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PRE-VISUAL DETECTION OF STRESS  
IN PINE FORESTS

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ABSTRACT

Remote detection of stress in forest trees prior to the appearance of visible symptoms has been a dream of foresters for several decades. Laboratory data indicate that pre-visual detection of some types of insect and disease attacks should be possible, either photographically or with multispectral scanners. All but two attempts to realize this potential under field conditions have produced negative results, and pre-visual detection has been largely discarded.

Extensive tree mortality due to recent attacks by the southern pine beetle (Dendroctonus frontalis Zimm.) has resulted in renewed interest in pre-visual detection of forest stress. Interest persists despite the lack of success at pre-visual, or early, detection of attacks by another bark beetle (Dendroctonus ponderosae Hopk.) realized by the U.S. Forest Service in the Black Hills during 1967-72. This report summarizes a review of available information relating to pre-visual, or early, detection of forest stress with particular reference to detection of attacks by pine bark beetles.

Available data indicate that early, or pre-visual detection is more likely with multispectral scanners (MSS) than with camera systems. Preliminary efforts to obtain early detection of attacks by pine bark beetles, using MSS data from the ERIM M-7 scanner, have not been sufficiently successful to demonstrate an operational capability, but indicate that joint processing of the 0.71 to 0.73, 2.00 to 2.60, and 9.3 to 11.7  $\mu\text{m}$  bands holds some promise. Ratio processing of transformed data from the 0.45 to 0.52, 1.55 to 2.60, and 4.5 to 5.5 or 9.3 to 11.7  $\mu\text{m}$  regions appears even more promising.

The view that prevention of beetle attack through better silvicultural treatment of pine stands will be more effective than control of the beetles is growing in popularity. When prevention through improved silvicultural treatment is economically feasible, early detection of beetle attack becomes an academic issue. However, early detection of moisture stress, an important pre-disposing invitation to beetle attack, may become more important as a guide to silvicultural treatment.

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INTRODUCTION

Remote detection of stress in forest trees prior to the appearance of visible symptoms has been a dream of foresters for several decades. Laboratory data indicate that pre-visual, detection of tree stress due to drought and some types of insect and disease attacks should be possible, either photographically or with multi-spectral scanners. All but two attempts to realize this potential under field conditions in pine forests have produced negative results (Roller and Thompson, 1972; Fox, 1973). Due to the severity of current attacks by several forest pests, interest in pre-visual detection of forest stress remains high among foresters.

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Murtha (1972) has described four types of symptoms of stress, or damage, that can be detected from remote sensor imagery:

- Type I: Trees are completely, or almost completely, defoliated.
- Type II: Trees show some defoliation through the presence of bare branches, or malformation.
- Type III: Trees show abnormal foliage coloration.
- Type IV: Trees show no visible sign of damage but appear different from non-stressed trees in non-visible parts of the spectrum.

Truly pre-visual detection of forest stress requires detection of symptoms of Type IV. By definition, this requires the use of remote sensors operating at non-visible wavelengths. Although infrared sensitive films in camera systems, and the even larger and varied wavelength capabilities of optical-mechanical scanners, have received greatest attention, microwave sensors may also have possibilities.

This report grew out of an assessment of the opportunities for pre-visual detection of attacks by the southern pine beetle (*Dendroctonus frontalis* Zimm.) funded by the Texas Forest Service and the Department of Forest Science at Texas A&M University. The support of both organizations is gratefully acknowledged, but the views expressed are those of the author and do not necessarily represent the official opinions of either sponsor.

#### RATIONALE BEHIND THIS ASSESSMENT

Airborne remote sensing systems record, and thereby permit analysis of, spectral intensities of energy flux at the collecting aperture of the sensor. Only to the extent that this energy flux has been modified by an object can analysis of the remote sensor record provide information about that object. To detect the presence of tree stress, that stress must alter the energy flux from highly stressed trees, as compared to the flux from trees with lower levels of stress. Not only must the higher level of stress alter the energy flux, but that alteration must be large enough to exceed the detection threshold of the detection and analysis systems. Since beetles and most other causes of stress are too small to permit direct detection with airborne remote sensors, any assessment of changes in energy flux resulting from their presence must be based upon tree responses. A review of known effects of stress in pines is, therefore, an essential beginning of the present assessment.

#### REACTIONS OF PINE TREES TO STRESS

Many types of insect and disease attacks that do not result in visible symptoms, such as defoliation or chlorosis, disrupt the water metabolism of attacked trees and lead to water deficits and reduced growth. Low levels of atmospheric pollutants and low level nutrient imbalance may also result in growth loss of affected trees, but without disruption of water metabolism.

##### Effects of Water Deficits

All forest trees, even those growing in moist environments, have negative water potentials in their upper extremities most of the time. These negative hydrostatic pressures vary diurnally, and may reach -60 bars in conifers. Water stress is considered to be increasing when water potential decreases (becomes more negative). Under such conditions, both the upward flow of water to the crown and downward flow of water from crown to roots are reduced; foliar water content declines; stomates close; and rates of transpiration and photosynthesis are reduced (Crafts, 1968). Loblolly pines (*Pinus taeda* L.) subjected to drought or continuous flooding have been found to have higher levels of reducing sugars, nonreducing sugars, and carbohydrates in their inner bark than trees not so stressed (Barras and Hodges, 1969; Hodges and Lorio, 1969). Hodges and Lorio (1975) also reported that the resin of loblolly pines subjected to moisture stress had a lower proportion of resin acids relative to monoterpene hydrocarbons. A drop in oleoresin exudation pressure (OEP) is also found in pines with low water potential (Vite', 1961).

Stoszek (1973) reported that increasing stress in Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] is accompanied by the emission of a series of volatile/aromatic compounds with a specific order of appearance as stress increases. This sequence of release of volatile/aromatic compounds was shown to influence insect behavior and regulate the order in which specific insects began their attacks on stressed trees.

Changes in geometric arrangement of needles and branches have also been observed as a result of moisture stress. Working with watered and non-watered red pine (*P. resinosa* Aitk.) seedlings under greenhouse conditions, Fox (1976) found measurable differences in the angle that needle fascicles made with the branch, and McCarthy (1977) observed that needle fascicles were more open and the uppermost branches began to droop sooner on stressed than control trees.

#### Effects of Air Pollutants and Nutrient Imbalance

Tree species vary in their response to air pollutants and nutrient imbalance, and genetic differences within species have been reported (Berry, 1971 and 1973). The effects of ozone and sulfur dioxide on pine trees appear to be similar and independent of tree age (Berry, 1971; Miller, 1973). Ozone has been shown to reduce the rate of photosynthesis in ponderosa pine (*P. ponderosa* Laws.) and the reduction was greatest when ozone dosage was greatest (Miller, et al., 1969). High levels of soil nitrogen appear to increase, while high levels of soil phosphorus appear to reduce, the severity of damage by air pollutants (Cotrufo, 1974). Additional interactions between air pollutants and other damage agents are known and synergistic relationships between "smog" and pine beetles are known to hasten death of pines (Miller, 1973).

When pines react to air pollutants and nutrient imbalance, the commonest effects seem to be chlorosis; necrosis, in which needles die back from the tips; needle dwarfing, with production of shorter needles than normal; thinning of the tree crown; shoot elongation that is less than normal; or reduced growth. These symptoms are all visually detectable if the observer knows what to look for, but are difficult to detect in their early stages. Early detection, even if not truly pre-visual, would be of assistance to foresters, but is beyond the scope of this report.

Some possibly pre-visual effects have been described. Linzon (1967), and Miller and Evans (1974) identified changes in the mesophyll cells of pine needles caused by ozone, sulfur dioxide, and a variety of oxidants. Similar internal changes in broadleaved species have been identified as the basis for claimed pre-visual detection of disease in citrus trees (Colwell, 1960).

#### REMOTE SENSING IMPLICATIONS OF STRESS RESPONSES IN PINES

Several responses of pine trees to stress have implications favoring pre-visual detection of stress with remote sensors. These implications affect remote sensing opportunities in several parts of the electromagnetic spectrum.

#### Water Deficits and Reduced Transpiration

Water deficits and reduced transpiration occur together and imply lower foliar moisture content. In broadleaved species lower foliar moisture content is accompanied by an increase in foliar reflectance which is most pronounced and dependable at wavelengths longer than 1.0 micrometers (Figure 1), too long to be recorded photographically (Olson, 1967; Rohde and Olson, 1971). Similar results were obtained with red pine by Weber (1965), Rohde (1971) and Fox (1976), but all also reported detectable changes at visible wavelengths.

Since transpiration is a cooling process, reduced transpiration is usually accompanied by increased foliage temperatures. Heikkinen and Alger (1977) used an AGA Thermovision 680 system to determine apparent temperatures of tree crowns of severely stressed loblolly pines. Stressed trees were as much as 2°C. warmer than control trees even though the crowns of the stressed trees showed no visible symptoms of stress. Weber (1965) and Rohde (1971) determined foliage temperatures for red pine and found that stressed trees were as

much as 5.5°C warmer than control trees. In subsequent work under field conditions, it was found that ponderosa pines infested with western pine beetles (Dendroctonus ponderosae Hopk.) were warmer than non-infested trees under some conditions; but at the same, or lower, temperatures than non-infested trees under other conditions (Weber, 1969). Drying of the soil root horizon with a resulting increase in moisture stress of non-infested trees, and a midday transpirational lag that resulted in a thermal equilibration of infested and non-infested trees, were identified as factors contributing to these results. Tests with airborne thermal scanners showed that, although infested trees could be detected on the imagery, so many non-infested trees were classified as infested that the "false-alarm" rate was too high to justify operational use (Weber, 1976).

#### Chemical Changes

None of the known changes in tree chemistry appear directly detectable with presently available remote sensing systems. Changes in sugar and carbohydrate levels, resin acids, OEP, or release in volatile/aromatic compounds may prove important, however, once their effects on water metabolism or geometric arrangement of branches and foliage are known.

#### Geometric Changes in Foliage and Branches

When branch angle or foliage position changes, the projection of the tree canopy "seen" by a remote sensor changes. The relative proportions of the reflected or emitted signal coming from foliage, bark and ground background may vary widely and permit detection of tree stress. Such detection would not be truly pre-visual, but might make earlier detection of tree stress possible from an airborne vantage point. Active microwave sensors (radars) are particularly sensitive to changes in target geometry and their capabilities for detection of forest stress should be investigated.

#### Air Pollution Damage

Studies of smog-damaged ponderosa pine near Los Angeles, California, have shown that trees with thinning crowns, needle dwarfing, or chlorotic foliage can be detected in normal color photographs. Reflectance data from one study show a detectable increase between 0.52 and 0.68  $\mu\text{m}$ , but negligible change in infrared reflectance out to 2.6  $\mu\text{m}$  (Heller, 1969). No pre-visual detection was reported even though damage to mesophyll cells in needles should be most detectable in the 0.7 to 1.0  $\mu\text{m}$  band, if present.

#### Exploitation with Remote Sensors

The only known case of supposedly pre-visual detection of stress in pines with camera systems is that reported by Fox (1973) for detection of Fomes annosus root rot in white pine (P. strobus L.). This result was achieved with color-infrared film exposed from an altitude of approximately 12,000 meters in mid-May of 1971, during the period of rapid shoot elongation. Visible symptoms of damage could not be detected from the ground sixteen months later. This study has not been duplicated and this evidence is, by itself, insufficient to justify operational use of photographic systems for pre-visual detection of stress in pine forests.

Single channel, optical-mechanical scanners have provided some cases where pre-visual detection of stress has been claimed, but not with sufficient accuracy to meet operational needs. Greater success has been realized with multi-spectral scanners (MSS) through ratio processing of signals in different spectral bands (Roller and Thompson, 1972). Extension of this work was planned as part of the U.S. Forest Service effort to obtain pre-visual detection of attack by the western pine beetle at the Black Hills Test Site in South Dakota in 1972-73. MSS data were collected with the Environmental Research Institute of Michigan's M-7 scanner in June 1972. Unfortunately, funds for processing these data were diverted to support LANDSAT investigations, and the data have not yet been thoroughly analyzed. A preliminary analysis of these data was made in March 1977, based on digitized data for twelve spectral bands

supplied by F. P. Weber, former study leader on the U.S. Forest Service Black Hills Study Team. Since a primary effect of pine beetle attack is a disruption of the water metabolism of the attacked trees, information on pine response to moisture stress was reviewed and the probable signal response in each spectral band determined. Probable signal response of several possible ratios of different spectral bands was also determined. Results of this analysis are summarized in Table I.

Based on these estimates of probable signal responses, it is apparent that normal color film should show stressed trees as a somewhat lighter green, with no real change in the blue or red spectral bands. Unfortunately, the small increase in green reflectance is no larger than the variation in reflectance normally encountered between individuals of one species. It is also apparent that color-infrared film will add little discriminating capability to that of normal color films. Thus, it is most unlikely that any photographic system, or any system utilizing only the photographic spectrum, will achieve dependable, pre-visual detection of moisture stress. This analysis agrees with the field results of the U.S. Forest Service (Weber, 1976).

Analysis of the non-photographic spectral bands (MSS Channels 9, 10, 11, and 12) indicated that a combination of these bands would offer greater probability of pre-visual detection. With the generous assistance of F. P. Weber and R. D. Dillman, several combinations of these spectral bands were examined on the digital image analysis equipment available at NASA's Johnson Spaceflight Center, Houston, Texas. Results with Channels 8, 11, and 12 suggest that the inability to obtain dependable pre-visual detection of attack by the western pine beetle may have been due to inability to separate stressed and infested from stressed but non-infested trees. Time and funding limitations have prevented implementation of the suggested ratio processing, as of this writing. Ratio processing is expected to provide better discrimination of moisture stress, however, and work is continuing. If subsequent work confirms the apparent result of this preliminary analysis, it may be possible to use MSS systems to detect moisture stress in pine stands early enough to permit corrective action to be taken before beetle attacks or growth losses reach epidemic proportions.

#### THE SOUTHERN PINE BEETLE: A CASE ANALYSIS

Continuing outbreaks of the southern pine beetle (SPB) have reached epidemic proportions in the southeastern United States. Loblolly pine (Pinus taeda L.) and shortleaf pine (P. echinata Mill.) are the most commonly attacked species, but successful attacks on several other southern conifers have been reported. Excellent summaries of our knowledge of the SPB appeared in the comprehensive reviews of Thatcher (1960), Dixon and Osgood (1961), and Coulson, et al. (1972). This brief review was drawn primarily from these sources and is focused on those aspects of the beetle's life history that seem to relate most directly to possible pre-visual detection of SPB attack through airborne remote sensing techniques.

Adult beetles initiate an attack by boring through the bark and constructing a winding gallery in the phloem, cutting the cambium. This gallery has a distinct component that is more or less horizontal and perpendicular to the vertical flow of sap through the phloem (R. F. Billings, personal communication, 1977). Eggs laid along the sides of the gallery hatch in three to nine days under optimum conditions, and emerging larvae construct lateral galleries in the phloem that widen abruptly after the first molt. Four instars are normal with the last three tunneling into the outer bark where pupation occurs before the new adult beetles bore to the surface and emerge (Fronk, 1947). One complete generation can occur in as few as twenty-six days in the summer but may take more than three months in winter (Thatcher and Pickard, 1967).

Concurrent invasion of the blue-stain fungus *Ceratocystis minor* (Hedgc. and Hunt) usually accompanies attack by the SPB and the fungus may penetrate and block the first one or two xylem rings within four days (Caird, 1935). The decrease in phloem moisture content at the point of attack, noted by many investigators and considered essential to brood survival by Gaumer and Gara (1967), may be enhanced by the localized phloem block created by the adult gallery and intensified by *C. minor*. The presence of *C. minor* appears to be non-essential, however, for many trees killed during the 1946-48 outbreak of SPB in Florida showed no evidence of blue-staining (Hetrick, 1949).

Biochemical analyses of loblolly pines have revealed many changes in the chemical composition of the sap, resin, and inner bark following inoculation with SPB and associated fungi, with the greatest changes occurring in trees which had lost much of their root systems to rootlet pathogens (Hodges and Lorio, 1975).

Resin flow into wounds caused by SPB reduces the rate of gallery construction by beetles that are not "pitched out". As resin flow moderates gallery construction increases and most galleries are entirely resin free (McAndrews, 1926). The drop in OEP associated with successful attack by the SPB may result from two different causes: (1) decreasing water potential caused by the disruption of the tree's water metabolism by attacking beetles and associated fungi; and (2) decreasing water potential resulting from physiologic drought that could result from excessive competition for available soil moisture (St. George, 1930; Mason, 1971), excessive soil moisture and resultant poor root development and poor aeration (Hetrick, 1949; Lorio and Hodges, 1968a, 1968b), attack by root-rotting fungi such as *Armillaria mellea* (Vah.) (Hetrick, 1949) or *Fomes annosus* (Fr.) Karst (Skelly, 1975), or a combination of these factors. Thus, decreasing OEP and water potential may be both a symptom of attack by the SPB and a preliminary condition inviting such attack.

Death of the host tree follows mass attack by large numbers of beetles that concentrate in an imperfectly understood response to pheromone exudation by attacking beetles (Vite', et al., 1964; Vite', 1974; Silverstein, 1974). This mass attack massively disrupts the water metabolism of the host tree. Visible fading and then browning of the foliage occur (Doggett, 1971; Heikkinen and Alger, 1977) in a pattern similar to the changes reported in red pine seedlings under severe moisture stress (Weber and Olson, 1967). Fading and browning of the foliage may not occur until several weeks after the bark has fallen from large sections of the mid-bole, indicating that the tree is functionally dead. Many of the adult beetles have emerged and moved on before this bark-fall occurs.

#### Factors Affecting Susceptibility of Attack

There seems little doubt that a high level of moisture stress increases susceptibility of a tree to attack by SPB. Moisture stress may result from low rainfall (Craighead, 1925; St. George, 1930; Hetrick, 1949; Kalkstein, 1974, 1976), poor root development on wet sites (Lorio and Hodges, 1971; Lorio, et al., 1972; Hodges and Lorio, 1975), attack by root rotting fungi (Hetrick, 1949; Skelly, 1975), or competition between trees (Coulson, et al., 1974; Leuschner, et al., 1976; Billings and Pase, 1977). Competition appears to be of particular importance in pure stands of high basal area and larger than average tree size. In large areas of east Texas, dense stands of small saw-timber with basal areas approaching 120 square feet per acre are common and seemingly present optimum conditions for epidemic development of SPB (Coulson, et al., 1974). Past timber stand improvement projects that removed hardwoods and promoted higher density (closer spacing) of pines appear to have increased the risk of epidemic attack by the SPB, for between tree spacings larger than 20 or 25 feet have been found to curtail expansion of individual infestations (Gara and Coster, 1968).

Seasonal differences in the behavior of the SPB also influence the probability that a given tree will be attacked. During summer, most new attacks are associated with active infestations and result in the enlargement of these infestations (Thatcher and Pickard, 1964; Coster, 1967). During winter and

early spring, enlargement of active infestations is slow or non-existent but many new infestations occur through population dispersal (Gara, 1967; Coulson, et al., 1972). These two patterns of spread, often referred to as "spot growth" and "spot dispersal", have distinct remote sensing management implications.

#### Remote Sensing Management Considerations

Whenever most beetle activity is of the spot growth pattern, and particularly in summer when a complete generation of the SPB may require only 26 days, the likelihood of obtaining meaningful early detection of attacked trees with an airborne remote sensor is low. Time required to record, process, interpret and supply actionable information to control crews virtually precludes effective control action before adult beetles emerge and move to new trees. Even if information could be supplied to ground crews in time to permit effective control action, weather conditions during the spring-summer period are such that airborne remote sensors cannot be depended upon to obtain the needed coverage at the appropriate time(s).

Early detection during late fall or early winter could, however, provide for more effective implementation of control measures. Spot growth has slowed and beetle generations are longer than in summer. The relatively low mobility of the over-wintering population lengthens the effective response time for control actions. In addition, flying weather during this season is usually good enough to permit development of an acceptably dependable, operational detection system if detectable early symptoms of attack can be identified. It appears, therefore, that primary attention should be devoted to early-indicators of attack that will permit detection during the late-fall and winter period. This agrees with the findings of the U.S. Forest Service researchers studying early detection of the western pine beetle, for they reported that detection probability is highest in the fall (Weber, 1976).

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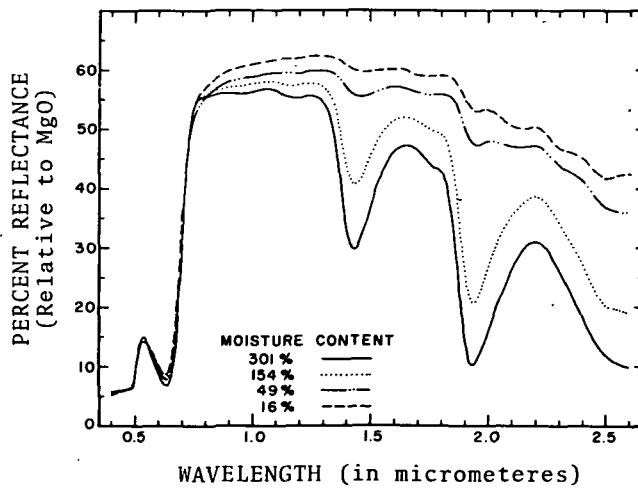


FIGURE 1. CHANGES IN REFLECTANCE OF A SYCAMORE LEAF AT DIFFERENT OVEN-DRY-WEIGHT MOISTURE CONTENTS AS IT DRIED IN AIR.

TABLE I. PROBABLE SIGNAL RESPONSE IN DIFFERENT SPECTRAL BANDS  
AS A RESULT OF MOISTURE STRESS IN PINES.

<u>Data Channel</u>	<u>Spectral Band (in <math>\mu\text{m}</math>)</u>	<u>Probable Signal Response of Pine Trees Under Moisture Stress</u>
1	0.41 - 0.48	Reflectance should remain unchanged or increase slightly (Olson, et al., 1964; Fox, 1976).
2	0.50 - 0.54	Reflectance should remain unchanged or increase slightly (Olson, et al., 1964; Fox, 1976).
3	0.52 - 0.57	Reflectance should increase (Olson, et al., 1964; Fox, 1976).
4	0.55 - 0.60	Reflectance should increase (Olson, et al., 1964; Rohde, 1971; Fox, 1976).
5	0.58 - 0.64	Reflectance should increase slightly (Olson, et al., 1964; Rohde, 1971; Fox, 1976).
6	0.62 - 0.74	Reflectance should remain unchanged or increase slightly (Olson, 1969; Rohde, 1971; Fox, 1976).
7	0.67 - 0.94	Reflectance should remain unchanged or increase slightly (Olson, 1969; Rohde, 1971; Fox, 1976).
8	0.71 - 0.73	Reflectance should increase slightly (Olson, 1969).
9	1.00 - 1.40	Reflectance should increase slightly (Olson, 1969; Rohde, 1971).
10	1.50 - 1.80	Reflectance should increase (Olson, 1967; Rohde, 1971).
11	2.00 - 2.60	Reflectance should increase faster than at 1.50 - 1.80 $\mu\text{m}$ (Olson, 1967; Rohde, 1971).
12	9.30 - 11.70	Emittance should increase (Weber, 1965; Rohde, 1971).
Ratio	$\frac{\text{Channel 3}}{\text{Channel 1}}$	Signal strength should increase slightly as stress increases.
Ratio	$\frac{\text{Channel 9}}{\text{Channel 5}}$	Signal strength should decrease as stress increases.
Ratio	$\frac{\text{Channel 10}}{\text{Channel 11}}$	Signal strength should decrease as stress increases.
Ratio	$\frac{\text{Channel 9}}{\text{Channel 11}}$	Signal strength should decrease as stress increases.
Ratio	$\frac{\text{Ch.10} + \text{Ch.11}}{\text{Ch.10} - \text{Ch.11}}$	Signal strength should increase rapidly as stress increases.