REMOTE SENSING APPLICATIONS IN FORESTRY

THE USE OF MULTISPECTRAL SENSING TECHNIQUES TO DETECT PONDEROSA PINE TREES UNDER STRESS FROM INSECT OR PATHOGENIC ORGANISMS

R-09-038-002

By

Robert C. Heller, et al.

Pacific Southwest Forest & Range Experiment Station
U.S. Department of Agriculture

Annual Progress Report 30 September, 1966

A report of research performed under the auspices of the
FORESTRY REMOTE SENSING LABORATORY,
BERKELEY, CALIFORNIA—
A Coordination Facility Administered Jointly By
The Pacific Southwest Forest and Range Experiment Station of the Forest Service, U.S. Department of Agriculture and by the School of Forestry, University of California

For

NATURAL RESOURCES PROGRAM
OFFICE OF SPACE SCIENCES AND APPLICATIONS
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Frontispiece.--Oblique photo of bark beetle induced tree mortality in ponderosa pine, Lead, South Dakota. Color photography (Anscochrome D-200) detects trees with discolored foliage only; dying green trees are not detectable. Note random pattern of groupwise killing; over 2,000 trees have been killed along this ridge in the past two years.

A B S T R A C T

Investigations are underway to determine the ground instrumentation, aerial sensing equipment, and techniques required to detect vigor loss and previsual signs of tree mortality caused by bark beetles in coniferous timber stands. Bark beetles are the most destructive insects confronting the forest manager the world over. Ground and aerial studies have been started in the center of a serious Black Hills beetle (*Dendroctonus ponderosae* Hopk.) outbreak near Lead, South Dakota. Data were collected on spectral reflectance, emissivity, and transpiration of ponderosa pine (*Pinus ponderosa* Laws.) trees and foliage. The analysis of these data and other biological and physical phenomena is being made to supply insight as to the likeliest aerial sensor for detecting tree stress. These results are not yet available.

Aerial photography (color and infrared color) was exposed over 11 infested test sites at four time intervals -- October 1965 and May, June, and July 1966. Optical-mechanical scanning imagery was taken diurnally on 3 days in May and June 1966. The earliest date that photography detected tree stress in 20 percent of the infested trees was 8 months after the trees were attacked by beetles. Almost 75 percent of the dying trees were not detected until 10 months had elapsed. No difference in interpretation accuracy was found between color and infrared color films but commission errors were slightly more numerous on the infrared color film.

Partly because of inclement weather, resolution of the thermal imagery was too poor to determine whether thermal differences of stressed trees could be detected from the air. Significant improvements have been made in the scanning equipment and further testing will be done.

AUTHOR

ACKNOWLEDGEMENTS

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Special thanks is given to the Homestake Mining Company and Anaconda Copper and Mining Corporation for use of their land and timber to conduct the study.

The Spearfish, Rochford, and Nemo Ranger Districts of the Black Hills National Forest have been particularly helpful in providing darkroom facilities, vehicles, and equipment.

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THE USE OF MULTISPECTRAL SENSING TECHNIQUES
TO DETECT PONDEROSA PINE TREES UNDER STRESS FROM INSECT
OR PATHOGENIC ORGANISMS

by

Robert C. Heller, W. F. McCambridge, R. C. Aldrich, and F. P. Weber

INTRODUCTION

Forests around the world have provided mankind with a wealth of wood products needed in modern civilization. This need is expected to increase and a shortage of raw materials develop because of future rapid increases in world population. United Nations' demographers estimate that the world population will double every 35 years from 1960. While trees are a renewable natural resource, we shall have to grow them faster, manage what we have more judiciously, and prevent the tremendous losses from epizootics to supply the expected need.

Insects and diseases, in the United States alone, account for a timber loss equal to our annual growth and exceeds the losses from fire by seven times.[1/] From 1963 to 1965, 40 percent of the pine resource in Honduras, C. A., was lost to an epidemic of southern pine beetle. Similar catastrophes can occur in other developing countries and have occurred even in the more technically advanced ones.

Some rapid method of detecting tree stress or loss of vigor, before visible symptoms occur, is badly needed so that abnormalities in the forest

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1/ Forest Service, U. S. Department of Agriculture. Timber Trends in the United States. Forest Resources Report No. 17, 1965.

can be pinpointed at an early stage. Thus, forest managers can direct their control action to those locations requiring sanitation cutting, presalvage cutting or other treatment and thereby reduce the timber loss. Ground survey detection techniques are too slow and costly -- and often discover the abnormality after it has grown to an uncontrollable epidemic. Some combination of aerial and ground detection methods must be worked out and this has a high priority on the forest manager's list of needs. If an airborne technique proves feasible the next step upward -- a space vehicle platform -- may provide the extensive and repetitive coverage needed for the detection of dynamic biological populations, provided that suitable image resolution capabilities can be reached by spacecraft.

The specific research objective is to learn which portions of the electromagnetic spectrum will differentiate dying from healthy pine trees. Problems to be solved are optimum altitudes for sensing, detectability of stressed trees with various film-filter combinations and electronic scanners, and development of sensitive ground instrumentation.

Colwell (1956), Myers (1963), and others have reported on the reflective and emissive characteristics of agricultural vegetation under stress and report that they respond differently from healthy vegetation in various portions of the electromagnetic spectrum. When the stressed plants were measured with a spectrophotometer, the red and near infrared bands, 0.68 to 1.1 microns, signalled an early loss of chlorophyll absorption and showed a decrease in infrared reflectivity. Their findings showed that panchromatic and color film emulsions did not detect early stress while the infrared sensitive emulsions did. Indications are that stressed plants reflect and emit light and heat at differential rates from healthy plants and that healthy plants have different rates from other plant species.

This may permit intelligent comparisons to be made, and ultimately it is hoped that each plant species or vigor class within species will have a detectable signature. Part of this experiment was designed to investigate this hypothesis.

A continuing outbreak of the Black Hills beetle, Dendroctonus ponderosae Hopk., in the Black Hills of South Dakota furnished a timely opportunity to test these new techniques under actual infestation conditions. At this latitude, only one generation of beetles occurs each year; usually a 3-9 month period elapses from the time a ponderosa pine, Pinus ponderosa Laws., is successfully attacked before it shows visible signs of decline (discoloration of foliage). Having one generation of beetles per year and therefore one population of dying trees present in the stand, this area furnishes an ideal situation to study. Those complex beetle problems in other parts of the country where 4-7 overlapping generations occur annually must be reserved until more findings are gleaned from this study.

PAST STUDIES ON BARK BEETLES AND SURVEY METHODS

The biology and methods for control of this serious insect enemy have been well documented by Beal (1939), Blackman (1931), and Massey (1954); however, survey methods for early detection have been made primarily on the ground. Knight and Yasenski (1956) reported on the random nature of attack and typical groupwise killing of trees which makes ground methods slow and expensive. Knight (1960) also developed a ground sequential sampling system for estimating beetle populations; this technique helped cut down the number of ground inspections needed to predict population trends. To estimate numbers of infested ponderosa pine trees within an outbreak area, Knight (1958) recommended ground inspection by sampling large areas with $\frac{1}{2}$-chain-wide strips (33 feet); he went on to say that aerial counts of straw-colored trees along with predicted changes based on insect population counts show promise as an appraisal survey method, but this has not been attempted.

In 1952-53, Heller *et al* (1959) made an aerial photographic study on the Roosevelt National Forest in Colorado and determined that experienced photo interpreters could count faded pine trees with an expected error of only 5 percent when examining color aerial transparencies taken in late summer at a scale of 1:7,920. On this study, smaller scales (1:15,840) and panchromatic film with red and orange filters (A-25 and G-15) were also tried, but with poor results. Thus, color photography could be used to detect presently fading trees which were attacked one year earlier (Frontispiece) but was of little help in locating newly attacked green trees.

Other photographic studies of bark beetle killed timber have been made in the south on southern pine beetle, *Dendroctonus frontalis* Zimm., by Heller *et al* (1959); in the west on Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk., by Wear *et al* (1964); and on western pine beetle, *Dendroctonus brevicomis* Lec., by Thorley *et al* (1965). None of these studies, however, were directed toward detection of dying trees before a visible change showed up in the foliage.

MULTISPECTRAL DETECTION CONCEPT

A concise and thoughtful discussion of this concept as it applies to detection of loss of tree vigor is quoted from Weber (1965) as follows:

> "The concept of multispectral detection is straight forward. Each object or condition in nature has a unique distribution of reflected, emitted or absorbed radiation. This information if applied wisely can be used to distinguish one object or condition from another.

Until recently we have embraced only a very small portion of the electromagnetic spectrum in our airborne detection programs. In the field of forest protection we have relied on our ability to "see" dead or dying trees, and infrequently have employed more than one visible channel of information at a time.

According to Colwell (1964) the idea behind multiband reconnaissance is that by comparing two or more images of the same object made in different regions of the spectrum we may learn something about the object that could not be learned by studying the tonal values on just one image.

A multiple lens camera system permits wide exploration of the concept of multiband reconnaissance throughout the visible and near infrared parts of the electromagnetic spectrum. With this type of camera one can photograph the same area with multiple simultaneous exposures and isolate spectral zones in the range from 400 to 900 millimicrons. The use of a spectrographic emulsion--sensitive over the whole range--in conjunction with narrow band-pass filters, permits controlled limits of each spectral zone where information is desired. Simultaneous examination of several spectral zones will reveal considerably more information about the reflective characteristics of most objects than from a study of tonal values of any one of them. For example, we find that a great deal of information is available without even moving from the realm of conventional imagery. This can be shown by adding information that can be gained from aerial color photography, which integrates tonal values in each of three spectral zones, and that obtainable from camouflage detection film, in which the red dye is activated by reflected infrared light (0.7 to 0.9 microns).

Colwell (1961) indicated that black-and-white photo-like images can be obtained by remote reconnaissance not merely in the visible and near infrared parts of the electromagnetic spectrum, but also in the heat-mapping infrared and the ultraviolet bands. According to Parker and Wolff (1965), ultraviolet is an intriguing place to look because certain objects like unpainted metal roofs and limestone outcrops show remarkably greater contrast than in other regions of the spectrum. However, the likelihood of productive sensing of forest disturbances in the ultraviolet is uncertain because of the strong atmospheric absorption of ultraviolet light.

As indicated, conventional photography is excellent for resolving recognizable objects, the same objects we normally see by the light they reflect. In the infrared region of the electromagnetic spectrum most objects are strong emitters of radiant energy and reflect very little. Whereas detection schemes employing the visible portion of the spectrum are limited to daytime application, thermal systems sample emitted radiation from terrestrial objects and are hence free of certain temporal and atmospheric restrictions.

There are certain reasons for believing that sampling the infrared portion of the spectrum may be useful in detecting declining vigor in vegetation. All objects at a temperature above absolute zero radiate electromagnetic energy. The total amount of emitted radiation increases with the body's absolute temperature and peaks at progressively shorter wavelengths. Assuming an average temperature of 300° K., the earth has a radiant power curve that falls off rapidly toward the visible from a peak near 10 microns and more gradually toward the microwave region in the other direction (Holter, Nudelman, Suits, Wolfe and Zissis 1962). This gives a relatively broad region at wavelengths longer than about 3.5 to 4.0 microns in which we can do remote sensing by detecting emitted radiation, while at wavelengths shorter than 3.5 to 4.0 microns solar radiation provides a sharp power peak around 0.3 microns which permits the capture of reflected light with conventional cameras and films.

In applying these principles to a loss of vigor problem the most obvious approach then is to look for some thermal difference between a healthy and a dying tree, whether absolute or emitted. In the case of a ponderosa pine infested with bark beetles, Beal (1939) explains that as a result of the numerous galleries constructed in the cambium region beneath the bark and the development of the blue stains in the sapwood, the movement of water from the roots to the leaves is cut off, and the tree is girdled and killed. In this declining process cessation of leaf transpiration, which results from the increasing leaf-water potential associated with blockage of the water conductive tissue, is the key act in a thermal differentiation between a healthy (transpiring) tree and a dying tree. In healthy needles in which the stomata are allowed to open naturally in response to light, temperatures are somewhat lower than needles in which the stomata are forced to remain closed. This idea is strengthened by Wolpert (1962) who showed that under normal conditions transpiration could account for approximately one-fourth of the heat removed from a leaf, which indicated that transpiration is at least a significant factor in the heat exchange phenomena of leaves.

There are reasons other than strictly the thermal aspects for looking to the infrared portion of the electromagnetic spectrum in developing a detection scheme, and here it is necessary to embrace the complexities of the physics of infrared radiation. All objects emit electromagnetic energy. The simplest emitters are theoretically perfect radiators, or black bodies, which emit radiation with a spectral distribution as described by Planck (1913). However Planck's Law--and the Stefan-Boltzmann law which is obtained by integrating Planck's equation over all possible wavelengths--is valid only for black bodies. Since few objects, if any, are perfect radiators it is necessary to consider the emissivity, or radiation efficiency, factor for an object. According to King, Limperis, Morgan, Polcyn and Wolfe (1963), if a black body has an emissivity of 1.00, then other objects have an emissivity which is either a constant less than 1.00, which they call a grey body, or it varies strongly with wavelength and is called a non-grey body. Application of Kirchhoff's Law, which states that good absorbers (such as vegetation) are also good emitters, shows that if alpha represents the percentage of power absorbed by a leaf per unit wavelength, then for that leaf at a given temperature, absorptivity equals emissivity or alpha equals epsilon. This points to the second consideration for considering detection of a dying tree in the infra-red portion of the spectrum. If in fact the absolute temperature of a dying tree is found to be the same as a healthy tree it is possible that a change in the molecular composition or gross structure of the foliage may cause a change in the emissivity at a particular wavelength or wavelengths. Thus, even if the needle temperatures remain the same the radiant emittance may change because of a shift in the radiation efficiency, which in theory still leaves the door open for detection of a less vigorous tree in the waveband range beyond reflected radiation."

HISTORY OF THE PRESENT OUTBREAK

Aerial photographs taken under Forest Service contract in late August of 1961 covered the Lead-Deadwood exemption area of South Dakota--an area of non-Forest Service land of mixed ownership. This photography showed numerous small groups of faded pine trees which were attacked by Black Hills beetles during August 1960. The increase in beetle populations probably started in 1959 but it is academic whether 1959 or 1960 was the first year of the present outbreak. Since 1960, the outbreak continued to rise substantially each year, probably reaching a peak with the beetle attacks of 1963. By that time, and extending through 1965, groups of several hundred trees were being infested annually, whole hillsides of timber were destroyed, and the total infestation in the exemption area ran to many thousands of trees killed each year. Beetle attacks in 1966 indicate the outbreak is continuing, possibly dispersing, due in part to stand depletion, and has reached a static level.

LOCATION OF STUDY AREA

The Black Hills are located in western South Dakota and eastern Wyoming. The hills rise up to 7,242 feet from the surrounding flat to rolling plains, which have elevations of about 3,500 feet. Ponderosa pine is the principal commercial tree and it occurs primarily above 4,000 feet. The total sawtimber volume in the Black Hills is estimated to be 2.3 billion board feet. The study area (Fig. 1) was selected because it still supported a high beetle population from the 1962 epidemic. In addition, we were assured by the owners, Anaconda Copper and Mining Corporation and Homestake Mining Corporation, that a research study could be conducted without interference.

METHODS

Biological observations which involve ecological, physiological, and meteorological interactions must be made over a time continuum. Since our objective is to detect loss of tree vigor before visual symptoms occur, we are interested in the rate at which changes take place. To capture these changes, measurements were taken of beetle populations, numbers of infested trees, foliage color, foliage internal temperatures, emitted foliage temperatures, transpiration, solar radiation, soil moisture, air temperature, humidity, and wind velocity. The field schedule and timing coincident with the collection of these data are presented in tabular form - Table 1.

GROUND PROCEDURES

Establishment of Attractant Sites

From previous work McCambridge found that by placing laboratory reared beetles in screen cages on host trees (Fig. 2) during the period of active beetle emergence in the summer, he could induce wild beetle populations to attack the tree with the caged beetles and many surrounding trees as well. In August 1965, a total of 11 sites were established in this manner within the study area (Fig. 3) to allow for possible failures and to provide for replication in the experiment.

Visual Determination of Tree Decline

Once a tree is attacked by beetles the success or failure of the attack may be in doubt for 3 to 9 months even when close ground examination is

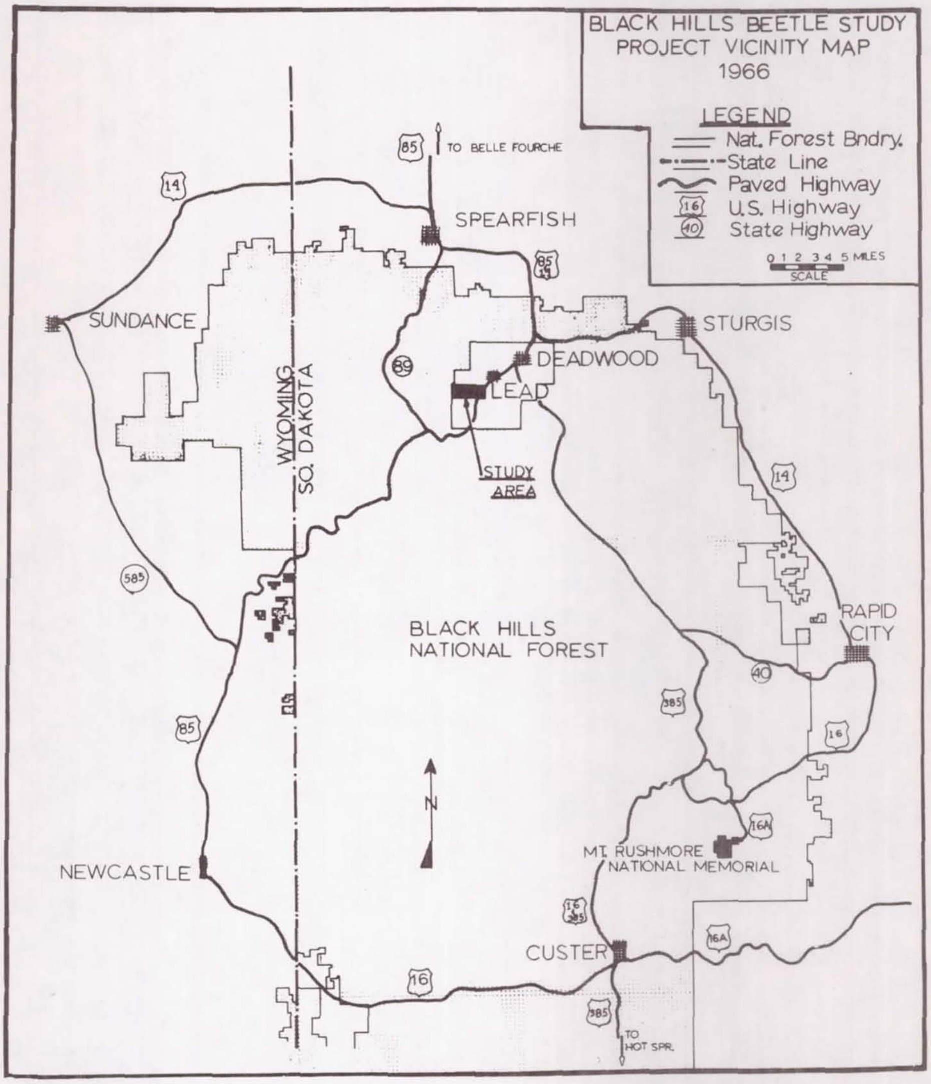


Figure 1.--Location of the study area is shown in black.

TABLE 1

TIMING OF GROUND AND AERIAL OPERATIONS -- BLACK HILLS BEETLE STUDY

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
1965					
Aug.	Beetles released at each site to establish 11 attractant sites				Color of healthy pines - 5GY 5/6
Sept. 25	Selected 8 sample trees - 4 healthy, 4 insect infested on attractant site 14. Began temperature, soil, and transpiration measurements.				
Oct. 12, 13		Exposed Ansco-chrome D-200, Ektachrome Infrared 70 mm film over 11 sites	Film processed Oct. 14		Infested trees same color as uninfested
Dec. 13-17				Edited film, determined scale	
1966					
Jan. 24-31				Interpretation of Oct. imagery by 3 experienced photo interpreters	
Apr. 28	Immediately following snow melt, began temperature, soil, and transpiration measurements				

TABLE 1 (Continued)

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
1966					
May 3-18	Made visual checks of beetle infested trees for bark and foliage symptoms of death				Very slight color change of 25% of trees from 5GY to 2.5 GY.
May 11-12					4 inches snow on ground and in trees
May 13	Thermal measurements during optical-mechanical scanner flights	Forest Service plane equipped with Texas Instr. Scanner RS-7 - Capability in 2.0-2.6, 4.5-5.5, and 8.0-14.0 microns	Instantaneous 5-inch film read-out and magnetic tape for later playback		Flights made at 1000, 1400, and 2000. Cloudy, cool weather
May 14	Thermal measurements during optical-mechanical scanner flights	Forest Service plane equipped with Texas Instr. Scanner RS-7 - Capability in 2.0-2.6, 4.5-5.5, and 8.0-14.0 microns	Instantaneous 5-inch film read-out and magnetic tape for later playback		Flight at 0500
14		Exposed Anscochrome D-200 and Ektachrome I.R. - 70 mm film over 11 sites	Film processed May 15		Scattered to broken clouds
May 17				Interpretation of May imagery of 5 attractant sites - by 3 P.I.'s	

TABLE 1 (Continued)

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
1966					
June 3	Thermal and physiological measurements during and after scanner flights	Same optical-mechanical scanner used May 13-14. 5 flight runs			Mostly scattered to broken clouds - not favorable for thermal recording
June 6	Thermal and physiological measurements during and after scanner flights	Exposed Anscochrome D-200 and Ektachrome I.R. - 70 mm film over 6 sites			Incomplete coverage - 50% of trees fading to 2.5 GY Scanner flight 2030
July 6	All ground measurements taken. Tallied condition of infested trees. Assigned Munsell ratings to fading trees				Dying trees mostly greenish yellow (2.5GY) to yellowish red (10Yr)
July 8	All ground measurements taken. Tallied condition of infested trees. Assigned Munsell ratings to fading trees	Exposed Anscochrome D-200 and Ektachrome I.R. - 70 mm film over 11 sites	July 9 Film processed		
Aug. 12					4 inches of hail in Lead, S.D., and on study sites. 90% of discoloring foliage stripped from dying trees
Aug. 15	Released beetles to establish new attractant sites				

Figure 2.--Screen wire cage stapled to ponderosa pine trunk. The cage is charged with live beetles to induce attack by indigenous beetles on a normally healthy tree.

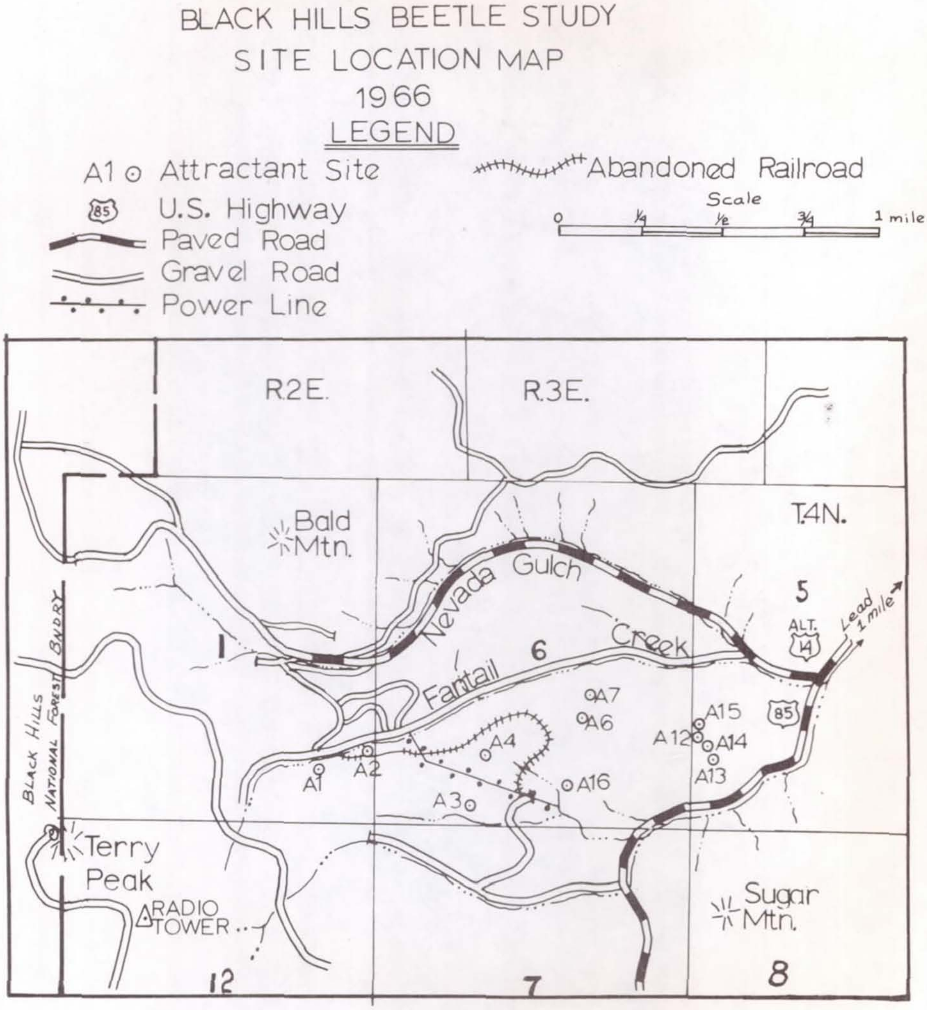


Figure 3.--Detailed map of 11 attractant sites near Lead, South Dakota. Site labeled attractant 14 was used for detailed ground studies.

continued. One manifestation of heavy attack is the presence of pitch tubes on the outer bark (Fig. 4). Another is boring dust--like fine sawdust--caused by the attacking beetles when boring in the cambial zone. This dust lodges in bark crevices near the ground and must be searched for very carefully. The surest method of determining whether the attack is successful and the tree will succumb is the observation of the presence of blue stain fungus, Ceratostomella spp., in the xylem. This fungus is carried into the cambial galleries on the legs and body of the beetle and is an accelerating agent in the death of the tree. On the ground, the presence of blue stain is discovered by making small hacks into the wood with an axe. The amount of time required to kill a tree and the likelihood that a given attacked tree will succumb are both uncertain; therefore, intensive ground examinations are required for accurate appraisal. The detection of small changes in tree vigor, even on the ground, is most difficult. A total of 243 infested trees were examined in this manner at each inspection.

During the last visual inspection in July 1966, most of the infested trees were showing some visible signs of foliage discoloration. These colors were identified by the Munsell color notation system as described by Nickerson (1940). In the field, one experienced observer compared the color of foliage of the upper tree crown in full sunlight with a series of Munsell color cards also held in sunlight. The color chips were mounted on hue cards with holes punched between the chips to facilitate comparison. The foliage is viewed through the punched holes; thus, the foliage and color chip are adjacent and the eye can readily compare them. Similar vegetation studies using Munsell notations have been conducted by Nickerson (1958) to discriminate between grades of cotton and by Heller et al (1964) to identify northern tree species.

Figure 4.--Pitch tubes (shown by arrow) are indications of heavy bark beetle attack.

Ground Markers for Flight Orientation

Markers of various kinds were used to assure photographic and line-scan coverage over the 11 attractant sites. Feed sacks, stuffed tightly with twigs and foliage, were wired to poles and erected in tall trees (Fig. 5). Such markers were used at each end of the five photographic flight lines. Ground panels of paper strips, arranged in the shape of a cross (Fig. 6) and spaced known distances apart on the ground, served for scale determination and orientation during photography. High intensity stroboscopic lights were used at night for orientation of the F-29 (Convair) airplane operated by the Northern Fire Laboratory of the Forest Service. This plane is equipped with a thermal mapping scanner (Texas Instruments-RS-7) and also with a doppler navigational radio which greatly reduces the need for extensive ground marking.

Intensive Study of Healthy and Infested Trees

Spectrophotometric measurements. In October 1964, replicated foliage samples were taken from the upper crowns of healthy uninfested, newly infested (August 1964), and old infested (August 1963) ponderosa pine trees and sent by airplane in refrigerated containers to the Metrology Division of the National Bureau of Standards, U. S. Department of Commerce, Washington, D. C. Standardized spectrophotometric procedures for handling vegetative samples have been worked out by Keegan, Schleter, and Weidner of that Bureau.

Reflectance measurements were made from each foliage sample on the General Electric Recording Spectrophotometer which recorded in the visible and near infrared spectral ranges 0.40 to 0.75 microns and 0.73 to 1.08 microns, respectively.

Figure 5.--Tree top markers were used to facilitate correct orientation on precision photo flights.

Figure 6.--Ground panels, each 6.6 feet long, were laid in the form of a cross for flight orientation and for scale determination of large-scale photography. Red paper panels were laid over white ones following a late snowstorm on May 11, 1966.

The Cary Model 14 Recording Spectrophotometer equipped with a Cary Model 1411 reflectance attachment was used primarily to extend the infrared readings of the foliage samples into spectral ranges 0.6 to 2.5 microns by using a tungsten source and a lead-sulfide detector. The measurements were made with the needles bound tightly together and still attached to the twig.

A Cary White Model 90 Recording Spectrophotometer was used to obtain reflective infrared readings from 2.5 to 22.22 microns by using a nichrome helix source operating at 100 watts and a thermocouple detector. The needles were removed from the twig and arranged in a tight mosaic on black electrical tape placed on a water-cooled metal specimen holder.

These specimens had been collected from the study area--as part of another test--one year prior to the present study and their spectral reflectance curves are shown under RESULTS (Fig. 19). Corroborating evidence was obtained in October 1965 by taking similar foliage samples and processing them through a Beckman DK-2 recording spectrophotometer which has a spectral range of 0.35 to 2.70 microns.

Needle temperature measurements. From the beginning of this study we believed that one of the important factors in the detection of a dying tree would be the identification and measurement of changing patterns of heat transfer. We needed to know how these heat patterns differed between healthy and attacked trees and also how they differed by time-of-day and by solar conditions.

The needle temperatures were obtained by inserting copper-constantan thermocouples, approximately 2.5 millimeters long and sharpened to a point, into living cell tissue of individual needles. These thermocouples were placed inside needles at three random locations within the upper crown of four healthy and four insect infested trees. Wires joined the thermocouples to a recording station on the ground and temperatures from the remote thermistors were recorded on a Brown Electronic Model 153 x 60 P16 multipoint recorder (Fig. 7). Power to run the recorder was supplied from a 1500 watt portable generator wired to a remote starting mechanism actuated by a preprogrammed timer. This setup permitted continuous recording of needle temperatures at pre-set intervals during the day and night.

Apparent temperature measurements. Apparent or emitted temperatures were measured with a Stoll-Hardy infrared radiometer of the type reported by Stoll (1952), manufactured by the Williamson Development Company. The radiometer was fitted with an infrared filter which cut out all shortwave radiation below 3.5 microns. This effectively eliminated most of the energy of reflected sunlight from the surface of the sample needles.

Field use of the radiometer was adapted from suggestions made by Dr. David M. Gates. The radiometer was carried and used directly in the tree crowns (Fig. 8) where it was found that a great many observations could be made in a short period of time. Radiant temperature measurements were made several times each day on each of the eight study trees (four healthy and four stressed). The radiometer readings were intended to provide a basis for the interpretation of the airborne thermal imagery of the same study site. These data might also help to explain the ability or inability to detect changes in the thermal patterns of a dying tree from the airborne thermal detector.

Relative transpiration measurements. To help explain thermal differences that may exist in pine foliage, it is necessary to consider all factors (and their interactions) which could contribute to temperature differences

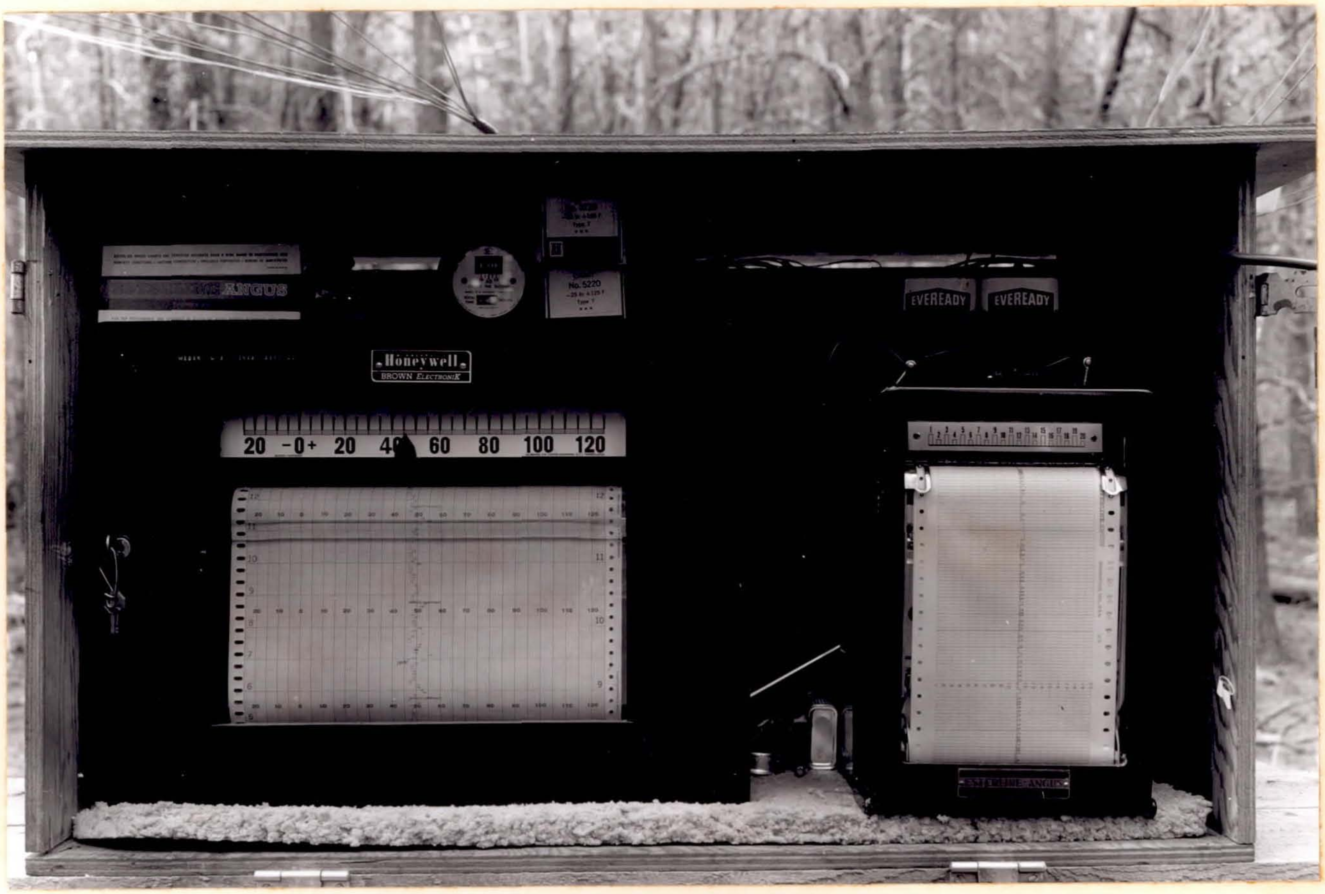


Figure 7.--Brown Electronic Model 152 x 60P16 multipoint temperature recorder on left and Esterline-Angus twenty-channel event recorder on right. Internal needle temperatures were recorded from crowns of infested and healthy trees; note wires leaving rear of instrument to attach to needles. The event recorder was used to measure wind direction and velocity.

Figure 8.--Stoll-Hardy infrared radiometer being used to measure apparent needle temperature in the upper crown of a ponderosa pine tree. The radiometer head is fitted with a 3.5 micron cut-on filter.

between the foliage of healthy and dying trees. These factors include absolute leaf temperature, emitted leaf temperature, ambient air temperature, wind velocity, and finally relative transpiration rates.

We decided on the basis of Weber's study in Michigan (1965) that sap movement would be measured with a specially constructed sap flow detector. This instrument is designed to measure the rate of sap flow by timing the rate of movement of a heat pulse from one point to another in a tree. Basically, the instrument consists of two miniature heat sensing thermistors which are inserted vertically into the xylem 1.5 centimeters apart, a 6-volt resistance-type heat probe which is inserted into the xylem 0.5 centimeters below the upper thermistor probe, an indicating meter, and a stop watch.

The rate of heat dissipation is a measure of velocity of sap flow and must be calculated from formulas derived by Marshall (1958). Heat-pulse velocity is in turn used to calculate sap flux which finally permits us to compare transpiration rates between trees. Increment cores were removed from the healthy and stressed trees so that oven-dry weight, green volume, and water content could be determined and used in the above formulas.

In July 1966, an improved portable microvoltmeter, Medistor Model A 60-C (Fig. 9), was incorporated into the system. With its increased sensitivity, sap flow readings can now be made near the ground instead of within the top ten feet of the crown.

Wind velocity measurements. Some quantitative measure of wind velocity is necessary so that a relationship can be established between needle temperature and heat flow into and out of the tree. Wind movement above 15 miles per hour causes stomata along the needles to close but permits the individual needles to act as fins on a radiator thus speeding heat dissipation.

Figure 9.--Portable micro-voltmeter, Medistor Model A-60-C, is used with two heat detectors and a heat source to measure relative transpiration rates between healthy and dying ponderosa pine.

Although the regulation of leaf temperatures is somewhat complex, thermal emission, in direct sunlight, is always affected by changes in the wind velocity. Therefore, recordings of wind velocity are useful in explaining the ability or inability of an airborne sensor to discriminate between temperature differences in stressed and healthy trees. A 3-cup anemometer was erected in a tall tree and the velocity transmitter input was wired to a 20-pen Esterline-Angus strip-chart event recorder (Fig. 7).

Soil moisture and temperature measurements. Soil moisture data are needed to determine availability of water to the roots throughout the growing season to correlate with transpiration and sap movement.

At the beginning of the growing season in April 1966 and immediately following snow melt, two soil pits were dug near the sample trees. The soil horizons were mapped and soil moisture and temperature probes were inserted at each horizon and the leads brought to a terminal box at the surface. Soil samples were collected and their field weights carefully determined. The soil pit was then refilled. Thereafter, measurements of soil moisture and temperature were taken each day with a Coleman Soil Moisture Meter (Fig. 10). Physical and organic characteristics of the soil samples will be determined in the soils laboratory.

In April, the soil was at field capacity as evidenced by the water which rose in the soil pits to within one foot of the surface of the ground.

Solar radiation measurements. A recording pyrheliograph which measures solar radiation (Fig. 11) was erected in the open on an instrument shelter housing a recording hygrothermograph. Data from the pyrheliometer can be tied in directly with the timing of the thermal scanner flights to show the total solar radiation to which the sample trees were exposed prior to and during the flights.

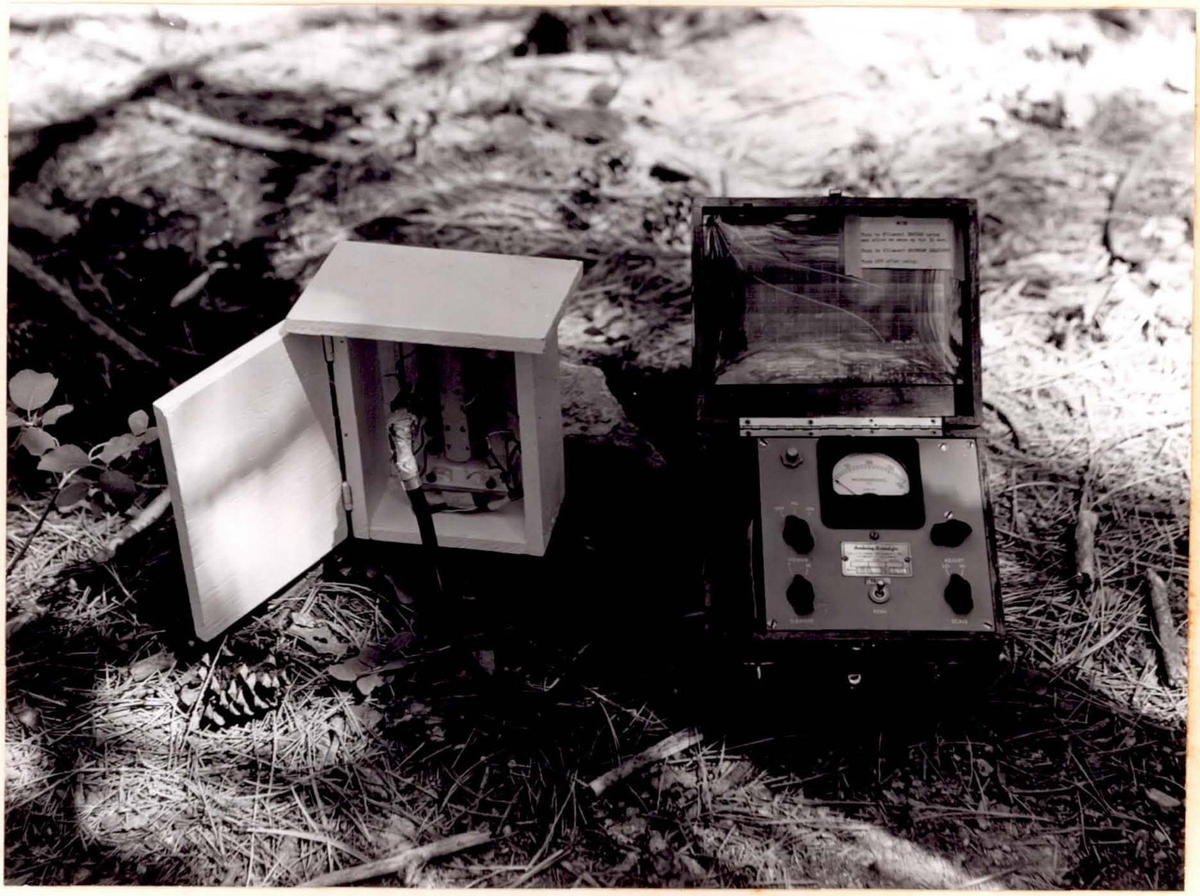


Figure 10.--Coleman Soil Moisture Meter being used to measure soil moisture and temperature from probes buried in the soil profile.

Figure 11.--Weather cabinet housing hygrothermograph in opening near healthy and infested sample trees. Recording pyrheliometer (resting on the roof of the weather cabinet) measures total solar radiation.

AERIAL PROCEDURES

Aerial Observation

During the periods that ground data were being collected, aerial observation flights were made over the 600 acres where the attractant sites were located. The frontispiece will give the reader an idea of the complexities of colors, terrain, and cultural features associated with the study area. There were all degrees of tree condition ranging from dead snags, which were attacked by beetles in 1962 and had since lost their foliage, to trees attacked in 1965 and just beginning to turn yellowish, and finally to healthy trees which were still a normal green-yellow color.

Flights were made over the marked attractant sites at 500 feet above ground with three observers in an Aero Commander 500 B aircraft flying at 100 miles per hour. The intent was to determine whether the eye could discern slight changes in color before other sensing media could.

Conventional Aerial Photography

As mentioned in the INTRODUCTION most aerial photographic studies conducted in the past were directed toward learning what film-filter-scale combination would be optimum for locating and accurately mapping discolored coniferous trees. Color films (both natural and false color) have been generally more useful than panchromatic or infrared emulsions. Medium scales from 1:5,000 to 1:8,000 have provided acceptable photographic interpretation accuracies when applied over large areas and when used with appropriate correction (regression) factors. However, certain limitations have been recognized in using these scales, viz, individual fading trees are difficult to detect and with the film emulsions currently available no early indications of mortality have been discernible.

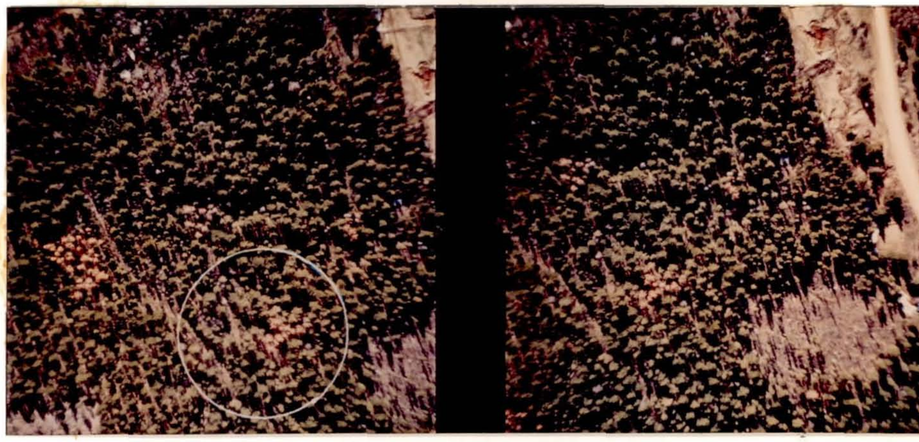
In this study we wanted to explore the largest possible scales of photography so that we could learn the earliest time at which loss of vigor could be detected from the air for individual trees. For these reasons we settled on two scales, 1:1,584 and 1:3,960 (Fig. 12).

Anscochrome D-200, rated at ASA 200, and having a resolution of 90-110 lines per millimeter was selected for the color film. Kodak Ektachrome Infrared film (Type 8443) was used to obtain a record, beyond the visible spectrum, of coniferous foliage under stress. It was exposed at an ASA rating of 160 with a number 12 (minus blue) filter.

Since the sizes of the targets (attractant sites) were generally less than one acre in size, small format, high-speed-shutter cameras were used. For the first photographic coverage in October 1965, we used a 70 mm Hulcher, Model 102, which was specially modified for aerial photography and was equipped with a 150 mm Schneider Xenotar lens. Photography was performed from a Forest Service-owned Aero Commander 500 B airplane flying at 100 miles per hour to obtain 60 percent overlap for stereoscopic coverage. Shutter speeds were 1/1200th second or faster to reduce image motion.

Subsequent aerial photography (May, June and July) was taken with two 70 mm Mauer, KB-8A, cameras equipped with 150 mm Schneider Xenotar lens (Fig. 13). The two cameras, impulsed simultaneously by an Abrams CP-3 intervalometer, gave identical photo coverage on the two film types. This eliminated photographic variables associated with time of day (shadow length, shadow direction, and crown illumination) on the two films and allowed a more valid comparison to be made.

Films were processed at Black Hills National Forest darkroom facilities using Nikor processing equipment. This allowed examination of films within



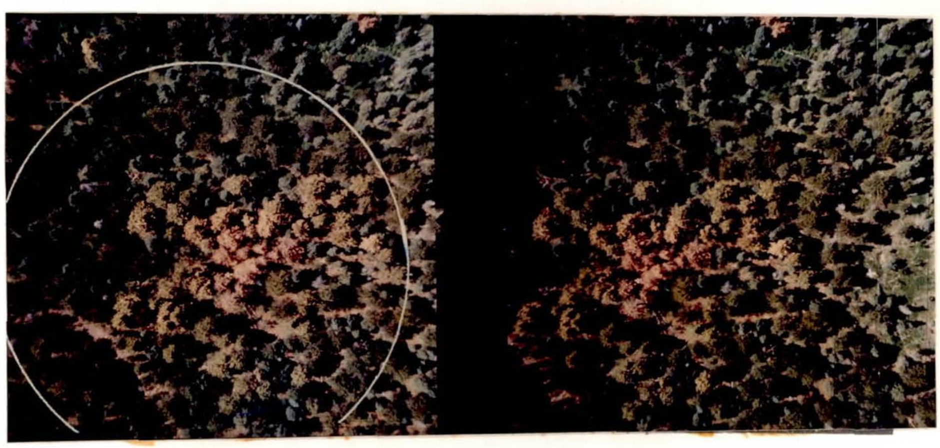


Figure 12.--Stereo pair of Black Hills beetle attractant site 7 on Anscochrome D-200 film, July 1966: (top) 1:3,960 scale, (bottom) 1:1,584 scale.

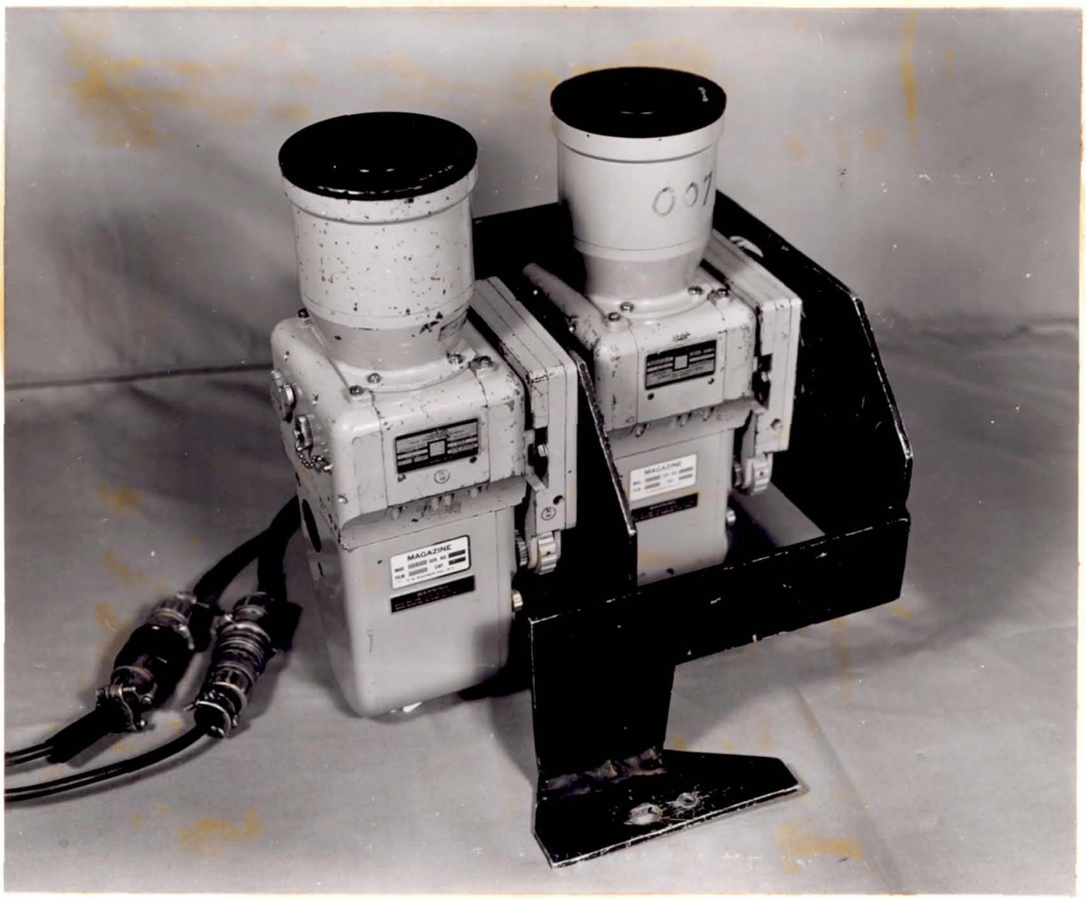


Figure 13.--Dual mount of 70 mm cameras.

a few hours after taking them to see whether exposures were of good quality and covered the desired areas. Reflights were made when necessary.

Conventional black and white photography was flown for the area covered by the infrared line scanner. These aerial photographs were taken at a scale of 1:12,000 to parallel the scale of the infrared imagery for a direct comparison of resolution. The Plus-X aerial films also provided small-scale coverage of the study areas for use in over-all planning.

Infrared Line Scanner

Aerial line scanners permit sensing beyond the visible and near infrared regions of the electromagnetic spectrum into the middle infrared. Most film emulsions are sensitive only to the visible and near infrared wavelengths (0.4 to 0.9 microns). Theoretically, the capability of Anscochrome D-200 film is from 0.4 to 0.7 microns and Ektachrome Infrared film extends this capability to 0.9 microns in the near infrared. The Texas Instruments RS-7 infrared line scanner used in this study extends the aerial spectral sensing capabilities into the intermediate infrared (2.0-2.6 microns, 4.5-5.5 microns, and 8.0-14.0 microns).

Basically the line scanner is made up of four separate but integral systems: (1) an optical system to collect emitted energy from a ground object and focus it on a suitable detector, (2) a scanning system to cover the area of interest on the ground, (3) a system for amplifying the signals received from the detector, and (4) a system for printing the information on the recording media. The Texas Instruments RS-7 scanner was equipped with a photographic print-out of the sensor imagery so that it was instantly available as the flight progressed. In addition, the electrical signals were recorded on magnetic tape to allow for corrections and a more precise and distortion-free print-out of the imagery at a later date.

The line scanner was mounted in an F-29 (Convair) airplane owned by the United States Air Force. The aircraft and scanner are assigned to the Northern Forest Fire Research Laboratory in Missoula, Montana, to implement a fire detection research program started there in 1961. Scheduling this aircraft for this study was understandably difficult and introduced problems that will be discussed later under RESULTS.

Flights were made over the study area on May 13 at 1000, 1400, and 2000 hours and again at 0500 hours on May 14. On all flights, weather conditions were poor for infrared radiation detection. Eight additional flights were made between 0745 and 1300 hours on June 3 under similar poor weather conditions.

INTERPRETATION OF AERIAL IMAGERY

Aerial Photography

The October 1965 aerial photography was examined at both the 1:1,584 and 1:3,960 scales to detect early signs of loss in tree vigor associated with the bark beetle attacks. Actual photographic scales were determined for each of the 11 attractant sites on both film types. This was done using an illuminated micrometer scale (Fig. 14) to precisely measure the distance on the transparencies between images of ground panel markers. The relationship between photo distance and ground distance determined the photographic scale.

Attractant trees were located on each site and marked on the transparencies. Using the attractant tree as the center, a circular plot was drawn to exact scale on transparent acetate material using the known radius of the ground plot. This procedure was repeated for both film types.

With the acetate templates attached to the films, three interpreters independently examined the films on an illuminated 70 mm stereo viewer (Fig. 15).

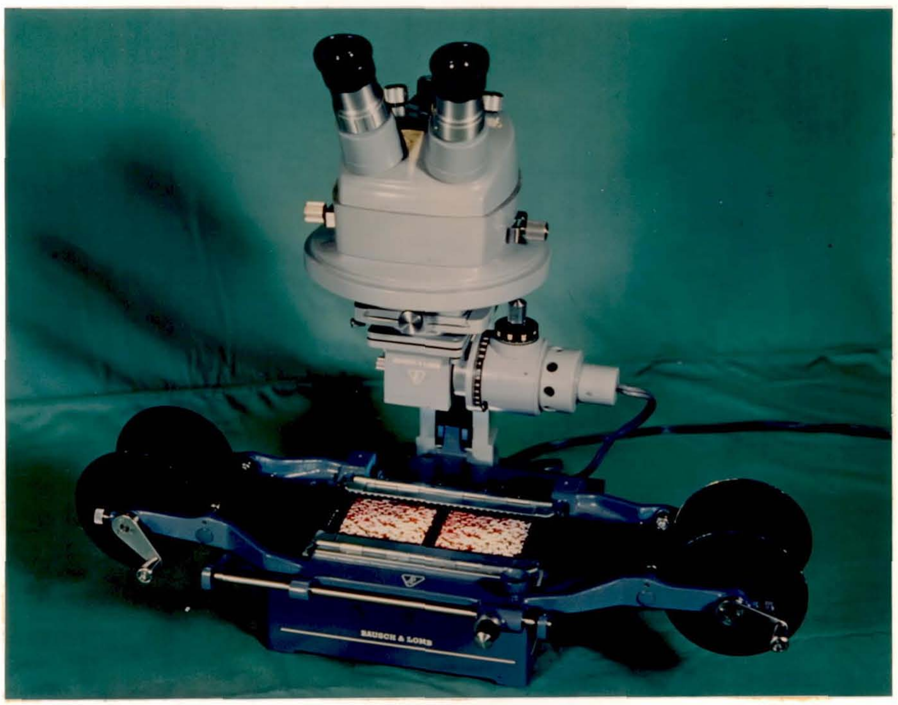


Figure 14.--Bausch and Lomb Zoom 70 Stereomicroscope with illuminated scale micrometer attached.

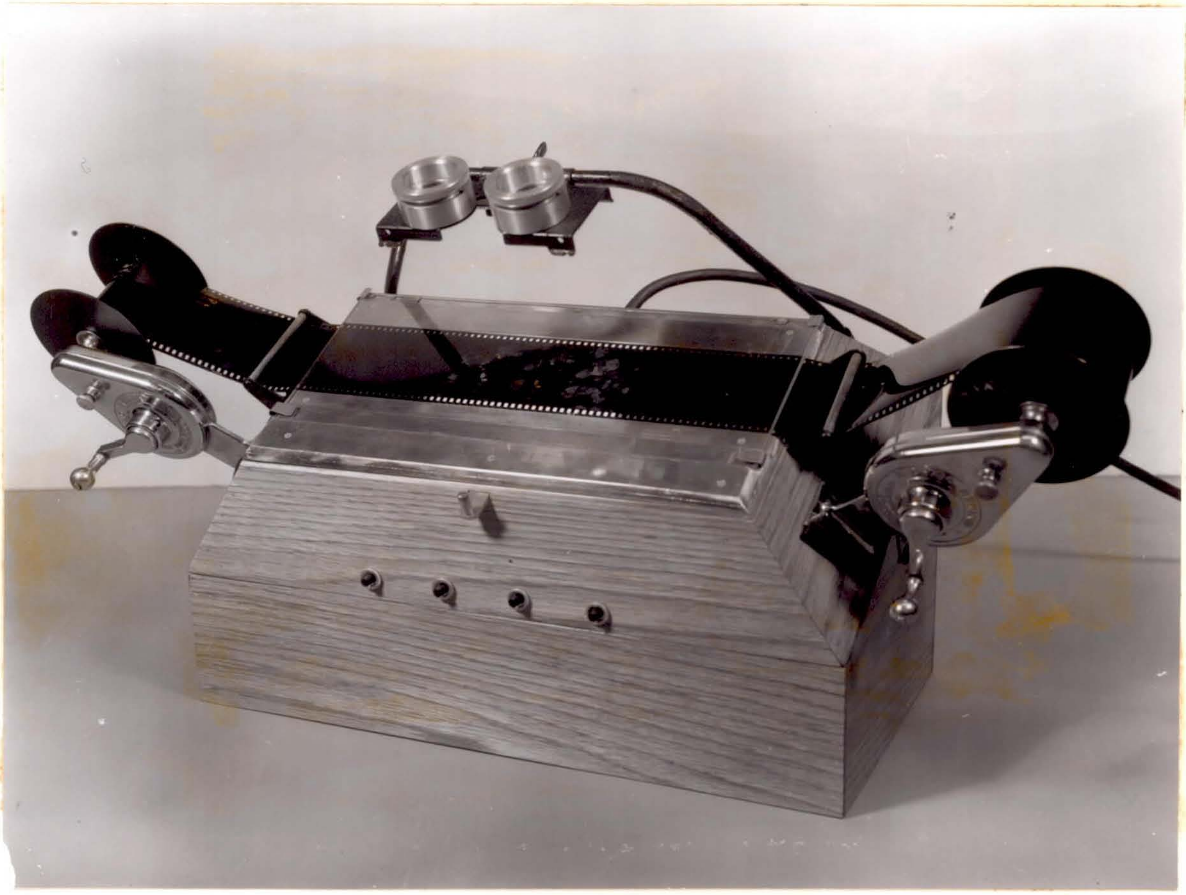


Figure 15.--Illuminated stereo viewer for 70 mm color photography.

In May 1966, new photographic coverage was examined. The attractant tree locations were marked on each site and new templates made for five of the most active sites. Since plot boundaries were already established in October, the plot limits were transferred by eye to the new templates. A master template was made for each of the five sites to show locations of trees infested by bark beetles on the ground and those that were visibly fading. Then two unbiased interpreters independently examined these films on a fluorescent light table (Fig. 16) and marked on templates the trees they considered to be beetle attacked. The order of interpretation was Anscochrome color first and Ektachrome Infrared second. Only the 1:1,584 scale was interpreted because it was felt that if there was a difference in detection value between the two films it should show best at the largest scale.

The June photographic coverage was poor and only two of the five sites interpreted in May were adequately covered. These two plots were transferred to both film types as had been done in May and were then independently interpreted by the same interpreters.

The final photographs in the sequence were taken in early July and excellent coverage resulted. New master templates were made to show the locations of infested trees tallied on the ground during the final (July) phase. As in May, two interpreters studied both Anscochrome color and Ektachrome Infrared films and independently marked trees that showed signs of crown fading or loss of vigor. Again, only the 1:1,584 scale was examined.

Interpretations for the May and July photographs were compared with each other and with the corresponding ground tallies.

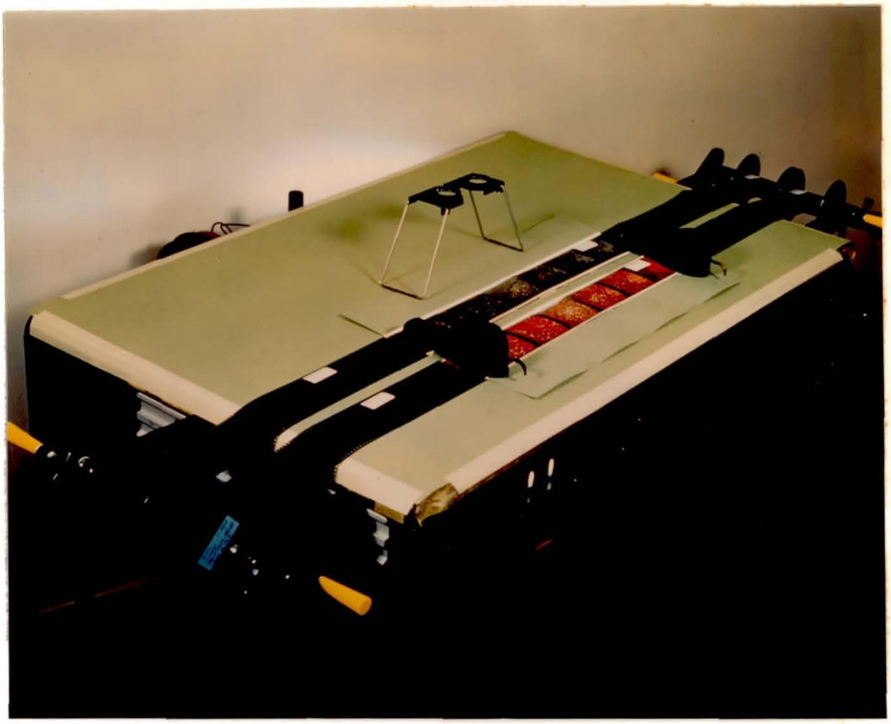


Figure 16.--Fluorescent light table for side-by-side viewing of 70 mm photography; Anscochrome D-200 and Ektachrome Infrared films shown.

Infrared Thermal Imagery

Following the aerial flights which used the infrared line scanner device, the photographic record of these scans was examined at Ellsworth Air Force Base, Rapid City, South Dakota. It was impossible to make an objective evaluation at that time for these reasons: the original record was of poor photographic quality and the classified status of the imagery prevented certain project personnel from examining it at that time. However, imagery electronically adjusted to counteract distortions and with improved resolution will be examined at a later date when magnetic tape recordings made of the scans are played back by the Michigan Institute of Technology, Infrared Laboratory.

RESULTS

We are in a position to report on partial findings only; for example, the final determination of tree mortality cannot be made until October 1966. Most of the biological and physical measurements are in the process of data analysis at the University of Michigan and will require multivariate analysis of the recorded data to determine which combination of effects are important in detecting tree stress with ground instrumentation only. We have presented examples of the aerial imagery which are not classified and the reader can comprehend the subtlety of differences which can be detected by experienced photo interpreters on very large-scale aerial photographs.

GROUND MEASUREMENTS

Biological

Infested tree counts. As indicated earlier, it is difficult to determine with certainty whether an infested tree will survive or succumb to beetle attack. Table 2 shows the tally of attacked trees at each attractant site

TABLE 2

NUMBER OF PONDEROSA PINE TREES ATTACKED BY ONE GENERATION (August 1965 Brood) OF BLACK HILLS BEETLES ON 11 ATTRACTANT SITES AND THEIR LIKELIHOOD OF SUCCUMBING

Attractant Site No.	Total Number of Trees Attacked by the Following Dates:			Expected Mortality[2] by October 1966
	8/31/65	5/6/66	7/8/66	
1	10	10	10	8
2	8	8	8	7
3	14	14	14	10
4	30	30	30	20
6	21	21	21	8
7	72	72	72	54
12	2	2	2	0
13	9	9	9	7
14	19	26 [1]	26	16
15	2	2	2	1
16	30	49 [1]	49	34
TOTALS	217	243	243	165

1/ More trees attacked after first examination.

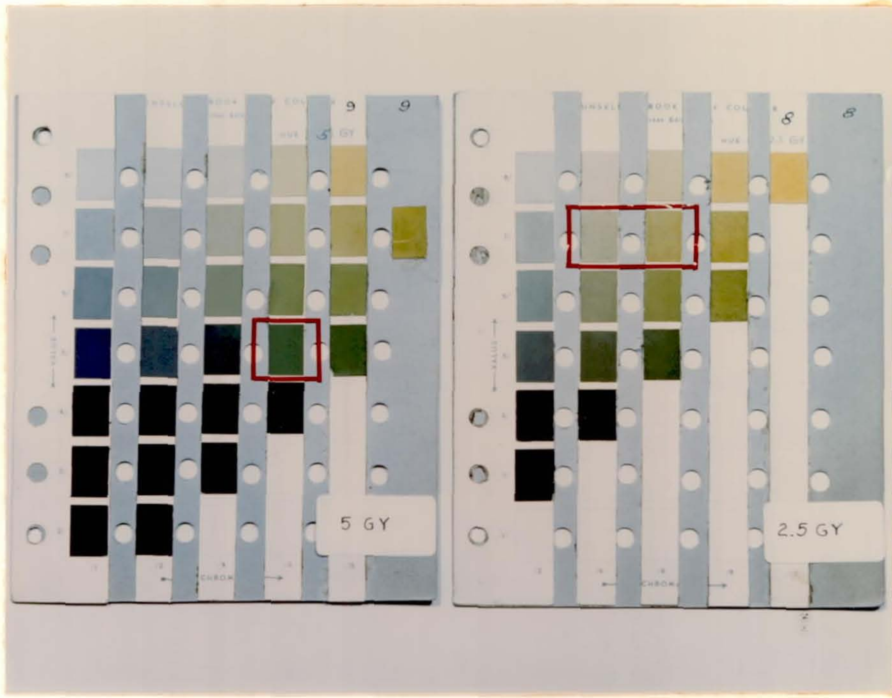
2/ Trees without fading or blue stain by 7/8/66 are not expected to die. These estimates will be verified in October 1966.

for each of the three dates. The last column shows expected mortality at each site and will be verified in October 1966.

While discoloration of foliage is a sure sign that a tree has died from beetle attack, the mechanisms that control the rate of fading have not been determined and are part of this investigation. The degree of foliage coloration that might be expected between April and July following an infestation the previous August ranges from the healthy green and the slightly off-color yellowish-green (Fig. 17) to the straw or sorrel color of the dead tree (Fig. 17). When Munsell color notations were used to rate the foliage color in July, it resulted in the selection of four hue cards that most closely described the conditions (Fig. 18). For instance, the hue card 5GY (green-yellow) most nearly approximates the color of a healthy ponderosa pine tree. Stated more specifically, the color of a healthy ponderosa pine is a hue 5GY, value 5, chroma 6 as shown outlined in red on the card. Three degrees of fading most often encountered were described by the hue cards 2.5GY (green-yellow), 10Y (yellow) and 10YR (yellow-red). In the order given, these hues describe the advancing rate of crown discoloration. If the reader checks these cards against the trees in Figure 17 he can see how the hue, value and chromas outlined in red correspond with crown colors of healthy and beetle attacked trees. As with mortality, the final assessment of foliage discoloration cannot be made until the sites are examined in October 1966. The rate of discoloration from October 1965 to July 1966 is shown in Table 3.

Data from May, June and July, the critical period for buildup of water stresses in beetle infested trees, showed the following strong correlations: xylem transport velocity with (1) time of day, (2) solar radiation intensity, and (3) soil moisture availability. A strong negative correlation is indicated between xylem transport and depth of blue-stain penetration.

Figure 17.--Black Hills beetle infestations near Lead, South Dakota; (top) new fader with healthy unattacked trees and (bottom) group of several fading ponderosa pine attacked in 1965 with old 1963 and 1964 killed trees.



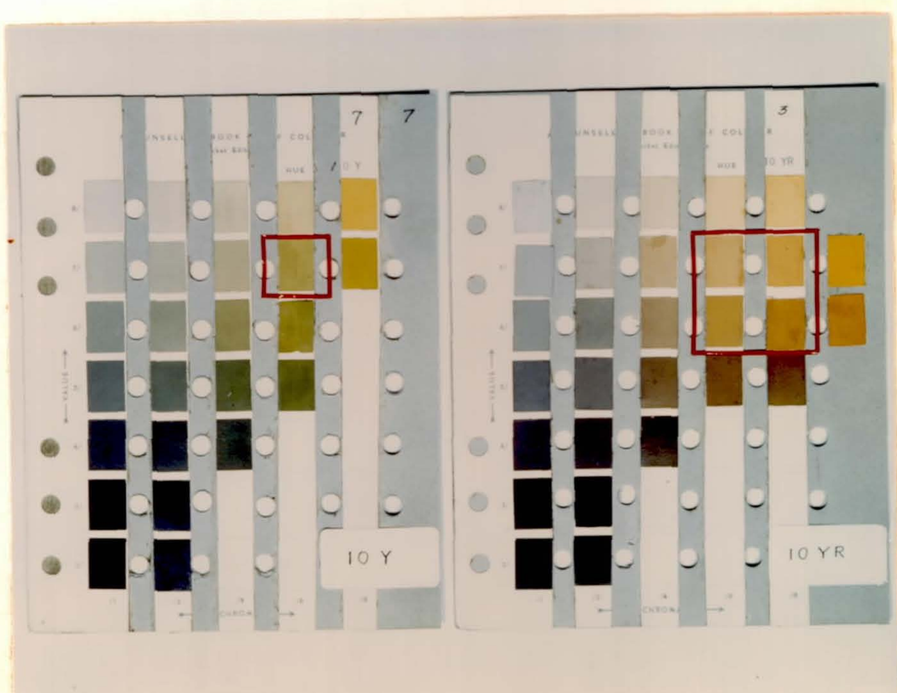


Figure 18.--Munsell color notation cards; color chips outlined in red most nearly describe crown color of healthy (5GY), new fader (2.5GY), more advanced new fader (10Y), and old 1964 attacks (10YR).

TABLE 3

RATE OF FOLIAGE DISCOLORATION ON BEETLE INFESTED PONDEROSA PINE TREES - OCTOBER 13, 1965 TO JULY 8, 1966

Attractant Site No.	Date Examined					
	10/13/66		5/6/66		7/8/66	
	Faded*	Not faded	Faded	Not faded	Faded	Not faded
1	-	10	5	5	8	2
2	-	8	4	4	7	1
3	-	14	7	7	10	4
4	-	30	12	18	20	10
6	-	21	9	12	8	13
7	-	72	46	26	54	18
12	-	2	-	2	0	2
13	-	9	4	5	7	2
14	-	26	13	13	14	12
15	-	2	-	2	1	1
16	-	49	20	29	34	15
Total	0	243	120	123	163	80

*Colloquialism for a dying tree showing visible discoloration of foliage.

The first significant differences in transport rates between healthy and stressed trees was measured the first week in May, under optimal solar radiation and soil moisture conditions. At that time the average transport rate for healthy trees was 8.2 cm./hr and for beetle infested trees 5.8 cm./hr.

The greatest difference was measured in July when soil moisture was well below field capacity, at which time healthy trees were measured at 6.7 cm./hr and stressed trees at 0-1.2 cm./hr.

Physical

The spectrophotometric recordings (Fig. 19) made by the National Bureau of Standards of healthy, newly infested, and old infested (discolored) foliage show comparative reflectance of the samples from 0.4 to 22.0 microns. The curves represent the mean of three samples. Each graph presents data taken from a different portion of the electromagnetic spectrum by a different spectrophotometer; the top graph by the General Electric in the range 0.4 to 1.08 microns; the middle by the Cary-White 14 from 0.4 to 2.2 microns; and the bottom by the Cary 90 from 2.5 to 22.0 microns. Note that the ordinate axes on all graphs are plotted at different percent reflectance scales.

The greatest deviation between the curves occurs between the old infested foliage and the healthy foliage and these differences can be seen in many parts of the spectrum. This same distinction, however, can be made on film--either color or infrared sensitive. There is very little difference that occurs between the foliage from newly infested trees and healthy trees at this early date (approximately 45 days after beetle attack). The newly infested foliage shows a slight increase in reflectance at 0.68 microns (the chlorophyll absorption wavelength) and a decrease in reflectance of 5 to 10 percent at 0.75 to 1.2 microns. It is unlikely that these small differences are detectable when the inherent reflectance variations within a species are taken into account.

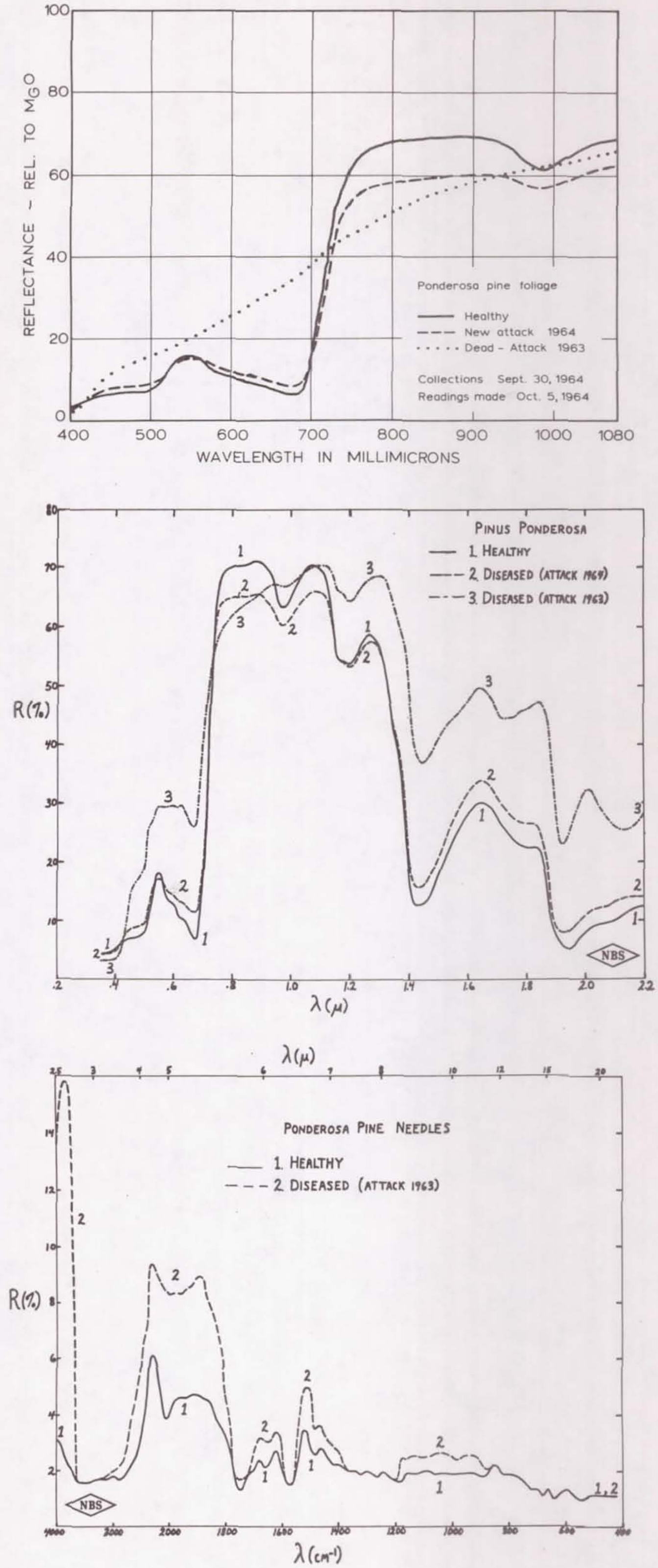


Figure 19.-- Spectral reflectance curves from foliage taken from healthy, newly infested, and old infested pine trees (Courtesy of the National Bureau of Standards). Top: foliage reflectance from 0.4 to 1.08 microns. Middle: 0.4 to 2.2 microns. Bottom: 2.5 to 22.0 microns.

EVALUATION OF AERIAL IMAGERY

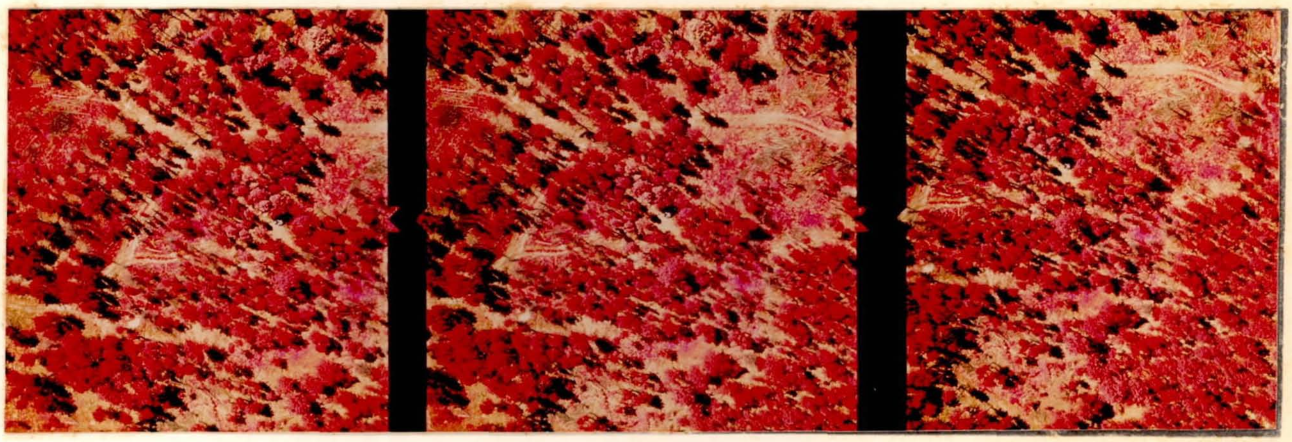
Photo Interpretation

Examples of the 70 mm imagery, taken during each of the four study periods, are illustrated in Figures 20, 21, 22, and 23 for both the Kodak Ektachrome Infrared and Anscochrome D-200 films. The most recent photos, those of July 1966, are shown first and the October 1965 photos last. Even though some loss of resolution occurs in making a print from a transparency the reader can gain an appreciation of the quality of the imagery and the subtle changes in foliage coloration which occur as the tree dies.

A lens stereoscope placed over any adjacent pair of photographs will enhance the resolution by providing a three-dimensional enlarged model for inspection.

A template has been taped along the top edge of the color print to aid in the location of trees which had faded by the July 1966 date. The triangles on the template are directly over tree crowns which are in the early stages of foliage discoloration. They are similar to the yellowing tree shown in Figure 17 and were described on the ground as being 2.5 green-yellow on the Munsell chart (Fig. 18). No yellow (10Y) or yellow-red (10YR) trees were found on this attractant site at this time. The green infested trees, to be found under the dots on the template, are difficult to separate from uninfested trees. On all pines harboring successful beetle attacks, foliage discoloration will continue and trees will progress from green-yellow (2.5GY) to yellow (10Y) and thence to the yellow-reds (10YR) as are shown in mass effect on the frontispiece.

When interpreters examined the photography taken to date, they were required to check each tree within the described attractant areas and decide



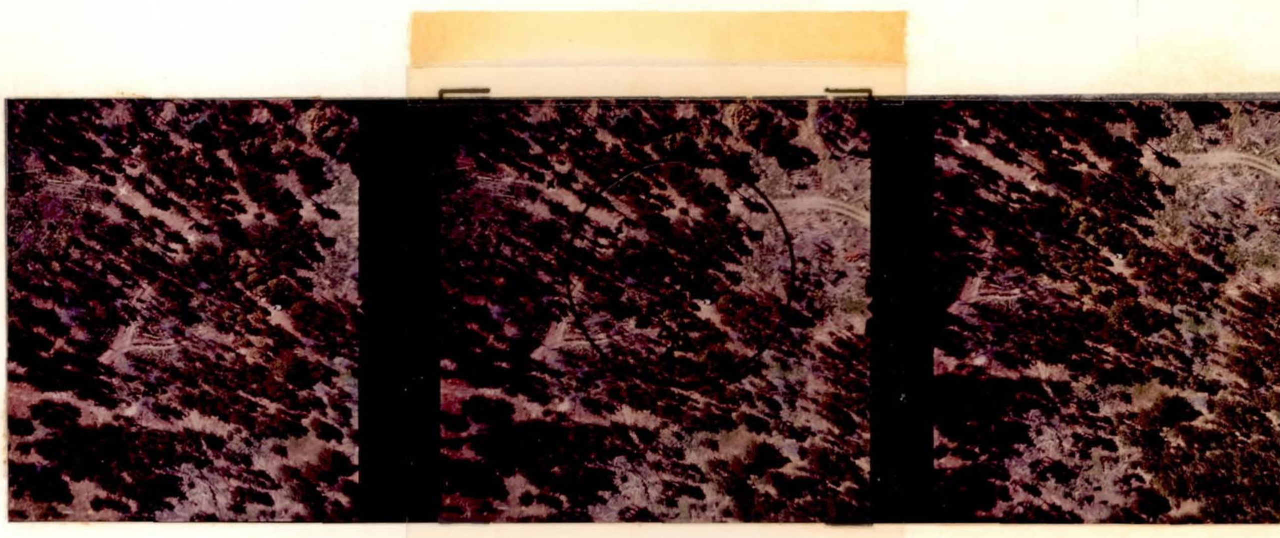


Figure 20.--Stereo prints made from Kodak Ektachrome Infrared (top) and Anscochrome D-200 (bottom) aerial transparencies taken at a scale of 1:1,584, July 7, 1966. Faded trees are indicated by triangles on the plastic overlay and green infested trees by dots. The scribed circle shows the boundaries of attractant site 14 and includes many uninfested trees.

Figure 21.--Stereo prints at 1:1,584 scale; June 1966. (Top) Ektachrome Infrared, (bottom) Anscochrome D-200.

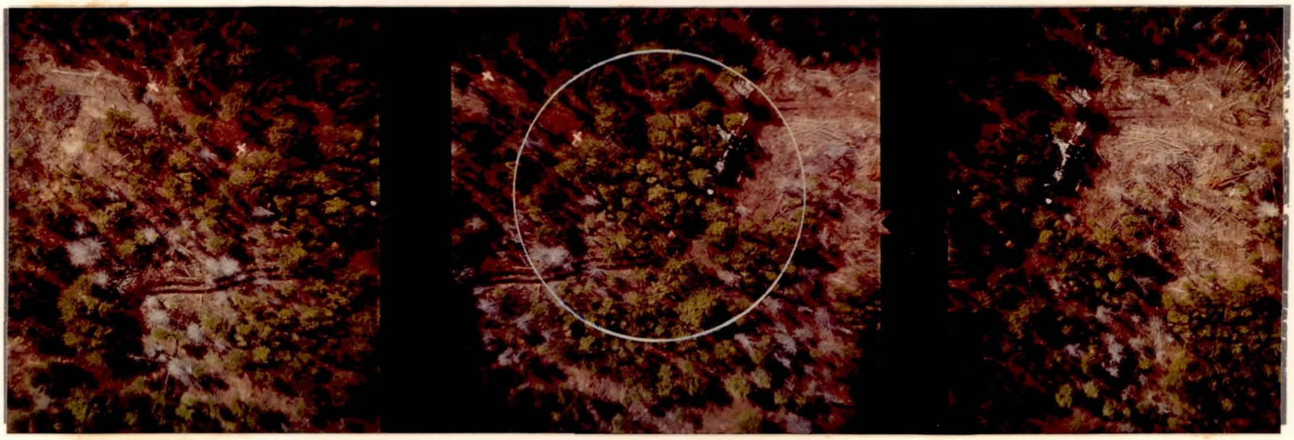
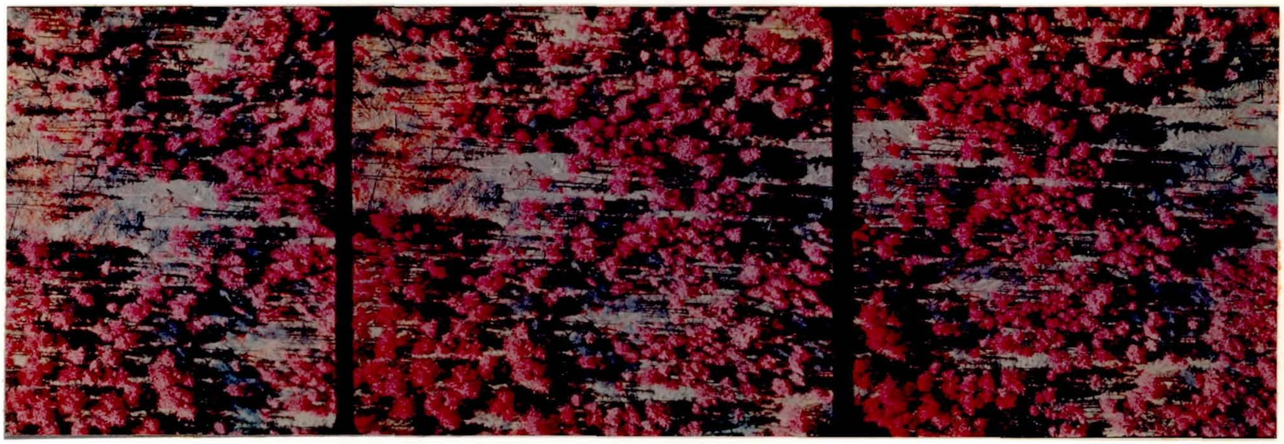


Figure 22.--Stereo prints at 1:1,584 scale; May 1966. (Top) Ektachrome Infrared, (bottom) Anscochrome D-200.



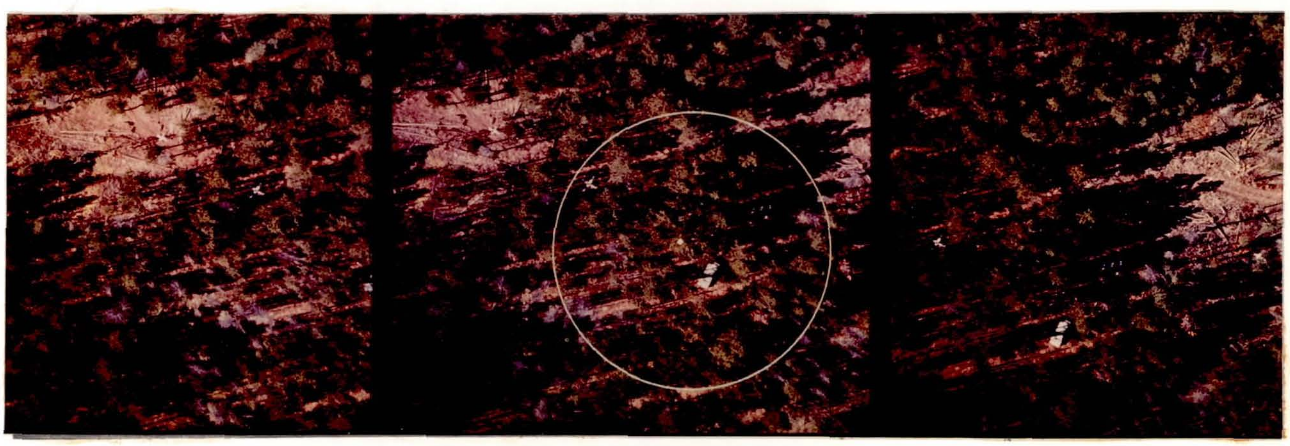


Figure 23.--Stereo prints at 1:1,584 scale; October 1965. (Top) Ektachrome Infrared, (bottom) Anscochrome D-200.

whether any color change from normal could be distinguished. This was a rather routine task on Anscochrome color film where objects are displayed in their natural color. However, the false colors of Ektachrome Infrared films required interpretation of changes from the deep magenta of healthy trees to the pink and white of new faders and to the yellow of dead trees killed some time ago. Thus, we have interpreters detecting differences in reflectance in the 0.4 to 0.7 micron band on the one hand and differences in reflectance in the 0.7 to 0.9 micron band on the other.

Interpretation of October 1965 photography resulted in the general conclusion that under the conditions imposed by this test, no beetle attacked trees could be detected at the early date on either of the two types of film. Because the June 1966 photography did not cover all attractant sites the results are not shown in Table 4. However, the interpretation of the two attractant sites with good photo coverage showed that little change occurred between the May and June flights of photography. Table 4 presents the results of interpretation averaged for two interpreters for both May and July. Here very definite changes are shown between the two dates. As the data indicates, in early July we can expect to detect 72 percent of all attacked trees that will die. It would be desirable to detect this many of the trees as early as mid-May (instead of 21 percent) to expedite control and salvage operations.

In both May and July the detection score for both films was the same. Since the number of commission errors (i.e., calling healthy trees attacked trees) is greater for the Ektachrome Infrared film in both May and July, this would indicate that interpreters are having difficulty in detecting the most subtle changes in false color. This does not preclude the use of Ektachrome

TABLE 4

DETECTION ACCURACY AND COMMISSION ERRORS BY GROUND SURVEY AND PHOTO INTERPRETATION OF AERIAL ANSCOCHROME D-200 AND IR EKTACHROME PHOTOGRAPHY; MAY AND JULY 1966

	Detection		Commission errors
Date	Number of trees	Percent 2/	Number of trees
May 1966			
Ground	94 1/	62	-- 3/
Color photos	31	21	17
IR Ektachrome photos	31	21	31
July 1966			
Ground	151 1/	100	-- 3/
Color photos	109	72	13
IR Ektachrome photos	110	73	18

1/ Beetle attacked trees showing visible signs of crown fading on the ground.

2/ Percentage of total trees faded in July 1966.

3/ Some 40 trees attacked in October 1965 did not die and may be called ground commission errors if they have not changed color (and have no blue stain) by October 1966.

Infrared in future studies. The addition of filters during the exposing and viewing of false color film may enhance the interpreter's accuracy.

Infrared Line-scan Imagery

We could not detect 1965 beetle attacked ponderosa pine trees on the May or June infrared line-scan imagery. This means that under the test conditions by which the imagery was collected and reproduced, the capability of the line scanner in the 2.0 to 2.6 micron, 4.5 to 5.5 micron, and 8.0 to 14.0 micron bands was not great enough to detect trees showing signs of loss of vigor and reduced transpiration rates. It should be noted that most of these flights coincided with periods of cool, cloudy weather which depressed leaf transpiration. Under more ideal conditions, more positive results may develop.

Magnetic tapes of the line scans recorded in May and June will be reproduced by playback procedures to correct distortions in the imagery. The Michigan Institute of Science and Technology will do this as soon as possible. When available the new infrared imagery will be re-evaluated and reported upon.

DISCUSSION

From the results of this study and others conducted over coniferous stands in the United States, we have determined that infrared sensitive films, even when used with recommended filters, do not detect dying coniferous foliage before normal color films. This is in contradiction to findings from studies by Colwell (1956) on cereal crops and by Myers (1963) on cotton plants. Both of these plants are broadleafed (Angiosperms) and reflect infrared light to a much greater degree than do needled plants (Gymnosperms).

When stress appears in broadleafed plants, loss of cell turgidity, and perhaps other morphological manifestations, occur; at this time, a reduction in infrared reflectance can be shown by spectral measurement or by infrared sensitive films. However, coniferous needles maintain cell turgidity longer than broadleafed plants because of their more rigid anatomical structure. In addition, the acicular shaped leaves of conifers have a different orientation to solar reflection and present a different pattern to the aerial camera than do broadleafed plants. According to the spectral reflectance curves taken of ponderosa pine foliage, a loss of infrared reflectance does occur, but is is apparently masked by other factors which are presently being studied.

Photo interpreters, then, can identify dying pine trees as accurately on color film as on the infrared sensitive films. However, the color film requires less interpreter training because tree images on color film appear very similar to the actual trees in nature, whereas, on Ektachrome Infrared film, the dying trees are detected by a lighter tone of pink or magenta. Some commission errors (i.e., falsely calling healthy trees as dying trees) were made because of low sun angle which caused higher reflectance of healthy trees making them appear as lacking in vigor.

Photography in both color and infrared color should be repeated at more frequent intervals during the period April through July to obtain more information on rate of fading during that period.

One advantage that may have space implications is the ability of the Ektachrome Infrared film to penetrate atmospheric haze. The minus blue filter (generally used with infrared film) cuts off most of the haze by blocking the blue end of the spectrum where haze is found. Then, since the infrared emulsions are sensitive to the near infrared wavelengths (0.88 microns) where vegetation is highly reflective, we may be able to capitalize on photography at smaller scales. Thus future studies should include infrared photography of small scale from a minimum of 22,000 feet. With a 1.5-inch lens this would give 1:176,000 scale photography that would simulate as nearly as possible what might be obtained from space. This small-scale infrared photography, if able to detect infestations, might permit the use of earth circling satellites for worldwide insect detection.

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APPENDIX

The following is a list of Forest Service, U. S. Department of Agriculture, personnel who have made contributions to this research study and represent a major salary contribution to it:

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