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

Soil Science and Biometeorology

(Biometeorology)

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

1974
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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 radiation 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 measurements 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 transmitted 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 reflectance 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 transmittance 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 mesophytic 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 characteristics 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 \text{cal cm}^{-2} \text{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 environment 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).
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 intensity. 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

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

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 \( E_\lambda \) above a plant surface is a function of wavelength and may be expressed as

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

[2]

The total flux then is

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

[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 \( t_\lambda \) (erg transmitted/incident erg), the spectral energy distribution becomes

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

[4]

The equation for the reflected radiation by \( m \) leaves is given by

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

[5]

where \( r_\lambda \) is the reflection coefficient (erg reflected/incident erg).

The energy flux density after reflection and transmission at any wavelength then becomes

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

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

\[ m,n = 0: \quad E = E_\lambda \; ; \quad [6a] \]
\[ m,n = 1: \quad E_{11} = E_\lambda t_\lambda r_\lambda ; \quad [6b] \]
\[ m,n = 2: \quad E_{22} = E_\lambda t_\lambda^2 r_\lambda^2 ; \quad [6c] \]
\[ m,n = 3: \quad E_{33} = E_\lambda t_\lambda^3 r_\lambda^3 . \quad [6d] \]

The total flux after transmission and reflection is given by

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

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

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

and the total flux at any wavelength interval as

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

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

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 \( E_\lambda, t_\lambda, \) and \( r_\lambda \) are available. These problems necessitate actual measurement of spectral quality under plant canopies \( (E_{\text{can}} \text{ and } E_{\text{mult}} \text{).} \) 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 diaphragm permits controlled reduction of the slit height down

\(^1\) Mention of trade names does not constitute endorsement of the product.
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 comparative 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. 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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1By Charles Craw, Research Engineer, Department of Soil Science and Biomeeteorology, 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 semiconductors. 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 suitable 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

<table>
<thead>
<tr>
<th>Deciduous</th>
<th>Coniferous</th>
<th>Single leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Platanus occidentalis</em></td>
<td><em>Pinus contorta</em></td>
<td><em>Pelargonia</em></td>
</tr>
<tr>
<td>(sycamore)</td>
<td>(Lodgepole pine)</td>
<td>(geranium)</td>
</tr>
<tr>
<td><em>Salix fragilis</em></td>
<td><em>Picea glauca</em></td>
<td><em>Scindapsus aureus</em></td>
</tr>
<tr>
<td>(willow)</td>
<td>(white spruce)</td>
<td>(water plant)</td>
</tr>
<tr>
<td><em>Fraxinus</em></td>
<td><em>Pinus nigra</em></td>
<td><em>Poinsettia</em></td>
</tr>
<tr>
<td>(ash)</td>
<td>(black pine)</td>
<td>(poinsettia)</td>
</tr>
<tr>
<td><em>Betula alba</em></td>
<td><em>Pinus mugo</em></td>
<td><em>Acer rubrum</em></td>
</tr>
<tr>
<td>(white birch)</td>
<td>(mugo pine)</td>
<td>(red maple)</td>
</tr>
<tr>
<td><em>Acer saccharinum</em></td>
<td><em>Pseudotsuga taxifolia</em></td>
<td></td>
</tr>
<tr>
<td>(silver maple)</td>
<td>(Douglas fir)</td>
<td></td>
</tr>
<tr>
<td><em>Ulnus</em></td>
<td><em>Picea pungens</em></td>
<td></td>
</tr>
<tr>
<td>(elm)</td>
<td>(blue spruce)</td>
<td></td>
</tr>
<tr>
<td><em>Liriodendron tulipifera</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(tulip tree)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Acer grandidentatum</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Rocky Mountain maple)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Populus tremuloides</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(quaking aspen)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Castanea mollissima</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Chinese chestnut)</td>
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</tr>
</tbody>
</table>
Figure 9. A Fish-Eye hemispherical photograph of mountain maple (*Acer grandidentatum*) with and without leaves.
Figure 10. A Fish-Eye hemispherical photograph of aspen with and without leaves.
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 ($R_\perp$) 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 ($R_L$) on a surface normal to the sun's rays, computed flux on a horizontal surface ($R_\perp$), 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 duration 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 woodstand 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 anthocyanin 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 *L. tulipifera* 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 interactions 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 transmitted through the top of the canopy, changes in the spectral composition within the canopy, multiple reflections within the canopy, and reinforcement 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 transmission 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 percent, the transmission of the blue light begins to predominate regardless of species.
0.72 to 1.35 microns: deciduous and conifers

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.

1.35 to 2.4 microns: deciduous and conifers

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.
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 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 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 knowledge of the conditions at clear and overcast skies is available.


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