Technical Report RSC-06

REMOTE SENSING OF CROP WATER DEFICITS AND ITS POTENTIAL APPLICATIONS

An Annotated Bibliography

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TEXAS A&M UNIVERSITY
REMOTE SENSING CENTER
COLLEGE STATION, TEXAS

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REMOTE SENSING OF CROP WATER DEFICITS AND ITS POTENTIAL APPLICATIONS

1. INTRODUCTION

Water deficits generally reduce plant growth. The reasons for such reduction are not completely known. It is believed that much of this reduction in growth is associated with the reduction of hydrostatic pressure (turgor) and cell wall expansion. In addition, the turgor pressure in the guard cells of the leaf epidermis regulates the stomatal opening and, thereby, the gas exchange between the leaf and the atmosphere. Thus, carbon fixation and dry matter accumulation can be decreased by leaf water deficits. Other factors affecting key metabolic reactions in plants such as hormonal balance, protoplasmic hydration, and thermal balance of plants under moisture stress are also believed to influence plant growth unfavorably.

It is obvious that when crop water balance conditions are allowed to become less than the optimum for plant growth, a corresponding reduction in crop yield will exist. Such reduction in yield may exist locally in a field because of the lack of uniformity in the water distribution or may be widespread as a result of the lack of precipitation in arid areas, unfavorable seasonal distribution of precipitation in humid areas, or the introduction of crops which can take advantage of favorable soil and temperature conditions but require more water than naturally provided.

Irrigation has been man's method of overcoming crop water deficiencies. It has played a strategic role in the continuous process of agricultural development. In most of the early civilizations, as in many nations of today, irrigated agriculture provided, and continues to provide the agrarian basis of society.

When a regular water supply is provided for the first time in any area, it permits the establishment of highly productive agricultural practices and the consequent expansion of human population.

Modern agriculture imposes heavy demands on water. According to the 1954 Census of Agriculture, irrigation accounted for approximately 46 percent of the total water use in the United States. The westward shift and the overall increase in population of the United States continue to contribute to these ever increasing water needs (Table 1).

The need for irrigation water faces an ever-growing competition with other needs for municipal, industrial, and recreational purposes. For example, the total municipal and industrial water requirements in the State of Texas are projected to increase from the 2.6 million acre-feet per year used in 1960 to about 6.5 million acre-feet by 1990, and to reach more than 12 million by 2020 (Texas Water Plan, 1968). These projected increases, as well as those for irrigation and recreational purposes are shown in Table 2. Water for recreational purposes has the greatest relative increases. The increases in population, disposable income, mobility, and leisure time in the recent years have magnified the importance of water for recreation and will result, as shown in Table 2, in a rapidly rising demand for more water oriented facilities.

The limited supply of inexpensive, good quality irrigation water prevents, in a great number of cases, the maximum utilization of existing land resources. The very wide extent of irrigated agriculture and the existence of an even more unirrigated land resource strongly suggest the need for the careful management of irrigation water. The efficient use of irrigation water will permit

TABLE 1

The change in the area of irrigated land in the United States since 1950. (From the 1964 Census of Agriculture,1968)

	Irrigated acres in millions			
Year	17 West. States and Hawaii	31 Eastern States	Total	Increase from preceding census
1940	-	-	18.0	-
1945	-	-	20.5	2.5
1950	24.1	1.7	25.8	5.3
1954	26.9	2.7	29.6	3.8
1959	31.0	2.2	33.2	3.6
1964	33.3	3.8	37.1	3.9

TABLE 2

Estimated water requirements for Texas:

(From the Texas Water Plan, 1968)

	Acre feet in millions		
Year	Irrigation	Municipal & Industrial	Others 1/
1960	12.5	2.6	0.2
1990	14.1	6.5	0.6
2020	16.9	12.3	3.1

1/ Water requirements for bays and estuaries, navigational, and other recreational purposes.

the irrigation of additional lands. Moreover, improved irrigation management can probably do more towards increasing food supplies and agricultural income than opening additional lands to agriculture. Present knowledge indicates that the magnitude of losses due to drought depend almost as much on when the crop water deficiency occurs,as it does on its magnitude.

Recurring droughts are a normal feature of climate in the western United States. In the humid areas of the Eastern States, supplemental irrigation is used to offset the effect of short-term water shortages during the critical stages of growth of the crop concerned. This suggests the need for a procedure in which the optimal timing of irrigation applications can be determined so as to permit minimizing the adverse effect of shortage.

Nearly 42 percent of the water delivered to irrigated areas is not beneficially used by plants. Frequently, a major portion of this loss is the result of not knowing when to irrigate. Continuous or frequent observation of crop water deficit conditions will help to minimize this loss.

General information on crop conditions is, at present, obtained from surveys on the ground. These surveys are costly and sometimes difficult to make. During the past few years, many scientists have been developing, and, to some extent, applying remote sensing techniques for acquiring data on crop conditions from aircraft, and more recently, from earth-orbiting spacecraft.

In the United States, information on the crop status is collected and prepared by three agencies:

a) The Crop Reporting Board, a unit of the statistical reporting service of the USDA, with statutory responsibility to issue crop forecasts and estimates for major crops, currently maintains 43 field offices engaged in collecting, summarizing, and reviewing this information.

b) The Bureau of Census prepares an agricultural census every five years.

c) The Agricultural Stabilization and Conservation Service of the USDA administers and checks compliance with production adjustment and conservation assistance as well as price and market stabilization programs.

The question at hand is whether aerial survey techniques by remote sensing can be used for the specific purpose of diagnosing crop water balance and the incidence or imminence of drought.

The economic benefits that are to be expected from the accurate predictions of the time of irrigation can be roughly estimated. To give an example, the world and U. S. cotton production in 1964 was 81 million and 14 million bales, respectively (Agr. Stat. USDA, 1965). Approximately 40 percent of the U. S. production was grown under irrigation. An increase of 10 percent in the yield of this irrigated cotton as a result of this technique would amount to an annual economic benefit of more than $100 million or about $30 per acre per year.

Most irrigated farms are organized into districts for the purpose of water distribution. Information on water needs of the crop that was centrally obtained and evaluated could probably also be effectively distributed to individual operators within such districts.

2. BASIC CONSIDERATIONS

2.1 Symptoms of crop water deficits

The science and art of detecting water deficiency symptoms in vegetation has a long and interesting history. For a considerable period of time it was believed that the state of water in the plant and the associated efficiency of its functioning was determined exclusively by the amount and the availability of water in the soil surrounding the plant roots. Accordingly, the evaluation of environmental influences and the timing of irrigation was based on measurements or estimates of soil water content and the associated activity of soil water, sometimes referred to as the soil water potential.

More recently, it has been recognized that the state of water in the plant tissues represents a balance between the water inflow at the root periphery and the outflow due to transpiration. Atmospheric demand must, therefore, be taken into consideration, even when the state of the water supply is known. This view, however correct, does not lend itself easily to practical schemes of measurement or prediction. Accordingly, the present emphasis is on finding meaningful criteria that can be observed on the plant itself, as it is the only true indicator of crop water deficit. Furthermore, it is becoming more and more clear that the practical management of water resources and of vegetation cannot be dependent on a very large number of essentially point measurements in the soil and in the lower atmosphere. It must depend on some area integrated evaluation which implies remote sensing from a platform well above the canopy under study.

There are several ways in which water deficits are manifest in plants. Of these, the two that might readily lend themselves to the remote sensing scheme are the changes in leaf water content which are evident from morphological and physiological changes within the leaf, and the changes in the leaf energy balance which are evident from a change in its temperature.

2.2 Relation between plant water balance and leaf reflectance

2.2.1 General

Figure 1 portrays a portion of the electromagnetic spectrum, showing the types of radiation that occur at different wavelengths. At the lower portion, the radiation reflected by leaves is dominant. With increasing wavelength the solar reflectance decreases until the radiation emitted by the leaves is dominant. The crossover point where the emitted radiation becomes dominant over the reflected radiation is approximately at 3 μ. In the 3 - 15μ portion of the spectrum, the energy recorded is mostly due to emission, which is a function of the surface temperature and the emittance of the object.

In order to determine the effect of water content on leaf reflectance, it is necessary to examine both the absorption characteristics of water and the influence of water balance on the leaf's morphological and physiological features which may affect reflectance. This suggests the examination of the spectral properties of leaves which may be represented by

$$R_\lambda + T_\lambda + A_\lambda = 1 \qquad [1]$$

where R_λ, T_λ, and A_λ represent the reflection, transmission, and absorption, respectively, at a given wavelength λ.

As indicated, the wavelength is an important consideration of the solar spectral response of the leaves. The principal region of interest is that portion of the spectrum from 0.4 to 2.6μ. Figure 2 shows the characteristic reflectance of a green leaf in this region. Based on the general response of leaves, this region can be roughly divided into three spectral regions. First

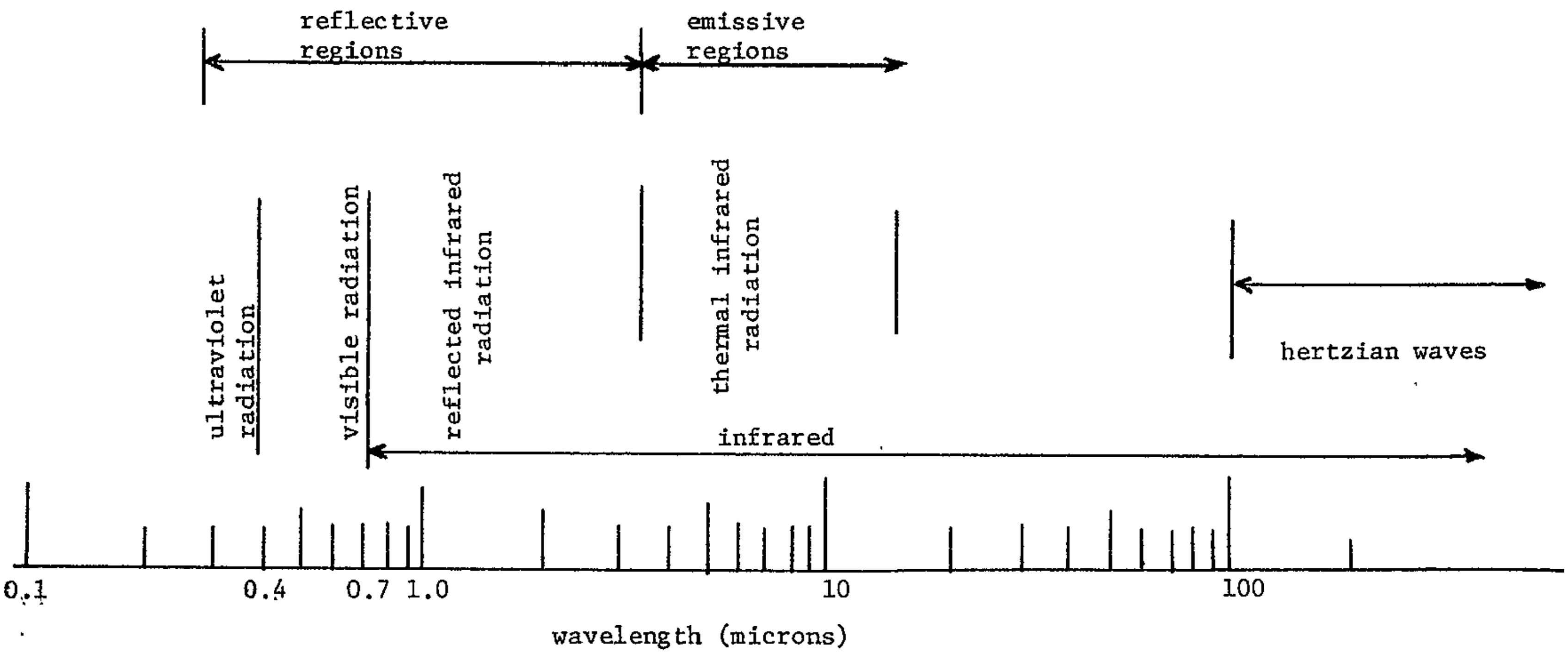

Figure 1. Portion of the electromagnetic spectrum.

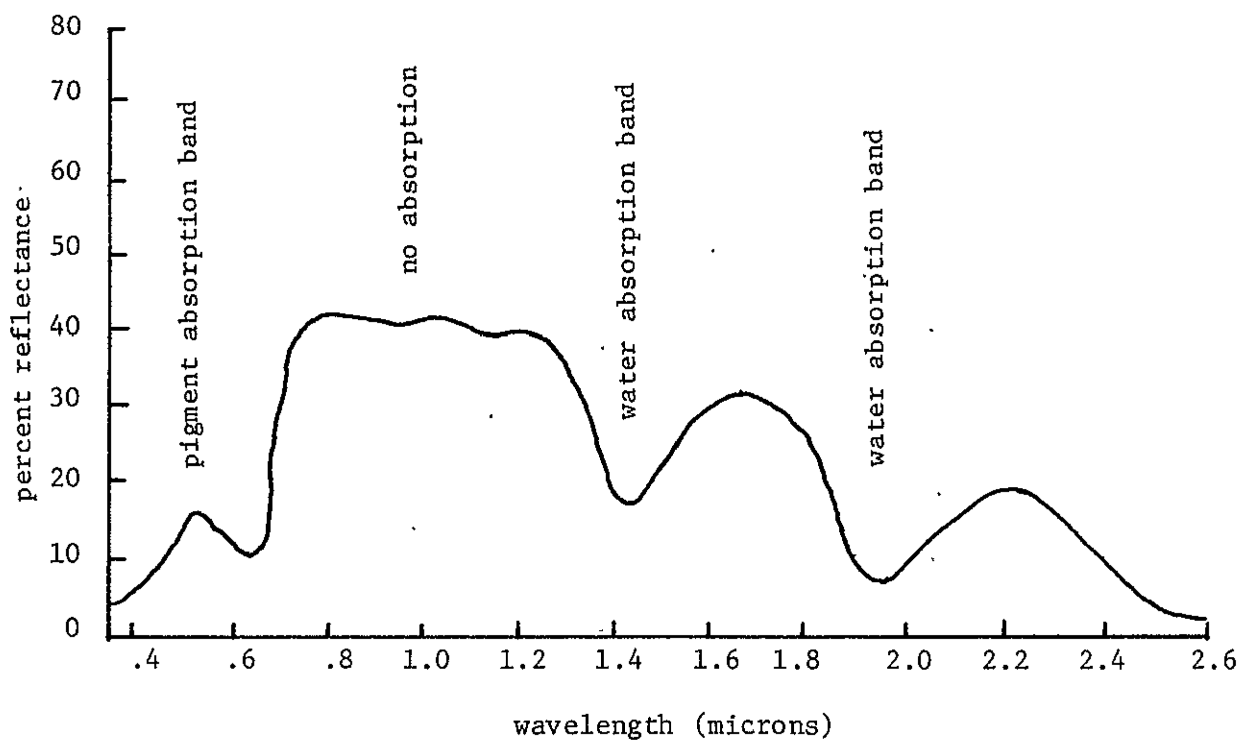

Figure 2. Three primary regions of response in relation to leaf reflectance.

is the visible wavelength region (0.4 to 0.7μ) in which plant pigments dominate the spectral response of plants. Second is the region from approximately 0.7 to 1.3μ where there is very little absorption by a leaf, and therefore, most of the energy impinging upon the leaf must be either transmitted or reflected. The third region is that of water absorption, extending from about 1.3 to 2.5 microns.

2.2.2 The water absorption region

Figure 3 shows the close relationship between water absorption and reflectance for a healthy, turgid, green leaf. In the wavelength where absorption is high, leaf reflectance is low. This is most apparent in the primary absorption bands centered at 1.45 and 1.95 microns.

From Figure 3, it is apparent that the reflectance of leaves in the 1.3 to 2.6μ region should be examined with particular attention to the water content of leaves. The experiments of Thomas, et.al. (1966) have shown that an increase in the leaf water content significantly decreased the reflectance of cotton leaves in this region. A later study conducted by Thomas, Wiegand, and Myers (1967) further showed that water content was the major factor affecting the reflectance of cotton leaves in the longer infrared wavelengths.

Experiments with apple leaves conducted at the Laboratory for Agricultural Remote Sensing (LARS) at Purdue University (1967, 1968) showed a fairly clear indication of the nature of the wavelengths in the water absorption regions. At the 2.20μ wavelength, the thick, more highly developed sunlit leaves had the highest absorptance as a result of their higher water content. Additional reflectance data on wheat, oats, corn, grain sorghum, and soybeans showed similar response; that is, the greater the water content the higher the

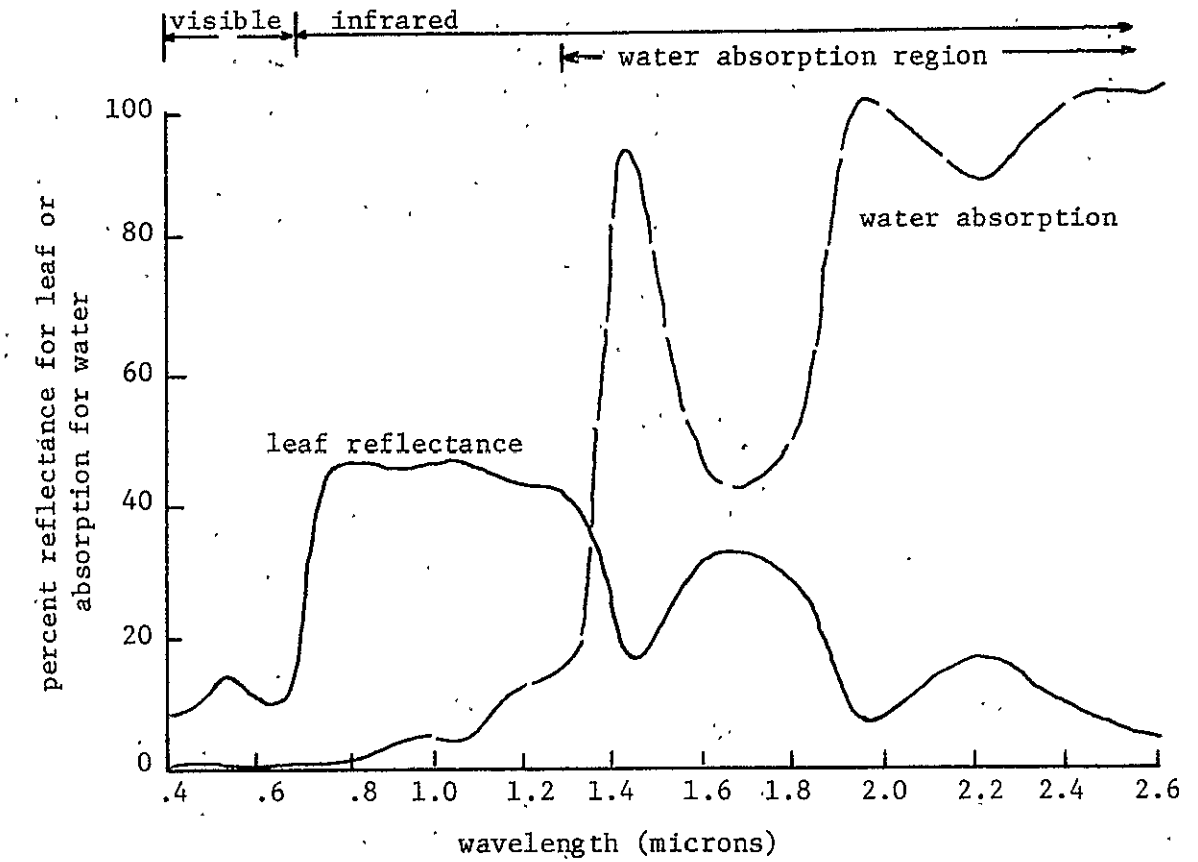

Figure 3. Relationship between leaf reflectance and water absorption in the 0.4 - 2.6 μ wavelength region.

absorptance and the lower the reflectance. The resulting curves, however, are significantly different for the same water content range. Soybean leaves have higher reflectance in the entire reflective infrared region. This is thought to be primarily due to the structural differences between monocotyledonous and dicotyledonous leaves.

2.2.3 The visible region

The visible wavelength region (0.4 - 0.7) is greatly influenced by pigment absorption (Hoffer and Johannsen, 1969). Therefore, the reflectance phenomena would be expected to closely relate to the presence of chlorophyll and other compounds in the leaf. Visually, this is observed by greenish color of the leaves.

The effects of water deficits on leaf reflectance in the visible region are not fully understood as they are closely related to the sequence of metabolic events associated with the imposition of water deficits. Water deficits slow down most of the metabolic processes occurring in the plant cells. This disruption in the normal cell metabolism results in the breakdown of carbohydrate and protein within the plant cell (Slatyer, 1967). As the stress becomes more severe, there will be an accelerated migration of soluble leaf phosphorus and nitrogen compounds, particularly from older leaves, to the stem. Finally, the degree of dessication reaches a critical level and the plant cells and tissues die.

The loss of chlorophyll accompanying the breakdown and migration of organic compounds in leaves results in a higher reflectance. Thus, in the visible wavelength, when dealing with normally green crop species, the amplitude of reflectance can be related to the amount of plant pigments. It should be emphasized, however, that the loss of chlorophyll in plants may also result from other causes such as leaf maturation, salinity and disease. At present, very little is known on the exact relationship between crop water deficits and leaf reflectance in the visible region.

2.2.4 The 0.7μ - 1.3μ region

The region from 0.7μ - 1.3μ, as mentioned previously, is typified by low absorption in comparison with other spectral regions. The reflectance behavior of a leaf in these wavelengths is highly correlated with the area and orientation of cell walls and the amount of intercellular space (Gates, et. al. 1965; Purdue University Laboratory for Agricultural Remote Sensing, 1968).

The results from studies examining the differences in crop reflectances clearly indicate that leaf morphology is the most significant factor in leaf reflectance at these wavelengths. A study made at Purdue University (1968) showed that sunlit apple leaves reflect more than shaded apple leaves. This was so because leaves exposed to sunlight develop 1 - 2 more palisade layers than shaded leaves. The palisade tissue has the greatest area of cell walls, which are considered to be potential surfaces at which reflection can occur. In the same study, the reflectances of soybean and cotton leaves under varying water content were compared. Soybean leaves have typical palisade layers while corn leaves have large cells of little structural orientation resulting in cell walls placed at random angles to the incident radiation. Soybean leaves with a water content of more than 49 percent are more reflective than corn leaves of the same water content. The significance of cell wall orientation becomes further evident when drier leaves were compared. The cells of the corn leaf collapse into a mat-like layer as the leaf dries. On the other hand, the soybean leaf does not collapse into a single horizontal layer as moisture is reduced. The results showed higher corn leaf reflectance at lower water content as a result of the structural changes in the cell wall orientation.

The reflectance of cotton leaves, grown hydroponically with low-, medium-, and high-salinity substrate levels were studied by Gausman, Allen and Cardenas (1969). The total reflectance of light in the 0.7μ - 1.3μ region was greater from leaves of cotton grown in medium- and high-salinity substrates than those grown in low-salinity substrates. This increase in reflectance and a lessening in absorptance were consistent with the observed thicker leaves of saline substrate-grown plants which had larger palisade cells and loosely arranged spongy mesophyll. The structural changes resulted in more intercellular spaces, thus increasing cell wall-air cavity interfaces which are believed to increase the internal scattering of light.

Water content has undoubtedly an influence on leaf morphology and hence, on leaf reflectance in the 0.7μ - 1.3μ portion of the spectrum. This region is of principal biological interest as it affords an opportunity to study the pathway of solar radiation as influenced only by reflection and transmission phenomena without the interfering absorption. Because the effect of leaf water content is mainly on the leaf structure, it may be possible to identify plant stresses due to different causes such as water deficits, salinity, and diseases. In order to do this, however, careful experiments need to be done relating such causes to the leaf morphology and leaf reflectance to the leaf morphology.

2.3 Relation between plant water balance and leaf temperature

2.3.1 Leaf temperature and energy exchange

The temperature of a leaf is an indication of its response and adjustment to the heat loads imposed upon it by its environment. The principal heat load comes from the radiant energy of the sun or thermal radiation of surrounding surfaces and the atmosphere. The radiant energy absorbed by the plant is partitioned and balanced by emission, convection, transpiration, and consumed in biochemical transformation, mostly photosynthesis. All energy absorbed by a leaf must be accounted for and hence the energy budget for the leaf must balance. The energy budget equation for a plant leaf as written by Gates (1968) is

$$Q = R \pm C \pm LE \pm P \qquad [2]$$

where Q is the radiant heat load imposed on the leaf by its environment, R is the radiation emitted by the leaf, C is gain or loss of energy by the leaf by convection, LE is the gain or loss of energy by transpiration or condensation, and P is the energy gained through photosynthesis or lost by respiration. Each term can be expressed in cal cm^{-2} min^{-1} or w m^{-2}.

Photosynthesis and respiration are generally small in relation to other terms, so that P can be placed equal to zero. The radiation emitted by a leaf surface is given by

$$R = \sigma E_\lambda T_\ell^4 \qquad [3]$$

in which E_λ is the emittance of the leaf surface, which is a function of the wavelength λ, σ is the Stefan-Boltzmann constant, and T_ℓ is the absolute temperature of the leaf. Since most leaves have two radiating surfaces, equation [2] when expressed on a unit leaf area basis yields

$$Q = 2\ \sigma E_\lambda\ T_\ell^{4} \pm C \pm LE \qquad [4]$$

A leaf is exposed to a radiation flux at all times. It absorbs a certain fraction of each incident stream of radiation, reflects a fraction, and transmits a fraction. The radiation absorbed, Q, by a leaf is

$$Q = a_1\ S + a_2\ s + a_3 r\ (S + s) + a_4\ (R_a + R_g) \qquad [5]$$

where a_1, a_2, a_3, and a_4 are the absorptances of the leaf surface to the stream of direct solar radiation, S, to the scattered skylight, s, coming from the hemisphere above, to the direct and scattered solar radiation reflected to the leaf from the ground and plant surfaces r (S + s), and to the infrared radiation emitted by the ground surface, R_g, and by the atmosphere, R_a. Each of the absorptances is wavelength dependent, as are also the intensities of various streams of radiation. The absorptance and reflectance (r) values must be determined for the specific spectral composition of each incident radiation streams. It should also be noted the absorptance and reflectance values, as well as radiation stream and surface exposure, may change with time.

The role of convection in the energy exchange of a leaf is difficult to evaluate. Two forms of convective cooling can occur: one is the natural or free convection in which the exchange of air masses is created solely because of the density differences caused by temperature differences in the air between the surface of the leaf and the free air away from the leaf. The other is forced convection in which the exchange air is caused by the external mechanical force of the wind.

The rate at which heat is transferred from a leaf by convection in calories per minute is given by

$$C = A\, h_c\, (T_a - T_\ell) \qquad [6]$$

where A is the surface area, T_ℓ and T_a are the temperatures of the leaf and the air in °C, respectively, and h_c is the convection coefficient in $cal/cm^2 min°C$. It will be noticed that C is positive when the air temperature, T_a, is greater than the leaf temperature, T_ℓ, since then energy will flow to the leaf from the air. The quantity C will be negative when the air is cooler than the leaf, thereby carrying away heat. The convection coefficient depends upon many factors including the geometry of the object, the roughness of the surface, the properties of the fluid (air), and the nature of the flow, whether the convection is natural or forced, and whether the flow is laminar or turbulent.

The complex geometry of the leaf makes it difficult to use equation [6]. Fortunately, however, the results of theory and experiment from physics and heat transfer engineering can be applied with reasonable accuracy (Gates, 1963, 1965). A deciduous leaf can be approximated by a flat plate and a coniferous leaf for pines and similar plants can be approximated by a cylinder. The theory, supported by experimental evidence, has been worked out for these geometrical shapes. The complications which arise with regard to heat transfer by wind involve turbulence and the complex behavior of leaves forming a branch. As moving air passes through a canopy of vegetation it becomes very turbulent. In addition, one leaf may be in the lee of another so that the rate of energy transfer from the leaf to the air is very different from a single isolated leaf in wind. Some of these details have been treated by Gates, et.al.(1965) and Tibbals, et.al.(1964).

Transpiration converts the water in the leaves of a plant from liquid to gas, a process requiring energy and tending to depress the leaf temperature. The water vapor passes from the leaf into the surrounding atmosphere, through the pores in the leaf called stomates. Typically, there are from 10,000 to 20,000 stomates per square centimeter on one or both sides of the leaf. Specialized sausage-shaped cells of the leaf epidermis, known as guard cells, control the opening and closing of the stomates.

The significance of transpiration for the total energy balance has been the subject of many experiments (Ansari and Loomis 1959; Gates 1963, 1966, 1968; Cook et.al. 1964; Idso and Baker 1967). There exists a great misunderstanding among investigators concerning the role of transpiration with regard to leaf temperature. The studies of Gates (1963, 1966, 1968) showed that transpiration plays a relatively significant role in reducing leaf temperatures, and that convection is a relatively unimportant process. Ansari and Loomis (1959), on the other hand, concluded that transpiration plays a relatively small role in the energy exchange process and that convection is a dominant factor in leaf temperatures. Idso and Baker (1967) came to the conclusion that reradiation is by far the most effective mode of energy dissipation. Their findings suggested that reradiation dissipates more than twice as much energy as transpiration and convection. Transpiration is effectively curtailed by environmental conditions such as low air temperature and high humidity. Convection is not so much related to either humidity or air temperature. It is enhanced by high wind speed and large temperature differences between the leaf and the air. Reradiation, on the other hand, functions about equally under any set of environmental conditions.

There can be no doubt that the loss of water from any object represents a certain amount of evaporative cooling since 580 calories are required to evaporate each gram of water. For example, on a bright sunny day, transpiration may make the leaf 5 to 15°C cooler than it would be when evaporation is suppressed (Ehrler and Van Bavel, 1967; Gates 1968). The confusion in publications stems from the fact that the three modes of energy dissipation are not independent of one another as shown in equations (2, 4, and 5). Convection and transpiration depend upon many independent variables of climate and plants acting in various combinations at any single moment. An increase in the temperature difference between the air and the leaf due to reduced transpiration would affect heat exchange by convection in a manner shown in equation [6]. The exact nature of the interrelationships between transpiration, convection, leaf temperature, and crop water balance are not fully understood. An attempt, however, will be made to explain these based on the limited information available at the present.

2.3.2 Plant water balance and transpiration

The rate of water loss through transpiration by a leaf can be understood in terms of a driving force and a resistance of a pathway. The driving force is the difference in concentration of partial pressure of water vapor within the substomatal cavity of the mesophyll and in the free or bulk air beyond the air layer next to the leaf surface. The water vapor must diffuse from the substomatal cavity through the stomatal channel and then through the boundary layer into the free air where the vapor is carried away by air movement. Figure 4 shows a simplified model of a leaf showing the diffusion resistances of the pathway. The total resistance, r_p, of the diffusion pathway is given by an internal resistance, r_ℓ, made up of the sum of substomatal plus stomatal resistances and an external resistance r_a, in the adhering air layer. If there is significant cuticular stream of moisture loss, the cuticular resistance r_c, must be treated as a parallel pathway to the stomatal resistance.

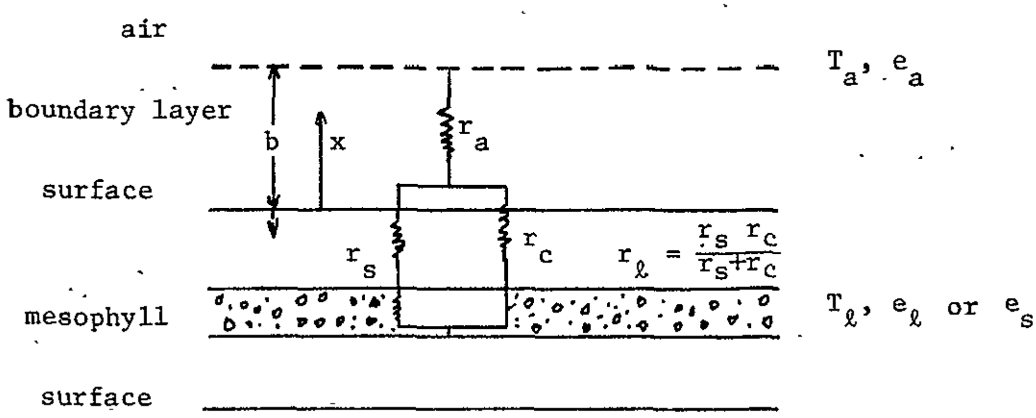

Figure 4. Leaf model showing the diffusion resistances to water vapor.. The driving force is the difference in concentration of vapor pressure (e) between leaf and free air.

From the foregoing, it follows that the evaporation rate from a leaf surface is

$$E = -D \, d\,(C)/dx \qquad [7]$$

where E is the evaporation rate in gm cm^{-2} sec^{-1}, D is the diffusivity of water vapor, and C is the concentration (g cm^{-3}), varying in the direction x. The term C can be replaced by

$$\rho \, \phi \, e_a \, / \, p \qquad [8]$$

where ϕ is the ratio of the densities of water vapor and dry air, e_a is the ambient vapor pressure (mb), p is the atmospheric pressure (mb), and ρ is the density of the air (g cm^{-3}). Equations [7] and [8] yield

$$E = D \, \rho . \phi \, (e_s - e_a) \, / \, b \, p \qquad [9]$$

where e_s is the vapor pressure of the transpiring surfaces within the leaf and b is an effective thickness of still air which can be expressed in terms of the diffusion resistances, as follows

$$b = D \, (r_\ell + r_a) \qquad [10]$$

Thus, the value of b is not to be taken as the actual thickness of the laminar boundary layer. The latent heat flux then may be expressed as

$$LE = L \, \phi \, \rho \, (e_s - e_a) \, / \, p \, (r_\ell + r_a)$$

or

$$LE = C_p \, \rho \, (e_s - e_a) \, / \, \gamma \, (r_\ell + r_a) \qquad [11]$$

where L is the latent heat of vaporization (cal/g), and γ is the psychrometric constant, $L \, \phi \, / \, C_p \, \rho$, in mb/°C.

It may be noticed that equations [6] and [11] have similar forms. The convective heat flux is also a diffusion process, partly molecular and partly turbulent, like the transfer of water vapor, so that it may be assumed in first approximation that it is impeded by effectively the same resistance, r_a. (See Figure 4). Hence equation [6], when expressed on a unit area basis, may be written as

$$C = \rho \, C_p \frac{(T_\ell - T_a)}{r_a} \qquad [12]$$

whereby h_c is replaced by $\rho \, C_p / r_a$. Implied in the derivation of [12] are the assumptions that the transfer coefficients for heat and water vapor are similar and that the exchange is uniform over the leaf surface. Monteith and Szeicz (1962) have shown this similarity assumption to be accurate when the atmosphere is close to neutral stability, implying that $T_\ell - T_a$ is small. Tanner (1967) and Fuchs, et.al., (1969) came into the same conclusion.

Combining equations [4], [11], and [12] and rearranging terms, the energy budget for a normal transpiring leaf may be written as

$$Q - 2E_\lambda \, \sigma \, T_{\ell,1}{}^4 = \rho C_p \frac{(T_{\ell,1} - T_a)}{r_a} + \rho C_p \, (e_{s,1} - e_a) \, / \, \gamma \, (r_\ell + r_a) \qquad [13]$$

and for a non-transpiring leaf.

$$Q - 2E_\lambda \, \sigma \, T_{\ell,2}{}^4 = \rho C_p \frac{(T_{\ell,2} - T_a)}{r_a} \qquad [14]$$

where the subscript (1) and (2) refer to a normal and non-transpiring leaf, respectively.

If both leaves have identical exposure and geometrical form, it can be assumed that both leaves absorb the same amount of radiant energy. Thus equations [13] and [14] may then be combined to give

$$T_{\ell 2} - T_{\ell 1} = 2\sigma E_\lambda \frac{r_a}{C_p \rho} (T_{\ell 1}{}^4 - T_{\ell 2}{}^4)$$

$$+ (e_{s1} - e_a) \frac{r_a}{\gamma (r_a + r_\ell)} \qquad [15]$$

It can be shown further that (see Impens et.al., 1967)

$$\sigma (T_{\ell 1}{}^4 - T_{\ell 2}{}^4) \cong 4\sigma T^3 (T_{\ell 1} - T_{\ell 2})$$

$$\cong h_r (T_{\ell 1} - T_{\ell 2})$$

$$\cong \frac{C_p \rho}{r_r} (T_{\ell 1} - T_{\ell 2}) \qquad [16]$$

where h_r is a radiative heat transfer number which may be symbolically replaced by a radiation resistance r_r. Combining [15] and [16], and assuming $E_\lambda = 1.0$ yields

$$(e_{s1} - e_a) \frac{r_a}{\gamma (r_a + r_\ell)} = T_{\ell 2} - T_{\ell 1} + \frac{2 r_a}{r_r} (T_{\ell 2} - T_{\ell 1})$$

$$= (1 + \frac{2r_a}{r_r}) (\Delta T_c) \qquad [17]$$

ΔT_c being the transpiration cooling in °C. Transpiration cooling as defined here is simply the difference in measured temperatures of a transpiring and a non-transpiring leaf.

It should be noted that equation [17] requires a knowledge of the leaf temperature of the transpiring leaf in order to find both $e_{s,1}$ and r_r. This temperature itself depends upon many external circumstances and [17] is not as useful or unambiguous as it may seem at first. Nevertheless, it can provide an estimate of the temperature differences one may expect between well watered and water deficient plants.

To show roughly the extent of transpiration cooling in plants, the following typical values for a corn crop were assumed: e_s = 42 mb, e_a = 15 mb, γ = 0.66 mb °C^{-1}, r_ℓ = 0.025 min cm^{-1}, r_a = 0.006 min cm^{-1}, and r_r = 0.04 min cm^{-1}. Equation [17] then yields $\Delta T_c \cong 6.0$ °C. The data of Gates et.al. (1965) for ponderosa pines showed slightly greater transpiration cooling depending upon sensible heat flux and the heat load. It must be further noted, however, that equation [17] assumes that the leaf reflectance and absorptance characteristics are not affected by the leaf moisture content. It is clear from the previous discussion on leaf reflectance that this is a gross oversimplification.

Equation [17] emphasizes the major role played by the diffusive resistance r_a and r_ℓ in leaf temperature. The average resistance r_a of the boundary layer for a crop canopy is given by Monteith (1962) as

$$r_a = [\ln (z - d) / z_o]^2 / k^2 u \qquad [18]$$

where u is the wind speed at height z above the ground, z_o is a roughness constant, d is a displacement factor to allow for the effect of the crop in effectively displacing ground level upward, and k is the von Karman constant equal to 0.41. The roughness length z_o and the zero plane displacement d are parameters of the wind profile such that above the canopy u is proportional to ln [(z - d) / z_o], and u = o at z = (z_o + d). It is thus seen that r_a is primarily affected by wind speed and the crop geometry. Detailed discussions on these interrelationships are given by Gates (1968) and Slatyer (1967).

Under field conditions r_a is usually smaller than r_ℓ. (Impens, et.al. 1967). The leaf resistance r_ℓ, which is primarily stomatal resistance, may thus be visualized as the primary factor affecting transpiration cooling in leaves. This relationship links crop water balance to the leaf temperature since stomatal resistance is primarily influenced by the leaf water content or more specifically, leaf water potential.

It is well established that as the soil water content decreases, the soil and the leaf water potentials decrease (Gardner, 1960). Consequently, a water deficit develops within the leaf and the guard cells lose hydrostatic pressure which cause the stomata to close. Thus, the stomatal resistance to water vapor diffusion is increased. The closing of the stomata due to water stress occurs within a narrow range of leaf water potentials (Ehlig and Gardner, 1964). Slatyer (1967) suggests that water deficit may not affect greatly the stomatal resistance until a certain leaf water potential is reached, and as the water potential decreases further, there is a rapid increase in the stomatal resistance. The data of Kanemasu and Tanner (1969) showed that stomatal closure occurs on the lower and upper sides of snap bean leaves at potentials of -11 bars and -8 bars, respectively. The critical leaf water potential at which permanent wilting occurs for most plants is approximately -15 bars.

Water deficits can clearly exert a direct effect on stomatal aperture by their effect on relative and absolute hydrostatic (turgor) pressure levels in guard cells and their surrounding cells. The ultimate effect of such stomatal aperture is manifest in a change in leaf temperature. It should be pointed out, however, that stomatal aperture is not only influenced by leaf water potential, but also is affected by such factors as light and CO_2 concentration. Furthermore, the change in leaf temperature may be due to fluctuations in convective heat exchange, implying the need to distinguish the temperature differences caused by water deficits from those of the other factors previously mentioned, before the thermal reconnaissance of vegetation can be accurately correlated with the crop water balance.

3. REMOTE DETECTION OF WATER DEFICITS IN PLANTS

3.1 Remote sensing of reflected radiant energy

3.1.1 General

It was pointed out earlier that water content influences the reflectance characteristics of plant leaves in the 0.4 μ - 2.5 μ portion of the electromagnetic spectrum, making it possible to remotely detect water deficits in crops by monitoring the changes in the canopy reflectance. It appears difficult, however, to evaluate such changes in terms of crop water deficits because of the following reasons:

a. The spectral quality of the reflected radiant energy from plant leaves varies with the plant species, maturity, and variety (Gates, 1965b). Also, plants of some species which may be diseased or nutriently deficient, will in some cases, exhibit very different relative amounts of each wavelength in reflectance (Gates, 1965b).

b. Atmospheric gases like CO_2, O_3 and water vapor absorption reduce the incoming solar and sky radiation in certain wavelength bands.

c. Irradiance from the sun and sky varies in intensity with numerous other conditions.

d. The radiance from field crops is affected by crop geometry, background soil reflectance, and other factors.

e. The intensity of solar radiation peaks at about 0.5 μ, falling off rapidly at shorter and longer wavelengths.

It is clear that this aspect of crop water deficit detection is enormously complicated and if remote sensing techniques were to be made feasible, foundations for the use of remote sensors must be provided by research on all of the above mentioned factors.

3.1.2 Reflectance characteristics of plants

A relatively small amount of research has been done on the reflectance properties of plants. In addition to sources previously mentioned, a few primary references will be mentioned here that contain extensive reference to earlier work.

Prior to 1930, most measurements on reflectance as well as transmittance of leaves were made with the direct beam. Leaves, however, range from those with extremely glossy cuticle where reflectance is largely specular, to those with essentially matte surfaces where reflectance is almost entirely diffuse. In most cases, both kinds of reflectance coexist, that from the lower surface being more diffuse than that from the upper surface (Myers and Allen, 1968). Rabideau, et.al. (1946) used an Ulbricht integrating sphere with a grating spectrophotometer to measure the reflectance and absorptance over the spectral range 0.40 μ to 0.85 μ for leaves from several assorted plants. These investigators were among the earliest to report the negligible absorptance of leaves in the near infrared.

Billings and Morris (1951) measured the reflectances of the upper surfaces of many plant leaves. Their measurements were made from 0.4 μ to 1.1 μ by means of Beckman DU quartz spectrophotometer with reflectance attachment. The spectral properties of leaves of agricultural crops in the visible region were investigated by Moss and Loomis (1952). The principal purpose of their investigation was to determine reflection and absorption characteristics of leaves, effects of unusual leaf surfaces, and of differences in leaf color. The instrument used was a Razek-Mulder recording spectrophotometer which utilized a diffuse light source.

The infrared specular reflection spectrum from 1.5 μ to 25 μ of many plants was reported by Gates and Tantraporn (1952). A Perkin-Elmer IR spectrophotometer, model 12C, with a NaCl prism was used for the determination of light reflectance in the region up to 3 microns. For measurements from 3 to 25 μ, a double beam, Baird IR spectrophotometer with a NaCl or KBr prism was used. They showed that the far infrared reflectance was generally less than 5% for a 65° angle of incidence and less than 3% for a 20° incidence angle. At far infrared wavelengths, the upper surface reflects more than the lower, old leaves more than young, and shade leaves more than sun leaves. In each instance, the inverse was true in the near infrared.

The spectral properties of plant leaves and stems were obtained for the UV, visible, and IR wavelengths by Gates, et.al. (1965). The spectral leaf reflectance, absorptance, and transmittance were given for a variety of plants. An evaluation of spectral properties of plant leaves during the early growing season was presented. Instruments used included a Hardy recording spectrophotometer and a Cary 14 spectrophotometer with reflectance attachments.

Howard (1966) studied the reflectance and transmittance of eucalypts in the spectral range from 0.40 μ to 0.95 μ at varying angles of incidence. Spectral reflectances were found to be higher in the near infrared (0.7-0.95μ) compared to those in the visible wavelengths. All leaf surfaces studied were found to be highly diffusing. In a study on the effect of pubescence on leaf reflectance, Gausman and Cardenas (1968) found pubescence to significantly increase total and diffuse reflectance in the 0.75 μ to 1.0 μ region, but significantly decrease total and diffuse reflectance in the 1.0 μ to 1.5 μ region. Hairiness had little effect on the reflectance of visible light within 0.50 μ to 0.75 μ waveband.

Wong and Blevin (1967) measured the total spectral reflectances of plant leaves over the wavelength range from 2.0 μ to 14 μ, with the radiation being at 10° to the normal. Most of the plant species studied showed considerable higher reflectance peak between wavelengths 2.0 and 3.0 microns. Within the wavelength range from 3.0 μ to 14.0 μ, most of the reflectances were less than 0.05, and with the exception of one species, all were less than 0.10. They also measured the directional distribution of infrared radiation and showed that leaves should not be regarded as either perfectly specular or diffuse reflectors in the infrared regions.

Reflectance data from many of the references cited here, plus additional unpublished data and foreign publications are being collected and computerized at the University of Michigan Infrared and Optical Sensor Laboratory. In addition, the Laboratory for Agricultural Remote Sensing at Purdue University (1967a, 1967b, 1968) has a continuing research program on spectral radiance measurements of a wide variety of plant species and other materials of interest in agriculture. The recent work of Wendlandt and Hecht (1966) gives a good summary on the subject of reflectance spectroscopy in general. This book contains an excellent treatment of modern instruments used in this discipline.

3.1.3 Other considerations

Some of the most difficult factors to evaluate in regard to the interpretation of the reflected radiance from a crop are crop geometry and background soil reflectance. It is less difficult to evaluate the data obtained for a single leaf, or for a solid, dense and fully grown canopy. When a crop produces only partial cover and soil of the underlying soil surfaces are exposed, the problem becomes exceedingly difficult.

Gates (1965b) gives an excellent discussion and mathematical treatment of spectral and thermal considerations involved in partial crop canopy to estimate quantitatively the amounts of energy received by different sensors. He described radiation exchange as a function of crop geometry. This was done in a generalized manner, so that the reflected and the absorbed radiation can be expressed as functions of canopy density.

One of the established causes of variation in plant reflectance is leaf density or leaf area index. Leaf area index is a number representing the ratio of leaf area to soil area. Thus, the leaf area index for a given crop is a function of the stage of crop growth. Leaf water content might to a certain extent affect leaf area index as a result of the foliar expansion and shrinkage associated with varying turgor pressure. Wind also has a pronounced effect on the leaf area seen from above. In some cases, wind erosion deposits a cover of dust on plant leaves so as to cause significant changes in canopy reflectance.

Some of the factors that are known to influence reflectance characteristics of the soil underlying the canopy are mineral and organic matter content, moisture content, particle size, structure, and the surface roughness. A brief discussion of these factors is given by Myers and Allen (1968).

Gases, water droplets, and other atmospheric constituents selectively absorb, scatter, and emit radiation. Investigators who desire to view surface phenomena from airborne or spaceborne sensors must take into consideration the influence of these atmospheric constituents. Optimum detection conditions can be obtained by selecting frequency domains in the electromagnetic spectrum of maximum atmospheric transparency. These domains are called atmospheric "windows" and the major ones are listed in Table 3. In addition to these major windows there are minor ones, which can also provide optimum detection conditions provided that the detector system is sensitive enough to give suitable signals in these narrow spectral windows. It should be pointed out that these windows are neither completely transparent nor sharply bound. The optical and infrared windows become opaque when clouds are in the field of view. The upper end of the microwave window may become obscured by raindrops.

Table 3 shows the two major windows in the 0.4 μ - 2.6 μ portion of the electromagnetic spectrum. In Figure 5, the spectral transmission of the earth's atmosphere in the region from 1.0 μ - 15 μ is shown, as well as those of its principal components. It may be noticed that in the region of interest (1.0 -3.0) in the near infrared, water vapor and CO_2 absorption predominate. It must be pointed out, however, that Figure 5 is still far from representing the complete picture of atmospheric transparency in the 1.0 μ - 16 μ region as new calculations of the atmospheric transmission and discoveries of hitherto unknown windows are continuously being made.

A comprehensive review of the atmospheric transmission properties have been made by Howard and Garing (1962). Some of the most extensive experimental investigations about the transmission of the atmosphere have been made by Yates

Table 3. Major atmospheric windows in the electromagnetic spectrum

window	wavelength, λ	Gases that absorb radiation at the boundaries of the window 1/		additional bands of absorption within the window region
		lower	upper	
optical	0.4 - 1.3 μ	all gases	H_2O	
near infrared	2.0 - 2.3 μ	H_2O	CO_2	
near infrared	3.6 - 4.0 μ	H_2O, CO_2	all gases	
thermal infrared	8 - 13 μ	all gases	CO_2, H_2O	O_3 band (9.5 - 10μ)
microwave	8 mm - 15 meters	O_2	ions 2/	H_2O band (1.2 - 1.5 cm)

1/ Boundaries are not exact and are due mainly to the gases listed

2/ Ions vary in strength and number and are located in the ionosphere

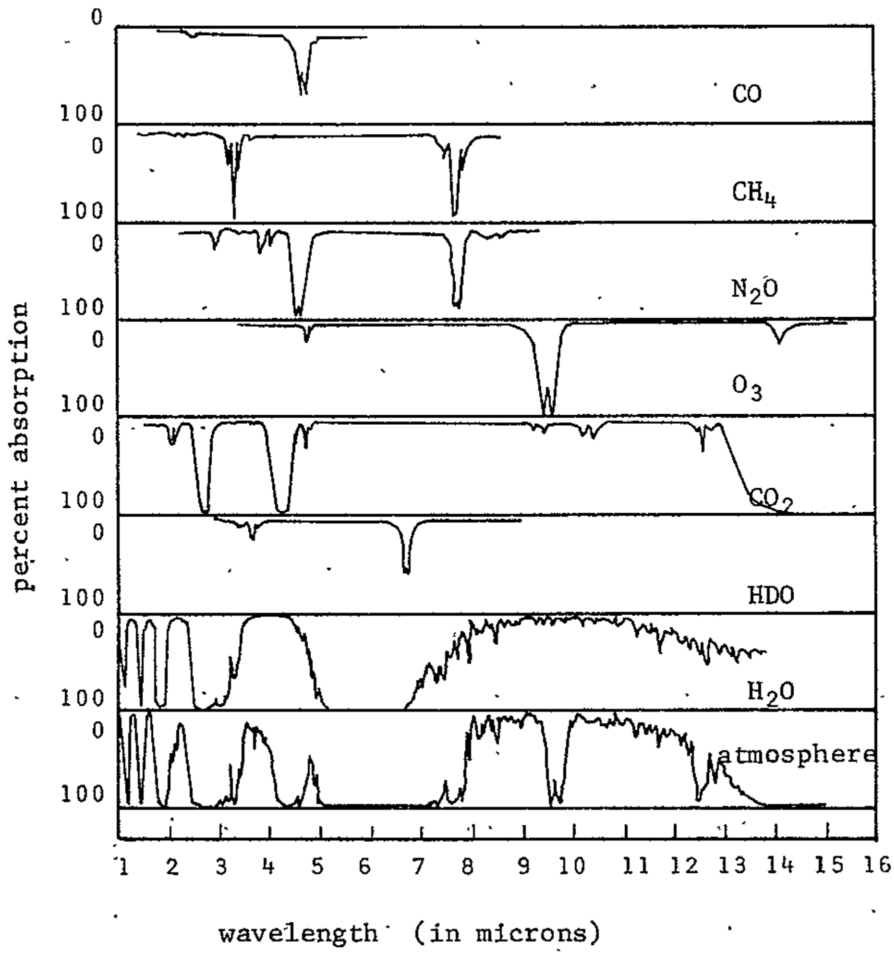

Figure 5. Absorption of radiation in the 1-15 μ wavelength region.

and Taylor (1957) and Gebbie, et.al. (1951). Their measurements are very useful for a determination of the transmission independent of atmospheric water vapor content. These measurements were, however, mainly made on the ground and it is impossible to generalize these results for higher levels of the atmosphere. Later studies by Stull, Wyatt, and Plass (1964a, 1964b), give tables that take into account the temperature and pressure dependence of water vapor absorption. They also give transmission data in a most practical way for the whole wavelength region from 1.0 μ to 20.0 μ for carbon dioxide.

A recent publication by Bolle (1965) discussed the influences of atmospheric absorption and emission in the spectral regions in between 0.5 to 26 microns. He presents a graphical method to determine the detection range for narrow infrared windows in dependence of atmospheric absorption and emission by using atmospheric transmission properties deduced from theoretical and empirical data under consideration of actual atmospheric pressure, temperature and humidity distributions.

In addition to the complications mentioned, there is a problem of identification inherent in almost all agricultural remote sensing schemes. Agricultural features such as vegetation, and soils must be delineated on the basis of crop types, individual crop species and their stages of growth, soil texture groupings, etc. At present, this problem of identification is being solved by simultaneous ground truth observations and subsequent statistical analysis of ground truth information and remote sensing data. Only partial success can, however, be expected because of the infinite number of ground parameters that exist in the complex natural environment of plants.

3.2. Remote sensing of emitted energy (surface temperature)

3.2.1 General

In the previous discussion, it was recognized that plant temperature may be a valuable qualitative indicator of differences in plant water regimes. Coupled with a better understanding of the heat transfer processes at the plant surfaces, it may serve to provide quantitative data on plant water status.

Early attempts to measure plant temperatures were hampered by the enormous problems of instrumentation and data processing (Lange 1965). Most plant temperature measurements reported in the literature have been made on individual well-exposed leaves. A leaf with the surface normal to incident solar radiation will be at a substantially higher temperature than a leaf that has a large angle of incidence or one that is shaded (Ansari and Loomis, 1959). Thus, severe sampling problems exist. Furthermore, the methods of common practice today which involve either attaching or inserting thermal sensors may affect the plant temperature that is to be measured.

Many of these difficulties can be surmounted by remote sensing of plant temperatures through thermal radiation measurements. The radiative measurement of plant temperatures may be integrated over the field of view of the sensor and does not interfere with the energy exchange of plants.

3.2.2 Theory of measurement

The theory of remote sensing of surface temperatures using radiometers has been extensively described by Fuchs and Tanner (1966) and by Lorenz (1968). The total apparent outward flux of radiation, R_o, measured by a radiometer is given by

$$R_o = \int_0^\infty \varepsilon_\lambda \, f(\lambda) \, \varepsilon(\lambda,T) \, d\lambda + \int_0^\infty (1-\varepsilon_\lambda) \, f(\lambda) \, B(\lambda,T_s) \, d\lambda \quad [19]$$

where $f(\lambda)$ is spectral sensitivity of the instrument, $E(\lambda,T)$ is the value of Planck's energy distribution law for the wavelength λ, ε_λ is the emissivity of the surface at wavelength λ, $B(\lambda,T)$ is the radiation flux incident to the surface from the environment, which has an integrated radiative temperature T_s, and T is the true surface temperature.

Radiometric surface temperature measurements are usually made in the 8-13 μ atmospheric window. (See Figure 5.) Fuchs and Tanner (1966) have shown that in this window equation [19] can be approximated by

$$R_o = \varepsilon f(T) \sigma T^4 + (1-\varepsilon) f(T_s) B_s \qquad [20]$$

where

$$B_s = \int_0^\infty B(\lambda,T_s)\, d\lambda \qquad [21]$$

and ε, $f(T)$, $f(T_s)$ are the weighted emissivity and filter functions, respectively. An assumption of constant emissivity was made in deriving equation [20].

Equation [20] can be solved for T by numerical methods provided that B_s and ε are known. A program in BASIC was devised for this purpose by Conaway and Van Bavel (1966). The solution, however, is long and cumbersome. Fuchs and Tanner (1966) further showed that for a bandpass filter between 8 μ and 13 μ, $f(T)$ may be considered constant in the range of biological temperatures encountered. The radiometer is then calibrated according to a quantity $R_b = R_o / f(T)$. Hence,

$$R_b = \varepsilon\sigma T^4 + (1-\varepsilon) B_s^* = \sigma T_a^4 \qquad [22]$$

where T_a is the apparent surface temperature and

$$B_s^* = [f(T_s) / f(T)]\, B_s \qquad [23]$$

Equation [22] can be solved easily for T provided R_b is related by a calibration curve to the output of the radiometer and ε and B_s^* are known. The calibration is done simply by means of a Leslie cube which contains a blackened reentrant cone at the temperature of the cube (Fuchs and Tanner, 1966, Conaway and Van Bavel,1967). The quantity B_s^* has little physical meaning since it is related to the general flux B_s of radiation incident on the surface whose temperature is being observed. The radiometer interprets the true surface temperature T to be the apparent surface temperature T_a. If $\varepsilon = 1$, then $T_a = T$. Also, if the radiative temperature of the surroundings is equal to the real surface temperature, then $T_a = T$. If the surface has an emissivity less than unity and if the surface views the sun or a cold sky, the apparent surface temperature as measured with an IR radiometer may be quite different from the true temperature.

3.2.3 Recent work

Tanner (1963) made some exploratory plant temperature measurements using a Barnes infrared radiation thermometer having an 8-13 μ spectral bandpass filter. He compared plant temperatures under different water regimes. The unirrigated plants were always at a higher temperature than the similar, irrigated ones. His measurements were, however, incomplete and the results were inconclusive since no attempts were made to measure or correct for incident radiation.

Monteith and Szeicz (1962) used a Linke-Feussner radiometer to measure the radiative temperature of natural surfaces. Considerable error was incurred due to atmospheric interference and the variation of surface emittance from the assumed value of one. These errors were estimated to be up to 2°C and 4°C, over vegetation and moist bare soil, respectively. Their analysis of surface temperature observations over vegetation showed that, when the aerodynamic character of a crop is known, the effective resistance of the stomata to water vapor diffusion can be related to the difference between surface and air temperatures.

Using a Stoll-Hardy infrared radiometer, Gates (1963) measured temperatures of vegetal surfaces. He found extreme variations in temperature of various leaves depending upon their geometry and degree of exposure to direct sunlight. In a later study, Gates (1968) reported plant surface temperatures for diverse ecological conditions as measured with a Barnes IR radiometer.

Using a Stoll-Hardy IR radiometer, Myers and associates (1966) made temperature measurements of cotton leaves under varying water stress conditions. A linear relation between the relative turgidity and temperature of the leaves was established when air temperature and solar radiation were approximately constant. They also obtained plant canopy temperature patterns using a Barnes Model T-5 infrared camera during a study of diurnal temperature changes in small, differentially irrigated cotton plants. The thermograms taken at various times of the day showed detectable temperature differences between the dry and the wet plots during the time of the day from 0900 to 2200 hours.

Conaway and Van Bavel (1966) made measurements of soil surface temperatures under field conditions using a Barnes infrared radiometer with a 7.5 - 16 μ bandpass filter. They explored the usefulness of such measurements in measuring latent and sensible heat flux over a bare, wet soil. They also pointed out the necessity of measuring surface emittance and sky radiance and described experimental methods for the calibration of radiation thermometers and the measurements of surface emittance and sky radiance.

A discussion of the radiometric determination of surface temperature is given by Lorenz (1968), with emphasis on the possible errors on this method. He presented several examples of airborne surface temperature measurements describing methods by which corrections can be made on the errors caused by atmospheric absorption and the non-blackbody characteristics and non-uniformity of natural surfaces.

Olson and Ward (1968) made a study concerning the ability of thermal infrared sensors to detect gross differences in moisture stress in forest stands. To produce moisture stresses, plots of balsam poplar and oak trees were girdled. Infrared imageries were obtained using an infrared line scanner having an 8 - 14 μ bandpass filter from altitudes of approximately 1,000, 2,500, and 4,000 feet above the terrain.

The results obtained were inconclusive as the balsam poplar stands were not differentiable from the ungirdled stand on any infrared imagery. The oak plots, however, were readily apparent in all the infrared imageries. One of the two oak plots studied, however, would not have been detectable if its exact location had not been known in advance.

Weigand, et.al. (1968) studied the thermal behavior patterns of plants, soils, and other objects of agricultural interest during overflights made by the University of Michigan thermal scanner equipped plane. The thermal scanner imagery was interpreted from microdensitometer film densities calibrated against Stoll-Hardy radiometer measurements made on the ground at the same time the plane was overhead.

Their results illustrate the range in temperature expected in agricultural landscapes in a subhumid climatic zone and the magnitude of influence of time of day, crop cover conditions, tillage, and irrigation on the thermal behavior of plants and soils. For example, freshly irrigated crops may be up to 20°C cooler under midday conditions than non-irrigated crops in the same field. At about 0600 hours, however, non-irrigated crops were usually 1 to 2°C cooler than freshly irrigated crops of the same field.

3.2.4 Some important considerations

In the preceding section, it was shown that no instrument can yield a correct estimate of the surface temperature if the emissivity of the surface is not taken into account. All the previously cited authors have recognized this problem. Only a few of them, however, applied the needed corrections, with the rest arguing that the emissivity of plant materials is very close to unity. Emissivities given by Gates and Tantraporn (1952) and Gates, et.al. (1965) range from 0.95 to 0.98. Monteith and Szeicz (1962) and Gates (1963) estimate that assuming $\varepsilon = 1$ may cause errors of, at most, 0.2°C. Rose and Thomas (1968) have, however, shown this estimate to be unrealistically low and gave reasonable error estimates of 3.8°C and 1.1°C for most land surfaces and dense vegetation, respectively.

Many studies have been conducted concerning the reflectance and emittance properties of individual leaves. These measurements are, however, of very little use in the present problem since the emissivity of a single leaf is not representative of that of a vegetal cover because of the internal reflections resulting from the cover geometry. The emissivity of a vegetal cover must, therefore, be determined in situ.

Land-based techniques for the in situ measurements of the emissivity of small surface areas have been developed by Buettner and Kern (1965) and Fuchs and Tanner (1966). In the case of satelliteborne radiometers where the field of view is in the order of a kilometer, these techniques are of limited use because large proportions of the area being viewed usually differ in emissivity. Rose and Thomas (1968) suggested a possible method where measurements are taken over several non-adjacent wavebands so that several equations can be formulated. These equations enable the solution of several unknowns including surface emissivity and temperature.

The possible errors caused by atmospheric interference have been mentioned previously in connection with the discussion on atmospheric transparency. In addition to the previously cited literature, further information dealing primarily on the problem of atmospheric interference in the 8-13 μ region of interest are given by Lorenz (1966), Streete (1968), Carlon (1966), Blythe and Kurath (1968), Lenschow and Dutton (1964), Wark et.al. (1962), Bell et.al. (1960), and Sloan et.al. (1955).

There are other important problems involved in the radiometric measurements of plant temperatures, when making integrated temperature measurements using portable infrared radiometers. Consideration should be given to the solar zenithal angle, viewing angle, and the field of view of the instrument (Fuchs et.al. 1967). Likewise, when deriving specifications for the flying of thermal infrared imagery and in interpreting vegetal temperature from imagery thus obtained, careful consideration should be given to the time of the day, the type of terrain, and the viewing angle (Colwell and Olson, 1965). The type of terrain affects the angle of incidence. Similarly, the time of the day affects the orientation of vegetal cover and hence, direct heating from solar energy. Also, shadow formation along the line of flight may cause sensors to see only cool spots and vice versa.

Finally, the interpretation problems pointed out earlier should be considered. Careful attention should be given to the background soil emittance as influenced by soil water content, leaf area index, heat exchange between the surroundings, and the diurnal history of soil thermal characteristics. The dependence of leaf temperature on such factors as wind, relative humidity, and ambient air temperature should also be kept in mind.

4. SUMMARY AND CONCLUSION

Remote sensing has an interesting potential in investigations of crop water balance conditions. Many billions of dollars have been spent for water resources development and irrigation works in the United States, for the exclusive purpose of maintaining a favorable water balance in economic plants. Since many million of acres are involved, there has been no practical way developed to verify whether the objective of all this effort is being obtained or whether this is done in the most efficient manner. The quantities of water involved are equally prodigious and this fact stands in contrast to the sobering consideration that more than one quarter of the nation's population in recent years has been forced to restrict the use of water because of drought-caused conditions. (National Academy of Sciences Report, 1969). Techniques for the remote detection of crop water deficits would seem to be useful in planning for efficient water resources management. Also, they have potential value for individual districts and farms in deciding upon the use and distribution of diverted irrigation water.

Furthermore, the successful operation of any agricultural business requires efficient reporting of crop conditions. Such an information system is valuable to the government in establishing agricultural policy and to business based upon farm commodities. At present, information on seasonal crop conditions has to be gathered by ground on-the-spot surveys. These surveys are costly, infrequent, incomplete and the information obtained often cannot be analyzed in time for user applications.

This paper reexamines the feasibility of using remote sensors in detecting water deficits in plants. Background information on the significance of crop water deficits to crop production, on the development and symptoms of crop water deficits, and on the energy environment of plants is presented. The characteristics of plants that influence both reflectance and emittance of electromagnetic or radiant energy are presented.

An extensive review of pertinent literature shows that two well established symptoms of crop water deficits lend themselves, at least in theory, to remote sensing. These are: (a) the morphological and physiological changes which are accompanied by changes in plant reflectance in the waveband from 0.4 to 3 microns and (b) the changes in canopy energy balance which are evident from the change in the canopy temperature and its radiance in the waveband from 6 - 20 microns. It is of interest to note, however, the absence as of date of cases of successful employment of remote sensing in detecting crop water deficits. This reflects the enormously complex nature of the method itself and, to a considerable extent, the newness of remote sensing technology.

The limitations facing the remote detection of crop water deficits are largely due to inherent characteristics of the object being sensed. The complex crop geometry, the variations in crop radiation and climatic environment, the incidence of diseases, of soil nutrient deficiencies, and other factors all contribute. Also, the remarkable adaptability of plants to their environment, as well as the ability of plants to make compensation for man-made influences, frequently brings about an alteration in the canopy of leaves which, in turn, influences the relationship between the various amounts of reflected, transmitted, or absorbed energy. At this point, it is worth mentioning once more that such an effect upon the crop canopy brought about solely by crop water deficit is what we hope to detect. In the presence of many other possible influences, it is likely that a stratagem common to many agronomic and hydrologic experiments and operational techniques must be used in the form of check or control surfaces. At least this approach must be fully explored.

Other limitations are state-of-the-art and can be overcome with the advancement of instrumentation and research technology. Such limitations include the reduction of large quantities of remote sensing data into useful information in a timely manner which requires automation of the data handling process, and interpretational problems associated with the problems of atmospheric interference.

In summary, it should be clearly stated that remote sensing may not prove a feasible solution to the problem at hand. Remote sensing is not a panacea as many of its facets are extremely complicated. Before more definite statements can be made on this particular problem, it is essential that further studies be made to answer the basic problems mentioned above. It is necessary to understand more fully the factors affecting reflectance and emittance from various plants and soil materials as well as those determining foliage temperature. To do this research properly requires an intergrated program of laboratory, field and aircraft experiments. Without such a program, the problem can be dealt with in an empirical manner only, inhibiting the transfer of knowledge and technology.

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The REMOTE SENSING CENTER was established by authority of the Board of Directors of the Texas A&M University System on February 27, 1968. The CENTER is a consortium of four colleges of the University; Agriculture, Engineering, Geosciences, and Science. This unique organization concentrates on the development and utilization of remote sensing techniques and technology for a broad range of applications to the betterment of mankind.