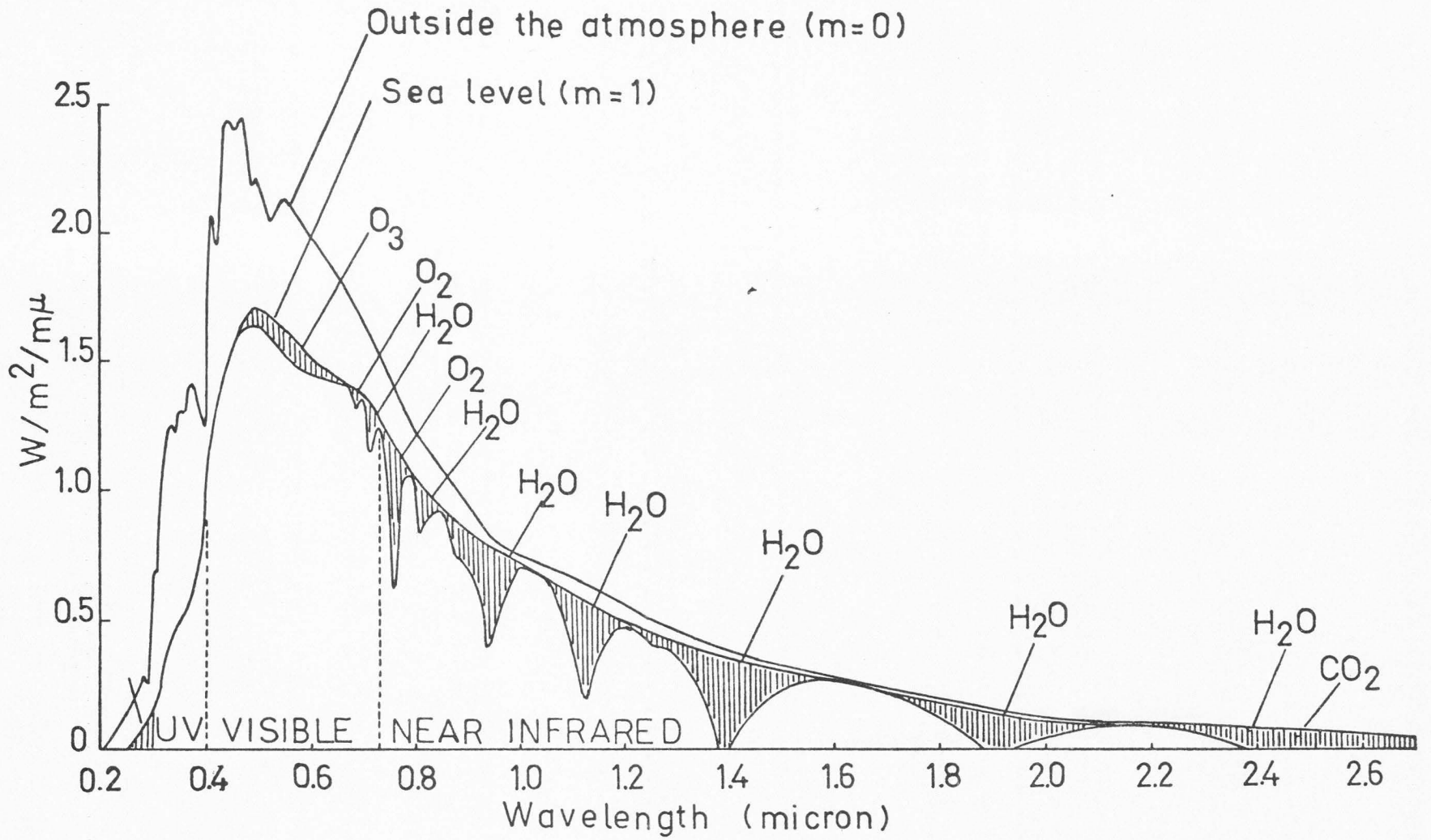
Figure 1. Energy distribution of the solar spectrum outside the atmosphere and at sea level (redrawn from the Handbook of Geophysics, 1960).

vapor or carbon dioxide absorption. The relative spectral character-
istics of global radiation under clear sky, cloud covered sky and a
clear sky without the direct component is shown in Figure 2 (Dirmhirn,
1967).

Gates (1966) calculated and presented the spectral distribution of
direct solar radiation at sea level as a function of the air mass and the
concentrations of aerosol, ozone, and water vapor. Gates also showed the
variation of the spectral distribution of direct solar radiation with
altitude zero to five kilometers. A solar constant of 2.0 cal cm^{-2} min^{-1}
and a fixed amount of five millimeters of precipitable water was used
in the computation while the values for altitudinal distribution of ozone
and aerosol concentrations and for molecular densities were taken from
Elterman (1964).

Taylor and Kerr (1941) measured the visible spectral distribution
of global radiation for various types of natural daylight in the vicinity
of Cleveland, about nine miles from the city center. The results showed
what the authors call "some normal variations". The measurements showed
that the most constant quality would be obtained on a horizontal plane
exposed to both sun and sky and not the one from the north sky as
previously believed. Later, Yost and Wenderoth (1969) showed that at
Davis, California in July 1967, the amplitude and wavelength of global
radiation in the wave range 0.36 to 1.3 microns in the natural environ-
ment constantly varied both with solar angle and atmospheric conditions.
For example, there was a large increase in the incident infrared band
at 0.75 micron in the afternoon compared to the morning. Yost and
Wenderoth attributed this as probably due to absorption of visible light
by large particles which have been churned up in the fields during the
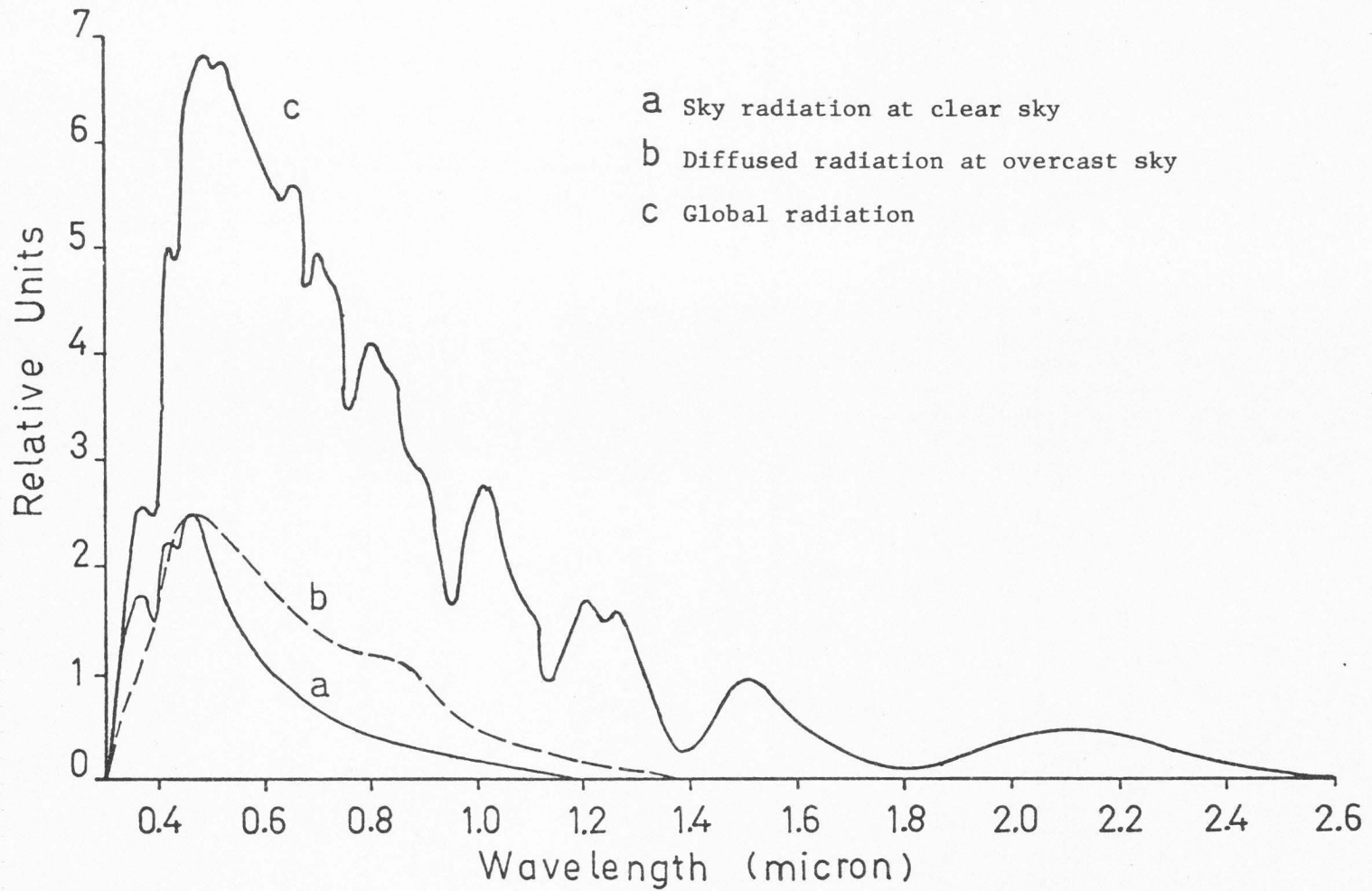
Figure 2. The relative spectral characteristics of global radiation at clear sky, cloud covered sky and a clear sky without direct component (Dirmhirn, 1967).

The labels in the figure:

a Sky radiation at clear sky

b Diffused radiation at overcast sky

c Global radiation

Axis labels: Relative Units (vertical), Wavelength (micron) (horizontal)

day. This agrees with the findings of Robertson (1966) who attributed the increase in the proportion of red and far-red bands to increased haziness or decreasing solar elevation.

The information about the spectral distribution of direct solar radiation outside the earth's atmosphere or of global radiation in the open at any altitude is important in the sense that it is the starting point from which the spectral distribution under the plant canopies can be estimated or compared.

THEORETICAL CONSIDERATIONS

Nature of the problem

The forest floor is exposed to variations in solar radiation
ranging from a few percent of the value in the open to about full inten-
sity. The problem of measuring solar radiation beneath the forest
canopy is complicated by the highly irregular distribution of the
radiation in both space and time. Added to this is the fact that
variations may occur in a matter of seconds or a few minutes as the wind
sways the branches or as the sunflecks move across the forest floor.

There has been various attempts to study the complex geometric
interrelationships between stand and leaf structure and the amount of
solar radiation received on any spot on the forest floor (Anderson, 1966;
Idso and deWit, 1970; Anderson and Denmead, 1970). However, as Anderson
pointed out, such theoretical analysis is subject to many practical
limitations.

A model for the penetration of global radiation through the canopy
has been presented by Reifsnyder, Furnival and Horowitz (1972). Four
components of global radiation reaching the forest floor were identified:
(1) penetrating direct beam radiation which passes through the canopy
largely unobstructed and causing sunflecks on the forest floor.
Sunflecks will not show full scale intensity unless the apparent canopy
hole has an angular diameter in excess of one-half degree which is the
apparent diameter of the solar disk; (2) reflected direct beam radiation
which is the rest of the direct beam reflected or diffused in the canopy;
(3) and (4) indirect or diffuse radiation emanating from the entire sky

also reaching the forest floor as penetrating and reflected components.
The penetrating component enters through the holes in the canopy where
the amount reaching the point on the forest floor is a function of the
pattern of canopy holes and the distribution of luminosity over the sky.

Earlier, Federer (1964) and Federer and Tanner (1966) also
considered radiation under the forest stands at any given wavelength as
the sum of four components expressed in the equation

$$L = t_{sd}I_s + t_{si}I_s + t_{hd}I_h + t_{hi}I_h \qquad [1]$$

where I_s is the beam radiation of the sun and I_h is the diffuse sky
radiation. The s and h subscripts on transmissivities t, indicate the
corresponding light source, and d and i subscripts indicate whether the
light is directly or indirectly transmitted through the canopy.

The measurements made by Reifsnyder, Furnival and Horowitz (1972)
did not take into consideration the spectral distribution of the global
radiation. On the other hand, Federer (1964) and Federer and Tanner
(1966) made spectral measurements at particular wavelengths 0.4, 0.45,
0.50, 0.55, 0.675 and 0.75 micron, with linear interpolation between.
Reifsnyder, Furnival, and Horowitz (1972) pointed out that solar radiation
penetrating deciduous and coniferous canopies will differ in spectral
distribution since approximately 50 percent of the radiation reaching the
forest floor beneath the hardwood canopy was first reflected from the
leaves and other vegetation elements in the canopy compared to only about
14 percent underneath a pine canopy. In the equation presented by
Federer (1964) and Federer and Tanner (1966) the radiation reflected
from the forest floor and again off the canopy was assumed negligible.

Also they assumed that transmissivities were constant for a given wavelength and independent of sky conditions which is not valid.

Theory

The energy flux density at any wavelength (E_λ) above a plant surface is a function of wavelength and may be expressed as

$$E_\lambda (\text{erg cm}^{-2}\text{sec}^{-1}\text{m}\mu^{-1}) = f(\lambda) \qquad [2]$$

The total flux then is

$$E = \int E_\lambda d_\lambda \text{ erg cm}^{-2}\text{sec}^{-1} \qquad [3]$$

The radiation inside the canopy is the result of a part of the uninterrupted radiation from sun and sky (global radiation and the radiation transmitted or reflected by one or more leaves or other plant organs. The spectral transmission and reflection of leaves are qualitatively similar. After transmission by n leaves, each with fractional transmission coefficient t_λ (erg transmitted/incident erg), the spectral energy distribution becomes

$$E_{n,\lambda} = \int E_\lambda t_\lambda^n d_\lambda \qquad [4]$$

The equation for the reflected radiation by m leaves is given by

$$E_{m,\lambda} = \int E_\lambda r_\lambda^m d_\lambda \qquad [5]$$

where r_λ is the reflection coefficient (erg reflected/incident erg). The energy flux density after reflection and transmission at any wavelength then becomes

$$E_{n,m,\lambda} = E_\lambda t_\lambda^n r_\lambda^m. \qquad [6]$$

For radiation transmitted and reflected by 0,1,2, and 3 leaves at any wavelength, equation [6] becomes:

$$m,n = 0: \quad E = E_\lambda ; \qquad [6a]$$

$$m,n = 1: \quad E_{11} = E_\lambda t_\lambda r_\lambda; \qquad [6b]$$

$$m,n = 2: \quad E_{22} = E_\lambda t_\lambda^2 r_\lambda^2; \qquad [6c]$$

$$m,n = 3: \quad E_{33} = E_\lambda t_\lambda^3 r_\lambda^3. \qquad [6d]$$

The total flux after transmission and reflection is given by

$$E_{n,m} = \int E_\lambda t_\lambda^n r_\lambda^m d_\lambda. \qquad [7]$$

The energy flux density at any wavelength under the canopy is the sum expressed in the equation

$$E_{can,\lambda} = P E_\lambda + Q E_\lambda t_\lambda^n r_\lambda^m \qquad [8]$$

and the total flux at any wavelength interval as

$$E_{can,\Delta\lambda} = P \int_{\Delta\lambda} E_\lambda \, d_\lambda + Q \int_{\Delta\lambda} E_\lambda \, t_\lambda^n \, r_\lambda^m \, d_\lambda, \qquad [9]$$

where P and Q are coefficients representing fractions of the area of the canopy and the sky, respectively, or the spatial distribution of the canopy. The above equations assume that the reflected radiation off the ground and again off the canopy is negligible. This is not true for certain parts of the spectrum, especially in the near infrared. In case we have to consider the multiple reflection, the energy flux density at any wavelength may be represented in the equation

$$E_{mult,\lambda} = E_{can} R_1 [1 + R_2 + R_2 R_3 + \ldots + (R_2 R_3 R_4 \ldots R_{n-1})R_n] \qquad [10]$$

where R_n are reflection coefficients, the odd subscripts representing reflection coefficients from the ground, the even subscripts, from the canopy.

The radiation fluxes under vegetation at a given wavelength in equations [3] to [10] represent equations which cannot be calculated unless average values of E_λ, t_λ, and r_λ are available. These problems necessitate actual measurement of spectral quality under plant canopies (E_{can} and E_{mult}). An analytical approach to this problem is extremely complicated, particularly since the leaves are oriented to different directions and a multitude of transmission and reflection processes occur. This study will determine the spectrum of the natural radiation field from 0.4 to 2.5 microns under specified canopies by actual measurements with a monochromator.

MATERIALS AND METHODS

A Leiss Double-Quartz monochromator was used to measure the spectral distribution in the wave range 0.4 to 2.6 microns. Photovoltaic selenium and photoconductive lead sulfide detectors were used as sensors. High-gain amplifiers were specially built to provide the gain necessary for recording. Electric power was provided by a 12-volt car battery through an inverter for 110 volts to run the recorder.

Description of instrument

The optical systems of the Leiss Double-Quartz monochromator[1] is shown in Figure 3. The light entering the entrance slit S_1 is deflected by the plane mirror A_1 and is collimated by the concave mirror H_1. The resulting parallel beam reflected from H_1 is refracted by the prism P_1 which has a mirror coating on its rear surface. The spectrally dispersed radiation returning from the prism is brought to a focus in the plane of the intermediate slit S_2 by means of the concave mirror H_2. The divergent beam emerging from slit S_2 is collimated by the second mirror H_3 and refracted by the second prism P_2. Whatever false radiation is present is dispersed again so that after reflection from the second focusing mirror H_4 and from the plane deflecting mirror A_2, the twice-purified light leaves through exit slit S_3.

The usable height of the slits is 10 mm. At the entrance slit, a built-in diaphram permits controlled reduction of the slit height down

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[1]Mention of trade names does not constitute endorsement of the product.
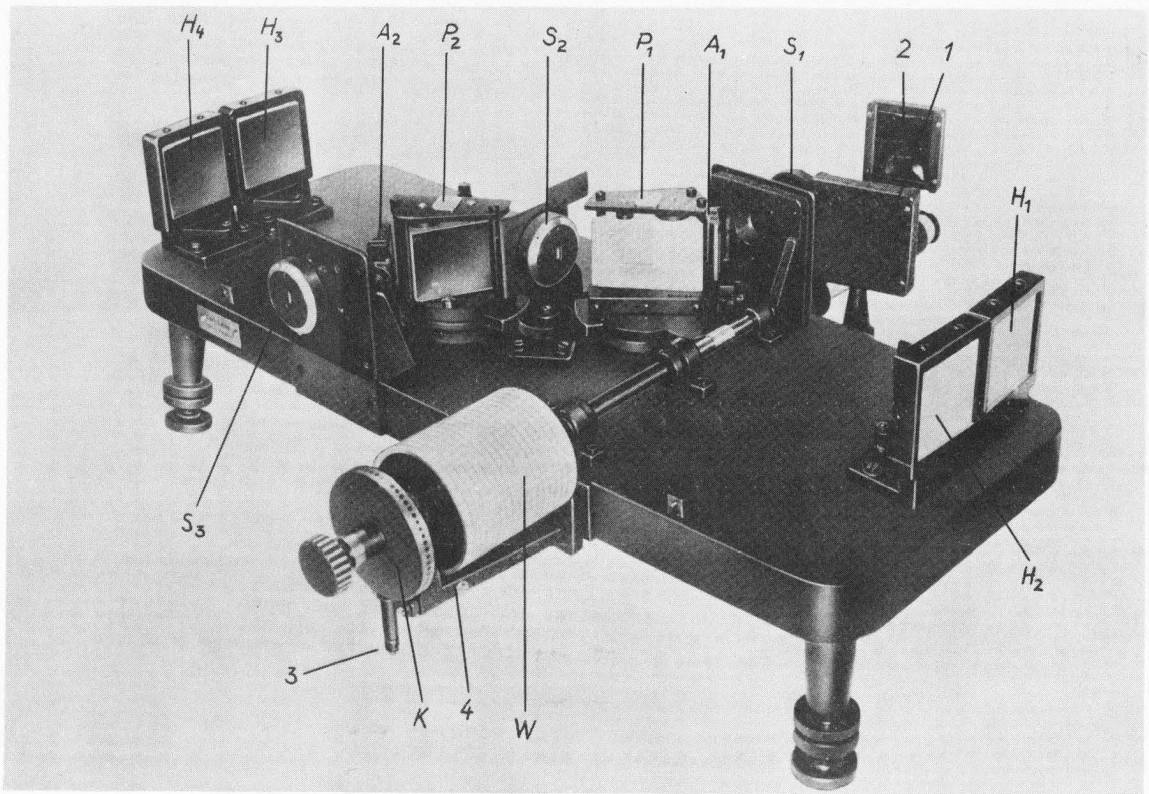
(a)

(b)

Figure 3. (a) Double-Monochromator with the cover removed showing (b) the mechanical construction and the optical system.

to one millimeter. The minimum mechanical slit width that can actually be employed will depend on the intensity of the entering radiation, the transmission prevailing at the particular operating conditions and the sensitivity of 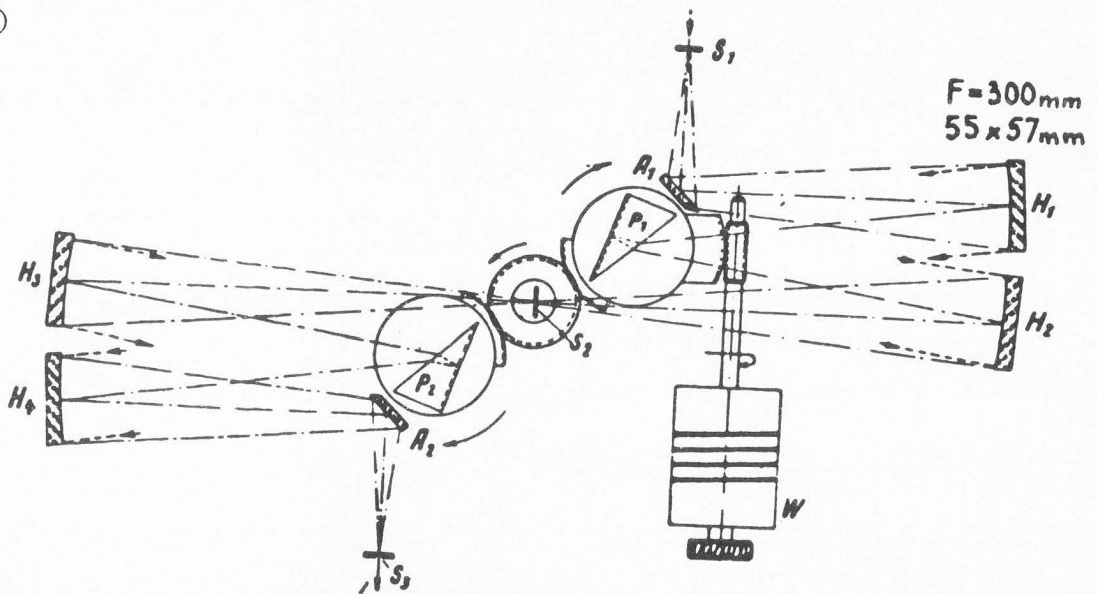the detector. Generally speaking, the spectral width of the waveband isolated by the monochromator depends upon the mechanical slit settings. If the slits are adjusted to a narrow width, the waveband is narrow also but is reduced.

The resolving power is proportional to the dispersion and thus increases from red to blue. At a slit width at which the limit of the resolution is reached, the energy available at the exit slit is obviously very low. Therefore, depending upon the sensitivity of the detector, it might be necessary to operate with appreciably wider slits so that the limit of resolution of the instrument is not fully utilized. This makes it necessary to operate with detectors of the highest sensitivity and use high-gain electronic amplifiers.

Calibration

The Leiss Double-Quartz monochromator was calibrated as to wavelength using a Cary spectrophotometer. The calibration curve obtained is shown in Figure 4.

Reflector

The Leiss monochromator is basically designed for laboratory use. One accessory is a concave mirror (1 in Figure 3a) which focuses the light source at a distance of twice the focal length into the entrance slit with the aid of plane mirror (2 in Figure 3a).

In this study, measurements were made under forest canopies with the sun as the light source. The illumination system described above is not possible. Therefore a reflector, shown in Figure 5, was
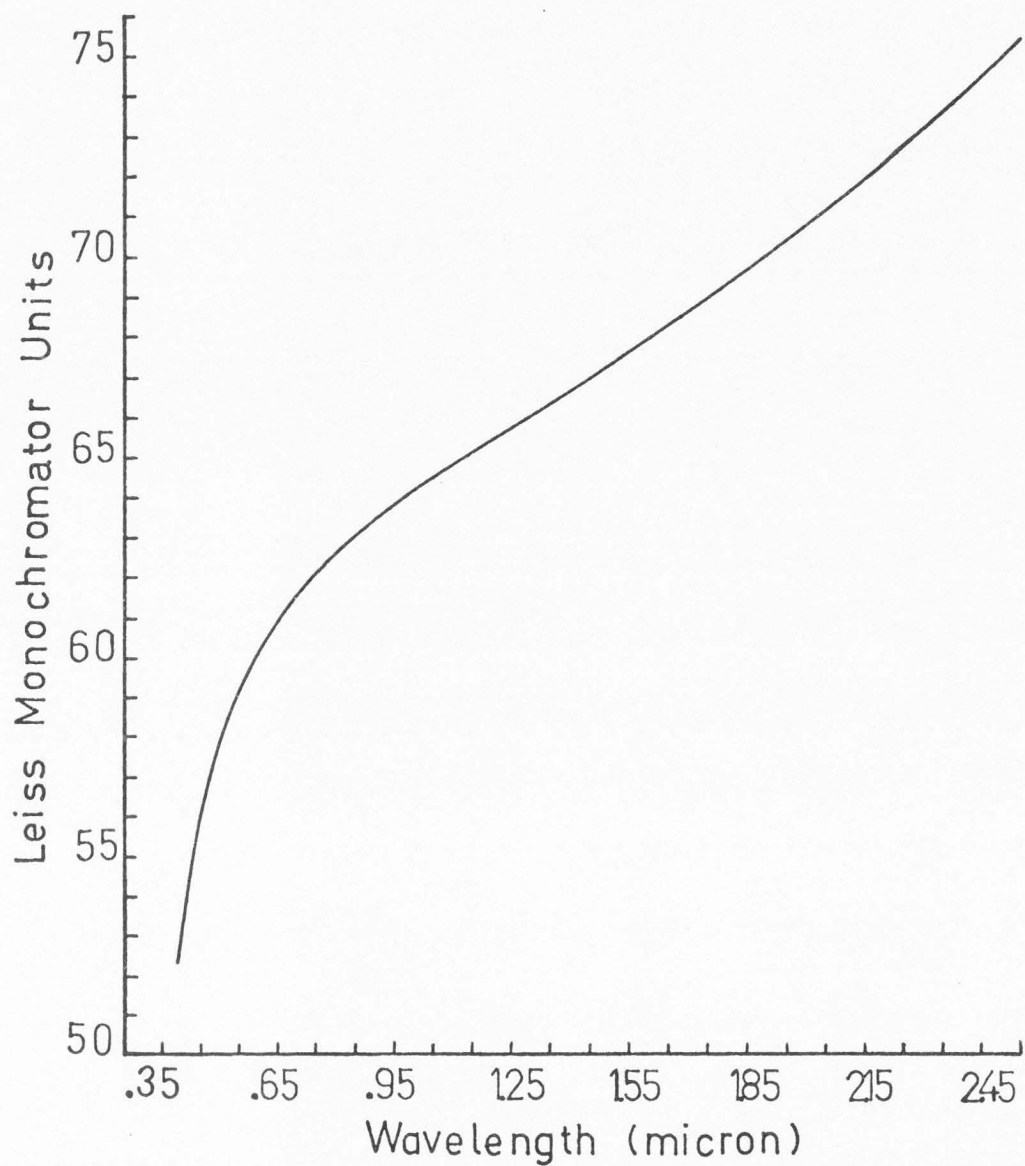
Figure 4.   The calibration curve of the Leiss Monochromator as to
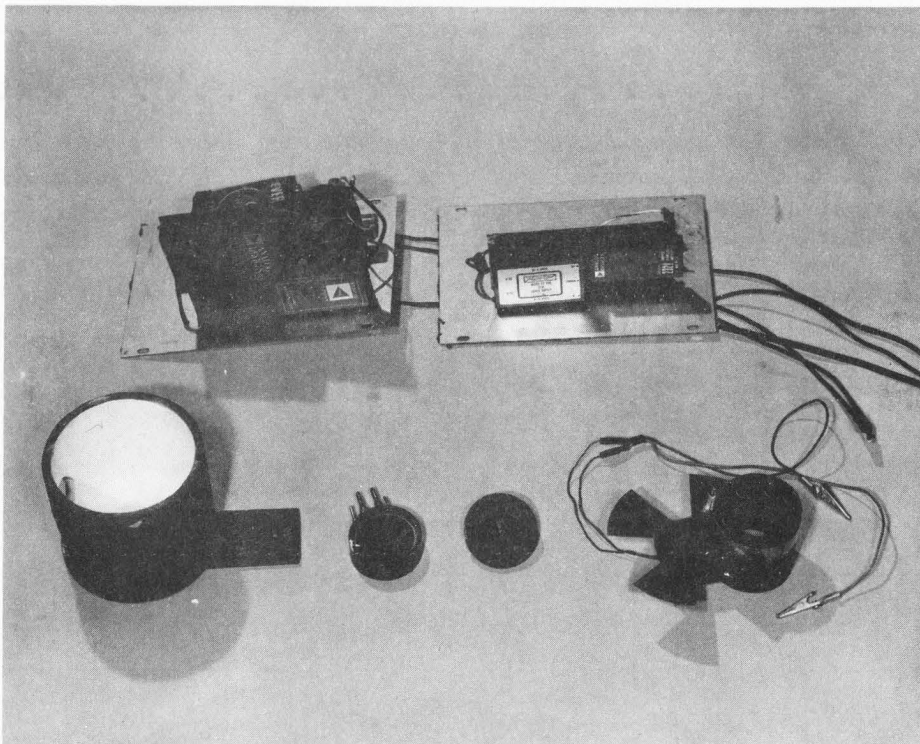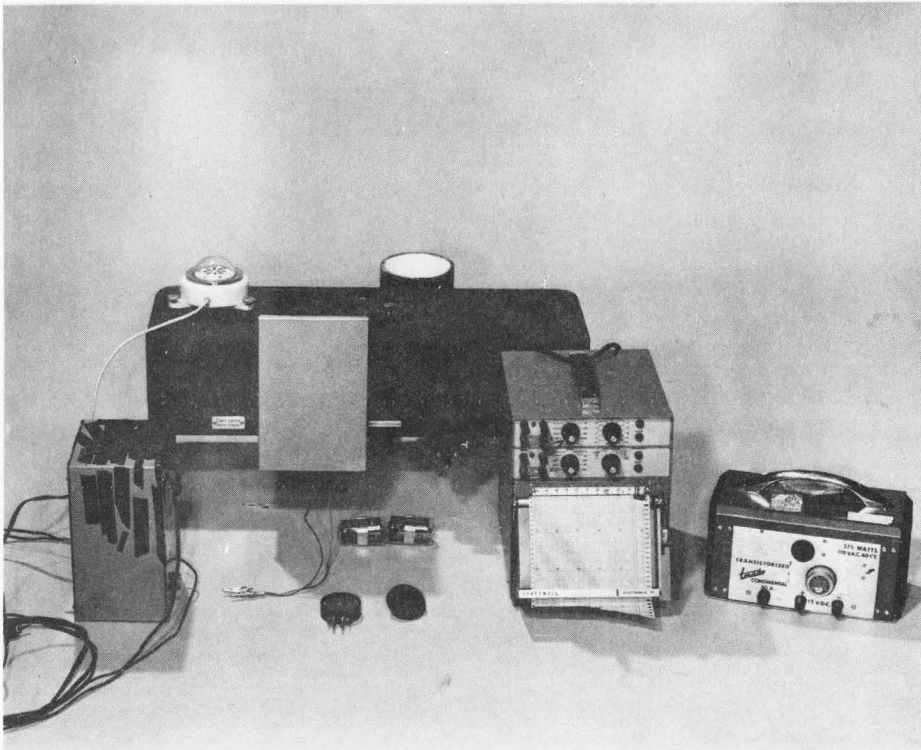   wavelength using a Cary spectrophotometer.

Figure 5.   The Leiss Monochromator, recorder, amplifiers, sensors,
            inverter, chopper, reflector, and a pyranometer.

designed and fitted to the entrance slit. It is a plastic cylinder with
a diameter and height of about 11 cm. The cylinder is fitted with a
plastic holder at the closed end. The outside is painted with a flat
black paint and the inside walls, including the bottom, are smoked with
burning magnesium. The magnesium oxide is about a millimeter thick.
This material is known to reflect more than 95 percent of the incident
radiation over the whole spectrum (Middleton and Sanders, 1951; Sanders
and Middleton, 1953). The monochromator is positioned under the forest
canopy such that the reflector is to the north of the entrance slit. The
reflector serves as an integrating sphere as well.

Detectors

The most commonly used photoelectric effect in the infrared region
of the electromagnetic radiation is the photoconductive process. The
photon energy is absorbed from infrared radiation producing a change in
resistance or conductivity independent of any heating effect. Among the
materials used, lead sulfide is the most common. It has a spectral
response extending to about 3.0 microns and exhibits excellent performance
at room temperature, and even better when cooled to solid carbon dioxide
or liquid nitrogen temperature. Its methods of preparation and compara-
tive performance is discussed by Kruss, McGlanchlin, and McQuistan (1963).

The lead sulfide used in this study is in the form of a simple flat
plate mounted in hardware (Figure 5). The detector is hermetically
sealed between a substrate and a window made of quartz. Normal glass
is not used because of undesirable polarization (an ion migration effect
under prolonged voltage application resulting in excessive noise, reduced
sensitivity, non-uniformity of sensitivity). Electrodes are of

evaporated gold for noise free contact with attached leads anchored in

the substrate for mechanical strength. The sensitive area is 1 x 2 mm

and the resistance of lead sulfide surfaces is independent of the size

of the area. As semi-conductors they exhibit a negative temperature

coefficient of resistance which means that resistance increases with

decreasing temperature and decreases with increasing temperature. The

time constant at 25°C is 10 to 10,000 microseconds and varies inversely

with temperature.

The spectral response of the lead sulfide at 25°C is shown in

Figure 6 (Technical Bulletin 2). It is relatively flat from 0.5 to 2.5

microns.

The amplifier was built in the Department[1]. The circuit is shown

in Figure 7. In order to take a voltage signal off the cell, a bias

of 90 volts is applied as specified by the manufacturer of the lead

sulfide. The 150 microfarad capacitor is a noise filter and the 622K

ohm resistor is a voltage divider with the lead sulfide cell across the

bias. As the resistance of the cell changes, the current through the

622K ohm resistor changes and therefore the voltage across it changes as

the resistance of the photoconductive cell. The .22 microfarad

capacitor is a blocking capacitor for DC voltage and filter for the AC

signal. The amplifier is a high-gain, low noise electrometer amplifier

connected in a current to voltage amplifier configuration. The signal

goes from this amplifier through a second .22 microfarad capacitor to

an amplifier with a gain of 100 to boost the signal up to a usable level

for rectification. The remaining part of the circuit is a 1/2 wave

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[1]By Charles Craw, Research Engineer, Department of Soil Science and
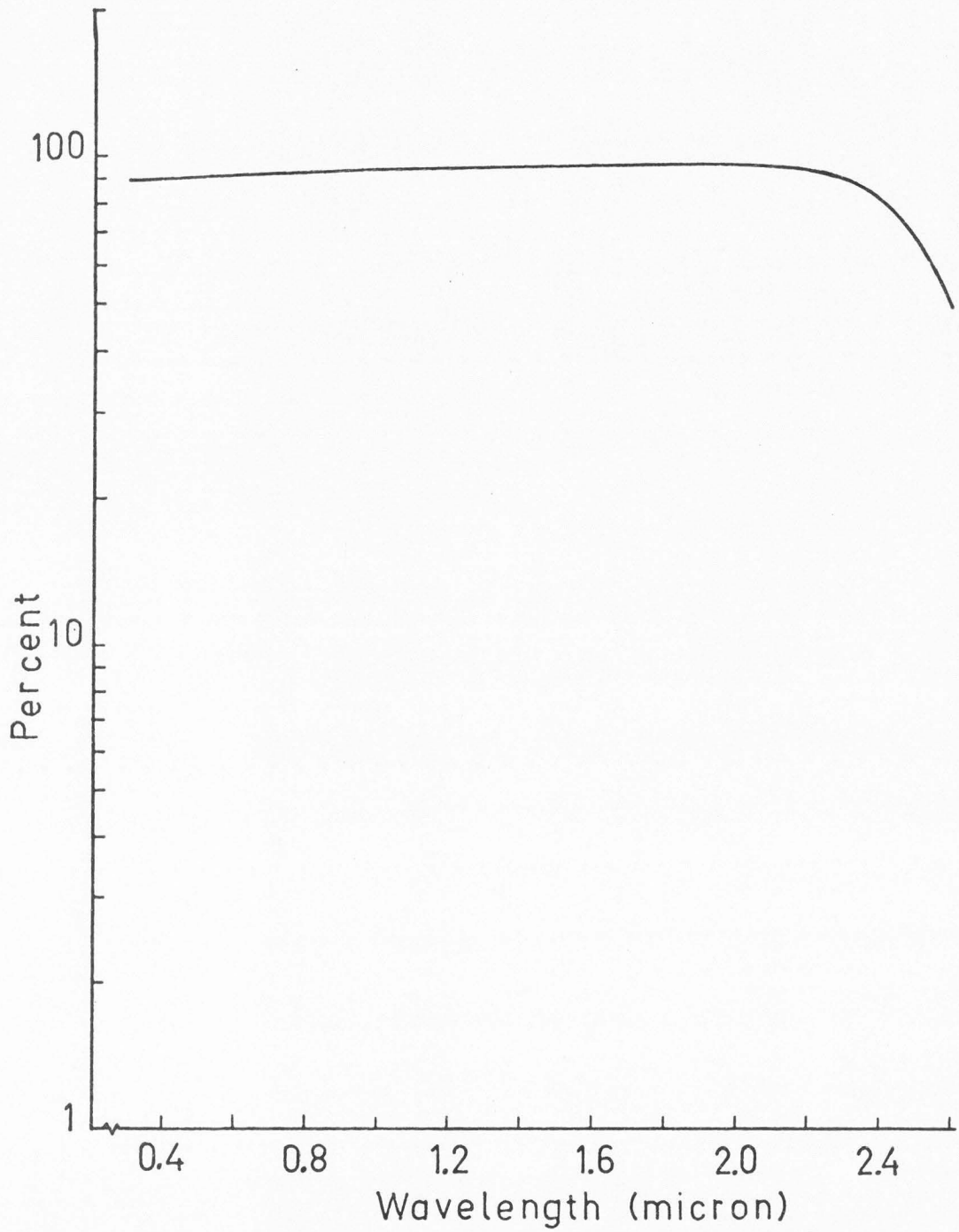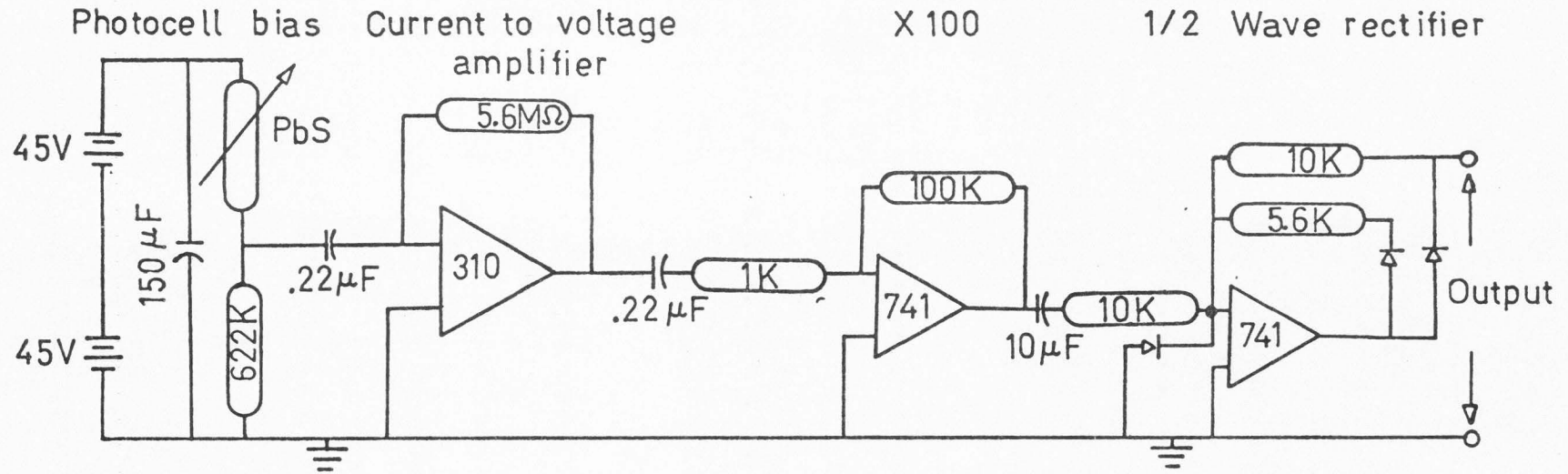Biometeorology, Utah State University, Logan, Utah.

Figure 6. Spectral response of the lead sulfide at 25°C (Technical
Bulletin 2, IR Industries, Inc.).

Figure 7. Infrared and visible amplifier circuit. Each amplifier circuit has its own + 15VDC power supply. The light received by the lead sulfide must be chopped to be applied to the amplifier.

rectifier for the purpose of changing the AC signal to DC. The signal is then recorded on a strip chart recorder (Figure 5). The amplifier is powered by a 15-volt supply.

The primary difficulty in building an amplifier for a lead sulfide cell is overcoming the high thermal noise (or electrical noise) which appears in any conducting or resistive material, whether metals or semi-conductors. This is due to the random motion of electrical charges in the materials. This noise was seen to depend upon the temperature and measurement bandwidth, and to be frequency independent. This makes it necessary to have high-gain amplifiers.

The selenium cell was used in detecting the visible region. The cell is ruggedly constructed, utilizing a base of thin steel, a thin layer of selenium, onto which are vacuum deposited molecular layers of cadmium selenide, cadmium oxide, and in some cases an additional thin transparent conductive film, serving as a current collector. A low melting alloy is then deposited in a line or a ring to provide a suit-able connection. The selenium cell used in this study is cylindrical in shape (Figure 5) having a diameter of two inches and a sensitive area of 2.4 square inches. It has a minimum output of 750 microamperes based upon a cell temperature of 75°F. The spectral response of a typical selenium cell is shown in Figure 8 (Bulletin SPV-4B, 1967). The response has a range in the visible region and peaks at about 0.57 micron.

The selenium photovoltaic cell needs no bias. It is connected to a high-gain low-drift amplifier (Figure 7) which amplifies the DC signal from the cell to a usable level for recording in a strip chart recorder. The amplifier is powered by a 15-volt power supply.
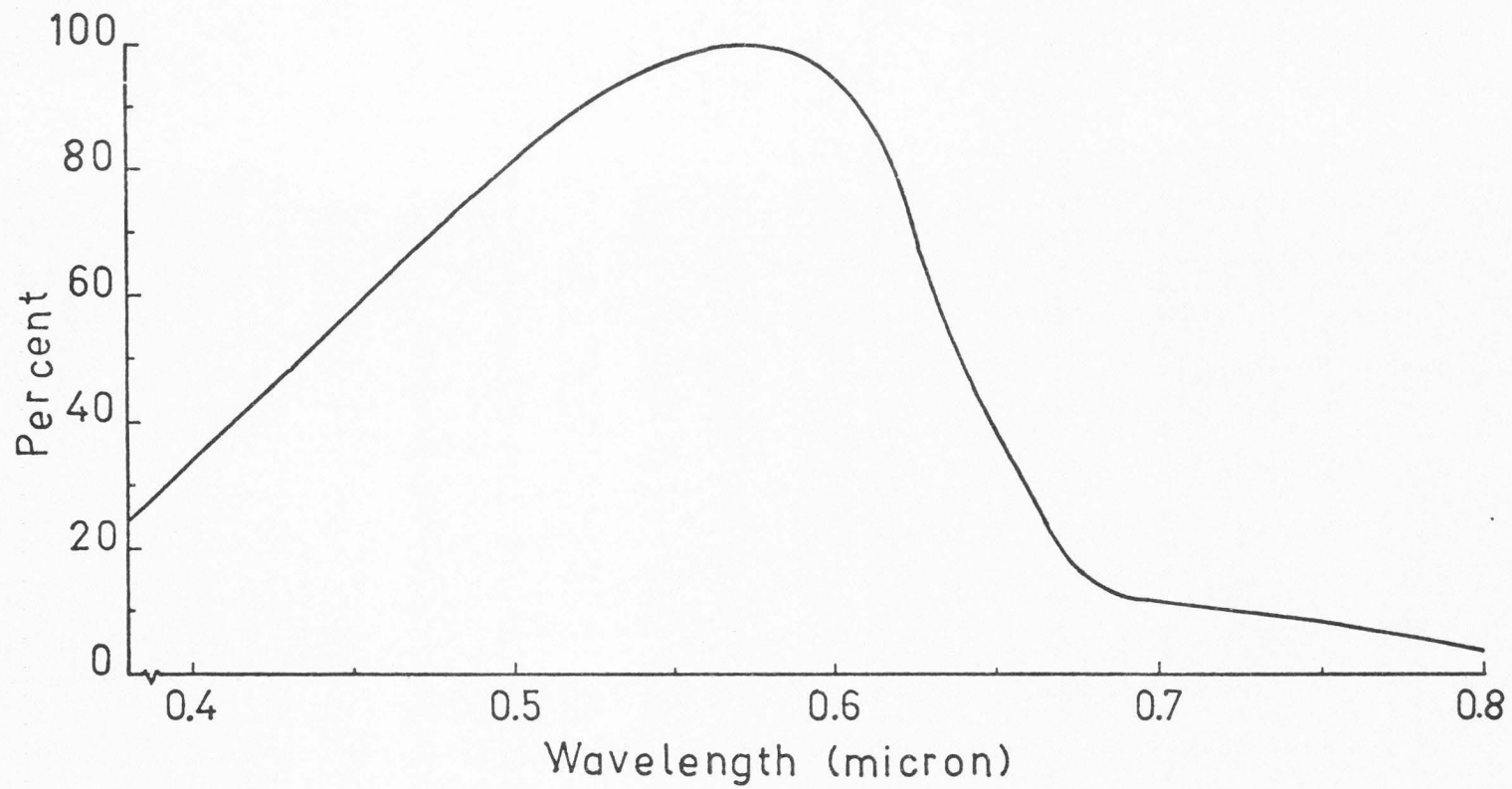
Figure 8.   Typical spectral response of a selenium cell (Bulletin SPV-4B, 1967).

Study areas

Measurements were made under different canopies around the Utah State University campus, in Logan Canyon and under Douglas fir canopy at the University of Washington Forest Experiment Station about 30 miles southwest of Seattle. The species of the different canopies as well as the single leaves used in this study are listed in Table 1.

A Fish-Eye camera was used in taking pictures of canopies used in this study. For the deciduous stands, pictures were taken also after the trees shed their leaves during the fall. Figures 9, 10 and 11 are representative of the canopies studied. Sun tracks are superimposed on the canopy pictures except for the Douglas fir canopy and the leafless stands.

Figure 11a and 11b shows that the lodgepole pine (Pinus contorta) and Douglas fir canopies are similar insofar as crown closure is concerned. It is very difficult to find a uniform canopy with respect to stem, branches, or needle distributions. For the Douglas fir stand, a tower may be noted signifying that this canopy was selected to be somehow representative at this site for diffusion studies at the University of Washington Forest Experiment Station.

Figures 9 and 10 are two contrasting canopy pictures of deciduous stands. The mountain maple (Acer grandidentatum) canopy seems to be very dense in comparison to the aspen (Populus tremuloides) stand. During the leafless stage, it can be clearly seen that while the stem density of the aspen stand is more than the mountain maple, there are less branches. As a consequence, the mountain maple has more leaves and therefore the crown closure is very different from the aspen stand. More radiation penetrates through the aspen than through the mountain maple stand.

Table 1. Species of the different canopies as well as the single leaves
          used in this study

Deciduous

      Plattanus occidentalis (sycamore)

      Salix fragilis (willow)

      Fraxinus (ash)

      Betuta alba (white birch)

      Acer saccharinum (silver maple)

      Ulnus (elm)

      Liriodendron tulipifera (tulip tree)

      Acer grandidentatum (Rocky Mountain maple)

      Populus tremuloides (quaking aspen)

      Castanea mollissima (Chinese chestnut)

Coniferous

      Pinus contorta (Lodgepole pine)

      Picea glauca (white spruce)

      Pinus nigra (black pine)

      Pinus mugo (mugo pine)

      Pseudotsuga taxifolia (Douglas fir)

      Picea pungens (blue spruce)

Single leaves

      Pelargonia (geranium)

      Scindapsus aureus (water plant)

      Poinsettia (poinsettia)

      Acer rubrum (red maple)
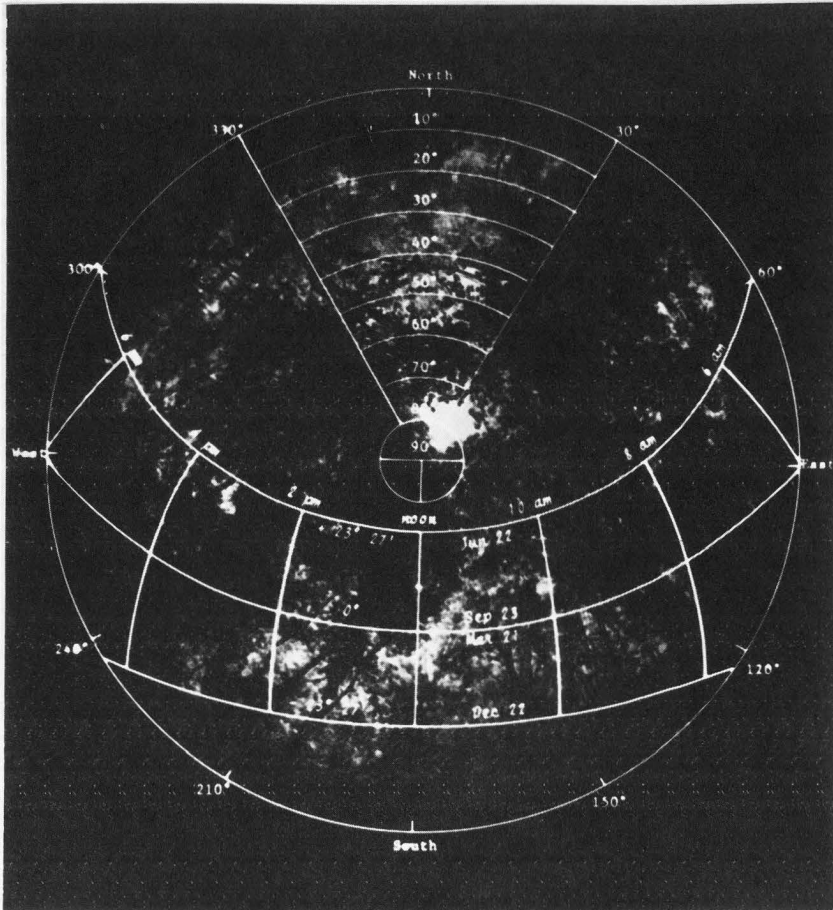
(a)

(b)

Figure 9. A Fish-Eye hemispherical photograph of mountain maple (<u>Acer</u> <u>grandidentatum</u>) with and without leaves.
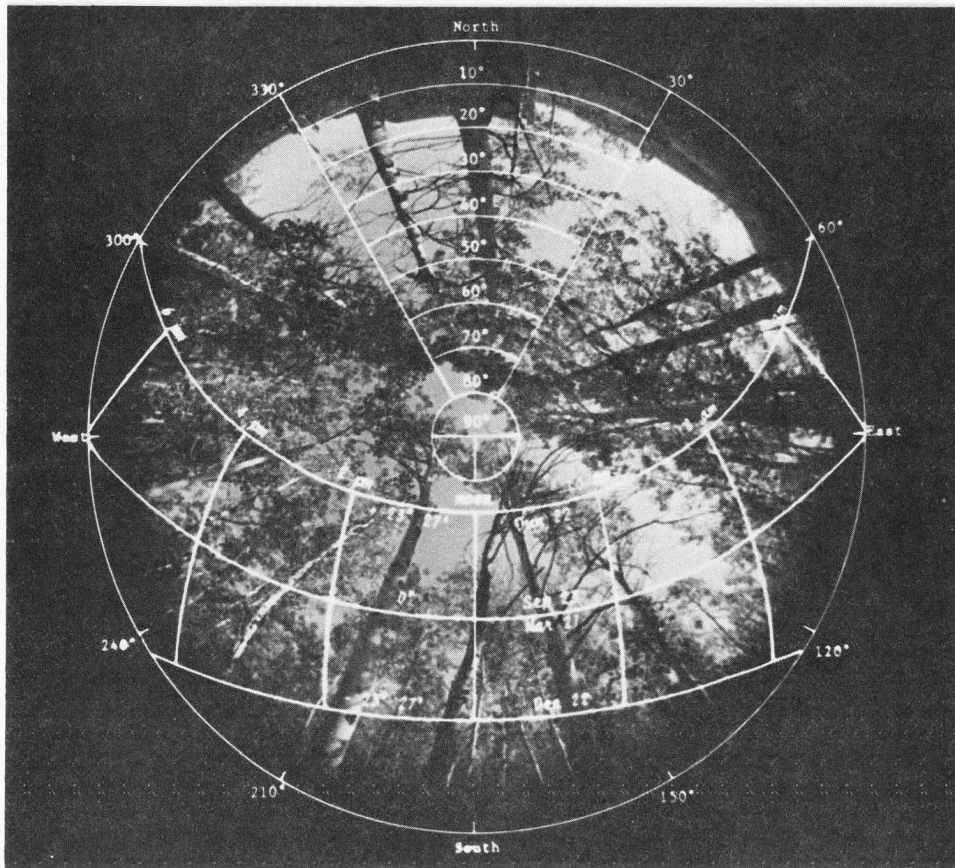
(a)
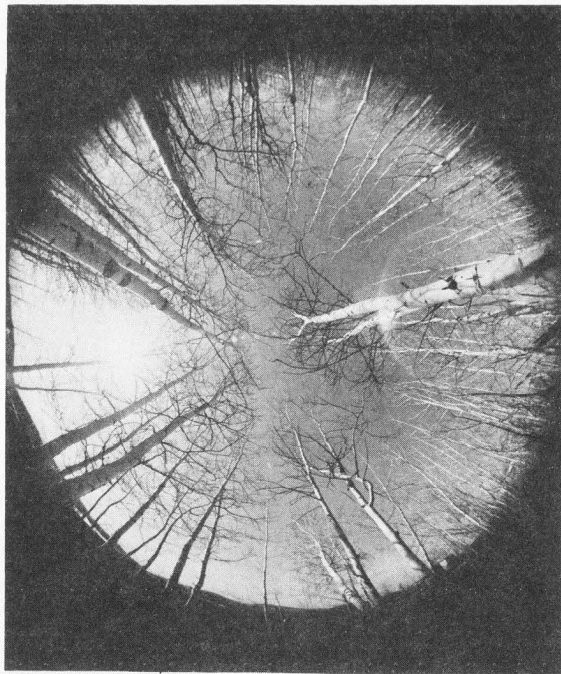
(b)

Figure 10. A Fish-Eye hemispherical photograph of aspen with and without leaves.
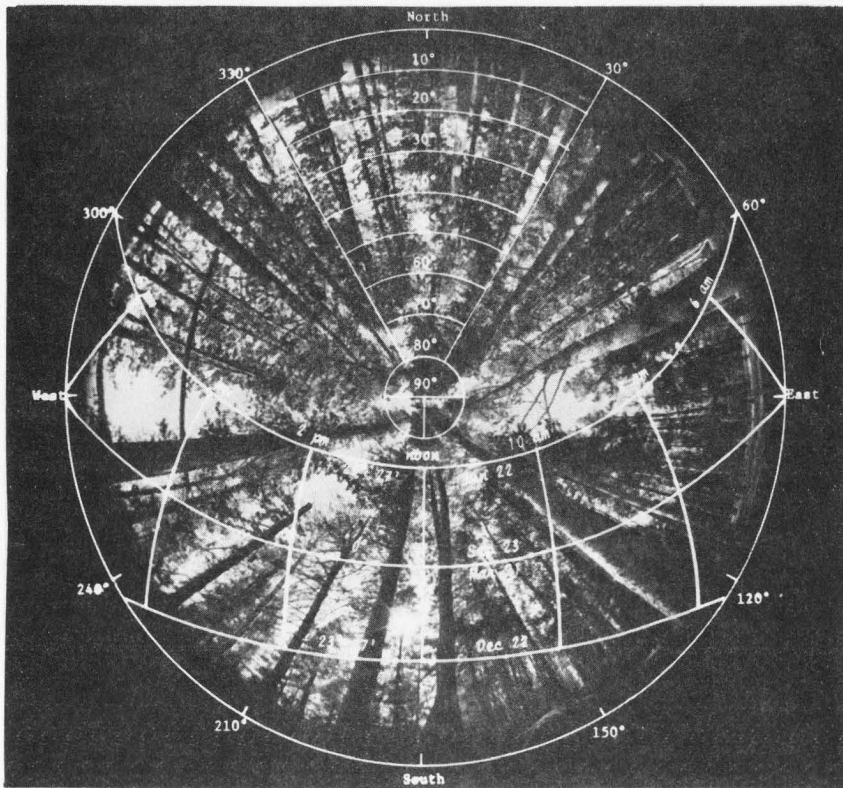
(a)
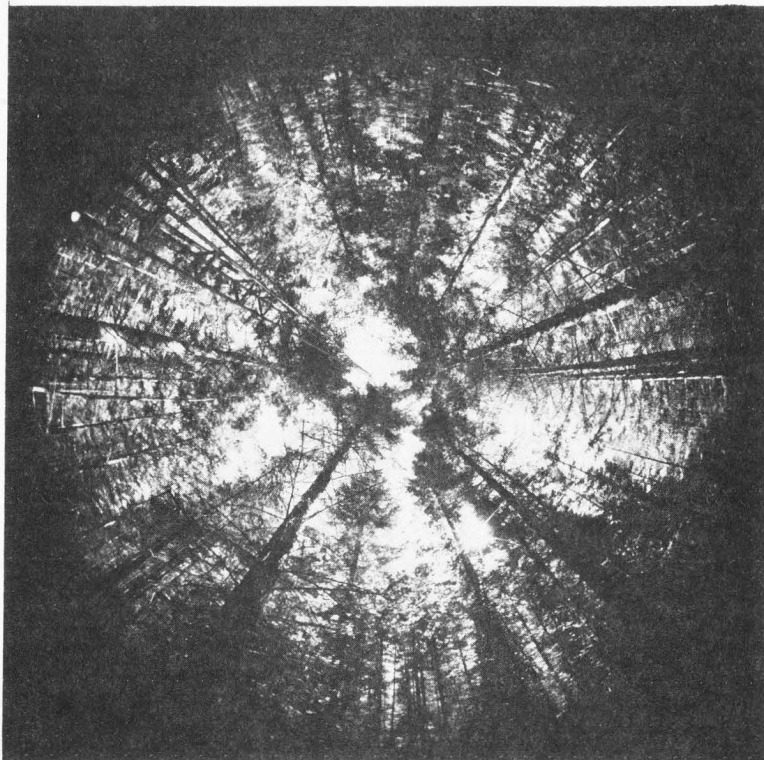
(b)

Figure 11.   A Fish-Eye hemispherical photograph of blue spruce (*Pinus contorta*) and Douglas fir.

This may be the reason why understory growth is more developed under the aspen compared to the maple.

The problem of sampling

It is very difficult to sample global radiation in a forest stand. There is always the complicated patterns of sunflecks and shadows present resulting in a diversity of values recorded throughout the day and throughout the stand.

Insofar as the measurement of the spectral composition of the global radiation reaching the forest floor is concerned, no periodic or areal sampling was ever attempted. This is a gigantic task if not impossible. Measurements under forest canopies so far were described as "apparently uniform shade with no visible sunflecks." Obviously this is not the representative condition under the forest floor. It is clear that the radiation regime under the forest stand will always be a combination of all the components identified by Federer (1964), Federer and Tanner (1966) and Reifsnyder, Furnival and Horowitz (1972). Of these components, sunflecks would probably be the most difficult to measure.

In this study the measurements under the canopies were made where the uniform crown shade is located. There is extreme difficulty in finding the right spot on the forest floor since it is only a matter of seconds and minutes for the apparent position of the sun to change. Under the deciduous canopies, it is relatively easier to find a uniform crown stand with no apparent sunflecks compared to the coniferous stand. Under conifer stands the whole set-up of instruments and accessories has to be moved one or more times to get a complete spectral measurement in the wave band desired. Beyond the visible region, the openings or holes

through the canopy do not make much contribution in the spectral composition as can be seen in Figure 2. The sky radiation is very low beyond the visible region of the spectrum. Therefore, under the needle-leaf canopies, care was exercised in positioning the monochromator, especially when measuring in the visible region since there are more holes through which the sky radiation can go through and reach the instrument.

Measurement procedure

The monochromator, recorder, and all the accessories except the inverter and the power supply (12 volt car battery) were placed on a wood table about a meter high from the forest floor. Since time is a limiting factor in this study because measurements could only be made during clear and calm days, the spectral distribution at one spot on the forest floor was measured at least twice and then the whole set-up was moved to another site. This procedure was repeated until all measurements possible were made. Measurements on a particular day were made as many times as possible. The spectral distribution of the global radiation in the open was always made around noontime for consistency. In this manner the spectral distribution under the canopy can be expressed as a percentage of the energy in the open for any wavelength. Measurements were made at every two-hundredths and five-hundredths of a micron in the visible and infrared, respectively. This gives an excellent spectral distribution of the global radiation under the canopies after a linear interpolation in between.

A strip chart 2-pen recorder was used to record the signal at each specific wavelength. The second pen was used to record the transmitted global radiation on the forest floor as detected by a star pyranometer.

This was originally intended to serve as a basis for making adjustments in the spectral measurements when sudden changes in the incoming radiation occur due to a change in the crown density as the sun moves through the sky or as the wind sways the leaves or branches. However, it was found that no matter how close the pyranometer is positioned with respect to the entrance slit of the monochromator, the radiation that is getting through the slit does not necessarily correspond to what is falling on the pyranometer. No matter how the shade appears to be uniform there is still some differences in the incoming radiation even on the very short distances of a few centimeters.

The measurements of the spectral composition of radiation under both deciduous and coniferous canopies were made during clear days between 10 a.m. and 2 p.m. only. During this period the variation of the intensity of the global radiation is minimum. The global radiation has a simple daily distribution with a maximum at about noon. The diurnal variation during conditions of cloudless sky is shown in Figure 12. At the latitude of Logan, the highest daily value is about June 22 with a maximum of 1.3 ly/min and lowest about December 22 with a maximum of about 0.67 ly/min, based on December 25, 1970 record. The noon maximum is caused by the shorter path length of the atmosphere which means lesser attenuation.

At the geographical point of USU Campus (41°45' N; 111°50' W), the features of the variation of the radiant flux (R_1) with solar height greater than 23 degrees is shown in Figure 13. There is quite a spread in the values but this could be explained by the prevailing atmospheric transparency at the time of the measurement. The radiant energy on a surface normal to the sun's rays is hardly influenced by solar height. On the other hand, the flux on a horizontal surface $(R_)$ is shown to be
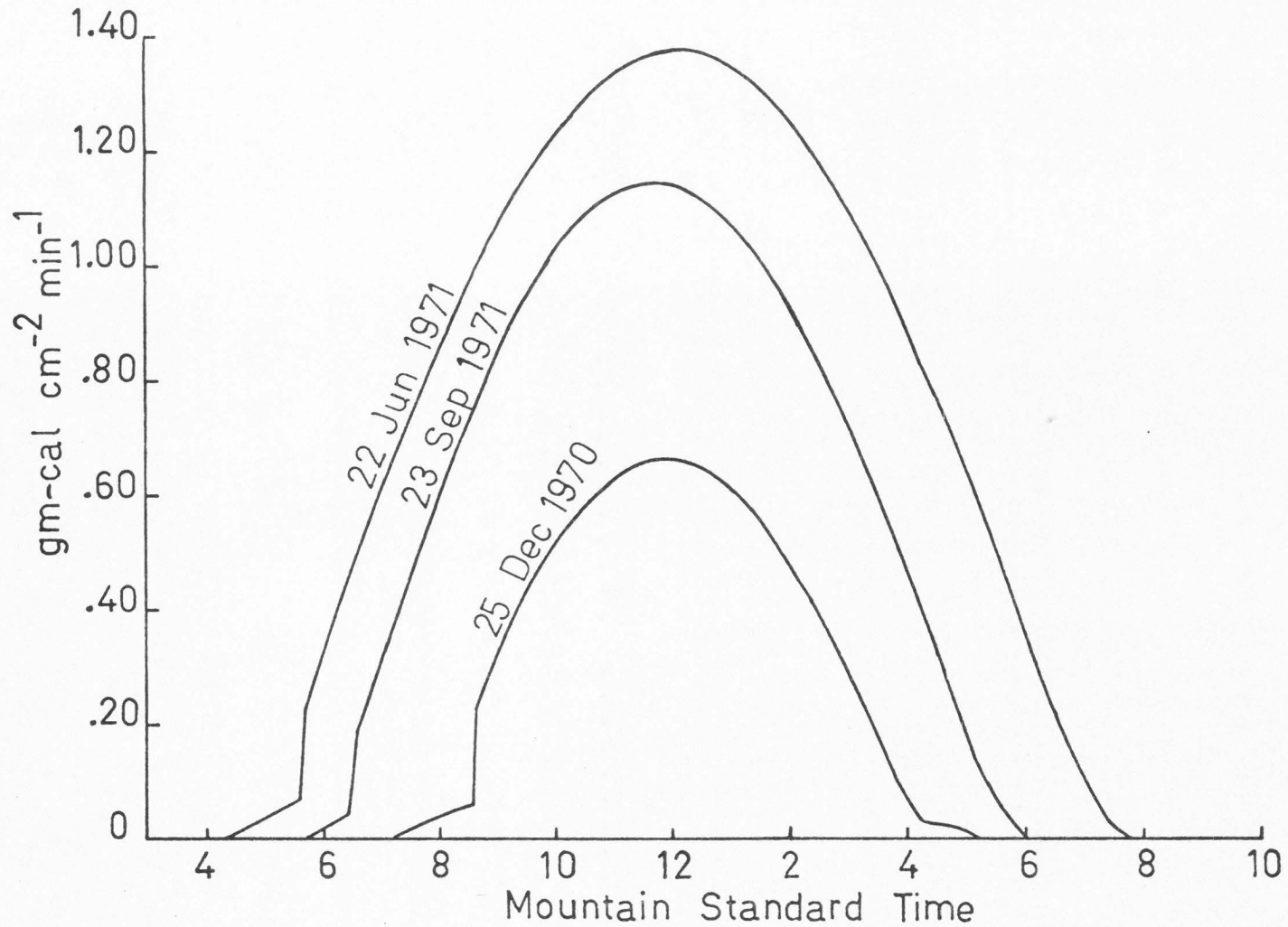
Figure 12. Daily variation of global radiation at the geographical point of Utah State University Campus (41°45' N; 111°50' W) on selected clear days.
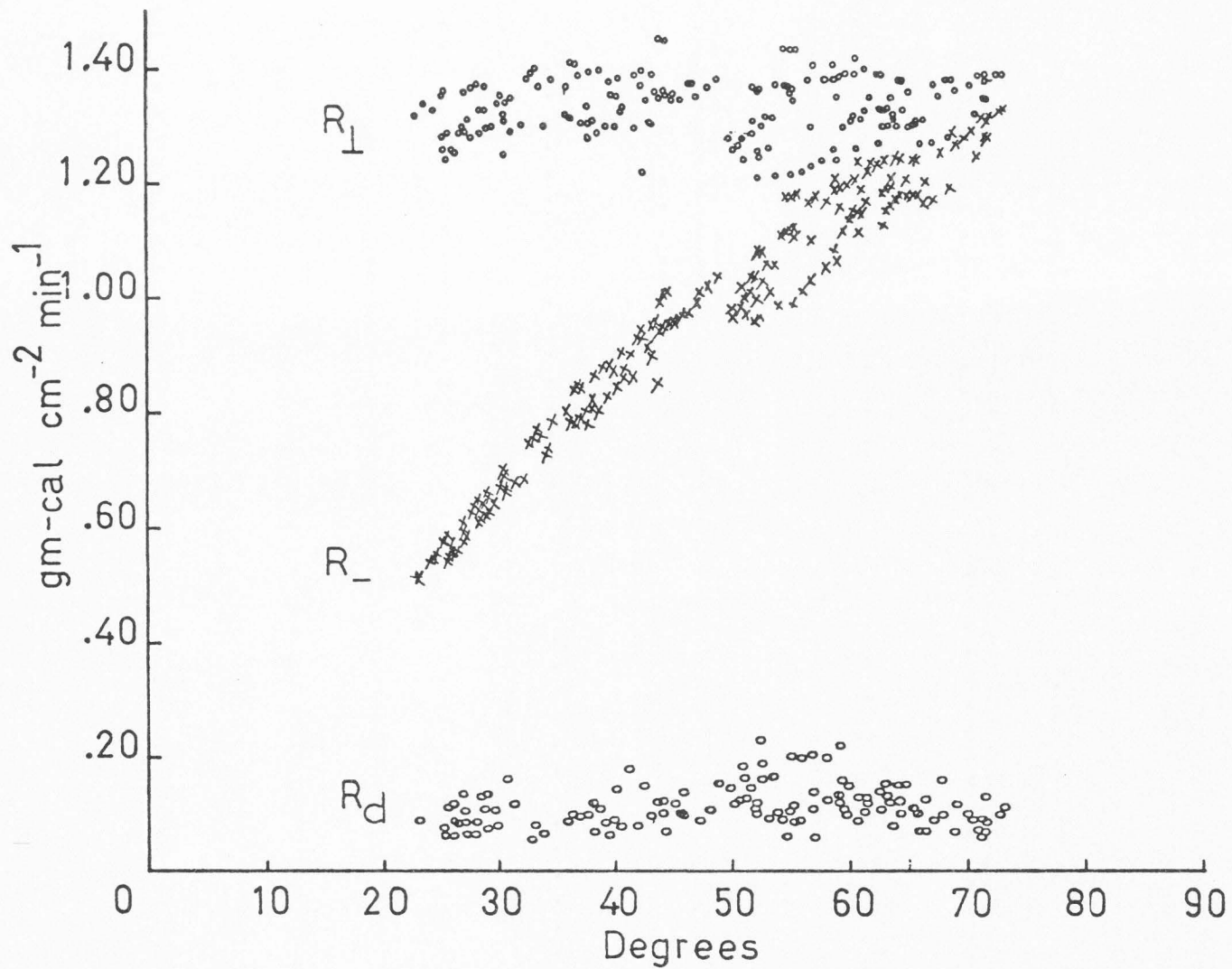
Figure 13. Measured radiant flux ($R_\perp$) on a surface normal to the sun's rays, computed flux on a horizontal surface (R_-), and diffuse sky radiation (R_d) at USU campus on certain cloudless days during the period from 1968 to 1973.

a function of latitude, declination, and solar time. In order to
emphasize the contribution of the diffuse sky radiation to the total
flux falling on any surface, this component is also shown in Figure 13.
On the average it is shown to have a value around 0.10 ly/min.

Analysis of data

The recordings in each specific wavelength took about five to ten
seconds. The readings were in percent of whatever scale was used,
usually volts or millivolts. The time involved in each complete
measurement from 0.4 to about 2.4 micron interval was around three to
five minutes. The value at each particular wave band was then the
average during the five or ten second period the monochromator was set
for that specific wavelength. The values were then tabulated and plotted
on a linear graphing paper. All measurements for a particular day under
canopies were analyzed in this manner in order to detect any possible
change in the calibration of the monochromator. Plotting the values on
the graphing paper in units of the recorder allowed detection of any
drastic change in the intensity of the incoming radiation during the dur-
ation of the measurement at each site. Only one measurement in the open
was made for any particular day. The values were also tabulated and
plotted on a linear graphing paper. The measurements under the wood-
stand were then expressed in percent of the value outside the forest.
This facilitated representation, comparison, and interpretation of the
spectral distribution obtained under the different canopies studied.
This procedure also eliminated instrument characteristics that influenced
the values. Therefore, the only effect was the one from the canopy.

RESULTS AND DISCUSSION

Spectral properties of plant leaves

The spectral transmittance and reflectance of some leaves in the visible spectrum are shown in Figures 14 and 15. The measurements were made in September 1971 as part of the test in building the amplifier for the photovoltaic selenium detector. Detectable transmittance differences were noted in the green (0.55 micron) where the silver maple leaf has about 11 percent followed by tulip tree, 8 percent; chestnut, 7 percent; and lilac, 5 percent. All four species had very low transmittance in the 0.44 to 0.5 micron and 0.6 to 0.66 micron intervals.

The reflectance curves (Figure 15) exhibited the same pattern as the transmittance. The spectral transmittance was measured by wrapping the leaf around the entrance slit of the monochromator. The reflectance curves, on the other hand, were obtained by placing the foliage of each plant species as a single layer about 10 centimeters in front of the entrance slit approximately normal to the incident radiation. The spectral distribution of both the reflected and transmitted radiation are similar but of different magnitudes. In the green portion the silver maple has about 14 percent reflectance, followed by the chestnut leaf with 13 percent, lilac, 12 percent; and tulip tree, 11 percent. Relatively lower reflectance values were obtained in the 0.44 to 0.50 micron and the 0.60 to 0.66 micron wavelength intervals. Both the reflectance and transmittance values increased very sharply beginning at approximately 0.68 micron.
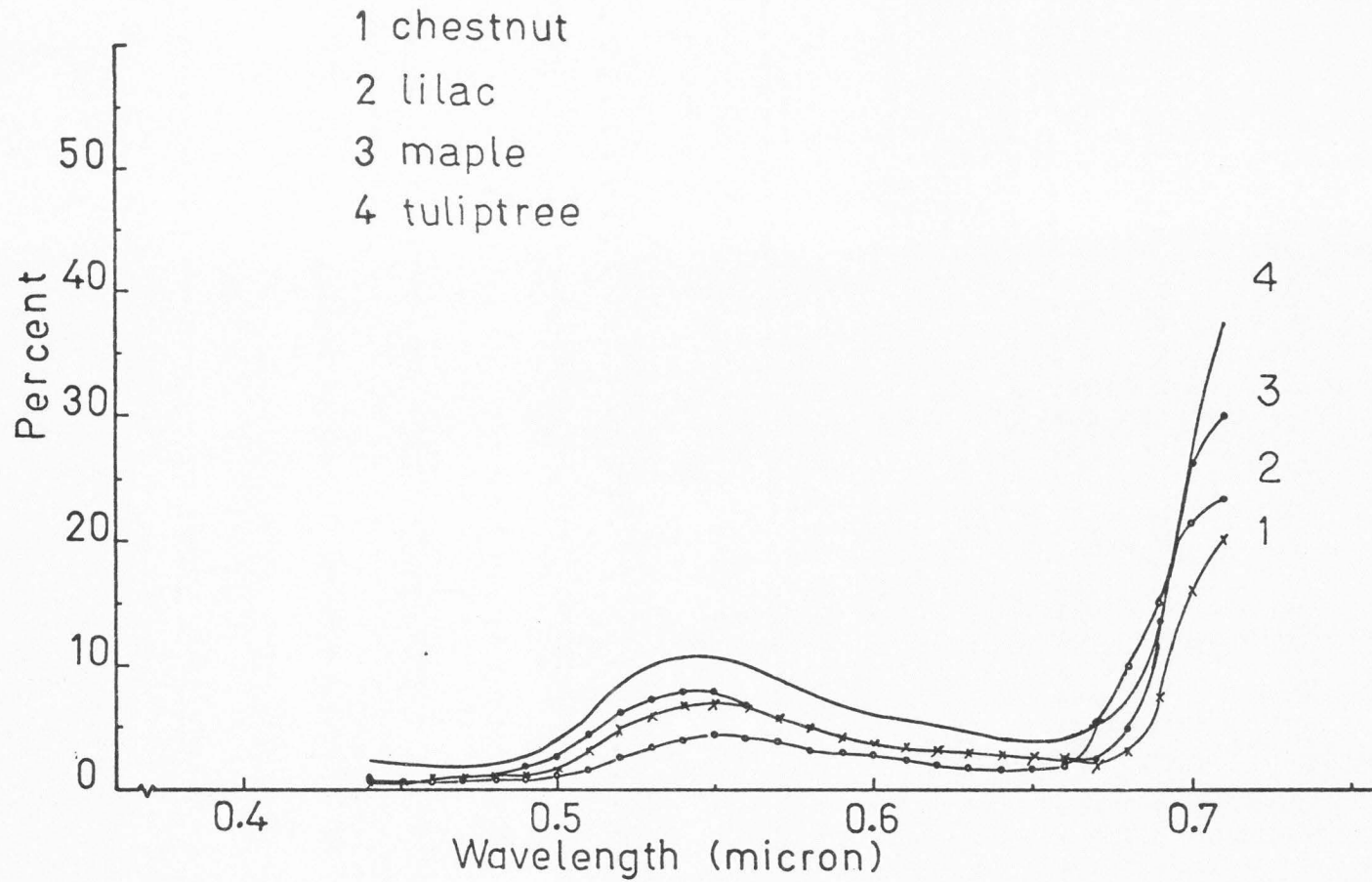
Figure 14. Relative spectral transmission of global radiation by single leaves from chestnut, lilac, tulip tree, and red maple.
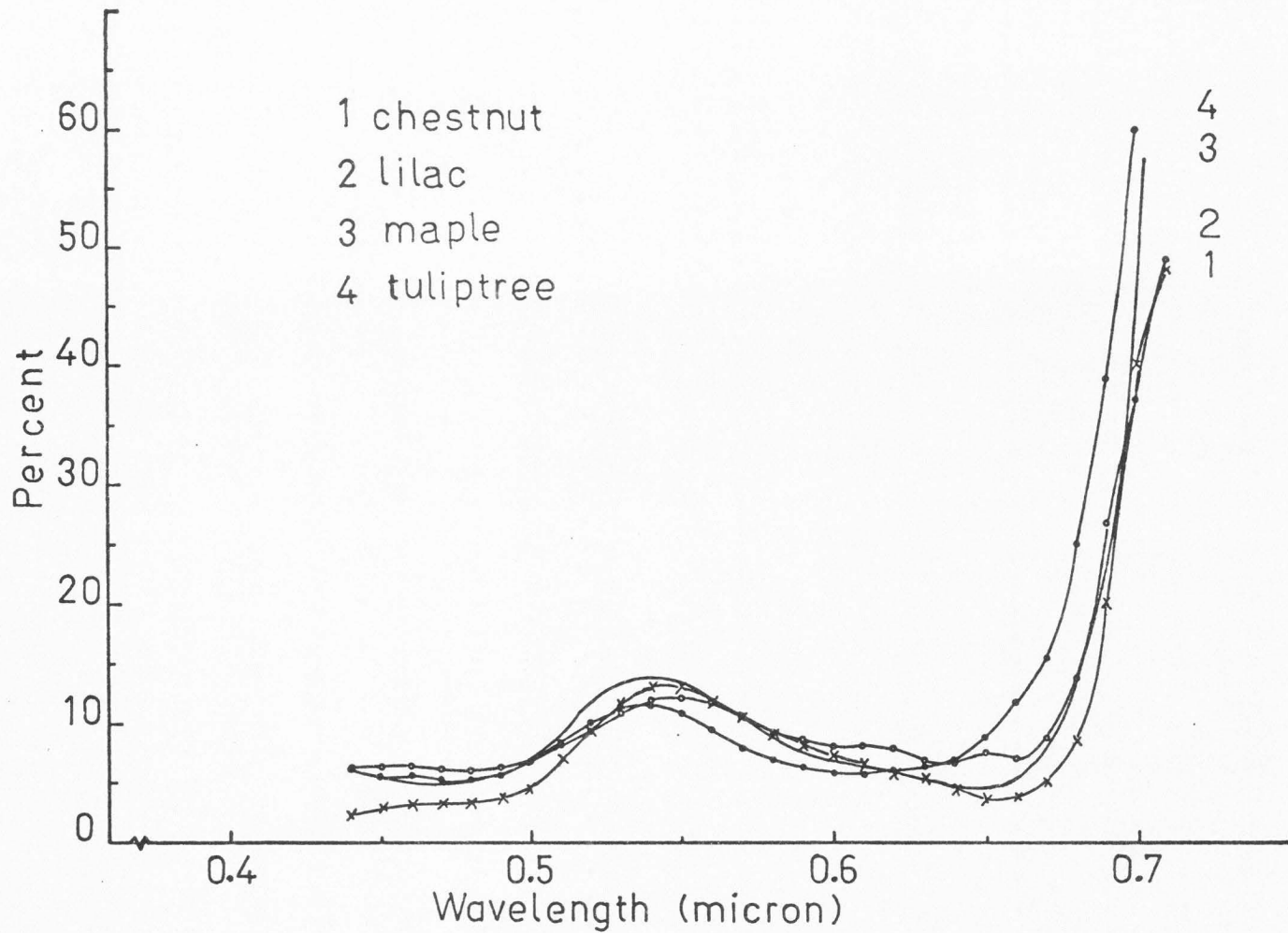
Figure 15. Relative spectral reflection of global radiation by single leaves from chestnut, lilac, tulip tree, and red maple.

In autumn, the spectral characteristics of broadleaf species change markedly. The chlorophyll is destroyed, leaving carotene and antho-cyanin pigments and then eventually all the pigments are destroyed as the leaf dies. This phenomenon is illustrated in Figures 16 and 17. The leaves were described as green (1), yellow (2), brown (3), and brown dry (4). The leaves were taken from the broad leaf species tulip tree. The spectral transmittance of these leaves was measured in October 1972. There was very little transmittance in the wave range 0.40 to 0.50 micron for all four leaves, barely one percent. The green leaf had a peak transmittance of about 7 percent in the green (0.55 micron) and decreased to about 3.5 percent at 0.65 micron and increased very sharply after 0.68 micron reaching 25 percent at about 0.80 micron. Transmittance of the yellow leaf increased markedly after 0.5 micron reaching 23 percent at 0.76 micron. The transmittance values of the brown and brown dry leaves increased gradually after 0.5 micron to about 20 percent at 0.74 micron. After the 0.72 micron, all four leaves had no pronounced pattern in their spectral transmittance.

Spectral measurements of a single leaf from a poinsettia and a geranium plant and foliage from blue spruce are shown in Figure 18 in the wave range 0.55 to 2.50 micron. The transmission coefficient for the two broadleaves rose very sharply beginning at about 0.68 micron to more than 40 percent in the wavelength interval 0.80 to 1.3 micron, with the geranium leaf being lower by a few percent. The dip at 1.45 and 1.95 micron is very distinct for the two broad leaves, with the geranium leaf showing no transmission beyond 1.9 micron.

The foliage of blue spruce was placed over the reflecting drum in Figure 5. The transmittance curve is about 5 percent at 0.4 micron,
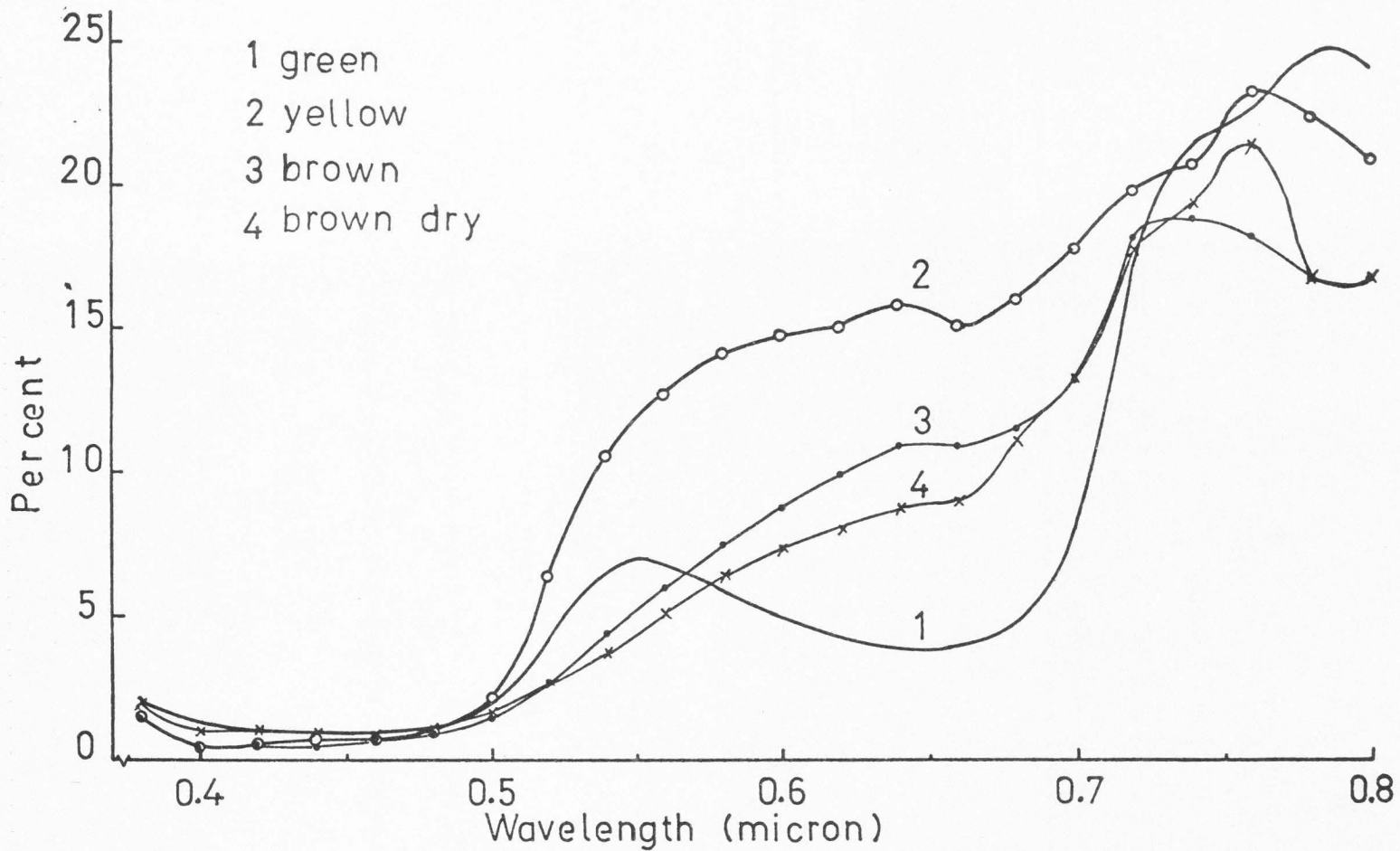
Figure 16. Relative spectral transmission of global radiation of <u>L</u>. <u>tulipifera</u> leaves undergoing color changes in autumn.
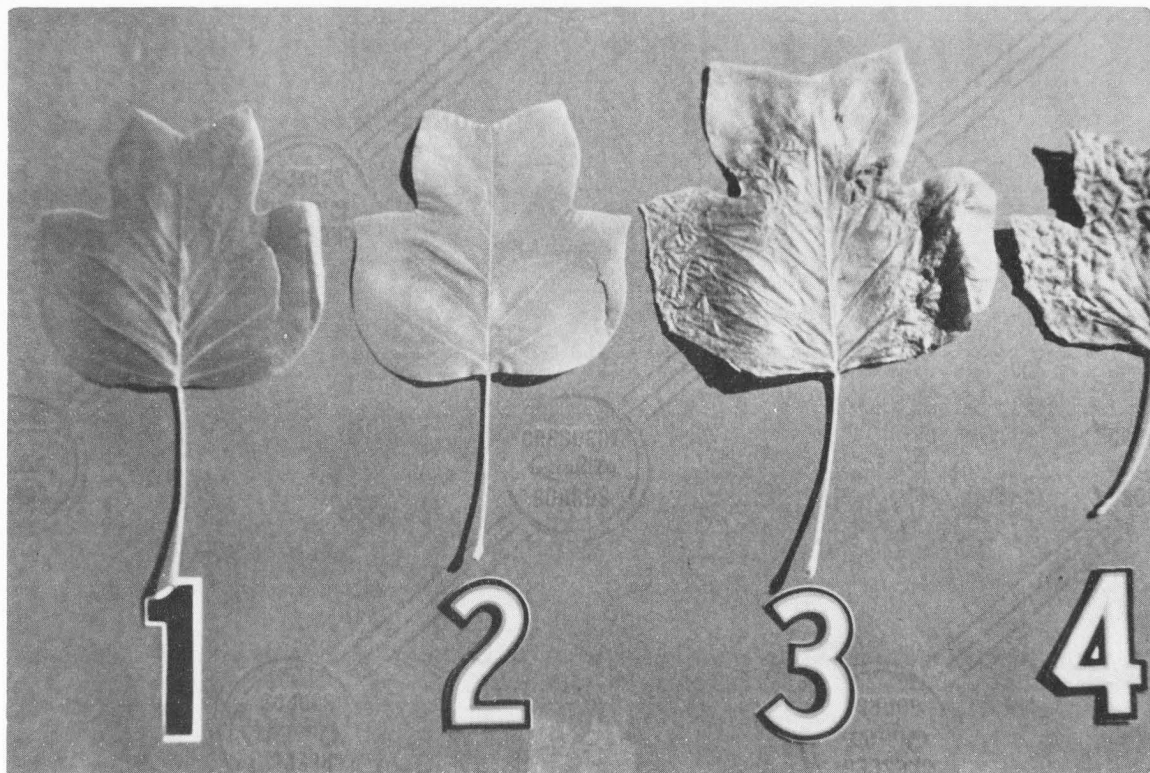
Figure 17. A color picture of the four leaves from the species L. tulipifera used in obtaining the spectral transmission in Figure 16.
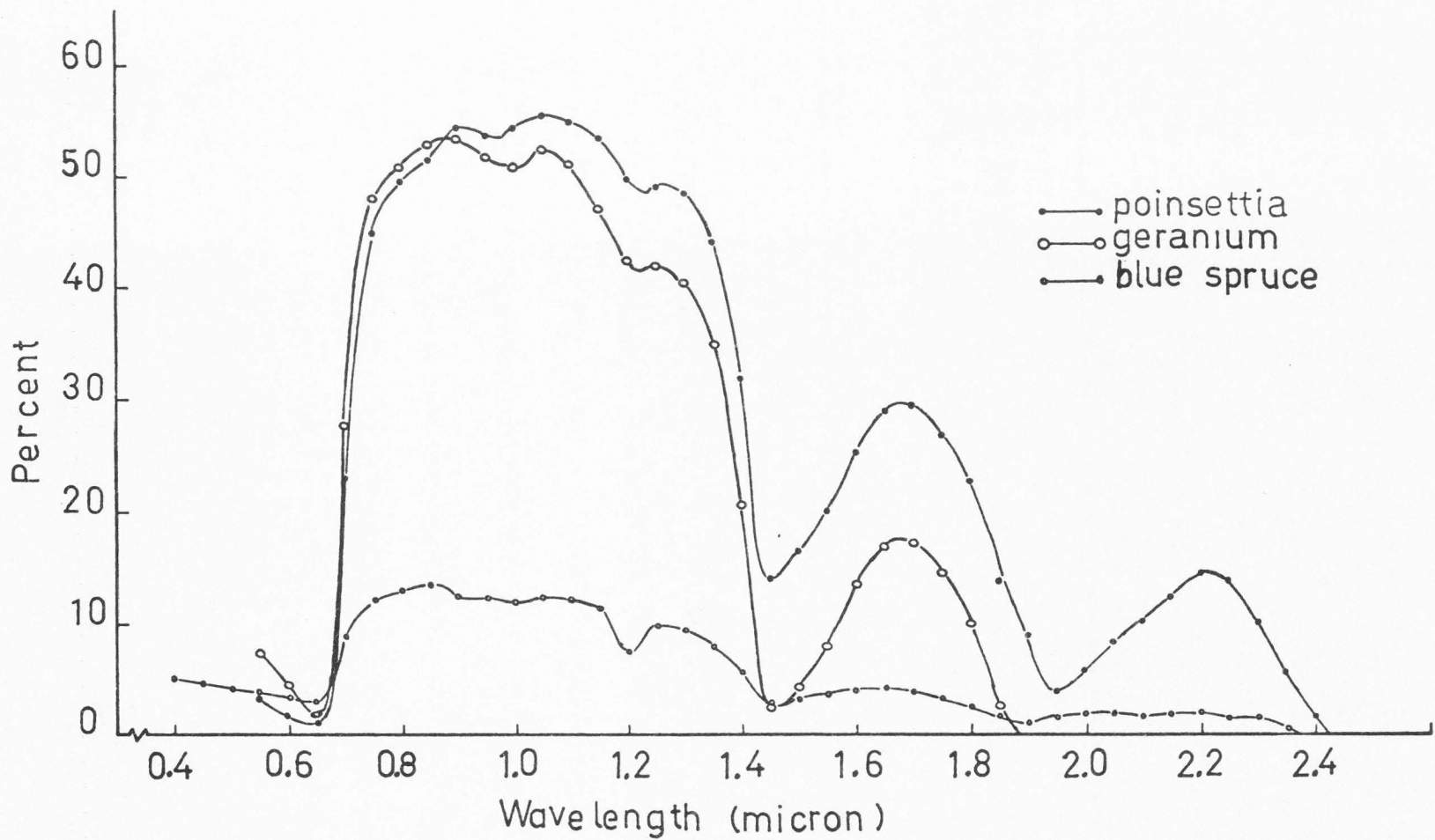
Figure 18.   Relative spectral transmission of global radiation using single leaf from poinsettia, geranium, and foliage from blue spruce.

slowly decreasing to about three percent at 0.68 micron, and rising to
more than 10 percent between 0.72 and 1.17 microns. The absorption
bands at the 1.2, 1.45, and 1.90 microns are still noticeable but the
transmission is less than 5 percent beginning at 1.45 microns.

All of the above measurements were made with the sun as the source
of illumination. Previous measurements cited in the literature were
made in the laboratory using mostly incandescent lamps as the light
source. As pointed out by Hoffer and Johannsen (1969), laboratory
studies are a very necessary step in understanding the radiation inter-
actions in plant canopies. However, it must be realized that the
capability for differentiating plants on this basis does not guarantee
similar results in the field. Recent model and field studies by Myers
et al. (1966) have shown that spectrometer studies of single leaves can
be very misleading for predicting reflectances and transmittances from
plant canopies. This is due to the near infrared radiation being trans-
mitted through the top of the canopy, changes in the spectral composition
within the canopy, multiple reflections within the canopy, and reinforce-
ment of reflectance from the top of the canopy. Therefore, any further
measurements in the laboratory using single leaves will not solve the
problem of finding the actual transmission or reflections under natural
conditions in the forest.

Spectral properties of selected
canopies

The relative spectral distribution of global radiation under
selected deciduous and coniferous stands are shown in Figures 19 and 20.
The curves indicate that the 0.4 to 2.4 micron wave range can be roughly
divided into three areas similar to what Hoffer and Johannsen (1969)
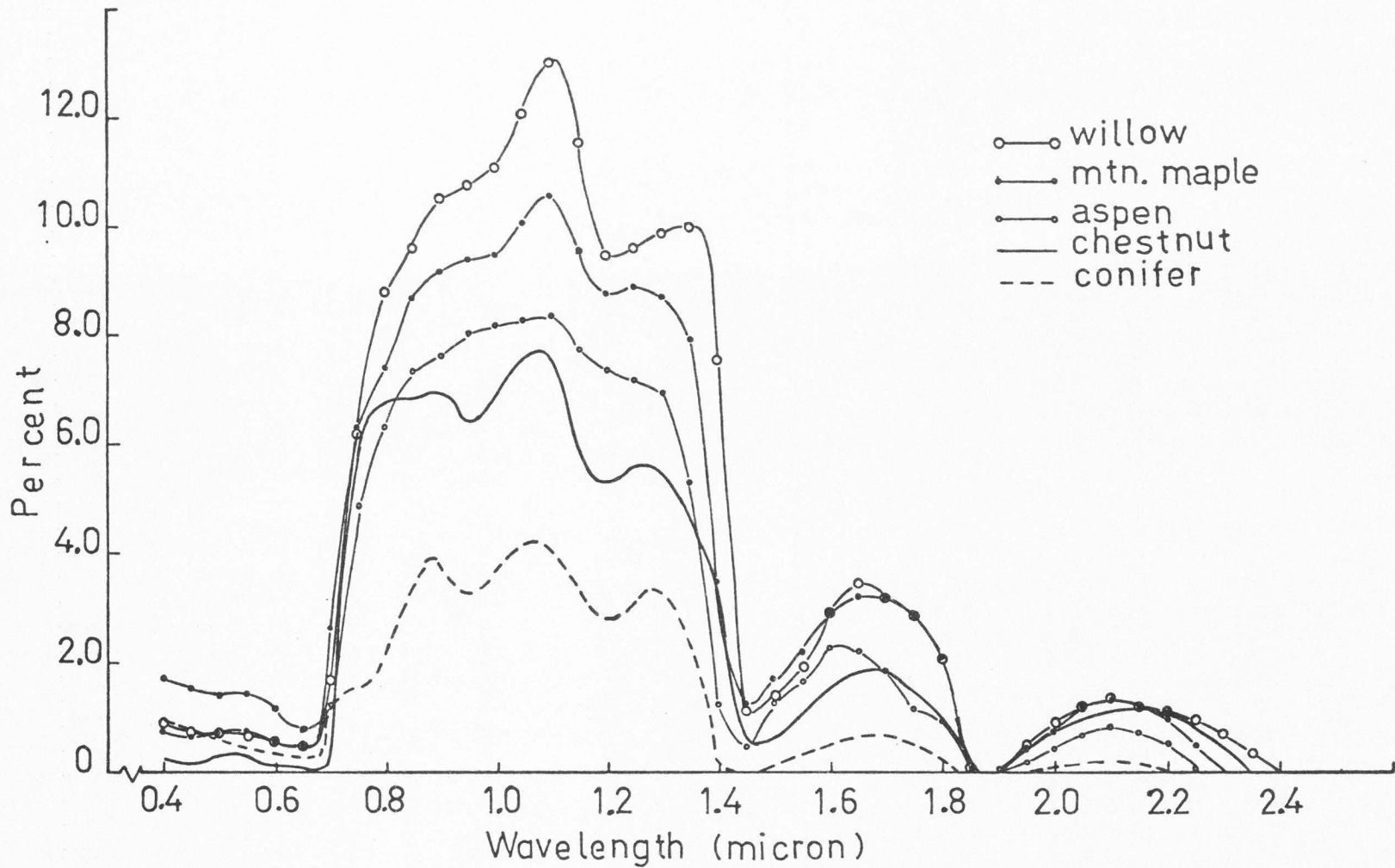
Figure 19. Relative spectral transmission of global radiation of selected deciduous canopies with a single curve for a conifer stand for comparison.
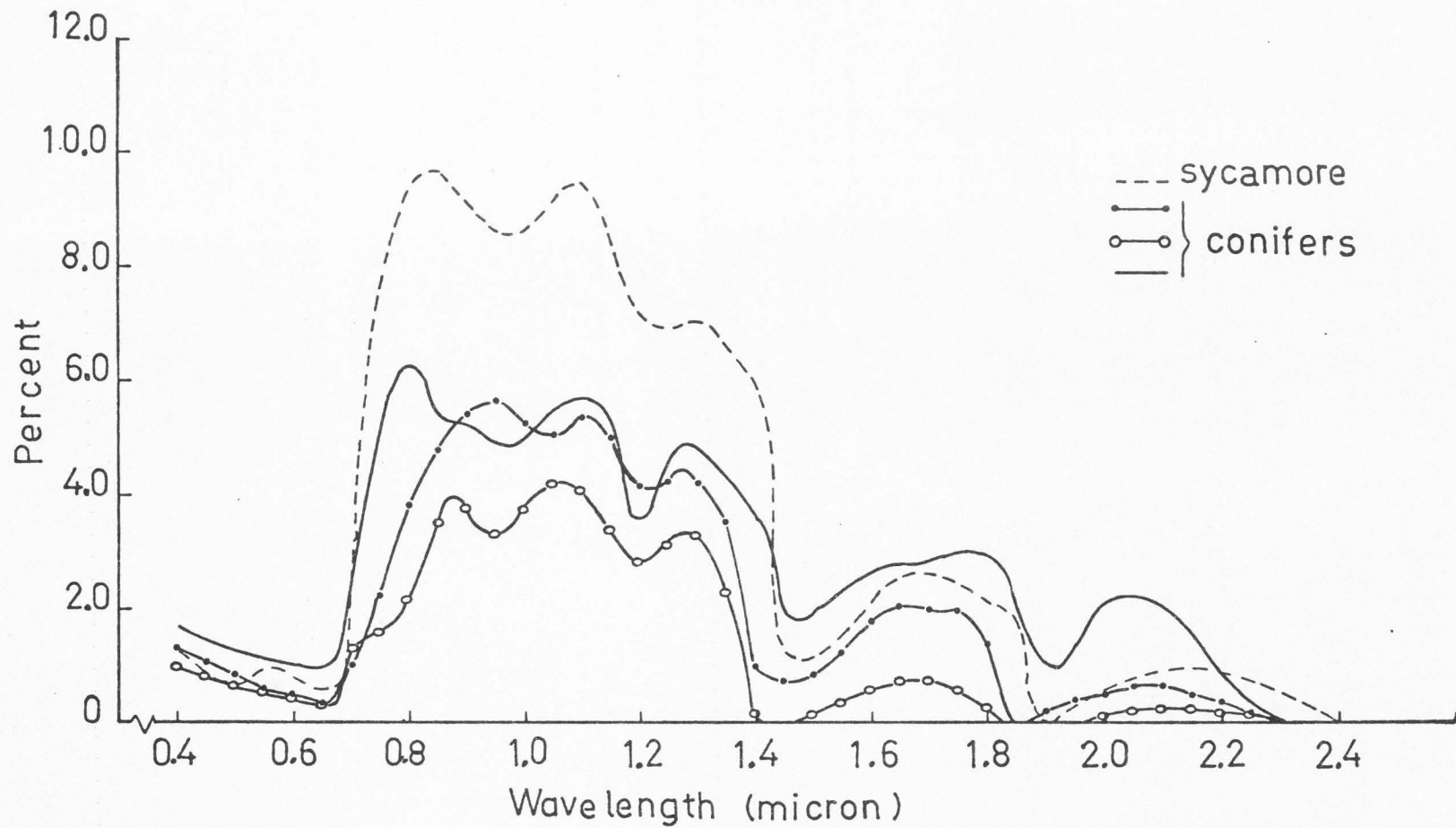
Figure 20. Relative spectral transmittance of global radiation of selected conifer canopies with a single curve for deciduous stand for comparison.

did for single leaves. First is the visible region in the 0.4 to 0.72 micron wave range where the plant pigments, especially the chlorophylls, dominate the spectral responses of the canopies. Second is the region from approximately 0.72 to 1.35 micron interval where there is greater transmission by the leaves. The third is the 1.35 to 3.0 micron wave range which is the region of water absorption. Figures 19 and 20 also indicate that forest canopies have three primary absorption bands, (1) the visible region at 0.4 to 0.72 micron caused by the chlorophyll, (2) the 1.45 and (3) 1.90 microns where water absorption accounts for the strong decrease in the transmittance.

Visible region (0.4 to 0.72 micron):

deciduous

In Figure 19, the willow and mountain maple canopies had about the same relative spectral transmittance in the visible region with less than one percent. The chestnut canopy had the lowest transmittance with barely two-tenths of one percent. The aspen had the highest spectral transmittance in the visible region among the four broad-leaf canopies with a little more than one percent. There was a small peak in the green (0.55 micron) and a minimum at about 0.67 micron for all species. The transmittance curve for the conifer was for reference only and will be discussed later.

The higher relative spectral transmission value in the visible spectrum under the aspen was due to the lesser leaf density plus the branches being more or less vertical rather than horizontal like other deciduous canopies, thereby creating more holes through the canopy. Under this condition, on a cloudless day, the shorter wavelengths tend to predominate in the diffuse sky radiation reaching the forest floor

through the holes in the canopy. This was evidenced by the transmission value for the aspen in the blue region of the spectrum which was even higher than in the green.

The chestnut had the lowest relative transmission in the visible because it had a more dense canopy. In the 0.67 micron there was no transmission at all. The transmission was also lower in the blue because there was hardly any contribution from the direct diffuse sky radiation component. The reflections and transmission from the leaves largely contribute to the radiation reaching the forest floor. However, in spite of the very low transmission values throughout the visible range, the green peak was still noticeable.

For the willow and mountain maple canopies the relative spectral transmissions did not exhibit the distinct minimum in the 0.48 and 0.67 micron wavelengths which were very prominent in single leaf transmission measurements. Here the contribution from the diffuse sky radiation coming through the holes in the canopy was not as much as in the aspen canopy. The crown density was, however, much less than the chestnut and this made the transmission higher by a factor of two.

Measurements by Shakov, Khasanov, and Stanko (1965) under the European bird cherry, horse chestnut, and birch canopies in the visible region were of similar distribution and magnitude. Measuring under a corn canopy, Yocum et al (1964) also noted the small peak in the green. Under oak and sugar maple stands, Federer (1964) and Federer and Tanner (1966) measured transmission values of about one percent in the green with somewhat higher transmission values in the 0.48 and 0.67 micron wavelength.

Visible region (0.4 to 0.72 micron):

conifers

The relative spectral transmission under conifers in Figure 20
were qualitatively the same. Two canopies of blue spruce at different
locations and a combination of white spruce, black pine, and mugo pine
are represented in Figure 20. The curve for the sycamore was for
reference only and was discussed earlier.

The canopies of the blue spruce on one location and the combination
of white spruce, black pine, and mugo pine had about the same magnitude
of relative spectral transmission in the visible region with values of
a little more than one percent beginning at 0.4 micron and decreasing
steadily to about three-tenths of one percent in the 0.67 micron. The
other blue spruce (solid line) had about twice as much transmission in
the same wave range.

Since the needle-leaf canopies used in this study had more gaps
through which the direct diffuse sky radiation can penetrate through
the forest floor as compared to deciduous canopies except aspen, the
higher transmission values in the blue was expected. The transmission
in the visible region under the pine canopies appears to be quite
similar to the "blue shade" light described by Seybold (1936) cited by
Coombe (1957) and Vezina and Boulter (1966). Previous measurements by
Federer (1964) and Federer and Tanner (1966) under spruce, white, red,
and jack pines had marked qualitative similarities with relative trans-
mission values of about one percent beginning at 0.4 micron but with a
relative minimum around 0.50 and 0.67 micron as well. According to
Akulova et al. (1964), with a gap area in the canopy of 20 to 30 per-
cent, the transmission of the blue light begins to predominate regardless
of species.

<u>0.72 to 1.35 microns: deciduous</u>

<u>and conifers</u>

In the wave range 0.72 to 1.4 microns the transmission was several orders of magnitude higher than in the visible region. Under deciduous canopies the relative transmission range from about 6 to 14 percent compared to about four to 10 percent under the coniferous canopies. All the spectral transmission had approximately the same general shape. However, there were some differences in the amplitude of transmission in certain wavebands. The water absorption in the 0.96 micron and 1.2 microns is generally low and therefore the influence on leaf transmission was minor. Under the deciduous canopy, the willow had the highest transmittance followed by mountain maple, aspen and aspen. All the canopies in both categories exhibited a steep increase in transmittance after the 0.68 micron wavelength. Because the incident radiation penetrating the canopies, whether as reflected, transmitted and scattered, was not very stable as the sun moved through the canopies, a definite conclusion cannot be made on the exact shape of the spectra obtained. However, it appears that under a uniform canopy, the general shape of the spectral transmission would be similar to that obtained in Figure 18 using single leaves. In this wave range (0.72 to 1.35 microns) the contribution from direct diffuse sky radiation coming through the gaps in the crown is very small.

<u>1.35 to 2.4 microns: deciduous and</u>

<u>conifers</u>

The primary absorption bands centered at 1.45 and 1.90 microns were very prominent under both deciduous and coniferous canopies in

Figures 19 and 20. In this wave range, the spectra obtained indicated

that the transmittance measurements made were strongly influenced by

moisture content of the leaves, particularly, but not exclusively in the

1.35 to 2.4 microns regions. Since in this region there is no component

coming from the diffuse sky radiation, the amount reaching the forest

floor depends on what has mainly been reflected, transmitted or diffused

by the crown. For coniferous canopies, the tendency of the needles is

to diffuse or scatter the radiation and, therefore, weakens the intensity

reaching the forest floor. It is also possible that in Figure 20 the

reflected direct component of the incident radiation or even the visually

undetected sunflecks may have contributed considerably to the magnitude

of the spectra obtained.

Average spectral properties of

deciduous and coniferous canopies

The average relative spectral transmission for deciduous and

coniferous canopies are shown in Figure 21.

The average spectrum for deciduous canopies was computed from 19

observations regardless of species. As mentioned earlier, the relative

spectral distribution under a particular canopy was the average of at

least two runs, going from 0.35 to 0.8 micron and back. Then the sensor

was changed for the infrared portion and another run was made from

about 0.6 to 2.6 microns and back. This gave a good overlap for the

two spectra and served as a check whether a big change in the intensity

occurred within the period, which was about five minutes. Therefore,

the nineteen observations under the deciduous canopies were at least

twice this number.
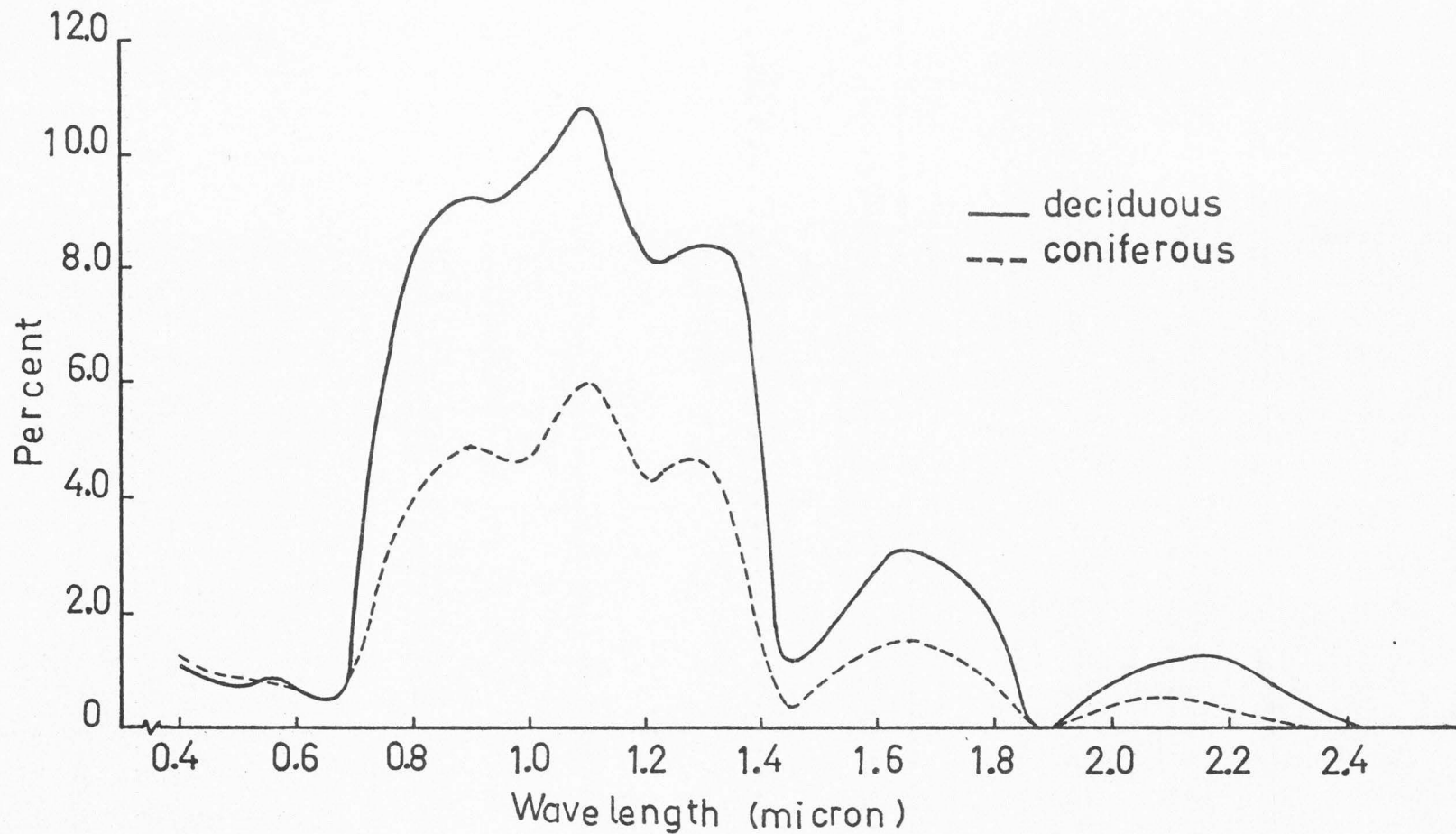
Figure 21. Relative spectral transmission of global radiation under deciduous and coniferous stands averaged from all observations regardless of species.

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The number of observations for the conifers is 13. Since there
were fewer conifer canopies used in the study, the runs under each
site were usually more. Another reason is the fact that it is less easy
to find a uniform shade under this type of canopy. Measurements were
made as late as April 1973. In September 1972 most of the measurements
were made under deciduous canopies.

In the visible region (0.4 to 0.72 micron) there was no significant
difference in the relative transmittance values between conifers and
deciduous stands used in this study. There was an absence of the strong
peak in the green which was rather prominent in measurements using single
leaves. On the other hand, the average relative spectral transmittance
under the coniferous stand did not exhibit the green peak. Both spectra,
however, had a slightly higher average relative transmission value in
the blue (0.4 micron). There was a strong indication that this was due
to gaps in the canopies where the component from the direct sky radiation
was considerable.

There was significant difference in the average relative spectral
transmittance in the region of 0.75 micron to 1.30 microns. The
spectral transmission under the deciduous stand was about twice that
under the conifer stand throughout the near infrared with very low
transmission in the water absorption band at 1.45 microns and practically
no transmission at all in the 1.90 microns.

Average spectral properties of

deciduous and coniferous stands

in absolute units

Spectral measurements presented as percentages of that in the open
may disguise important features of the variation of the absolute amounts
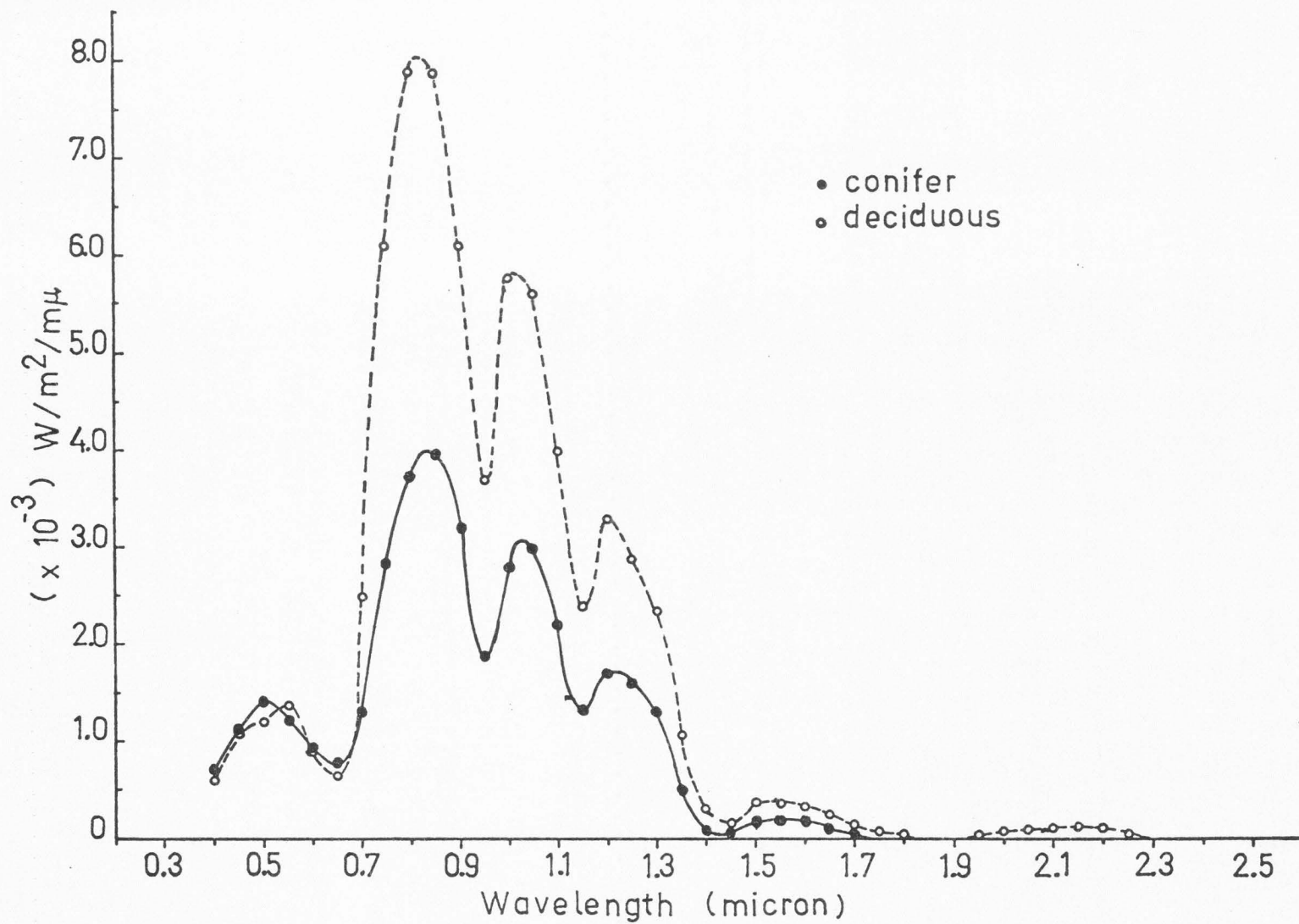
Figure 22. Absolute spectral transmittance of deciduous and conifer stands as computed from Figures 1 and 21.

of the radiative flux. Therefore, the absolute quantities were calculated based on the solar spectrum at sea level in Figure 1. The spectral transmission of the deciduous and coniferous canopies was presented in Figure 22.

The entire shape of the spectral transmission under both canopies exhibited a somewhat different distribution, especially in the visible region. The slightly higher relative transmission in the blue compared to the green in Figure 21 was now lower in the absolute value in Figure 22. Since the highest intensity of the solar spectrum in the open is in the 0.5 micron band, this was now reflected in the absolute values. The small peak in the green was reflected as a slight shift of the peak to the 0.55 micron band.

In the infrared region the water absorption bands were rather distinct at 0.95 and 1.15 microns and there was hardly any transmission beyond 1.7 microns. The transmission values of the deciduous stand still appeared to be approximately twice that in the conifer stand.

SUMMARY AND CONCLUSIONS

The spectral distribution of the global radiation from 0.4 to 2.5 microns were measured during clear days between 10 a.m. and 2 p.m. under deciduous and coniferous canopies.

In the visible region (0.4 to 0.7 micron) the average relative spectral transmissions under both canopies are about one percent, beginning at 0.4 micron and decreasing to about half a percent at 0.67 micron. There is a small peak in the green (0.55 micron) transmission under the deciduous stands but there is none under coniferous canopies. The slightly higher transmission in the blue (0.4 micron) is attributed to the direct sky radiation penetrating through the gaps or holes in the canopies. There is a steep increase in the transmission at about 0.7 micron. The increase is relatively higher under deciduous compared to coniferous stands.

In the infrared region from 0.8 to about 1.4 microns the average relative spectral transmission under deciduous stands is about ten percent which is double the transmission under the coniferous canopies. The transmission under deciduous stands is about twice that of the coniferous stands throughout the nea infrared with very low transmission in the water absorption band at 1.45 and practically no transmission at all in the 1.90 micron band.

The absolute spectral transmission exhibits a somewhat different distribution, especially in the visible region. Since the highest intensity of the solar spectrum in the open is located in the 0.5 micron band, this is now reflected in the absolute values. The small peak in

the green under deciduous stand is now indicated as a slight shift of the peak to the 0.55 micron band. The water absorption bands are also distinct at the 0.95 and 1.15 microns with hardly no transmission at all beyond 1.7 microns.

The spectral transmittance of forest canopies differs from those reported for single leaves in the proportion of radiation transmitted in the visible and infrared regions. For example, the ratio of the transmission at 0.55 micron to that at 1.10 micron band is about one to twelve compared to about one to five in single leaves. Although the spectral reflectance and transmittance of single leaves of deciduous canopies are of similar distribution and magnitude, the spectra under actual canopies are not so.

In theory, a conclusion can be made that an ideal canopy without gaps consisting of several layers of leaves will only allow a very small amount of transmission mostly in the green portion and somewhat more in the infrared between 0.72 and 1.40 microns. Under natural conditions in the forest there exists a very weak "green" shadow and a somewhat stronger "infrared" shadow. Under a coniferous stand without gaps in the canopy, there can hardly be any transmission in the visible region although there may still be a much weaker infrared shadow. The altered spectral composition may influence the understory vegetation as regards to photosynthesis, seed germination, and the photoperiodic responses. Where the canopy is very dense there can be no understory vegetation.

RECOMMENDATIONS

Due to the complexity of the radiative field under the canopy, studies of the spectral composition of the solar radiation in different forests should continue and other species should be included. Data gained by measuring transmissivity and reflectivity of single leaves cannot readily be applied to the integral effect under canopies. Field measurements are necessary.

Measurements should be extended to study under both clear sky and cloudy sky conditions.

For physiological as well as heat budget considerations, the absolute values of the spectrum have to be considered; data preparation, however, is facilitated by using graphs of spectra, relative to the solar spectrum.

Since many parameters influence the transmission and reflection of plant leaves, auxiliary data with each measurement are of advantage. They are: leaf area index, leaf maturation, leaf structure, and water content, as well as soil salinity. A log book of solar zenith angle, condition of the sky, and cloudiness (if applicable) is indicative. Measurements at disturbed sun, except for entirely overcast sky, should be avoided not to overcomplicate the measurements until a solid know-ledge of the conditions at clear and overcast skies is available.

Anderson, M. C. 1970. Interpreting the fraction of solar radiation available in forest. Agricultural Meteorology 7(1):19-28.

Anderson, M. C., and O. T. Denmead. 1969. Short wave radiation on inclined surfaces in model plant communities. Agronomy Journal 61:867-872.

Andreeva, T. F., and G. F. Korozheva. 1964. Influence of the spectral composition of light and its intensity on the formation of amino acids in leaves. Soviet Plant Physiology 11(6):810-817.

Angstrom, Anders. 1969. Apparent solar constant variations and their relation to the variability of atmospheric transmission. Tellus (1970) 2:205-218.

Aston, A. R., R. J. Millington, and D. B. Peters. 1969. Radiation exchange in controlling leaf temperature. Agronomy Journal 61(5):797-800.

Atkins, W. R. D., H. H. Poole, and F. A. Stanbury. 1937. The measurement of the intensity and the color of the light in woods by means of emission and rectifier photoelectric cells. Royal Society of London Proceedings, Series B. 121:427-450.

Atzet, T., and R. H. Waring. 1970. Selective filtering of light by coniferous forests and minimum light energy requirements for regeneration. Canadian Journal of Botany 48:2163-67.

Baldy, C. M. 1973. Contribution to the study of the distribution of solar radiation under a pine canopy. Agricultural Meteorology 11(1):123-133.

Billings, W. D., and R. J. Morris. 1951. Reflection of visible and infrared radiation from leaves of different ecological groups. American Journal of Botany 38:327-331.

Birkebak, R., and R. Birkebak. 1964. Solar radiation characteristics of tree leaves. Ecology 45(3):646-649.

Bonner, James. 1962. The upper limit of crop yield. Science 137(3523): 11-15.

Bowers, S. A., and R. J. Hanks. 1965. Reflection of radiant energy from soils. Soil Science 100:130-138.

Brooks, F. A. 1955. Notes on spectral quality and measurement of solar radiation. pp. 19-29. In Daniels, F., and J. A. Duffie (Eds.). Solar Energy Research. The University of Wisconsin Press.

Bulletin SPV-4B. 1967. Selenium photovoltaic cells. VACTEC, Inc. St. Louis, Mo.

LITERATURE CITED

Aboukhaled, A. 1966. Optical properties of leaves in relation to their energy balance, photosynthesis and water use efficiency. PhD Thesis. University of California, University Microfilms, Davis, California. 127 pp.

Ajello, J., J. King, Jr., A. L. Lane, and C. W. Odd. 1973. Ground level ultraviolet solar flux in Pasadena, California. Bulletin of the American Meteorological Society 54(2):114-115.

Akulova, E. A., V. S. Khasanova, Yu. L. Tsel'niker, and D. N. Shishov. 1964. Light transmission through a forest canopy depending on the incident radiation and density of the tree crowns. Soviet Plant Physiology 11(5):694-698.

Allen, W. A., H. W. Gausman, A. J. Richardson, and J. R. Thomas. 1969. Interaction of isotropic light with a compact leaf. Journal of the Optical Society of America 59(10):1376-79.

Allen, W. A., and A. J. Richardson. 1968. Interaction of light with a plant canopy. Journal of the Optical Society of America 58(8):1023-28.

Allen, L. H., C. S. Yocum, and E. R. Lemon. 1964. Photosynthesis under field conditions. VII. Radiant energy exchanges within a corn canopy and implications in water use efficiency. Agronomy Journal 56:253-259.

Anderson, M. C. 1964. Studies of the woodland climate. I. The photographic computation of light conditions. Journal of Ecology 52:27-41.

Anderson, M. C. 1964. Studies of the woodland climate. II. Seasonal variation in the light climate. Journal of Ecology 52:643-663.

Anderson, M. C. 1964. Light relations of terrestrial plant communities and their measurements. Biological Review (Cambridge Philosophical Society) 39:425-486.

Anderson, M. C. 1966. Stand structure and light penetration. 2. A theoretical analysis. Journal of Applied Ecology 3:41-54.

Anderson, M. C. 1966. Some problems of simple characterization of the light climate in plant communities. p. 77-90. In Bainbridge, R., C. C. Evans, and O. Rackham (Eds.). Blackwell Sci. Pub., Oxford.

Anderson, M. C. 1969. A comparison of two theories of scattering of radiation in crops. Agricultural Meteorology 6:399-405.

Carlson, R. E., and D. N. Yarger. 1971. An evaluation of two methods for obtaining leaf transmissivity from leaf reflectivity measurements. Agronomy Journal 63(1):78-81.

Carlson, R. E., D. N. Yarger, and R. H. Shaw. 1971. Factors affecting the spectral properties of leaves with special emphasis on leaf water status. Agronomy Journal 63(3):486-489.

Coombe, D. E. 1957. The spectral composition of shade light in woodlands. Journal of Ecology 45-823-830.

Cowan, I. R. 1968. The interception and absorption of radiation in plant stands. Journal of Applied Ecology 5:367-379.

Czarnowski, M., and J. Slomka. 1959. Some remarks on the percolation of light through the forest canopy. Ecology 40(2):312-315.

Daynard, T. B. 1969. The quality of short-wave radiation within plant canopies. Canadian Journal of Botany 47(12):1989-94.

DeWit, C. T. 1959. Potential photosynthesis of crop surfaces. Netherland Journal of Agricultural Science 7:141-149.

Dirmhirn, Inge. 1957. Zur spectralen verteilung der reflexion naturlicher medien. Wetter u. Leben 9:41-46.

Dirmhirn, Inge. 1958. Die Weitwinkel-Himmelsaufnahme als Hilfsmittel fur die Strahlungsforschung. Arch. Met., Wein, 8:336-351.

Dirmhirn, Inge. 1964. Das Strahlungsfeld im Lebensraum. Akademische Verlagsgesellschaft Frankfurt am Main. 426 pp.

Dirmhirn, I., and F. Sauberer. 1958. Ein kleiner Interferenzfilter-monochramator fur Spectralmessungen mit Fernablesung. Wetter u. Leven 10:159-163.

Doraiswamy, Paul C. 1971. Energy balance and spectral properties of a reflectorized soybean canopy. MS Thesis, University of Nebraska, Lincoln, Nebraska.

Dutch Committee on Plant Irradiation. 1953. Specification of radiant flux and radiant flux density in irradiation of plants with artificial light. Journal of Horticultural Science 28:177-184.

Egle, K. 1937. Zur Kenntnis des Lichtfeldes der Pflanze und der Blattfarbstoffe. Planta 26:546-583.

Elterman, L. 1964. Atmospheric attenuation in the ultraviolet, visible, and infrared regions for altitudes to 50 km. Environmental Research Papers No. 46. Air Force Cambridge Research Laboratories.

Evans, G. C. 1956. An area survey method of investigating the distribution of light intensity in woodlands, with particular reference to sunflecks. Journal of Ecology 44:391-428.

Evans, G. C., and D. E. Coombe. 1959. Hemispherical and woodland canopy photography and the light climate. Journal of Ecology 47:103-113.

Evans, G. C., T. C. Whitmore, and Y. K. Wong. 1960. The distribution of light reaching the ground vegetation in a tropical forest. Journal of Ecology 48:193-204.

Federer, C. A. 1964. Measuring the light regime under vegetation. PhD Thesis, University of Wisconsin, Madison, Wisconsin. 124 pp.

Federer, C. A. 1971. Solar radiation absorption by leafless hardwood forests. Agricultural Meteorology 9:3-20.

Federer, C. A., and C. B. Tanner. 1966. Sensors for measuring light available for photosynthesis. Ecology 47(4):654-657.

Federer, C. A., and C. B. Tanner. 1966. Spectral distribution of light in the forest. Ecology 47:555-560.

Freyman, S. 1968. Spectral distribution of the Douglas fir zone of southern British Colombia. Canadian Journal of Plant Science 48:326-328.

Gaastra, P. 1965. Radiation measurements for investigations of photo-synthesis under natural conditions. In F. E. Eckardt (Ed.). Proc. Copenhagen Symposium 1965: Functioning of Terrestrial Ecosystems at the Primary Level. pp. 467-478. Natural Resources Research V, UNESCO, Paris, 1968.

Garner, W. W., and H. A. Allard. 1920. Effect of the relative length of day and night and other factors of the environment on growth and reproduction in plants. Journal of Agricultural Research 18:553-606.

Gates, D. M. 1964. Characteristics of soil and vegetated surfaces to reflected and emitted radiation. Proc. 3rd Int. Symp. Remote Sensing of the Environment, pp. 573-600.

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

Gates, D. M. 1965. Radiant energy, its receipt and disposal. Meteorological Monographs 6(28):1-26.

Gates, D. M. 1966. Spectral distribution of solar radiation at the earth's surface. Science 151(3710):523-529.

Gates, D. M., H. J. Keegan, J. C. Schleter, and V. R. Weidner. 1965. Spectral properties of plants. Applied Optics 4(1):11-20.

Gates, D. M., and W. Tantraporn. 1952. The reflectivity of deciduous trees and herbaceous plants in the infrared to 25 microns. Science 115(2997):613-616.

Gatherum, G. E. 1961. Variation in measurement of light intensities under forest canopies. Forest Science 7:144-145.

Gausman, H. W., W. A. Allen, R. Cardenas, and A. J. Richardson. 1971. Effects of leaf nodal position on absorption and scattering coefficients and infinite reflectance of cotton leaves, Gossypium birsutum L. Agronomy Journal 63(1):87-91.

Gausman, H. W., W. A. Allen, V. I. Myers, and R. Cardenas. 1969. Reflectance and internal structure of cotton leaves, Gossypium birsutum. Agronomy Journal 61(3):374-376.

Gausman, H. W., W. A. Allen, C. L. Wiegand, D. E. Escobar, and R. R. Rodriguez. 1971. Leaf light reflectance, transmittance, absorptance, and optical and geometrical parameters for eleven plant genera with different leaf mesophyll arrangements. Proc. 7th Int. Symp. Remote Sensing of the Environment III:1599-1625.

Gay, L. W., K. R. Knoerr, and M. O. Braaten. 1971. Solar radiation variability on the floor of a pine plantation. Agricultural Meteorology 8:38-50.

Gupta, R. K., and J. T. Wooley. 1971. Spectral properties of soybean leaves. Agronomy Journal 63(1):123-126.

Handbook of Geophysics. 1960. U.S. Air Force, Macmillan, New York. Revised Edition.

Hoffer, R. M., and C. J. Johannsen. 1969. Ecological potentials in spectral signature analysis. pp. 1-16. In P. L. Johnson (Ed.). Remote Sensing in Ecology. University of Georgia Press, Athens.

Howard, J. A. 1966. Spectral energy relations of isobilateral leaves. Australian Journal of Biological Science 19:757-766.

Howard, J. A., R. D. Watson, and T. D. Hessin. 1971. Spectral reflectance properties of pinus ponderosa in relation to copper content of the soil-malchite mine, Jefferson County, Colorado. Proc. 7th International Symposium Remote Sensing of the Environment. I:285-297.

Idso, S. B., D. G. Baker, and B. L. Blad. 1969. Relations of radiation fluxes over natural surfaces. Royal Meteorological Society Quarterly Journal 95(404):244-257.

Idso, S. B., and C. T. de Wit. 1970. Light relations in plant canopies. Applied Optics 9:177-184.

In, Chen. 1964. Effect of the spectral composition of light on the absorption of mineral nutrients by plant roots. Soviet Plant Physiology 11(5):699-701.

Johnson, T. B., F. B. Salisbury, and G. I. Connor. 1967. Ratio of blue to red light: a brief increase following sunset. Science 155:1663-65.

Jordan, C. F. 1969. Derivation of leaf-area index from quality of light on the forest floor. Ecology 50:663-666.

Kasanaga, H., and M. Monsi. 1954. On the light transmission of leaves and its meaning for the production of matter in plant communities. Japanese Journal of Botany 14:22-52.

Keegan, H. J., J. C. Schleter, and W. A. Hall. 1956. Spectro-photometric and colorimetric record of some leaves of trees, vegetation, and soil. National Bureau of Standards, Report No. 4528. U. S. Department of Commerce.

Klugh, A. B. 1925. Ecological photometry and a new instrument for measuring light. Ecology 6:203-237.

Knipling, E. B. 1967. Physical and physiological basis for differences in reflectance of healthy and diseased plants. Proc. Workshop on Infrared Color Photography in the Plant Sciences, Florida Dept. of Agriculture, Winter Haven, Florida.

Knipling, E. B. 1969. Leaf reflectance and image formation on color infrared film. In P. L. Johnson (Ed.). Remote Sensing in Ecology, p. 17-29. University of Georgia Press, Athens.

Knuckel, H. 1914. Spectrophotometrische Untersuchungen im Walde. Mitt. schweiz Zent Anst. forstl. Versuchsw., 11:1-94.

Kruse, P. W., L. O. McGlauchlin, and R. B. McQuistan. 1963. Elements of infrared technology: generation, transmission, and detection. John Wiley and Sons, Inc. New York. 448 pp.

Kriedman, P. W., T. F. Neales, and D. H. Ashton. 1964. Photosynthesis in relation to leaf orientation and light interception. Australian Journal of Biological Science 17:591-600.

Logan, K. T., and E. B. Peterson. 1964. A method of measuring and describing light patterns beneath the forest canopy. Department of Forestry Publication No. 1073. 26 pp.

Loomis, W. E. 1965. Absorption of radiant energy by leaves. Ecology 46:14-17.

Mansfield, T. A., and Hans Meidner. 1966. Stomatal opening in light of different wavelengths: effects of blue light independent of carbon dioxide concentration. Journal of Experimental Botany 17(52):510-521.

McPherson, H. G. 1969. Photocell-filter combinations for measuring photosynthetically active radiation. Agricultural Meteorology 6:347-356.

Middleton, E. E. Knowles, and C. L. Sanders. 1951. The absolute spectral reflectance of magnesium oxide. Journal of the Optical Society of America 41:419-424.

Miller, E., Jr. 1938. Light in some plant associations. Ecology 19:390-395.

Miller, P. C. 1969. Solar radiation profiles in openings in canopies of aspen and oak. Science 164:308-309.

Monteith, J. L. 1965. Light distribution and photosynthesis in field crops. Annals of Botany 29(113):17-37.

Moss, R. A., and W. E. Loomis. 1952. Absorption spectra of leaves. I. The visible spectrum. Plant Physiology 27:370-391.

Myers, V. I., C. L. Wiegand, M. D. Heilman, and J. R. Thomas. 1966. Remote sensing in soil and water conservation research. pp. 801-813. Proc. 4th Symposium Remote Sensing of the Environment.

Newton, J. E., and G. E. Blackman. 1970. The penetration of solar radiation through leaf canopies of different structure. Annals of Botany 34(135):329-348.

Norman, J. M., and C. B. Tanner. 1969. Transient light measurements in plant canopies. Agronomy Journal 61(6):847-849.

Norman, J. M., C. B. Tanner, and G. W. Thurtell. 1969. Photosynthetic light sensor for measurements in plant canopies. Agronomy Journal 61(6):840-843.

Ovington, J. D., and H. A. I. Madgwick. 1955. A comparison of light in different woodlands. Forestry 28:141-146.

Pearman, G. I. 1966. The reflection of visible radiation from leaves of some western Australian species. Australian Journal of Biological Science 19(1):97-103.

Popp, H. W. 1926. A physiological study of the effect of light of various ranges of wavelength on the growth of plants. American Journal of Botany 13:706-736.

Rabideau, G. S., C. S. French, and A. S. Holt. 1946. The absorption and reflection spectral of leaves, chloroplast suspensions, and chloroplast fragments as measured in an ulbricht sphere. American Journal of Botany 33:769-777.

Rabinowitch, E. I. 1951. Photosynthesis and related process. Vol. II Part I. Interscience Publishers, Inc., New York. 1208 pp.

Reifsnyder, W. E., G. M. Furnival, and J. L. Horowitz. 1970. Spatial and temporal distribution of solar radiation. Agricultural Meteorology 9:21-37.

Robinson, N. 1966. Solar Radiation. Elsevier Publishing Co., New York. 347 pp.

Robertson, G. W. 1966. The light composition of solar and sky spectra available to plants. Ecology 47(4):640-643.

Robertson, G. W., and R. M. Holmes. 1963. A spectral light meter: its construction, calibration and use. Ecology 44:419-423.

Rodsjer, Niels and Alois Kornher. 1971. On the determination of the radiant energy between the wavelengths 0.3-0.7 micron in plant stands. Agricultural Meteorology 8(1):139-150.

Sachs, J. 1861. Sitzber. Akad. Wiss. Wien. Math. naturw. Klasse, 43:265.

Saeki, T. 1963. Light relations in plant communities. In L. T. Evans (Ed.). Environmental Control on Plant Growth, p. 79-94. Academic Press, New York.

Salisbury, F. B. 1971. The biology of flowering. The Natural Press, Garden City, New York. 173 pp.

Sanders, C. L., and E. E. Knowles Middleton. 1953. The absolute spectral reflectance of magnesium oxide in the near infrared. Journal of the Optical Society of America 43(1):58.

Scott, D., P. H. Menalda, and R. W. Brougham. 1968. Spectral analysis of radiation transmitted and reflected by different vegetations. New Zealand Journal of Botany 6:427-449.

Seginer, Ido. 1969. The effect of albedo on the evapotranspiration rate. Agricultural Meteorology 6(1):5-31.

Seybold, A. 1936. Uber den Lichtfaktor photophysiologischer Prozesse. Jb. wiss. Bot. 82:741-795.

Seybold, A. and K. Egle. 1937. Lichtfeld und Blattfarbstoffe. I. Planta 26:491-515.

Shakov, A. A., V. S. Khasanov, and S. A. Stanko. 1965. On the spectral light absorption coefficient of leaves of tree crowns. Soviet Plant Physiology 12(1):16-19.

Shaw, R. H., and C. R. Weber. 1967. Effects of canopy arrangement on light interception and yield of soybeans. Agronomy Journal 59(2): 155-159.

Shirley, H. L. 1929. The influence of light intensity and light quality upon growth and survival of plants. American Journal of Botany 16:354-390.

Shirley, H. L. 1932. Light intensity in relation to plant growth in a virgin Norway pine forest. Journal of Agricultural Research 44:227-244.

Shirley, H. L. 1945. Light as an ecological factor and its measurement. II. Botanical Review 11:497-532.

Shul'gin, I. A. 1965. Influence of spectral composition and light intensity on the development of plants during various photoperiods. Soviet Plant Physiology 12(2):245-254.

Shull, Charles A. 1929. A spectrophotometric study of reflection of light from leaf surfaces. Botanical Gazette 87:583-607.

Skamoto, C. M., and R. H. Shaw. 1967. Light distribution in field soybean canopies. Agronomy Journal 59(1):7-9.

Taylor, A. H., and G. P. Kerr. 1941. The distribution of energy in the visible spectrum of daylight. Journal of the Optical Society of America 31(1):3-8.

Technical Bulletin 2. (No date). Photoconductors: a state of the art report. Infrared Industries, Inc. 11 pp.

Thekaekara, M. P., and A. J. Drummond. 1971. Standard values for the solar constant and its spectral components. Nature (Physical Science) 229:6-9.

Thomas, J. R., V. I. Myers, M. D. Heilman, and C. L. Wiegand. 1966. Factors affecting light reflectance of cotton. pp. 305-312. International Symposium of Remote Sensing of the Environment.

Thomas, J. R., C. L. Wiegand, and V. I. Myers. 1967. Reflectance of cotton leaves and its relation to yield. Agronomy Journal 59(6): 551-554.

Van Wijk, W. R. 1963. Physics of Plant Environment. Chap. 9, p. 307-309. North-Holland Publishing Co., Amsterdam.

Vezina, P. E., and D. W. K. Boulter. 1966. The spectral composition on near ultra violet and visible radiation beneath forest canopies. Canadian Journal of Botany 44:1267-84.

Vezina, P. E., and G. Pech. 1964. Solar radiation beneath conifer canopies in relation to crown closure. Forest Science 10:443-451.

Wassink, E. C., and J. A. Stolwijk. 1956. Effects of light quality on plant growth. Annual Review of Plant Physiology 7:373-400.

Wilson, W. J. 1965. Stand structure and light penetration. Journal of Applied Ecology 2:283-390.

Wilson, J. W. 1967. Stand structure and light penetration. III.
    Sunlit foliage area. Journal of Applied Ecology 31(121):159-165.

Yocum, C. S., L. H. Allen, and E. R. Lemon. 1964. Photosynthesis under
    field conditions VI: Solar radiation balance and photosynthesis
    efficiency. Agronomy Journal 56:249-259.

Yost, E., and S. Wenderoth. 1971. The reflectance spectra of mineralized
    trees. Proc. 7th International Symposium Remote Sensing of the
    Environment I:269-284.

Zederbaur, C. 1908. The light requirement of forest trees and the
    methods of measuring light. Forestry Quarterly 6(3):255-262.

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