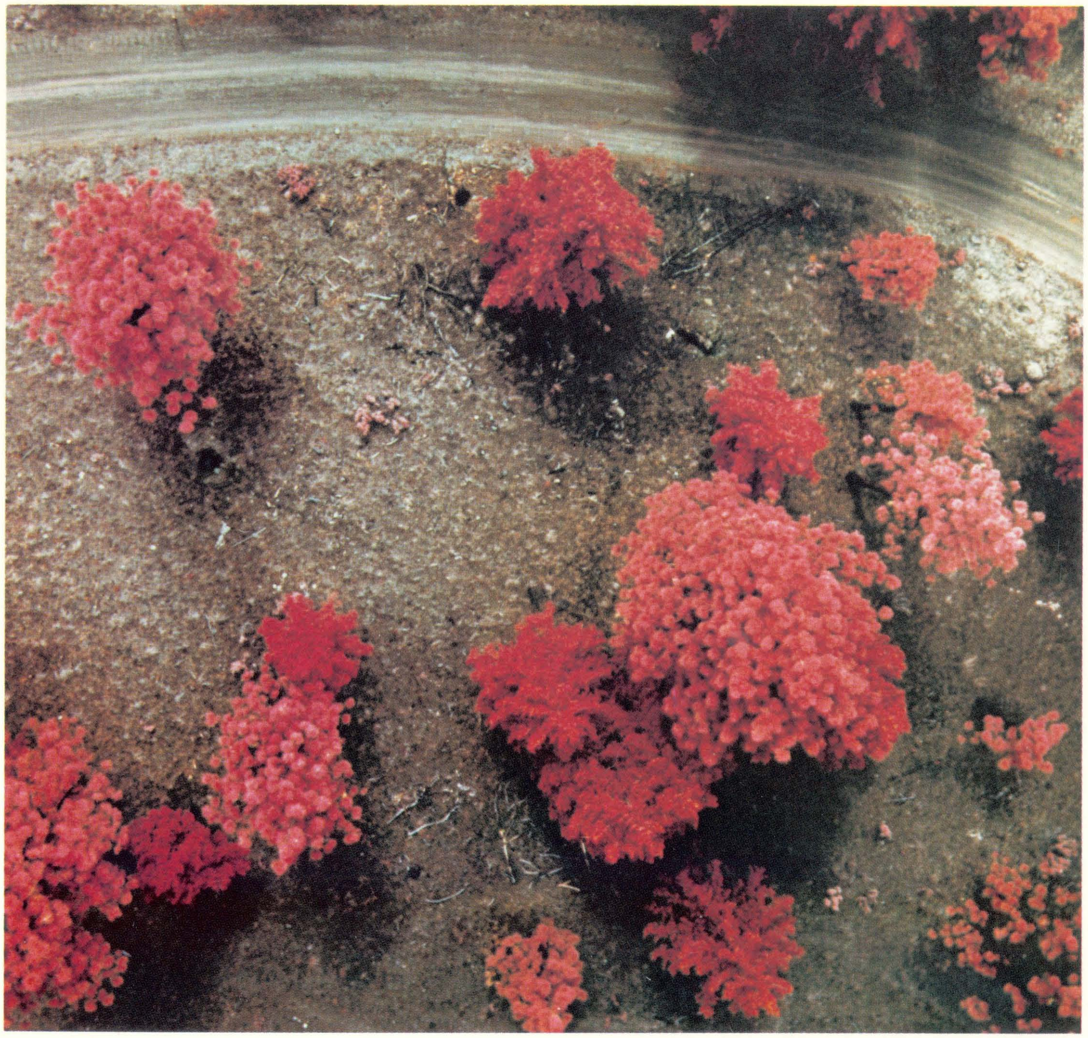
Nonvisual Remote Sensing of Trees Affected by Stress

A Review

by George S. Puritch



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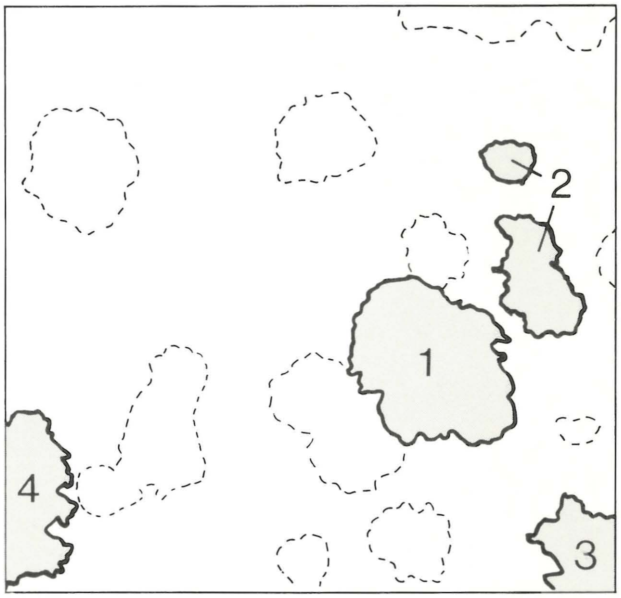

Cover photo

Aerochrome infrared (2443) photo showing open-grain ponderosa pine and interior Douglas-fir in a ponderosa pine-bunch grass plant community at Lower Dewdrop range, Kamloops, B.C. The varying magenta hues in the ponderosa pine are related to the health of the pine; dark magenta indicates a healthy tree (1) and the light magentas indicate varying degrees of stress (see the three pines, 2). The level of defoliation (i.e., noticeable loss of older foliage) is indicative of advanced physiological damage (note especially the pine in the upper right corner, 3). Another pine (4) shows (visual) red-brown foliage, and some thinning of the crown. A succession of range fires have passed through this section of range land and the fires have affected the health of the trees.

Air photo by Integrated Resources Photography, Vancouver, B.C. Research supported by a National Sciences Engineering and Research Council (NSERC) grant to Dr. P.A. Murtha, Faculty of Forestry, University of British Columbia, for studies in remote sensing for vegetation damage assessment.

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d'arbres soumis à des contraintes —
Examen critique*

Contents

Abstract

This paper provides a review of research dealing with the nonvisual remote sensing of stress-affected trees. A general background is provided of the characteristics of electromagnetic radiation (EMR) and some of the most commonly used sensing systems. The interaction of EMR with the foliage and the resulting effect on spectral reflectance are discussed for each region of the electromagnetic spectrum: visible, near-infrared, far-infrared, and thermal. A discussion is provided of the terminology of stress, strain, and previsual sensing, and more precise definitions are proposed. Research on the remote nonvisual sensing of strain in plants is reviewed according to the particular stress factor, which include water, insect, fungal disease, air pollution, chemical, and mechanical.

It is concluded that there is at present no *unique* spectral signature associated with all stress conditions that could be detected nonvisually. Strains of specific stresses, such as water, have been successfully sensed nonvisually by relating thermal infrared emissions to the water and energy balance of the plant. It is suggested that existing techniques may provide evidence of nonvisual strain, but they must be interpreted with a thorough understanding of the physiological alterations of stressed plants.

Résumé

Ce rapport présente une rétrospective des recherches portant sur la télédétection, par voie non visuelle, des arbres soumis à des contraintes. Il fournit des renseignements généraux sur les caractéristiques du rayonnement électromagnétique et de certains des capteurs les plus courants. On y examine l'action réciproque du rayonnement électromagnétique et du feuillage ainsi que l'effet produit sur la réflectance spectrale dans chacune des régions du spectre électromagnétique, soit le visible, l'infrarouge proche, l'infrarouge lointain et l'infrarouge thermique. Le document traite aussi de la terminologie relative aux termes contrainte, tension et détection prévisuelle, et propose des définitions plus précises. Il passe en revue les recherches portant sur la télédétection non visuelle des tensions dans les végétaux selon le facteur particulier de contrainte, c'est-à-dire eau, insectes, champignons, pollution de l'air, facteurs chimiques et facteurs mécaniques.

Le rapport conclut qu'il n'y a pas, à l'heure actuelle, de caractéristique spectrale *exclusive* associée à toutes les contraintes décelables par voie non visuelle. Des tensions résultant de contraintes spécifiques, par exemple celles de l'eau, ont été détectées au moyen d'instruments en associant les émissions thermiques (infrarouges) à l'équilibre hygrostatique et énergétique des végétaux. On estime finalement que les techniques actuelles peuvent fournir la preuve de tensions non visuelles. Toutefois, il faut savoir les interpréter à la lumière d'une connaissance approfondie des modifications physiologiques des végétaux soumis à certaines contraintes.

1 Introduction

Remote sensing has proved to be a valuable procedure for detecting, surveying, and appraising damage to forest trees. Large areas of forest stands, many inaccessible from the ground, can be assessed quickly; in some cases, the costs would be lower than with conventional ground assessment (Heller 1968). Sequential records can be obtained to detect the rate and extent of the spread of damage (Heller and Bega 1973). Different tree species can be identified, and in many cases, the damaging agents identified (Murtha 1972a). Remote sensing has also provided the capability of detecting damage at the time it occurs. This early detection is of real benefit to the forest manager as it permits corrective action to be taken before the occurrence of substantial losses and before the damaging agent (e.g. fire or insect epidemics) reaches uncontrollable proportions.

The ultimate in early damage detection would be to detect stress-affected trees before they could be identified visually. Accordingly, this area has been intensively investigated, involving many different types of stress, including drought, insect, disease, pollution, and a wide variety of tree species. As might be expected, the success of nonvisually detecting stress-affected trees has been highly variable, depending upon the particular system tested. The present review provides an examination of these reports on nonvisual detection and an evaluation of their usefulness.

As a preliminary to the actual review, a description is provided of the characteristics of electromagnetic radiation and the interaction of radiation with normal healthy plant foliage. This information is presented to provide a meaningful basis for understanding the spectral reflectance characteristics of stress-affected foliage. A section is also included on the terminology of stress, strain, and damage, because a proper evaluation of research on stress-affected trees can only be realized by the precise definition of the components analyzed. In other words, one must understand what stress and strain are before one can proceed to detect them. Finally, this review deals with research involving the sensing of nonvisual stress-affected trees and does not encompass the entire area of vegetation damage assessment.

2

The Electromagnetic Spectrum

2.1 General

As a consequence of the atomic and molecular interaction of energy and matter, energy is emitted and transmitted as a wave function called electromagnetic radiation (EMR). The velocity of propagation (c) is directly proportional to wavelength (λ) and to its frequency (f); i.e.,

$$c = f\lambda$$

Wavelength, in the equation, refers to the distance usually measured in micrometres, μm, between the two peaks of the wave (Fig. 1), and frequency is the number of waves per unit time.

The velocity of EMR is constant at 3 X 10^8 m/s (Suits 1975), a value readily recognizable as the speed of light. EMR consists of a whole range of waves, from very short gamma rays with a length of 0.003 μm to extremely long waves from oscillatory circuits up to 10 000 km in length (Weber et al. 1974). This range of EMR is termed the electromagnetic spectrum. Figure 2 (from Colwell et al. 1963) illustrates the spectrum along with the sources and interactions of the energy and various detector systems. At the bottom of the figure, the spectrum is identified according to the wave frequency measured in cycles per second (cps).

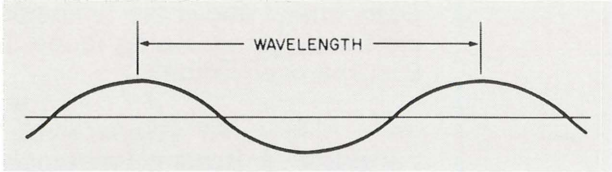

Figure 1. An electromagnetic wave.

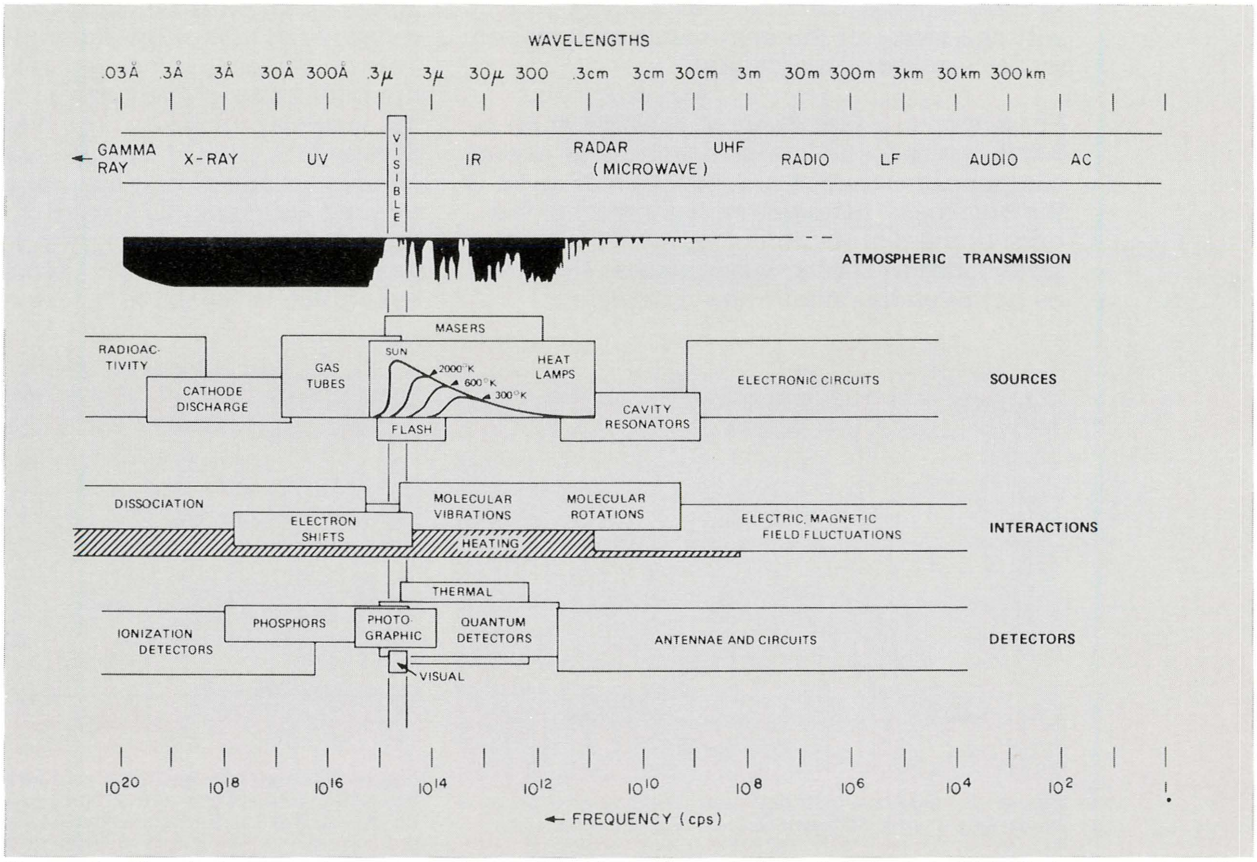

Figure 2. The electromagnetic spectrum. (Reproduced from Figure 1, Colwell, R.N. et al. 1963, Photogramm. Eng. 29; with permission of Photogrammetic Engineering and the authors).

2.2 Factors affecting EMR

Every object above the temperature of 0 K emits energy according to the Stefan-Boltzmann equation:

$P = \sigma AT^4$ (Weber et al. 1974)
where P = Radiant Emittance (watts/m^2)
A = Emissivity Factor
σ = Stefan-Boltzmann Constant (5.70×10^{-8} watt/m^2(K)^4)
T = Temperature in kelvins (K)

Since the amount of the emitted radiation is dependent on the fourth power of the temperature, small changes in temperature can cause relatively large changes in the amount of energy emitted. For the purposes of comparison, a standard called the "blackbody" is used as reference. A blackbody transforms heat energy into radiant energy at the maximum rate permitted by thermodynamic laws (Suits 1975). Thus it has an emissivity factor of unity. A blackbody emits energy as a continuous distribution across all wavelengths with the shape of the distribution determined by the blackbody temperature.

For example, a blackbody at a temperature of 300 K, emits a continuous spectrum of energy with a peak emission around 9.6 μm (Fig. 3). If the blackbody temperature is increased, the peak of the distribution of its emitted energy would shift to shorter wavelengths. This may be better understood if one considers a heated iron bar. At room temperature, 300 K, the bar will emit most of the radiant energy around 9.6 μm in wavelength; that is, in the thermal infrared region. As the bar is heated, its emitted energy wavelength maximum will shift to shorter and shorter wavelengths until it enters the visible wavelength range (0.4 to 0.7 μm). The emitted energy will then be seen as a red glow. Further heating will cause further shifts in the energy distribution pattern, causing the bar to appear successively orange, yellow, and finally white (Scherz et al. 1970).

The sun is the most important source of energy emission with respect to earth. It acts similar to a blackbody with a temperature of 6000 K, and thus has a peak energy emission at about 0.5 μm (Fig. 4). The bulk of the sun's energy, therefore, is expressed in the ultraviolet, visible, and infrared wavelengths (Coulson 1975). As illustrated in Figure 4, the actual energy flux reaching the earth's surface differs from that of the theoretical blackbody. This discrepancy is caused in large part by the interaction of the earth's atmosphere with the incoming radiation. The main absorption of energy is caused by water vapor, which creates several strong absorption bands in the infrared wavelengths. Ozone in the upper atmosphere absorbs strongly in the ultraviolet region. Oxygen along with ozone causes some absorption in the 0.6 to 0.7 μm region, and car-

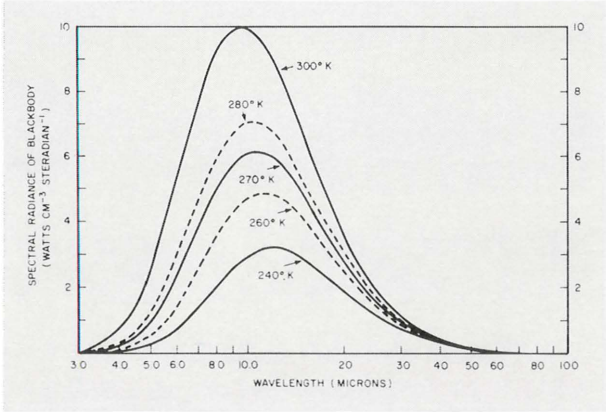

Figure 3. Spectral distribution of radiation emitted by a blackbody at various temperatures. (Reproduced from Figure 1.4, Coulson, K.N. 1975. Solar and Terrestrial radiation; with permission of Academic Press Inc. and the author).

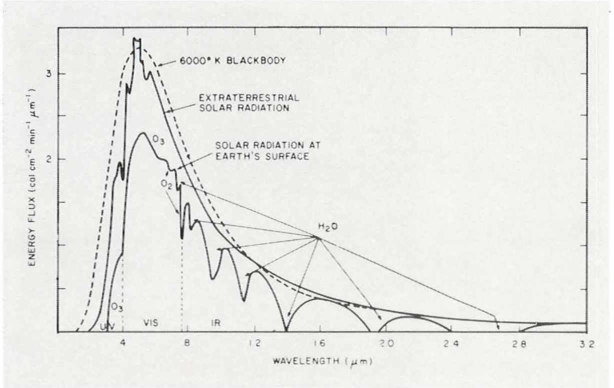

Figure 4. Spectral distribution of solar radiation at the top of the atmosphere, and a typical distribution of that which reaches the Earth's surface, compared with the radiation by a blackbody at a temperature of 6000 K. (Reproduced from Figure 3.1, Coulson, K.N. 1975. Solar and terrestrial radiation; with permission of Academic Press Inc. and the author).

bon dioxide absorbs to some extent in the infrared spectrum. Areas of the electromagnetic spectrum not affected by atmospheric components, and where energy reaches the earth virtually unhindered, are termed windows (Fig. 5).

Radiation from objects on earth fall into two main categories, reflected solar radiation and emitted radiation. As discussed, solar radiation at the earth's surface consists of energy contained mostly within wavelengths extending from the ultraviolet (0.3 μm) to the infrared (4.0 μm), and it is this region that is primarily utilized in remote sensing systems (Janza et al. 1975). These wavelengths also comprise what is generally termed light and, in particular, visible light (0.4 to 0.7 μm). Visible light can be further subdivided, because individual wavelengths in this portion of the electromagnetic spectrum are visible to the human eye as different colors (Scherz et al. 1970). Wavelengths between 0.4 to 0.5 μm appear blue, 0.5 to 0.6 μm appear green, and 0.6 to 0.7 μm appear red. When all these wavelengths are combined, the resultant color appears white. The ultraviolet (0.3 to 0.4 μm) and near-infrared (0.7 to 1.2 μm) are generally invisible to the human eye but can be detected easily with photographic techniques.

Each object in nature will appear to have its own color because of the selective reflection of sunlight. Reflection from the object will not only be dependent upon incoming radiation, but on certain morphological and physiological properties that influence absorption and spectral reflectance. These aspects will be considered in detail for leaf structures in the next section. Thus, when sunlight strikes an object, some wavelengths of energy will be reflected while others will be absorbed, and still others transmitted. Generally there is a distribution of energy so that all the energy received is either reflected, transmitted, or absorbed. The reflected wavelengths will cause the object to have a unique appearance that can be identified and used for remote sensing. Absorbed energy is transformed to thermal energy, which may raise the temperature of the object.

Thermal energy emission is the second basic category of radiation. Most objects on earth normally have temperatures between -40°C and +50°C (233 and 323 K) (Drying 1973). According to the laws governing energy emissions of blackbodies, they would emit most energy at wavelengths in the infrared region, with minor emission in the shortwave region (Fig. 3). Maximum intensity of energy emission would occur around 5 to 15 μm (Drying 1973). This region of the electromagnetic spectrum is also termed the thermal infrared and can be detected readily by means of carefully constructed thermal detectors. In certain cases, thermal emissions can be useful indicators of particular living plant functions, such as transpiration (Gates 1970).

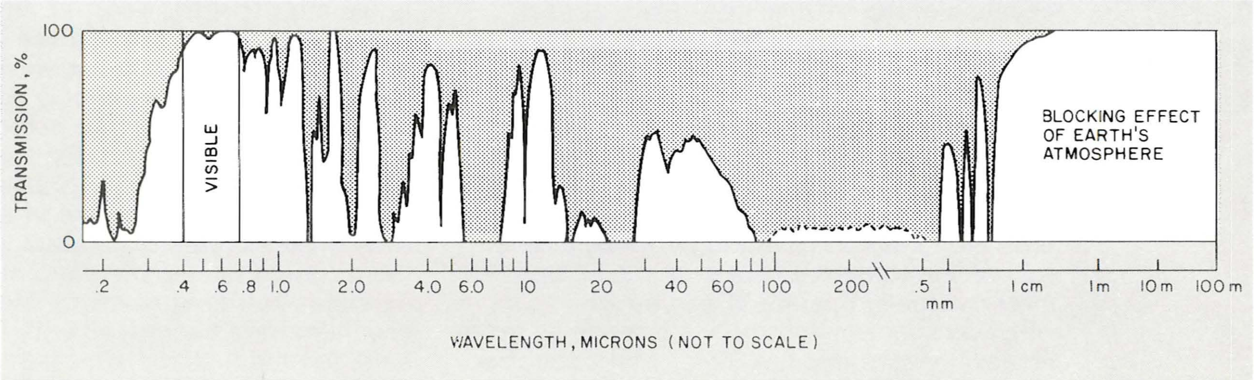

Figure 5. Effect of absorption by the atmosphere on electromagnetic radiation reaching earth. (Reproduced in adapted form, from Figure 1, Scherz, J.P. et al. 1970; with permission from the authors).

2.3 Techniques for sensing EMR

There exists a wide variety of techniques and instrumentation to detect and measure changes in EMR. These systems can be broadly divided into two main groups: the imaging-photographic systems, including black and white, color, and color-infrared films, and the nonimaging systems, including spectrophotometers, spectrometers, line-scanners, radar, microwave, etc. (Lowe et al. 1975). It is beyond the scope of this review to cover these systems in detail; however, it would be useful to examine those most commonly used in remotely sensing vegetation damage.

Photographic techniques are among the oldest and still most commonly used of the sensing procedures. Black and white film is sensitive to wavelengths from 0.36 to 0.72 μm and presents the variation in radiation as different shades of gray on a photographic print (Heller 1970a). Color film is sensitive over the same wavelength range as black and white, but allows much better discrimination because the three different dye-forming layers in the film (yellow, magenta, and cyan) respond to specific wavelength regions (blue, green, and red, respectively). Also, the human eye can separate 5 000 000 color combinations compared to about 200 shades of gray (Slater 1975). Color-infrared film (also called infrared-color, false color, and camouflage-detection film) extends the wavelength range sensed up to 0.9 μm. This film, like color, consists of three dye layers, but the yellow, magenta, and cyan dye-forming layers are sensitive to green, red,and near-infrared, respectively (Fritz 1967). Many of the investigations on sensing stress-affected trees utilize color-infrared film because of the relative sensitivity of near-infrared reflectance of the foliage to stress conditions of the plant.

For more precise measurements of EMR, measuring devices called spectrometers or spectrophotometers are generally used. A spectrometer is simply a sensor that measures the radiation from the target as a function of wavelength (Lowe et al. 1975). Spectrometers usually operate at and beyond 1 μm, whereas spectrophotometers operate at shorter wavelengths and the more recent spectrophotometers have ranges extending to about 2.5 μm. Spectrophotometers are commonly used in laboratory studies to obtain measurements of reflectance and transmittance from plant tissues, and to indicate areas of the electromagnetic spectrum that are most sensitive to changes in the plant stress conditions (Myers et al. 1970). Spectrometers are frequently used in the field and have been incorporated in many remote sensing systems, including various satellite systems, such as NASA's Skylab (Lowe et al. 1975).

Another widely used device for the aerial detection of EMR in the infrared region is the optical-mechanical scanner. These instruments sense over the entire infrared range and are particularly suited for detecting thermal infrared in the atmospheric windows of 4.5 to 5.5 μm and 8.5 to 13.5 μm (Lowe et al. 1975). The object-plane scanner basically consists of a rotating mirror that receives the radiation and reflects it through an optical system, where it is focussed onto a detector (Holter et al. 1970). The detector converts the photons of incoming radiation into free electrons, which are detectable as voltage or current variations. These output signals are, in turn, amplified and processed and used to modulate the intensity of light emitted from a glow tube. This light is then focussed onto a photographic film and scanned across it by a mirror on the same shaft as the main rotating mirror (Murtha 1972b). More recently, the infrared detector signal has been recorded directly on magnetic tape. As the aircraft moves along, the scanner provides a strip map of the image of the ground scene in the selected wavelength.

A variation of the optical-mechanical scanner is the multispectral scanner. In most scanners, filters are inserted in the radiation path to restrict only a particular wavelength range. In the multispectral scanner, detection is recorded in a number of discrete wavelength bands (Lowe et al. 1975). By observing these narrow spectral intervals, greater contrasts can be obtained among the images scanned. Also these contrasts are usually different in the different bands, thereby improving discrimination (Holter et al. 1970). Multispectral scanners have been used with favorable results to detect stress-affected trees (Heller 1970a) and have demonstrated good potential for future analyses.

3

Spectral Properties of Nonstress-affected Trees

As solar radiation comes into contact with the tree, it is primarily intercepted by the leaves, and it is the spectral reflectance of these structures that is mainly detected with the remote sensing systems. The interaction of radiation with the leaves is dependent upon many factors, including cuticular composition and structure, cellular organization, intercellular air spaces, cytoplasmic inclusions, pigments, water content, emissivity characteristics, and temperature. Once the leaves are developed on a tree, their spectral properties remain fairly stable unless affected by a stress-induced strain or naturally by aging. By identifying the various leaf components influencing reflectance in normal healthy leaves, clues can be obtained as to changes in reflectance that may occur as a consequence of strain.

3.1 Leaf structure

Figure 6 illustrates the cellular structure of a normal Douglas-fir needle at two stages in its development (Owens 1968). Very young leaves consist of an outer layer of epidermal cells (E), a compact mesophyll (M) with few air spaces, two resin ducts (R) extending along the edges of the leaf, and a central vascular bundle (VB) (Fig. 6a). At maturity the Douglas-fir needle loses its compact structure and is composed of large-lobed, spongy mesophyll cells (SM) interspaced with large air spaces (AS) and elongated palisade parenchyma cells (PP) (Fig. 6b). These cells along with the epidermal cells contain abundant chloroplasts. During maturation, a thick cuticle forms external to the epidermis (Owens 1968) and this, in turn, is coated with a layer of tubular wax crystals (Thair and Lister 1975). Stomata develop in two parallel bands of 6 to 10 rows on either side of the midrib of the abaxial (lower) surface and are encrusted with a thick layer of wax crystals. No stomata develop on the adaxial (upper) surface.

3.2 Interaction of leaves with radiation

As radiation contacts the leaves, it interacts in various ways, as illustrated in Figure 7 (Gates 1970; Colwell et al. 1963). A small amount is immediately reflected by the cuticular wax (Knipling 1970), while the bulk is transmitted into the inner surface of the leaf. Within the epidermis and palisade parenchyma, the radiation is diffused and scattered by encountering cell walls and protoplasmic constituents with different refractive indices (Gates 1970). Further scattering occurs within the spongy mesophyll when the radiation encounters intercellular air spaces (Gausman 1974). Much of this radiation, along with radiation reflected directly by cellular constituents (Gausman 1977), is reflected back through the leaf surface. The remaining radiation passes through the leaf, where it is termed transmitted radiation. On its passage through the leaf, certain wavelengths of radiation are absorbed by internal constituents of the leaf, such as chloroplasts and cellular water (Colwell et al. 1963). All the radiation contacting the leaf is thus reflected, transmitted, or absorbed (Woolley 1971).

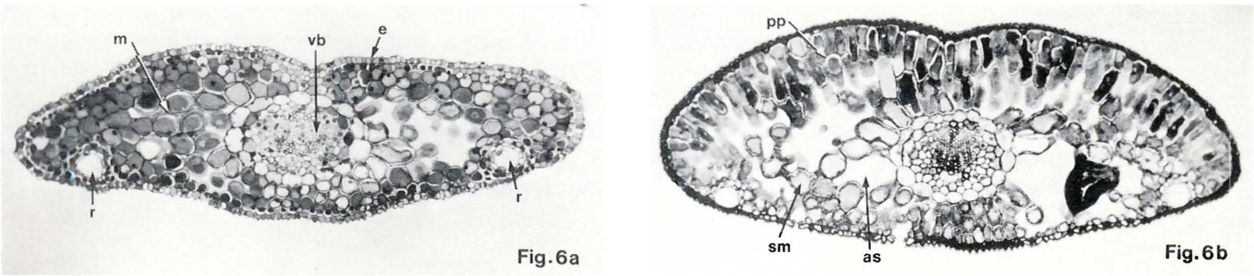

Fig.6a

Fig.6b

Figure 6. Internal structure of immature (a) and mature (b) Douglar-fir needles. m, mesophyll; vb, vascular bundle; e, epidermis; r, resin canals; pp, palisade parenchyma; sm, spongy mesophyll; as, air space. (Reproduced from Figures 13 and 14, Owens, J.N. 1968, Can. J. Bot. 46; with permission of the Canadian Journal of Botany and the author).

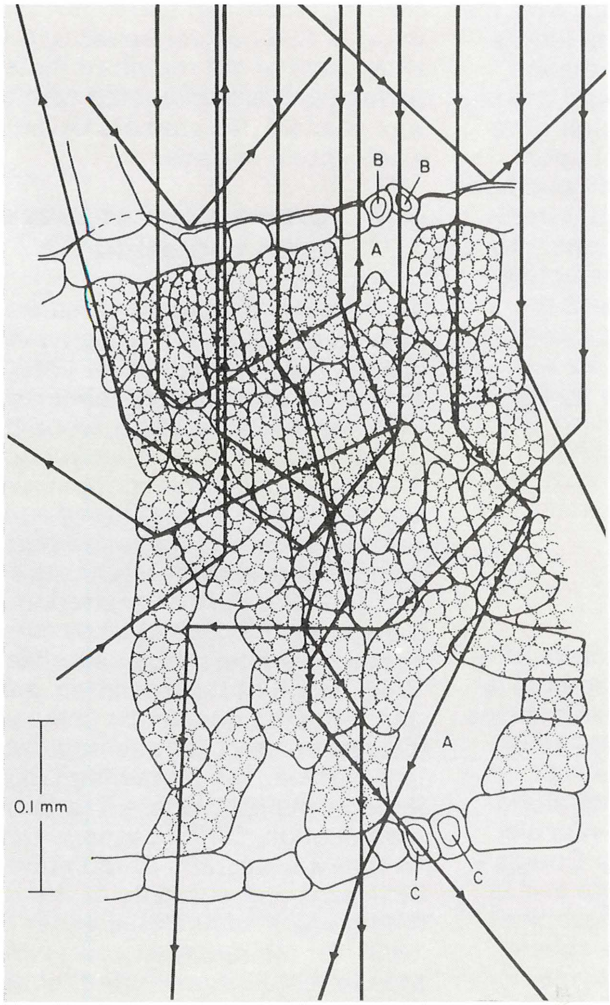

Figure 7. Cross section of leaf showing possible pathways of radiation. A, substomatal cavity; B, guard cells upper surface; C, guard cells lower surface. (Reproduced from Figure 3, p. 227. Remote sensing with special reference to agriculture and forestry (1970); with the permission of the National Academy of Sciences, Washington, D.C., and the author).

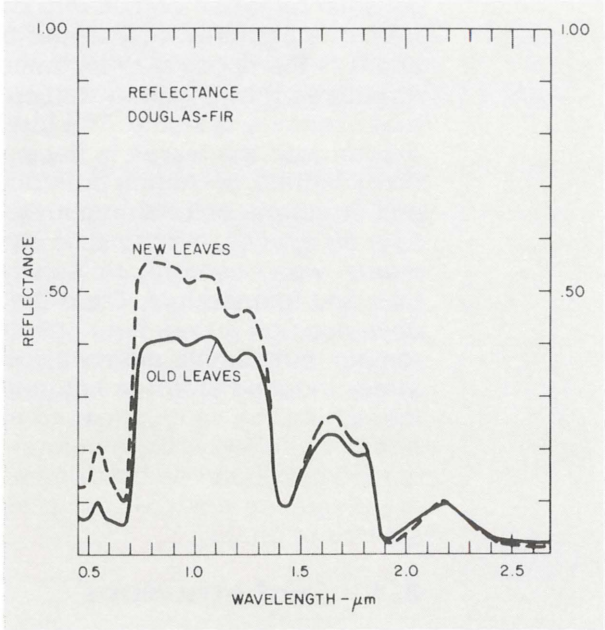

Figure 8. Reflectance of old and new leaves of Douglas-fir. (Reproduced from Figure 9, Woolley, J.T. 1971. Plant Physiol. 47; with permission of the American Society of Plant Physiologists and the author).

The special reflectance characteristics of old and new needles of Douglas-fir in late spring are demonstrated in Figure 8 (Woolley 1971). This pattern for Douglas-fir leaves is typical of most healthy green leaves (Gates 1970). Reflectance in the visible part of the spectrum is low, around 10%, and peaks around 0.55 μm. This peak is in the green region and results in the green appearance of foliage. At about 0.7 μm, the near-infrared region, reflectance abruptly increases and remains high until 1.3 μm, where it rapidly decreases, reaching a low point about 1.4 μm, which is one of the liquid water absorption bands (Gates 1970). Water also causes strong absorption at 0.9, 1.1, and 1.9 μm. The pattern of spectral absorption is exemplified in Figure 9, along with reflectance and absorption for the broadleaf poplar *Populus deltoides* (Gates 1970). Absorption is high in the ultraviolet, blue, and red regions but low in the green because of interaction with the plant pigments. In the near-infrared, absorption is virtually nil, but it is strong in the far-infrared. Transmittance, like reflectance, is low in the visible and far-infrared but high in the near-infrared.

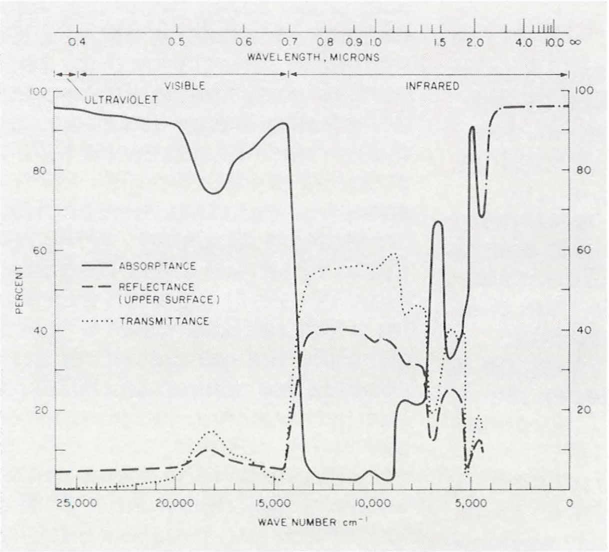

Figure 9. Spectral reflectance, transmittance, and absorptance for *Populus deltoides.* (Reproduced from Figure 1A, p. 225, Remote Sensing with special reference to agriculture and forestry (1970); with the permission of the National Academy of Sciences, Washington, D.C., and the author).

3.2a Interaction in the visible region of the electromagnetic spectrum

Pigment molecules, especially the chlorophylls, carotenes, and xanthophylls, are the main leaf factors affecting reflectance and absorption of radiation in the visible part of the electromagnetic spectrum. These molecules have the capacity of directly absorbing energy from the incoming radiation. This energy is used to move electrons to excited levels, which are then used in chemical reactions, or to create conditions in other materials that favor chemical reactions (Colwell et al. 1963). This complex biophysical-chemical interaction is the main driving force of photosynthesis (Goodwin 1976). Each pigment absorbs energy of different wavelengths within the visible region, as shown in Figure 10 (Gates 1970), but the main absorption occurs within two bands, one in the blue region and one in the red region. Absorption in the red is much less than in the blue (Fig. 10), but radiation scattering within the mesophyll cells produces complete absorption over a narrow wavelength region in the red (Gates 1970). With degeneration of chlorophyll, reflectance in the green region remains virtually unchanged, but the red reflectance increases, causing the color of the leaves to shift from green to yellow to orange and finally to deep brown (Fox 1978).

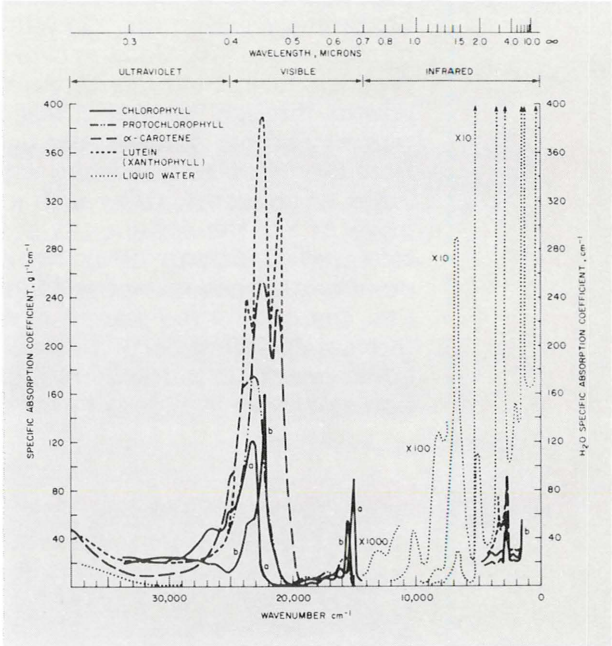

Figure 10. Spectral absorptance of some plant pigments and liquid water. (Reproduced from Figure 4, p. 228, Remote sensing with special reference to agriculture and forestry (1970); with the permission of the National Academy of Sciences, Washington, D.C., and the author).

3.2b Interaction in the near-infrared region of the electromagnetic spectrum

There is virtually no absorption of radiation at wavelengths between those absorbed by pigments and those absorbed by water; i.e., the near-infrared region. This "gap" in absorption occurs because liquid-water absorption results from molecular vibration and rotational changes that require radiation of lower energy than those absorbed by pigments (Colwell et al. 1963). The near-infrared region is thus characterized by high reflectance and transmittance (Gates 1970). Reflection in this region is dependent mainly upon refractive index discontinuities within the leaf and leaf morphology (Knipling 1970; Gausman 1974, 1977; Woolley 1971; Gates 1970). As the radiation passes through the leaf, it frequently encounters air cavities between the cells. By passing from the hydrated cell walls with a refractive index of about 1.4, to air with a refractive index of 1.0, the radiation is scattered or reflected (Gausman 1974). The greater the number of these refractive index discontinuities, the greater the degree of reflection from the leaf (Knipling 1970). Replacing the air with liquid results in a drastic reduction of reflection as shown in Figure 11 for cotton leaves (Gausman 1974). Reducing the relative water content of leaves by about 20% results in increased reflectance (Fig. 12). The increased number of air-cell interfaces that develop in dehydrated leaves has been suggested as a major cause of increased reflectance of water-stressed plants (Woolley 1971). Cellular constituents including membranes, cell walls, and protoplasts (Gausman 1974, 1977) also contribute to refractive index discontinuities, and Woolley (1971) reported that they accounted for a leaf reflectance of 8% at 0.8 μm. Besides affecting the number of refractive index discontinuities, Gausman (1977) reported that leaf components, including stomata, nuclei, cell walls, crystals, and chloroplasts, contribute directly to reflectance within the 0.7 to 1.1 μm wavelength range. Leaf cellular arrangement can likewise directly influence reflectance, and leaves with compact mesophyll have lower reflectance than leaves with more porous mesophyll (Gausman 1974).

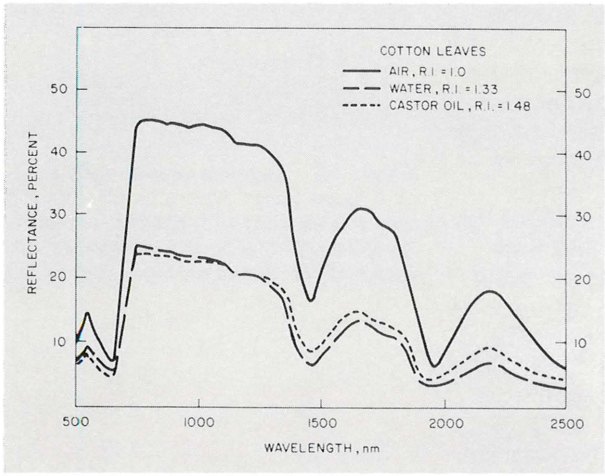

Figure 11. Effect of replacing air in cotton leaves with liquid on leaf reflectance. (Reproduced from Figure 1, Gausman, H.W. 1974. Photogramm. Eng. 40; with permission of Photogrammetric Engineering and the author).

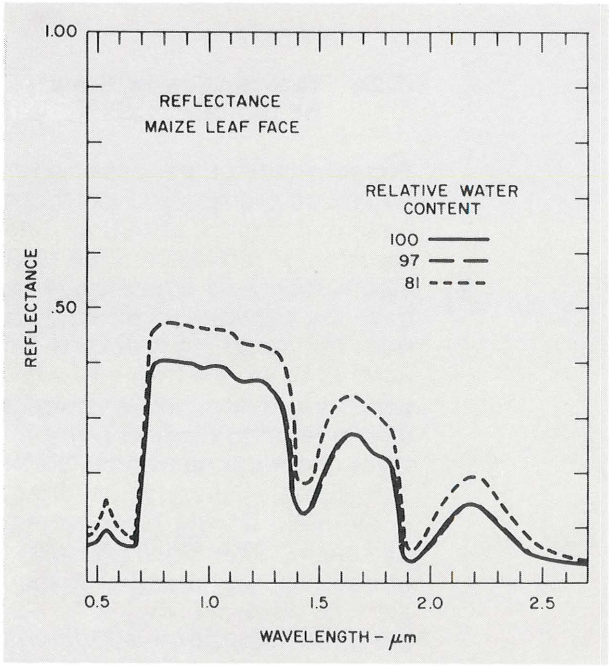

Figure 12. Reflectance of maize leaves containing different relative water contents. (Reproduced from Figure 20, Woolley, J.T. 1971. Plant Physiol. 47; with permission of the American Society of Plant Physiologists and the author).

3.2c Interactions in the far-infrared region of the electromagnetic spectrum

Spectral characteristics in this region are dominated by absorption of energy by liquid water within the leaf (Myers et al. 1970; Knipling 1970; Gates 1970). The main water absorption region occurs from 2.6 to 2.8 μm, with minor absorption bands at 1.93 μm and 1.45 μm (Myers et al. 1970). Figure 13 shows how absorption of radiation by water within the leaf changes the reflectance of a bean leaf (Knipling 1970). Allen et al. (1969) and Gausman et al. (1970) calculated the thickness of a sheet of water that would account for the absorption spectrum of a leaf (equivalent water thickness [EWT]), and found a close correspondence between the calculated value of 150 μm and the measured amounts of water in cotton and corn leaves. Gates (1970) stated that only large changes in leaf water content, such as drying, would significantly reduce reflectance in the far-infrared system.

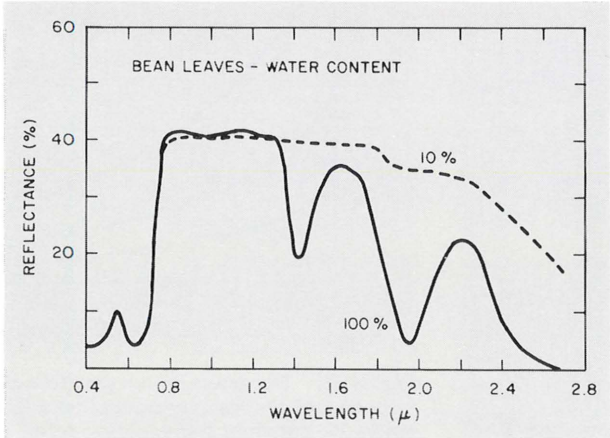

Figure 13. The effect of leaf dehydration on the spectral reflectance of bean leaves. The numbers on the curves, 10 and 100, refer to the water content of the leaves at the time of sampling as a percentage of their water content when fully hydrated. (Reproduced from Figure 3, Knipling, E.B. J. Remote Sens. Environ. 1; with permission of the American Elsevier Publishing Co. and the author).

3.2d Interactions in the thermal-infrared region of the electromagnetic spectrum

This region is dominated by emitted radiation from the leaves. At wavelengths beyond 2 μm, leaves act like blackbodies, emitting almost all radiation absorbed. This emission is mainly in the region around 10 μm (Gates 1970). As discussed in Section 2, The Electromagnetic Spectrum, the amount of energy emitted from an object is dependent upon its emissivity factor and the fourth power of its temperature according to the Stefan-Boltzmann equation (Smith and Cooper 1957). The emissivity of leaves is about 0.97 and is dependent upon the molecular and gross structure (Gates and Tantraporn 1952). The main factor affecting the radiation emission of leaves is therefore leaf temperature which, in turn, is dependent upon the leaf energy budget.

The complex relationship between leaf temperature and energy exchange processes has been the subject of intensive investigations (Gates and Tantraporn 1952; Tibbals et al. 1964; Gates 1964, 1968). Gates (1964) expressed the steady state energy exchange processes between the leaf and its environment, other than photosynthesis, by the following equation:

$$a_s (S + s) + a_t (R_a + R_g) = R_1 + C + LE$$

where a_s is the absorptivity of the leaf to sunlight, and a_t is the absorptivity to long wave thermal radiation. In this equation, Gates indicates the factors responsible for radiation absorption on the left of the equation and those responsible for dissipating radiation on the right side of the equation, where S is the incident direct solar radiation and sky light, s is the reflected sunlight from the ground, R_g is the incident thermal radiation from the ground, R_a is the incident thermal radiation from the atmosphere, R_1 is reradiation (emission) from the leaf, C is convection, and LE is transpiration. Photosynthesis, respiration, and other metabolic processes affect the energy balance, but their contribution to the balance is negligible (Gates 1964). (This is an important aspect in the consideration of sensing strain in trees using thermal infrared sensors.)

Thus, the three main mechanisms for altering leaf energy are reradiation, convection, and transpiration. Thermal infrared emission both affects and is affected by leaf temperature. Convection may heat or cool the leaf, depending upon the relationship between leaf temperature and air temperature (Gates 1964). If air is cooler than the surface temperature of the leaf, the air will cool the leaf by conducting heat from it. On the other hand, air will conduct heat to the leaf if the air is warmer than the leaf. Figure 14 (Gates 1964) demonstrates the influence of reradiation and convection on leaf temperature. This figure shows that if the total radiation absorbed by the leaf is 1.0 cal/cm^2·min and the air temperature is 30°C, the leaf temperature would be (i) 62°C (32°C above air temperature) if only reradiation cools the leaf, (ii) 48°C if convection and reradiation cool the leaf in the absence of air, and (iii) 37°C if the wind speed was 5 mph (223 cm/sec) and both convection and reradiation cool the leaf. A nontranspiring leaf can remain below a lethal temperature (about 50°C) if the air temperature is sufficiently low or if there is some air movement (Gates 1964).

Fortunately, plants are not solely dependent upon the fluctuations of air temperature and wind speed, but can physiologically alter their

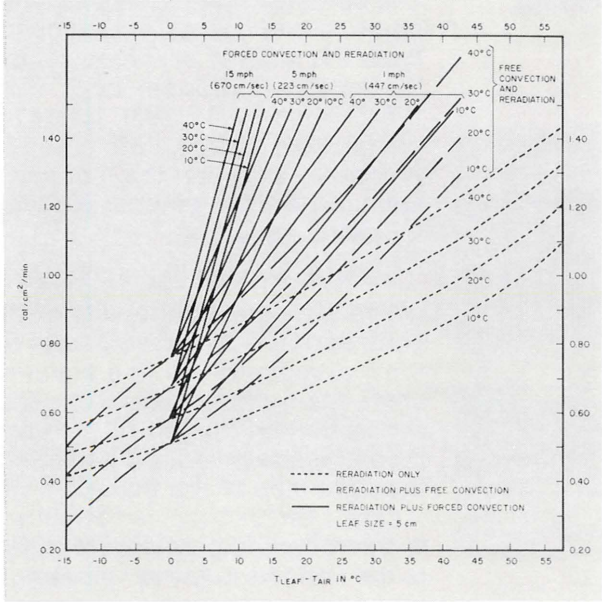

Figure 14. Energy exchange diagram for a leaf of width 5 cm showing the mechanisms by which absorbed radiation is dissipated by reradiation, convection, and transpiration as a function of the temperature difference between the leaf and the air. Each curve in the diagram represents the energy dissipated for a given value of air temperature as marked on the curve.
(From Fig. 1, Gates 1964a).

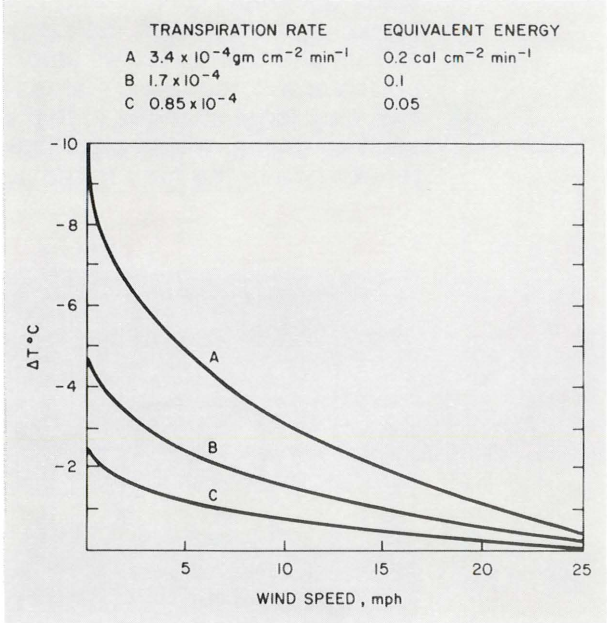

Figure 15. Departure of temperature of transpiring leaf from that of nontranspiring leaf as a function of wind speed for constant transpiration rates. (From Fig. 2, Gates 1964a).

leaf temperature by the process of transpiration. Transpiration is the loss of water vapor from the plant and mainly occurs through the stomatal pores of the leaf. By altering the size of the stomatal openings and the resistances of the water vapor diffusion pathway, the leaf can actively alter the rate of transpiration. This allows the plant to protect itself in times of adverse environmental conditions. The magnitude of transpirational cooling is quite substantial. Gates (1964) reports that a transpiration rate of $1.7 \times 10^{-4} g/cm^2 \cdot min$ reduces the radiation load on the leaf by $0.1\ cal/cm^2 \cdot min$, which would result in a drop of leaf temperature by 5°C below that occurring in the absence of transpiration in still air. The main influence of transpiration on leaf temperature occurs in still air or low wind speeds, as shown in Figure 15 (Gates 1964). With air movement, the effects of forced convection on leaf temperature become dominant and under these conditions, relatively large changes in transpiration rate are required to produce significant changes in leaf temperature (Gates 1964).

Since leaf temperature is directly affected by transpiration, and transpiration, in turn, is dependent upon the physiological state of the plant, changes in plant metabolism are reflected in the thermal infrared emissions. Thus this process is of major importance in utilizing thermal infrared analysis to detect changes in tree physiology. This aspect will be covered in more detail in the next section.

4 Remote Sensing of Stress-affected Trees

4.1 Terminology

Before embarking on an examination of remote sensing techniques used to evaluate stress-affected trees, it is essential to clarify exactly what stress means and what is being sensed. The requirement for precise definitions was emphasized by Murtha (1972a), who defined damage as "any type and intensity of an effect on one or more trees, produced by an external agent, that temporarily or permanently reduces the financial value or impairs or removes the biological ability of growth and reproduction, or both." Murtha (1978a) again indicated that lack of proper identification of the meaning of plant damage hindered evaluation of remote sensing procedures for detecting damage. This concern was acknowledged by participants at the 1978 Symposium on Remote Sensing for Vegetation Damage Assessment, and a resolution was passed calling for authors to take greater care in use of the words damage, injury, and damage class, and to carefully define them (Murtha 1978b).

Actually, the use of the word damage, and particularly stress, has caused concern not only to remote sensing specialists but to plant physiologists in general. Stress has sometimes been used to indicate the external force that causes physiological and morphological changes in the plant, whereas in other cases, it is used to indicate the changes themselves. Thus, it is used both as the cause and the effect. Levitt (1972) attempted to resolve this problem in his review on the responses of plants to environmental stresses by using the mechanical definitions of stress to develop a terminology for biological organisms. In the physical sense, stress is a force acting on a body measured in force per unit area. Based on this definition, Levitt described biological stress as any environmental factor capable of producing a potentially injurious physical or chemical change (strain) in living organisms. These environmental factors encompassed biotic factors, such as insects and disease, as well as abiotic factors, such as climatic extremes and mechanical damage. It should be emphasized that Levitt's definition restricts stress to *environmental factors* and not to the *condition* of the tree. In the literature, stress is frequently used in the latter context, i.e., indicating impairment of the tree's physiological functioning. An important aspect of Levitt's definition of stress is that the environmental factor can *potentially* cause injurious change to the organism. Thus, stress may cause strains that are not injurious over short periods of time. Stress factors are many and varied and are usually expressed in terms of energy units such as bars of water stress. Each stress will cause its own syndrome of responses in the plant, although frequently these responses are common to more than one stress.

The chemical or physical changes that occur in plants as a result of stress are termed strains by Levitt (1972). He considers strains to consist of two types; one that is reversible upon release of stress, termed elastic strain, and one that is irreversible, termed plastic strain. The irreversibility of plastic strain consists solely in the thermodynamic sense, and the strain can be repaired by the expenditure of metabolic energy. Strains are, therefore, the physiological state of the tree that occurs as a result of stress.

In sensing vegetation damage, the object is to detect the strain in plants and not the stress. Time is a major factor in considering if strain will cause damage. For instance, elastic strains will be detected as long as the plant is stressed, but will disappear if the stress is removed. An example of this is the effect of water stress on transpiration. If leaf cells are subjected to water deficits, the free energy of water (water potential) in the leaf cells decreases. When this water potential reaches a certain level, for example -12 bars for *Abies balsamea* (Puritch 1975), the stomata close and transpiration is drastically reduced. As long as the leaf water potential is maintained below -12 bars, the strain of impaired transpiration persists. Once the water deficits are removed, the water potential increases, stomata open, and transpiration resumes. Strains of this nature occur frequently in healthy trees during warm summer days when water deficits reach levels that impair transpiration during part of the normal diurnal cycle. While experiencing this strain, the temperature of the trees will increase, as discussed in the last section, and this increase will be detectable in thermal infrared emissions. Later in the day, the water deficit of the trees will decrease and the trees will again transpire, decreasing the thermal infrared emission. The strain of reduced transpiration will not cause permanent damage to the plant unless it persists for some time, thereby causing secondary effects.

Elastic strains, being reversible, are usually of short duration and, consequently, it is the longer-lasting plastic strains that usually cause damage and are generally detected in remote sensing systems. Perhaps the best example is the effect of water stress on leaf growth. In conifers, leaf primordia are formed within the buds during the summer growing period, overwinter in the bud, and grow during the following spring (Duff and Nolan 1958). If the trees experience drought during mid- and late-summer, the number of leaf primordia formed will be substantially reduced (as much as 40% in *Pinus strobus*) (Zahner 1968) and the number of leaves maturing the following spring will be correspondingly less. Thus, even though water stress is relieved during the winter and spring, the strain of reduced leaf primordia formation persists into the next year. Water stress during the period of leaf growth will cause other plastic strains, such as changes in internal leaf anatomy (Parker 1952), stomatal number, and cuticle thickness (Thames 1963). Plastic strains will therefore occur both during stress and for varying periods after stress.

Because of the diversity of strains and their interaction with time, it is evident that proper evaluation of stress-affected trees requires a thorough understanding of the types of strain resulting from each particular stress. Thus, if one wishes to sense trees affected by water stress, one should become familiar with both the short-term strains, such as reduced transpiration and higher leaf temperature, and the long-term strains, such as reduced leaf size and number that result from this stress. The same holds true for biotic stresses and their resulting strains. In fact, Murtha (1972a) developed a valuable key to forest-damaging (stress) agents based on the characterization of the damage (strain) types.

An appreciation of the type and degree of strain resulting from various stresses is most important for assessing previsual stress or more correctly, strain. Previsual strain is generally regarded as strain that can be detected by sensing systems before it can be detected visually; i.e., by the unaided human eye. Murtha (1978a) hypothesized that changes in the reflectance of stressed plants would occur first in the near-infrared region, and he also stated that previsual strains may not appear later in the visible region. For these reasons, he coined the term extra-visual to indicate the first near-infrared reflectance changes. For the purposes of this review, however, it was felt that changes in the reflectance characteristics, which could not be detected visually regardless of wavelength, would be included because they would be useful as early indicators of strain in stressed plants. These changes even include changes in the wavelengths described as visual (0.4 to 0.7 μm) that cannot be detected by the human eye, but are measurable by other means. However, in agreement with Fox (1978), they do not include changes not evident visually because of lack of proper sensor orientation or close scrutiny.

It was decided, therefore, to simply use the term *nonvisual* rather than previsual, or extra-visual to indicate these strains. Nonvisual strains are consequently defined as strains that can be detected by sensing systems, but which are not evident visually. Nonvisual strains may be both elastic and plastic, but tend to fall mainly into the former category because plastic strains usually involve pigment or morphological changes that are readily evident visually. Thus, it is the short-term, reversible, biochemical or physical changes that are generally detected as nonvisual strains. The proper assessment of the damaging effects of these strains on the plant necessitates an understanding of the affected physiological functions and their responses over time. Specific examples of this will be shown in the next section.

4.2 Review of the application of remote sensing techniques to detect nonvisual strain in plants

Following the clarification of terminology for stress and strain in Table 1, it is now possible to evaluate the various remote sensing techniques used to assess strain in plants. The detection of visual strain in plants has been described in a number of excellent articles (Murtha 1972a; Heller 1971; Myers 1974; Hildebrandt 1969), and will not be covered in detail in this review. Rather, emphasis is placed on the reports dealing with nonvisual sensing of plants. These reports are examined and the usefulness of the applied techniques evaluated. In view of the dependence of strain on the particular stress giving rise to that strain, the reports are dealt with according to the particular stress investigated.

4.2a Sensing of plants affected by water stress

Many researchers have reported that water stress causes increased reflectance in the near- and far-infrared region (Thomas et al. 1966, 1967; Carlson et al. 1971; Knipling 1970; Woolley 1971; Myers et al. 1970; Olson et al. 1971). Thomas et al. (1966) reported that reflectance of cotton (*Gossypium hirsutum* L.) leaves increased throughout the spectral range 0.4 to 2.5 μm as leaf moisture decreased below a relative turgidity of 80%, and that the greatest change occurred at 1.45 μm. Thomas et al. (1967) used a spectrophotometer to analyze reflectance of single cotton leaves from plants grown under different conditions of soil salinity. They found a significant correlation between decreased relative turgidity of the leaves and increased leaf reflectance

Table 1.
Terminology of stress, strain, and damage

Term	Category	Definition
Stress	Cause	Any environmental factor capable of producing a potentially injurious strain in living organisms[1].
Strain	Effect	Any biochemical or physical change caused by stress.
Elastic Strain	Effect	Strains immediately reversed upon release of stress.
Plastic Strain	Effect	Strains that persist in the organism after stress has been relieved[2].
Damage	Effect	Any type and intensity of strain, on one or more trees, produced by a stress that temporarily or permanently reduces the financial value, or impairs or removes the biological ability of growth and reproduction, or both[3].
Nonvisual Strain	Effect	Strains not evident visually that can be detected by remote sensing systems.

[1] Adapted from Levitt (1972).
[2] Note that plastic strains can be reversed by the expenditure of metabolic energy (Levitt 1972).
[3] Adapted from Murtha (1972a).

throughout the spectral range 0.5 to 2.5 μm. The chlorine content of the leaves also had a significant effect on reflectance, except at 1.45 and 2.2 μm, where only relative turgidity was significant.

Carlson et al. (1971) investigated the relationship between reflectance of individual leaves of corn (*Zea mays* L.), sorghum (*Sorghum bicolor*), and soybean (*Glycine max* L. Merr. Hawkeye) at four wavelengths (1.1, 1.45, 1.95, and 2.2 μm) and relative water content (RWC) of the leaves. They found RWC significantly correlated with reflectance, and except for the 1.1 μm wavelength, RWC accounted for more than 80% of the variability in leaf reflectivity. Reflectivity was increased by about 4% for every 10% decrease in RWC. This increase in reflectivity was not due to altered leaf thickness, but the inclusion of a leaf thickness term added a significant contribution to the regression of reflectance to RWC. The change in reflectivity with RWC is not unique, however, to the infrared wavelengths.

Woolley (1971) reported that reduction in RWC altered reflectivity in the visible region, especially around 0.54 μm, although the direction and magnitude of the altered reflectivity depended on the plant species tested. A decrease in RWC from 97 to 77% caused an increase in reflectance (at 0.54 μm) in maize, no change in soybean, and a slight decrease in cotton.

Olson et al. (1971) investigated the relationship between leaf moisture and reflectance of individual leaves of several broadleaf trees. They obtained a close correlation between leaf moisture content (oven dry weight basis) and infrared reflectance for yellow birch (*Betula alleghaniensis* Britton), sugar maple (*Acer saccharum* Marsh), and white ash (*Fraxinus americana* L.). In all cases, reflectance increased as leaf moisture decreased, the largest differences within and between species occurring at wavelengths between 1.3 and 2.6 μm.

Both time and plant characteristics can affect the spectral response to water stress. Olson (1969) reported that the effects of water stress on reflectance of yellow poplar (*Liriodendron tulipifera* L.) depended upon the time stress was applied. If the leaves had developed before stress occurred, the leaves increased in reflectance at wavelengths of 0.8 and 1.65 μm, but did not differ from controls at other wavelengths. Analysis of leaves formed under stress showed that they were less reflective than controls in the visible region (0.55 μm), but greater in the infrared region. Olson et al. (1971) investigated the relationship between leaf spectral reflectance and water stress during the growing season for two species of ring porous trees (white ash and red oak [*Quercus rubra* L.]), and two species of diffuse porous trees (sugar maple and yellow poplar). Reflectance of individual white ash leaves, which leafed out under water stress and which were stressed after reaching full size, increased at all wavelengths from 0.5 to 2.6 μm. Reflectance differences of 4 to 5% were found at wavelengths from 1.5 to 1.8 μm and 2.0 to 2.6 μm, respectively, *before* any change in visible reflectance. Sugar maple and red oak also showed increased reflectance as a result of stress, but with yellow poplar, only the leaves that had reached full size before being subjected to stress increased in reflectance. Leaves that flushed out and matured under water stress, during the growing season, were less reflective at all wavelengths from 0.5 to 2.6 μm than well-watered controls.

Olson et al. (1971) attributed the variation in type of response to stress of the different species to the time of leaf flushing and to growth characteristics. They suggested that leaves of yellow poplar, which grew under water stress, developed xeromorphic characteristics that caused decreased reflectance. Leaves of white ash, however, were developed before stress occurred and therefore were affected more by an increase in cell wall-air interfaces, resulting in increased reflectance. These results again demonstrate the need for understanding the types of strains resulting from stress, as discussed in the previous section, although Olson et al. (1971) did detect nonvisual strain resulting from water stress in white ash at least. With the other species, changes in the visual spectrum did occur, but small changes in moisture content did not change visible reflectance until high levels of water stress were reached.

These studies show that, in most cases, water stress can be detected through the strain of reduced moisture content of the leaves and its effect on infrared reflectance. However, there are certain disadvantages to the application of this technique. Reflectance changes in the plant canopy may not conform to the reflectance changes of individual leaves because the canopy has it own characteristics, including size, shape, and orientation of the plants, all of which can alter reflectance. For instance, Myers et al. (1970) reported that, although individual cotton leaves increased in infrared reflectance when subjected to water stress, the reflectance of the canopy as a whole decreased. Knipling (1970) indicated that this type of situation could occur because of leaf loss or change in leaf orientation owing to wilting and the resulting increase in the amount of background surfaces exposed to the sensors. It has been suggested that the magnitude of moisture content changes required for alteration of infrared reflectance are too great to indicate the initial stages of water stress where most of the physiological damage occurs (Knipling 1967).

The value of using the technique for conifers is also doubtful. Murtha and Hamilton (1969) were unable to correlate moisture content and infrared reflectance in mechanically damaged white pine (*Pinus strobus* L.), white spruce (*Picea glauca* [Moench] Voss), eastern white cedar (*Thuja occidentalis* L.), and balsam fir (*Abies balsamea* [L.] Mill.). Conifer leaves are very dense and are composed of thick, rigid cell walls (Fig. 6); consequently, small changes in needle moisture are associated with large changes in needle water potential (Puritch, unpublished data). Thus, substantial strains may occur before spectral reflectance changes can be detected.

It would appear, therefore, that the usefulness of using infrared reflectance to detect strains resulting from water stress has to be evaluated for each particular plant system tested. On the other hand, in certain cases, such as white ash (Olson et al. 1971), the technique may prove very valuable as a means of sensing nonvisual strains resulting from water stress.

While the practical use of near- and far-infrared emissions to sense water stress still requires further investigation, the thermal infrared region has already been utilized with considerable success on certain crop plants. Unlike the near- and far-infrared regions, the factors affecting thermal infrared emissions have been intensively investigated for a number of years, primarily as part of research on evapotranspiration and plant water relations (Clum 1926; Curtis 1936; Tanner 1963; Slatyer and Bierheuzen 1964; Gates 1964, 1968; Ehrler and van Bavel 1967; Bartholic et al. 1972; Ehrler 1973; Ehrler et al. 1978). As discussed previously, transpiration was recognized as playing a major role in the energy budget of the plants (Gates 1968). Reduction of transpiration, without changing wind speed and radiation balance, led to increased leaf temperatures and consequently increased thermal infrared emissions, whereas increased transpiration caused the reverse effect (Clum 1926; Curtis 1936; Gates 1968). Numerous studies had shown that transpiration was strongly correlated to water stress via the effect of leaf water potential on stomatal opening (Slatyer 1967). Consequently, various investigations were undertaken to compare the effect of different levels of water stress on leaf temperature.

Wiegand and Namken (1966) subjected field-grown cotton plants to varying levels of water stress (as determined by relative turgidity of the leaves), and assessed the effect on leaf temperature (T_L) (measured with a radiometer). They reported that a decrease in relative turgidity from 83 to 59% resulted in an increase of 3.6°C in T_L relative to control plants. Ehrler and van Bavel (1967) compared the water relation and T_L responses of grain sorghum (*Sorghum vulgare* var. RS-610) in dry and wet soils.

They found that limited soil water in the drier soil restricted evapotranspiration and caused the T_L (measured with thermocouples) to increase relative to that of air. Ehrler (1973) reported that moderate soil water depletion was sufficient to cause a measurable rise in the leaf-air temperature difference (ΔT) (measured with thermocouples) of four cotton cultivars, but that interpretation of the ΔT values required knowledge of the saturation deficit of the air (i.e., difference between the saturation vapor pressure and the existing vapor pressure at any given temperature). Sandhu and Horton (1978) grew spring oats (*Avena sativa* L.) under different levels of soil moisture by controlling the amount of applied water. They measured T_L with thermocouples and reported that the T_L of water-stressed oats was 2.5 to 4°C warmer than the T_L of well-watered plants during the period of maximum solar radiation on cloudless days. Ehrler et al. (1978) compared the water potential (ψ) of wheat (*Triticum durum* Desf.) leaves to changes in ΔT, detected by a radiometer, for plants subjected to varying amounts of irrigation. They found that ΔT responded specifically to changes in ψ as shown in Figure 16 (this figure also shows the variation of ΔT with time of day, indicating the diurnal fluctuation in transpiration). They concluded that the temperature difference method for monitoring plant stress in wheat could be reliably used in monitoring large acreages of wheat from aircraft, or satellites, if frequent measurement of ΔT could be made.

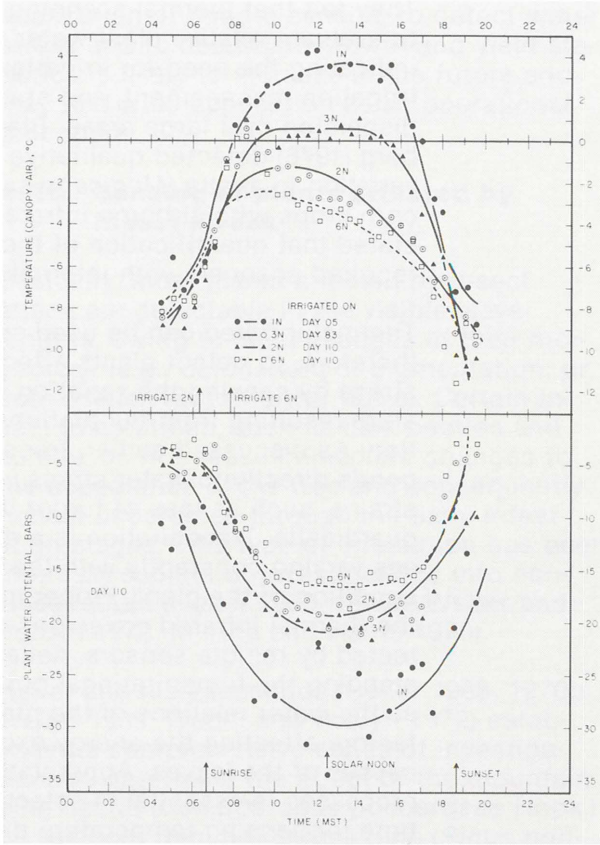

Figure 16. The daily course of the whole-plant water potential and temperature of the canopy minus the air temperature at 1.5 m above the crop on 22 Mar. 1976 (day 110 after planting) as affected by four levels of soil water content: 1N, 0.159; 3N, 0.210; 2N, 0.287; and 6N, 0.326, by volume. (Reproduced from Figure 4, Ehrler, W.L. et al. 1978. Agron. J. 70: 251-256; with permission of the American Society of Agronomy and the author).

Various studies have shown that T_L differences between stressed plants can be detected by airborne thermal sensors. Myers et al. (1970) analyzed the canopy temperature of small, differentially irrigated, cotton plots and obtained temperature differences between dry and wet plots of 0.1, 0.3, 2.0 and 0.2°C at 5:40 a.m., 9:35 a.m., 3:20 p.m., and 10:10 p.m. local standard time, respectively. These temperature differences again reflected the daily fluctuation of transpiration. Rohde and Olson (1970) girdled balsam poplar (*Populus balsamifera* L.), red maple (*Acer rubrum* L.), and oak (*Quercus* spp.) in four different plots in May and July, and measured temperature differences with thermal infrared sensors. They were able to detect the plots of girdled oak during the day (2:00 p.m.), but not during the night, and were unable to detect the balsam poplar plots. Bartholic et al. (1972) used an aerial thermal scanner to detect temperature differences in cotton grown in plots subjected to severe, moderate, and no water stress. They reported that the severely water-stressed plot had a temperature of 37°C and a water potential (ψ) of -24 bars, whereas the well-watered plot had a temperature of 30°C and a ψ of -15 bars, and the moderate stressed plot, a temperature of 31°C and a ψ of -17 bars.

They felt that thermal scanning could be used to evaluate relative plant water stress, thereby indicating the need for irrigation, evaluation of irrigation management, and study of rainfall dispersion over large areas. Blad and Rosenberg (1976) detected qualitative temperature variation in alfalfa (*Medicago sativa* L.) and corn crops with airborne infrared sensors, but stated that quantification of the differences required scanners with internal calibration.

Thermal infrared can be used successfully, therefore, to detect plants affected by water stress by sensing the variation in leaf temperature resulting from fluctuations in transpiration. As discussed earlier, transpiration responds directly to water stress via various strains, such as loss of turgor in the stomatal guard cells. Transpiration is a dynamic process varying constantly with the physiological condition of the plant. Proper interpretation of the thermal infrared emissions of leaves, detected by remote sensors, necessitates understanding the transpirational process as well as the water relations of the plant and other factors affecting the energy exchange processes of the leaves. Appreciation of all these processes is essential in selecting the proper time for sensing temperature differences. The successful remote detection of plants affected by water stress is not the final step, however. There must be a further evaluation of the levels and duration of water stress that cause damage.

An excellent example of this procedure is the work of Idso et al. (1977) on the remote sensing of crop yield in wheat (*Triticum durum* Desf. var. Produra). Based on the difference in temperature between the leaf and air (ΔT), they devised a stress degree day (SDD) relationship, where the final yield (Y) of the wheat crop was linearly related to the total SDD accumulated over a certain period. This relationship was defined by the following equation:

$$Y = \alpha - \beta \left(\sum_{i=b}^{e} SDD_i \right)$$

where SDD was the midafternoon (around 2 p.m.) value of ΔT, on day i, and b and e represent, respectively, the days on which the summation procedure was to begin and end.

Idso et al. (1977) tested the SDD concept by varying the irrigation on six plots of wheat. They selected the period from the initiation to cessation of head growth as the period to sum values of ΔT, and determined that this period could be ascertained from changes in albedo of the crop. They found a good linear relationship between the SSDs accumulated during the crucial head growth period, and both the length of the growth period and the total grain yield (Fig. 17). They also showed that the air temperature could be adequately estimated from calculations involving the midafternoon - presunrise canopy temperature differential and ambient air temperature obtained within a few kilometres of the field site.

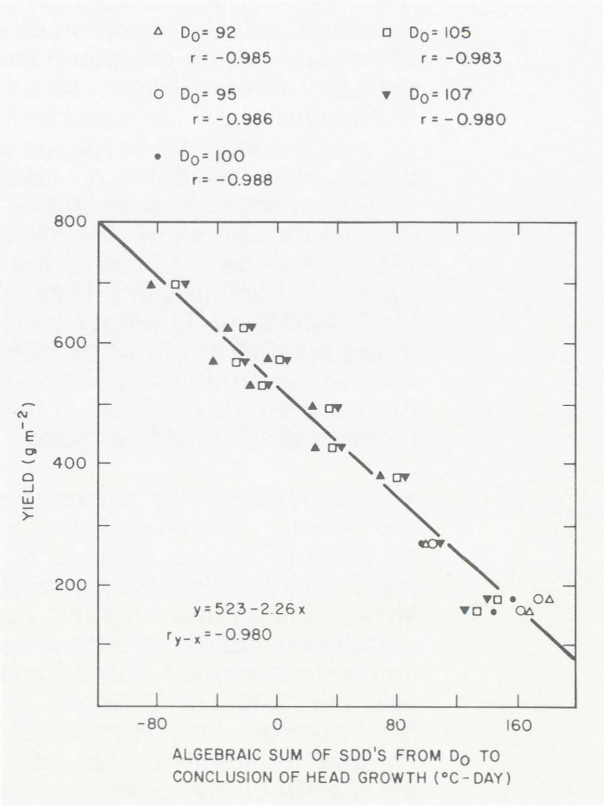

Figure 17. Final grain yields for 12 field sites of wheat versus the total accumulation of SSDs from head emergence to the cessation of head growth. Results are shown for five different starting dates (D_O). (From Fig. 4, Idso et al. 1977).

Millard et al. (1978) used airborne thermal sensors to detect the canopy temperatures of the same wheat plots tested by Idso et al. (1977). They found a highly significant correlation between the canopy temperature obtained from the air and that obtained from the ground, and demonstrated the validity of using data obtained from airborne sensors to calculate the SDD of the crop. They also found that canopy temperatures at about 2:00 p.m. were closely correlated with predawn plant water potential.

Thus, it is practical to use remote thermal infrared sensing to detect the strains of water stress in certain field crops and to provide reliable estimates of crop yields and schedules for irrigation. There are, however, certain limitations in applying thermal infrared sensing techniques.

Leaf temperature is very sensitive to the effects of transpiration at low wind speeds. Slight breezes, even less than 1.6 km/h, can reduce leaf temperature to near air temperature (Gates 1970). Also, since solar radiation exerts an even stronger influence on leaf temperature than transpiration, variable solar radiation due to cloudiness and shading by other leaves will mask leaf temperature variations because of transpiration. Consequently, sensing is primarily restricted to clear, sunny days with very little wind. In addition to these climatic limitations, there are various aspects of the plant crop itself to consider. If the plants do not cover the soil surface, the soil will contribute to the radiance sensed and may cause considerable errors (Myers et al. 1970). Variation in plant size will result in shaded areas that will influence the temperature of the total crop. Heterogeneous crops will also interfere in the overall crop temperature, owing to the variation in emissivity characteristics of the different plant species and their differing response to water stress.

Fortunately, as Ehrler (1973) points out, crops likely to experience water stress conditions are usually situated in dry, sunny areas. Also, most of the commercially important crops are homogeneous and consist of the same size and age. This is true even of reforested, uniform, even-aged stands of conifers. Thus, the application of remote sensing to detect water stress and to determine growth and yield statistics is likely to increase in the future and may find wide application as an operational procedure.

4.2b Sensing of plants affected by insect stress

Basically, most plants affected by insect attack are detectable in the visible wavelengths, owing to rapid changes in their morphology (e.g., defoliation) or pigmentation, or both (Heller 1971; Murtha 1972a). Certain insect infestations, such as bark beetles and aphids, do not cause immediate changes to the appearance of the tree and consequently remain undetected through the early infestation stages. This type of infestation has been the main subject of investigations into nonvisual strain (Heller 1968, 1970b; Weber and Polcyn 1972; Murtha and Harris 1970).

Heller and his associates (Heller 1968, 1970b; Weber 1969; Weber and Polcyn 1972) established a comprehensive series of investigations to determine the effect of the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) on the host tree, ponderosa pine (*Pinus ponderosa* Laws.) and the feasibility of detecting nonvisual strain in the infested trees. The mountain pine beetle enters the bark of the trees in midsummer and chews through the phloem, where it mates and lays eggs. During its penetration into the bark, the insect introduces several microorganisms, including two blue stain fungi, *Ceratocystis montia* and *Europhium clavigerum* (Safranyik et al. 1975). These fungi penetrate the ray cells and, in susceptible trees, spread radially and vertically in the stem, where they disrupt the movement of water through the sapwood. The fungi are further spread by the mining of the beetle larvae around the stem during the following few weeks. As a consequence of the fungal colonization, large areas of sapwood are eliminated as conducting pathways, and the trees experience severe water deficits. If this induced water stress occurs quickly, the trees will undergo rapid decline and die during the latter part of the summer and early fall. Frequently, however, the trees show no visible change until the following spring. It is this period after beetle infestation, but before beetle damage is visible, that has been assessed for detecting nonvisual strain.

Because the strains induced by the bark beetle mainly involve those induced by water stress, Heller (1968) concentrated on measuring parameters of water relations (e.g., needle water potential, transpiration, soil moisture) and tree energy balance (e.g., leaf and air temperature, solar radiation, humidity, and wind velocity). Measurements were continuously collected throughout a 2-year period, from August 1965 to October 1967, on these parameters as well as on foliage color, beetle populations, and number of infested trees.

Spectral characteristics of the test trees were determined from aerial photographs (color and color-infrared) in October 1966 and in May, June, July, and August 1967, and from optical-mechanical scanned imagery in three wavebands (2.0 to 2.6 μm, 4.5 to 5.5 μm, and 8.0 to 14.0 μm) in October 1966 and in June 1977.

Forty-five days after beetle attack, spectrophotometric readings of foliage from the newly infested trees showed a slight increase in reflectance at 0.68 μm and a decrease in reflectance of 5 to 10% at 0.75 to 1.2 μm. Heller (1968) felt that these small differences would not be detectable, however, when the normal reflectance differences within the species were taken into account. It is interesting that he was unable to observe structural changes in the needles during this period.

Interpretation of the aerially-obtained color (visible and near-infrared) photography showed that infested trees could not be discriminated from healthy trees three months after beetle attack. This interpretation was accomplished by making three templates of the photos for each site; one enclosing the boundaries of the site, one indicating the trees designated as off-color by the photo interpreter, and one identifying the trees as discolored, or not discolored, as seen from the ground. The order of photo interpretation was randomized for each site, film, and photo date to prevent bias. Radiometric measurements made from adjacent trees or towers showed that in June 1967, known dying trees were 6 to 8°C warmer at 10 a.m. than healthy trees and 4 to 6°C warmer at 2 p.m. Unfortunately, Heller had difficulty in resolving individual tree crowns as healthy or dying with airborne thermal sensors. He concluded that the successful application of thermal techniques required scanners with improved optical qualities, providing improved spatial and thermal resolution.

In 1970, Heller (1970b) reported on further work on the bark beetle research and stated that visibly indistinguishable infested trees still could not be discriminated with color or color-infrared film, using their photo interpretation techniques. Detection of differences in thermal emissions between infested and healthy trees was improved, using a University of Michigan multispectral line scanner, but discrimination was still not adequate. Weber and Polcyn (1972), reporting on the same investigation, stated that although attacked green pine could be distinguished on 8.2 to 13.5 μm imagery, the few degrees temperature difference between infested and healthy trees indicated that radiance from the former was frequently masked by radiance variations of healthy trees. Both Heller (1970b) and Weber and Polcyn (1972) felt that the development of a single aperture, multispectral scanner combining thermal, near-infrared, and visible channels would greatly assist the sensing of nonvisual strain in trees attacked by bark beetles.

Another insect stress interaction that has been investigated for the detection of nonvisual strain is that of balsam woolly aphid (*Adelges piceae* Ratz.) (Murtha and Harris, 1970; Murtha 1972a). This aphid populates the stems of mature trees and feeds on nutrients in the living bark cells. Through components in its saliva and its disruption of the bark cells during feeding, it alters the physiology of the tree and causes deterioration and death after several years (Balch 1952). Like the bark beetle, it also disrupts the water flow through the stem and causes water stress conditions (Puritch 1971). The effects of aphid on the tree are not as rapid as with bark beetles, and the trees will support aphid populations for several years before being damaged.

Several early papers showed that aphid-induced tree mortality could be satisfactorily determined from aerial photographs (Pope 1957; Aldrich and Drooz 1967; Heller et al. 1967). Heller et al. (1967) reported that interpretation of color aerial photographs correctly detected damage in 14 trees that had been designated as healthy from ground assessments. Murtha and Harris (1970) measured the density of the developed cyan dye layer of color-infrared film and inferred reflectance differences of aphid-infested amabilis fir (*Abies amabilis* [Dougl.] Forbes). They obtained an accuracy of 83% in distinguishing trees with aphids and were able to correctly identify trees as infested, based on their appearance on the color-infrared film, although these trees appeared normal from the ground. They felt that it might be possible to delineate aphid damage prior to visible strain in the tree.

4.2c Sensing of plants affected by fungal disease stress

Similar to insects, pathogens usually cause serious disruption of the normal physiological functions of plants and cause morphological changes that are visibly evident. Unlike the situation with insects, however, there can be a significant interval between the time of infection by the pathogen and the onset of visible symptoms in the host. There is more opportunity for sensing of nonvisual strains in diseased plants and this area has been actively investigated.

Colwell (1956) determined the effect of rust (*Puccinia graminis avenae*) infection on the spectral reflectance of mature, field-grown oats (*Avena* spp.). He reported that there was an observable reduction in infrared reflectivity very shortly after the plants became diseased and 2 to 3 weeks before any changes in the visible wavelengths. He suggested that the early change in infrared reflectivity was caused by invasion of the fungal hyphae into the mesophyll cells, thereby reducing their reflectivity to infrared radiation. In a later paper (Colwell 1964), he proposed that another contributing factor to the reduction in infrared reflectance may have been the collapse of mesophyll cells, because of water stress caused by the effects of the rust on the plants' water supply. This latter suggestion seems unlikely because later work (Knipling 1970) has shown that loss of turgor and collapse of mesophyll cells would increase, not decrease infrared reflectance. Olson et al. (1971) proposed that a lower infrared reflectance could occur if the plants grown under water stress developed xeromorphic characteristics compared to well-watered plants. If this occurred in the diseased oats, it may have contributed to the lower infrared reflectance observed by Colwell (1956).

Manzer and Cooper (1967) reported that they were able to detect potatoes (*Solanum* spp.) injected with late blight before the occurrence of visual symptoms, using densitometry on color-infrared films. Wallen and Jackson (1971) used infrared film to photograph white bean (*Phaseolus vulgaris* L.) infected with the bacterial blight, *Xanthomona phaseoli.* They detected more diseased plants by the infrared films than by visual observation. In one case, only 50% of the disease centers recognized from the air were observed from the ground. A few days later, additional disease foci appeared on the ground and these correlated with the earlier foci detected by remote sensing. In later investigations, Jackson and Wallen (1975) were unable to detect differences between diseased and healthy plants until the late stages of infection, when visual symptoms became prominent. Basu et al. (1978) carried out similar analyses of peas (*Pisum sativum* L.) infected with root rot (*Fusarium solani* f. sp. *pisi*), and found that they could not detect the moderately diseased plants.

There have been many attempts to detect nonvisual strain in root-rotted trees (Neuberg 1969; Murtha and Kippen 1969; Wear 1970; Weber and Wear 1970; Weber 1971; Heller 1971; Weber and Polcyn 1972; Heller and Bega 1973; Murtha 1972b), or vascular-wilted trees (Murtha 1970; Roth et al. 1963; Olson et al. 1971; Meyer and French 1972; Fairweather et al. 1978). In the root rot syndrome, the fungal pathogen (e.g. *Fomes annosus* [Fr.] Cke. or *Phellinus* [*Poria*] *weirii* [Murr.] Gilbertson) invades the roots of the trees and penetrates into the sapwood and heartwood. Within these tissues, the pathogen seriously disrupts the cellular organization and water conduction pathways of a tree. With severe infection, water flow through the stem can be restricted and this leads to water deficits in the crown. The rate of spread of both these pathogens depends upon several biotic and abiotic factors, but is relatively slow, in some cases extending over several years. Trees are able to cope with a substantial reduction of their conducting pathways without visually showing ill effects (Kramer 1969), although they may be infected by root rots for a number of years but outwardly appear normal.

The vascular wilts, e.g. *Ceratocystis ulmi* (Buism.) C. Moreau, which causes Dutch elm disease (DED), and *Ceratocystis fagacearum* (Bretz) Hunt, which causes oak wilt, seriously affect the water relations of their hosts. These fungi are usually spread by an insect vector, typically a bark beetle, and penetrate the vascular system of the tree. Within the xylem, the fungi interact with the host cells and cause metabolic and structural changes (Olson et al. 1971). This host-pathogen reaction leads to the formation of tyloses within the vessels, which restrict water flow, and also results in metabolites that may act as toxins (Ayres 1978). These disorders in the vascular system disrupt water flow through the stem, and diseased trees exhibit symptoms similar to water stress. Unlike root rots, the vascular wilts cause visible reactions in the host soon after infection occurs.

Weber and Wear (1970) presented results of a comprehensive study on the remote sensing of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) infected with *Phellinus (Poria) weirii* (Murr.) Gilbertson. Earlier research by Wear (1970) and Neuberg (1969) had shown that diseased trees generally displayed higher thermal infrared emissions when sensed with a helicopter-borne radiometer, although certain diseased trees had lower temperatures. Weber and Wear (1970) set up detailed experiments to clarify these anomalies. They constructed a tramway system above the mature healthy and diseased trees and used this to carry short- and long-wave sensors. These sensors were continuously monitored for the complete growing season (120 days). Measurements were included of environmental (rainfall, soil moisture, wind speed, dew point, and air temperature) and physiological (sap flow velocity, xylem pressure potential, and leaf temperature) parameters, and imagery of the trees was obtained with an airborne, University of Michigan optical-mechanical line scanner. They reported that, contrary to expectations, the infected trees recorded slightly lower water stress than healthy trees and similar rates of sap flow throughout the summer. The infected trees also had lower thermal infrared emission than healthy trees, and Weber and Wear (1970) attributed this to reductions in the physiologic processes of respiration and metabolism. In a few isolated situations, infected trees did show temperatures above those of healthy trees, but these were inconsistent and not considered relevant.

Analyses of the remotely sensed photographic and multispectral data likewise indicated no differences in the spectral characteristics of the healthy and diseased trees. The energy data, however, revealed that the infected trees consistently had a higher average albedo (ratio of reflected shortwave energy ([0.4 to 4.0 μm] to incident shortwave energy), than healthy trees. Weber and Wear (1970) concluded that *Poria* infection had little effect on water balance and energy exchange of the trees and was more of a low-grade stress that affected respiration and metabolism over long periods of time. Because of the effect on albedo, they suggested that if *Poria* could be sensed nonvisually, it would be done in the range between 0.32 to 2.6 μm.

Investigations on sensing *Fomes annosus* in conifers have produced results similar to those of *Phellinus.* Heller (1971) and Heller and Bega (1973) both reported that research to that date had not detected *Fomes* infection on color or color-infrared film before visible foliar discoloration. Olson (1972) reported on several studies involving the detection of *Fomes* infection in pine plantations. He stated that correlation of the 1.5 to 1.8 and 1.0 to 1.4 μm channels gave good results for detecting openings in the crown canopy and adjacent trees. There was no conclusive evidence, however, of the detection of nonvisual strain in the diseased trees. Murtha and Kippen

(1969) analyzed two centers of *Fomes* infection in a pine plantation using color-infrared film. By measuring the density of the cyan dye layer of color-infrared film, using a red-filter on an optical densitometer, they found there was a decrease in tree image density of the cyan dye layer with increasing distance from the infection center. In his airphoto guide to forest damage, Murtha (1972a) suggested that the variation in density of the cyan layer may be indicative of nonvisual strain. Analysis of *Fomes*-infected red pines, using airborne thermal sensors, failed to detect any differences between the diseased and healthy trees (Murtha 1972b).

Overall, the attempts to detect nonvisual strain in trees infected with root rots have been unsuccessful. The same is basically true for trees diseased by vascular wilts, although there have been a few possible exceptions. Murtha (1970) located Dutch elm diseased trees using airborne thermal infrared sensors at a time when the trees had a visibly normal complement of green foliage. Only the 3 to 5 μm night-time imagery revealed the distinction between healthy and diseased trees. In a later paper, Murtha (1972b) reported that he could detect a diseased elm with no visual symptoms, by using a thermal scanner at night. Infected elms have been detected with color-infrared film (Meyer and French 1972), but there has been no success in using these films to detect nonvisual strain (Fairweather et al. 1978).

Olson et al. (1971) reported on experiments undertaken by J.A. Bruno on foliar reflectance changes during oak wilt pathogenesis. Reflectance was affected by changes in leaf moisture, similar to the situation with water stress; however, the leaf moisture levels of diseased trees varied radically. Because of this, and also the short time between changes in leaf moisture and appearance of visible symptoms, it was concluded that nonvisual sensing of strains of oak wilt was even less likely than sensing of water stress. Other reports (Roth et al. 1963; Ulliman and French 1977) have indicated that even aerial detection of visual strains of oak-wilted trees posed certain problems.

Besides root rots and vascular wilts, there have been attempts to sense nonvisual strains of various other tree pathogens. Douglass et al. (1972) reported on the results of their investigations on sensing dwarf mistletoe (*Arceuthobium pusillum* Peck) in black spruce (*Picea mariana* Mill.). Dwarf mistletoe is a parasitic plant that penetrates the host tree tissues and lives off the water and nutrients of the host. It causes deterioration of the metabolism of the tree and may cause mortality after several years. Douglass et al. (1972) tested various color and color-infrared films, and combinations, but found no evidence of nonvisual strains in the infected trees. They were unable to detect any definite spectral signature associated with dwarf mistletoe. They also reported on the sensing of aspen infected with hypoxylon canker (*Hypoxylon mammatum* Miller), a stem disease, using color or color-infrared film, but they were unable to detect infected living trees.

4.2d Sensing of plants affected by air pollution stress

With the increasing awareness of the effects of air pollution on the environment, investigations have been undertaken, using remote sensing to detect pollution damage. One air pollutant that has been assessed is ozone, O_3, a gas formed by photochemically induced reactions involving nitrogen oxides and hydrocarbons. Ozone affects plants by damaging the mesophyll cells of the leaves and by inducing necrotic spots. In some plants, the leaves exhibit wilting and older leaves become senescent (Heggestad and Heck 1971). Experiments on poplar, *Populus deltoides,* (Lillesand et al. 1975) and cucumber, *Cumis melo* L., (Gausman et al. 1978) have shown that ozone-induced leaf damage can be detected nonvisually.

Lillesand et al. (1975) subjected young poplar to ozone fumigation at 0.03 ppm while under laboratory conditions. They were able to detect resulting strains in the leaves, using infrared film and a 8.0 μm narrow band filter, before any changes were visible on normal color film. Damage was visible at the end of 6.5 hours on the infrared film, but not until

24 hours on the color film. Gausman et al. (1978) carried out similar experiments on cantaloupe. They exposed the plants to ozone at 0.18 ppm and measured the reflectance characteristics of the leaves in both the laboratory and field. There was no difference between treated plants and controls in either the visible or near-infrared wavelengths, but stressed plants had greater reflectance at the 1.45, 1.65, 1.95, and 2.2 μm wavelengths, the regions of water absorption. The stressed leaves had correspondingly lower water contents than the control leaves. Damage of the treated plants was detected on Polaroid photographic film 16 hours before it could be seen visually.

4.2e Sensing of plants affected by chemical stress

Plants are frequently stressed as a result of an excess or deficiency of certain chemicals in their growing media. Each type of stress causes particular types of strains within the plant that are visible as abnormalities, such as leaf curl, chlorosis, tip burn, necrotic spots, and wilting. These visible manifestations of chemical stress have been identified and categorized and are commonly used as diagnostic aids (Chapman 1966). As with other types of stress, the visual changes in the plants are the end result of physiological and morphological alterations within the leaf cells. There have been attempts to sense these nonvisual strains in certain chemical disorders, especially soil salinity.

Salinity stress occurs when plants are grown in soils containing an excess of salts, especially NaCl, $CaCl_2$, and $MgCl_2$ (Thomas and Wiegand 1970). As a result of the salt concentration, the osmotic potential of the soil water is decreased, and this necessitates the formation of lower than normal water potentials within the plant to permit water absorption. In other words, the water in saline soils is less available to the plant than in nonsaline soils and, consequently, the plants are exposed to a greater degree of water stress. Besides water stress, the plants are affected by an excess of salt ions. The leaves of the saline-stressed plants are thicker than normal, owing to expanded growth of the spongy mesophyll and palisade cells. Cell size is decreased and the leaf blade is hairier (Thomas et al. 1967). Early in the growing season, the leaves of the saline-stressed plants are more succulent than the nonstressed plants, but later, as water stress occurs, the water content is reduced in the saline-stressed leaves.

Most of the research on sensing saline-stressed plants has been concentrated on the water-stressed condition of the affected plants (Myers et al. 1970; Thomas et al. 1967; Gates 1970). Thomas et al. (1967) reported that soil salinity increased the percentage reflectance of single cotton leaves and decreased the percentage transmission of the incident radiation from 0.5 to 2.5 μm. They attributed the increase in near-infrared reflectance to a greater number of cell wall-intercellular spaces, resulting from more mesophyll cells being available. Increased reflectance at wavelengths beyond 1 μm was correlated with a lower leaf moisture content in the stressed plants. Myers et al. (1970) stated that water-stressed plants differed from saline-stressed plants in that the reflectance of the former was unchanged at wavelengths greater than 1.35 μm. They suggested that the changes in the reflectance of saline-stressed plants at wavelengths greater than 1.35 μm might be due to increased solute concentration within the cell cytoplasm. The increase in solute content does not occur with water stress. Myers et al. (1970) showed that by using thermal infrared emissions saline-stressed cotton plants could be distinguished from nonstressed plants. They attributed the increased temperature of stressed plants to the increase in water stress and resulting decrease in transpiration. Gates (1970) reported that saline-stressed alfalfa plants were 2 to 3°C warmer than normal plants.

There have been few reports of detecting nonvisual strains of chemical stress other than that of salinity. Thomas and Oerther (1972) measured reflectance of nitrogen-deficient sweet pepper (*Capsicum annum* L.) leaves with a spectrophotometer. They reported that nitrogen-deficient leaves had a higher reflectance than normal leaves at visible and near-infrared wavelengths, but a lower reflectance in the far-infrared (1.3 to 2.5 μm) region. Although visual changes did occur in stressed plants, they were able to measure differences in reflectance before observing them. Press (1974) reported that bean plants (*Phaselus vulgaris*) grown on soil contaminated with heavy metals could be distinguished by a higher reflectance at 0.55 μm and a lower reflectance in the near-infrared. This distinction, however, was only evident by spectroradiometric measurements and not by color-infrared or multiband photography.

4.2f Sensing of plants affected by mechanical stress

Murtha (1968) and Murtha and Hamilton (1969) investigated the effects of simulated animal damage on the spectral reflectance of four conifers: white pine, white spruce, eastern white cedar, and balsam fir. Murtha subjected the trees to three levels of crown-clipping (50, 75, and 95%) and three levels of stem girdling ($^1/_3$, $^2/_3$, and complete) during the fall, and recorded the reflectance changes before treatment and throughout the following growing season. Murtha reported that damaged trees were reduced in near-infrared reflectance before any changes in the visual green color of the trees. Differences in the near-infrared reflectance were difficult to see, but were measurable on the density readings obtained from the original color-infrared photos, using an optical densitometer equipped with a red filter. As discussed earlier in the section on water stress, Rohde and Olson (1970) girdled balsam poplar, red maple, and oak and were able to detect treated oak trees with thermal infrared sensors, but could not distinguish treated poplar or maple. Hagner (1969) was able to detect higher temperatures in a spruce (*Picea abies* [L.] Karst.), severed from its roots, using an AGA Thermovision system at a time when few visual changes were evident.

5

Discussion

After examining the literature, is it possible to answer the question "can strain in stress-affected trees be sensed nonvisually?" Unfortunately, it is now evident that this question is too simple and cannot be answered without qualification. As described in this review, there are many types of stress factors and each causes particular syndromes of biochemical and physical changes. It is not adequate to simply refer to stress or strain in the general sense. Each particular stress factor, and even the type of strains analyzed, should be defined. This is particularly true with insect or disease stress, where the specific insect or fungal pathogen should be identified. It is also apparent from the literature that knowledge of the physiological and morphological characteristics of normal healthy plants and their alterations with stress are essential to the proper understanding and interpretation of reflectance characteristics. This is most clearly demonstrated with the sensing of water-stress affected trees, as will be discussed later. Similarly it should be realized that strains can occur during stress and for varying lengths of time after stress is removed. Finally, nonvisual, as defined in this review, means not distinguishable by the human eye and does not exclude changes in the visible wavelengths that are measurable, but not visible.

With these points in mind, what is the status of nonvisual sensing? With respect to water stress, the thermal infrared region has been used successfully in numerous studies to identify nontranspiring, water-stressed plants. The success of these analyses stems primarily from well-documented studies of thermodynamic water relationships of plants and their interaction with the environment. This knowledge has permitted meaningful interpretation of data and direct correlation between the energy emittance of leaves, their transpiration water flux, and the degree of water stress existing in the plant. The use of thermal infrared emissions to detect strains of water stress is more than just of academic interest, as demonstrated by the work of Millard et al. (1978) on wheat. By using the remote sensing data, and further correlating duration and extent of water stress with wheat crop yields, they were able to accurately quantify the grain yield from crops exposed to different watering regimes. Thus, this technique has not only provided a way to detect water stress conditions, but has provided a practical procedure for estimating agricultural crop yields by remote sensing. However, thermal infrared sensing of water stress conditions may not be equally successful in all applications. As was outlined in the previous section, several factors, especially the existing climatic conditions, may significantly interfere with the thermal infrared emittance from the leaves.

Strains, due to water stress, other than those of reduced transpiration and increased leaf temperature, have been detected at wavelengths other than the thermal infrared region, but reported results are highly variable. In several cases, water stress has caused increased reflectance in the near-infrared region before any visible changes (Thomas et al. 1966; Knipling 1970; Olson et al. 1971); in other cases, it has caused a decreased near-infrared reflectance (Olson et al. 1971). As discussed earlier, Olson et al. (1971) attributed these discrepancies to variations in the strains of water stress resulting from timing and duration of stress, plant species, and growing characteristics. Because water stress can cause immediate strains (such as reduced water content and increased air-water interfaces) and lingering strains (such as restricted leaf cell growth), the reflectance of the leaf in the near-infrared region will be the net result of many interacting factors. Sometimes, the reduced water content will predominate and infrared reflectance will increase; at other times, a compact leaf structure will be the major influence and infrared reflectance will decrease. These interactions make it apparent why adequate knowledge of the strains induced by water stress are necessary for interpreting spectral reflectance data. Changes in the near-infrared reflectance could be useful under certain conditions for nonvisually sensing water stress, especially if the strains of water stress are thoroughly understood. However, because of the opposing effects of different strains on leaf reflectance, it is unlikely that the near-infrared region will be as useful as the thermal infrared region for nonvisual detection of water stress.

Investigations on insect-stressed trees, particularly those infested by bark beetle and aphid, have shown little success in detecting strains nonvisually. There was evidence of changes in the near- and thermal infrared reflectance in the infested trees, but these differences were slight and extremely difficult to resolve in sensing the canopy as a whole. These studies encountered the problem common to most studies of conifers (Murtha 1972b), that of poor interpretation of thermal imagery caused by the uneven size of the trees and contained shadows. This problem is minimized when sensing vegetable crops such as wheat (Millard et al. 1978), but further development of sensing systems is required for the analyses of mature conifers (Heller 1970). Although the existing studies on insect infestation have had limited success in detecting nonvisual strain, it is known from physiological studies (Mullick 1977) that a tree responds immediately upon being damaged by insects. Many different morphological and chemical changes take place throughout the infestation, and it is only the end results that are evident as needle discoloration and defoliation. It is quite probable that as more knowledge is obtained about the sequence of physiological changes that occur in the host tree after infestation, it will be possible to focus remote sensing techniques more precisely on what to sense and when to sense it. New developments in sensing techniques and equipment, such as the multispectral-scanners, coupled with an increased understanding of insect-tree interactions, should make nonvisual sensing of insect-stressed trees more practical in the future.

Strains, due to fungal diseases, have been detected nonvisually in certain crop plants (Colwell 1956; Manzer and Cooper 1967), but generally there has been no success in dealing with the fungal diseases of trees, including root rots, vascular wilts, dwarf mistletoe, and cankers. Murtha and Kippen (1969) indicated that subtle differences might occur in pine infected with *Fomes annosus* and be detected by densitometry of the cyan dye layer. This aspect would be worthwhile pursuing in future research. It is evident from the analyses of most tree diseases that the metabolism of the plants undergoes a gradual deterioration, but there is little outward effect. Eventually a threshold is reached when the plant can no longer sustain itself. At that point, the tree rapidly dies and the infection quickly becomes visibly evident. If changes in metabolism such as reduced respiration could be detected, it might be possible to get an indication of a pathological stress. In this regard, the reduced thermal infrared emissions of *Phellinus*-infected Douglas-fir, as detected by Weber and Wear (1970), are promising. Metabolic changes, however, are subtle and often masked by other conditions. It seems unlikely that these changes could be detected using the current remote sensing systems and further developments in technology will be required.

The situation with crop plants is more encouraging. Since crops are annuals, most diseases develop relatively rapidly and are not "low-grade" infections like most tree diseases. This aspect, coupled with the uniformity of the crop, may account for the successful nonvisual detection of different diseases in these plants. It is likely that remote sensing to detect diseases in crop plants will increase in the future.

The few investigations on pollution indicate that strains owing to ozone stress can be detected nonvisually in both the near-infrared and visible wavelength regions (Lillesand et al. 1975; Gausman et al. 1978). These strains have been detected in species as diverse as poplar and cucumber. According to Heggestad and Heck (1971), ozone injury may vary considerably among different species and even among plants of the same variety. Although this may be true for visible damage, perhaps the nonvisible internal cellular changes caused by ozone may be similar for most plants affected. Sensing in the nonvisible wavelengths may therefore provide a less variable measure of ozone damage in many different plant species, as well as provide early indications of ozone stress.

Strains resulting from salinity stress are basically the same as those of water stress and, consequently, they have been detected nonvisually in both the near- and thermal infrared wavelengths. The few studies on chemical stress other than those of salinity (Thomas and Oerther 1972; Press 1974) have shown that strains not visibly evident can be detected through measurements of the reflectance in the visible wavelength region. This type of precise spectrophotometric measurement of the reflectance of stressed plants as well as densitometer measurements of the dye layers in the *original* photographic film, as discussed by Murtha and Kippen (1969), appear to be promising approaches to sensing nonvisual strains.

Research on sensing strains resulting from mechanical damage has shown variable success in nonvisual strain detection. Murtha (1968) obtained measurable changes in the near-infrared reflectance of damaged conifers before visual change, and Rohde and Olson (1970) used the thermal infrared region to detect girdled oak trees. The latter investigations, however, were unable to detect damaged poplar or maple trees. All of these studies involved stem girdling, a treatment that usually leads to water stress. The strains of these treatments would basically be the same as those of water stress and would cause the same alterations in reflectance.

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Conclusions

The existing research involved in sensing nonvisual stress in trees has been primarily aimed at testing the premise that there is a unique spectral signature associated with the stressed condition which could be detected, using existing techniques for sensing the visual, near, far, and thermal infrared regions of the electromagnetic spectrum. Scrutiny of the reported research results reveals that a unique nonvisual indicator of stress has not been identified, and that strains induced by stress are not the same, but are complex and variable, depending upon the particular stress factor involved. Nonvisual detection of strains has only been accomplished for certain types of stress and, even then, only with certain plant species and growing conditions.

Basically, remote sensing, particularly in the thermal infrared region, can be used to detect plants affected by water stress before the signs of stress can be seen visually. This success can be attributed to the direct correlation between water stress and reflectance characteristics of the foliage, and to existing basic knowledge of the effects of water stress on the physiology, growth, and development of the plant. Nonvisual detection of strains due to water stress has been particularly successful with grain crops, where remote sensing systems have not only provided an indication of the degree of water stress, but have also permitted an accurate prediction of crop yields. Unfortunately, remote sensing of conifers affected by water-stress has proved more difficult because of various factors, including heterogeneity of the tree species, uneven tree size distribution, and variability of ground cover. There is also relatively little information available on the water relations of forest stands. Some of these drawbacks may be relieved by the current practices of intensive forest management, where cutover stands are reforested with even-aged stock of one species. Further research aimed at integrating the techniques of remote sensing with conventional water relations measurements will be required to determine if it is practical to remotely sense water stress in conifer stands.

There has been virtually no success in nonvisually sensing trees stressed by insects or fungal diseases. Perhaps the main contribution to this failure is the small knowledge base of the intricate field of host-pathogen interactions. Most of the reports reviewed concentrated on the water-stress condition that usually accompanies the damage to the host. Water stress, however, is only one facet of many diverse changes that occur in the plant after attack, and it is usually the last. Plants start responding at the first instance of cellular damage and undergo complex physiological and morphological alterations. These processes involve many tissues, and vary not only with the type of host and pathogen, but with a myriad of other factors, including age of tissues, tissue structure, biochemical composition, climatic conditions, genetic composition, etc. Few of these many changes have been identified and described, and many of those that have been, are quite subtle and not easily detected. It is not surprising, therefore, that damaged trees generally cannot be remotely sensed before they are visibly distinguishable.

Another aspect that has hindered the detection of nonvisual strains in pathogen-attacked trees is the current state of the science of remote sensing. Most of the research on remote sensing applications has involved the use of only a small part of the electromagnetic spectrum, particularly the visible, near, and thermal infrared regions. There have been virtually no investigations into reflectance characteristics of the ultraviolet region or beyond the thermal infrared region. The fluorescence response of plants has also been largely unexplored. This is an area well worth examining, because most living cells will fluoresce and the fluorescence is affected by the metabolic state of the plant (Udenfriend 1969). Also, development of laser technology has given a means of providing excitation energy of specific wavelengths (Brach and Mach 1975). Sundbom and Bjorn (1977) have reported that delayed fluorescence could be detected from leaves of whole plants, and it has been proposed that this type of detection could provide an early indication of stress. Thus there is ample room for more research and development into new sensing systems as well as refinement of existing ones for sensing stress. This type of research, coupled with more detailed studies of host response to pathogen attack, should improve chances of sensing nonvisible pathogen stress.

Sensing of stresses caused by soil salinity has shown similar results to sensing of water stress because the main impact of salinity is to create a physiological drought condition. Reports on ozone stress have demonstrated that strains can be detected nonvisually in the near-infrared and visible wavelengths. For example, strains due to ozone stress in cantaloupe were detectable on Polaroid photographic film 16 hours before they could be distinguished by examining the plants (Gausman et al. 1978). These reports are promising and indicate that remote sensing can be of practical use in the early detection of ozone damage.

In summary, current techniques of remote sensing have provided a means of sensing trees affected by stress before the effects can be seen visually. Unfortunately, this has not been true for all stresses and many, especially those caused by living pathogens, have not yet been detected nonvisually. Remote sensing is a dynamic field, rapidly expanding in technological development and applications. With the discovery of new techniques and refinement of existing ones, most of the remaining obstacles to nonvisual detection of trees affected by stress will likely be overcome in the future.

7

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