DETECTION AND CHARACTERIZATION OF STRESS SYMPTOMS IN FOREST VEGETATION

by

Robert C. Heller

BIOGRAPHICAL SKETCH

Robert C. Heller is a research forester and project leader of a Forest Service, U. S. Department of Agriculture nationwide project called "Remote Sensing Related to the Forest Environment." The project is located at the Pacific Southwest Forest and Range Experiment Station in Berkeley, California. Studies are being conducted in forest and range inventory, insect and disease detection, spectral reflectance and emittance responses from forest vegetation, and automated interpretation systems.

He attended Duke University, Durham, North Carolina, for both his undergraduate and graduate studies in botany and forest management. Supplementary graduate work was taken at the University of Maryland in entomology. Aerial color, infrared color, and 70 mm. sampling photography have been adapted to many forestry applications as a result of Mr. Heller's efforts. He has been a member of the Committee on Remote Sensing for Agricultural Purposes formed by the National Academy of Sciences - National Research Council. This committee recently published (1970) a comprehensive book called Remote Sensing, with special reference to agriculture and forestry which is relevant to the presentation at this meeting.

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INTRODUCTION

Forest managers in the United States must keep 212 million hectares (509 million acres) of commercial forest land under their surveillance. Much of this area is roadless. The condition of the forest varies seasonally and annually, depending upon weather and destructive agents at work. About 40 percent of the ownerships are large and employ some level of forest management; the remaining ownerships are small, privately owned, and mostly are not under management. Inaccessibility, rapid changes, and differences in practice have made it increasingly clear that better remote sensing methods are needed to develop new techniques to aid decision making in resource management.

I know that remote sensing requirements will vary widely in your own countries, according to size and availability of timber stands and the level of forest management practiced. Let me describe our work, at the Pacific Southwest Forest and Range Experiment Station, to detect advanced and previsual symptoms of vegetative stress. Perhaps you can benefit from our good and bad experiences.

I will talk primarily about stresses caused by bark beetles in coniferous stands of timber, because beetles induce stress more rapidly than most other destructive agents. Bark beetles are also the most damaging forest insects in the United States. Our studies have been carried out jointly by the Forest Service, U. S. Department of Agriculture, and the Earth Resources Survey Program, National Aeronautics and Space Administration. In the work on stress symptoms, we have two primary objectives: (1) to learn the best combination of films, scales, and filters to detect and locate injured trees from aircraft and spacecraft and (2) to learn if we can detect stressed trees before visual symptoms of decline occur.

VIGOR LOSS IN PLANTS

What do we mean by stress symptoms in vegetation? Stress is caused by loss of vigor which indicates an abnormal growing condition. Causes for loss of vigor are disease, insects, moisture deficiency, soil salinity, absence of trace elements or soil fertility, etc. Because stress symptoms to vegetation are similar regardless of agent, the particular cause must be verified on the ground. Unique patterns or differential rates of spread often reveal the cause. Such a situation

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occurred in Honduras, Central America, in 1963 and 1964, when a tiny bark beetle (Dendroctonus frontalis, Zimm.) multiplied to epidemic proportions and killed about 60 percent of the merchantable sawtimber in an 18-month period. Successive rings of dying trees could be marked by the differential coloring of the pine foliage. The first-killed timber appeared red, the next ring yellow-red, then yellow to yellow-green, and around that green timber, perhaps dying from the insect attack but not yet showing discoloration.

When the foliage discolors over wide areas, aerial color photography (natural color or false-color transparencies) is an efficient sensor at medium scales (1:5,000 to 1:8,000). For example, photo interpreters with training can locate, separate, and plot dying trees accurately enough on transparencies to plan control and salvage operations (1, 3). They can also estimate losses from epidemics over wide areas (11) in a short period of time. One must recognize, however, that such techniques provide the forest manager with de facto evidence. That is, the vegetation has long passed the stress point and is, in fact, dead.

The forest manager could be many times more effective if he could detect the trees in early stages of stress. He could apply insecticides or remove the beetle populations from the woods by salvage operations before new and perhaps larger beetle populations emerged and began a new round of tree killing. Forest entomologists hope to locate, by remote sensing methods, trees which are under stress to give advance notice of an abnormal condition and to permit early evaluation of insect population trends.

This is just one example of the importance of detecting tree stress before visible symptoms occur. Recently, sensors that detect conditions beyond the visible spectrum have been developed. Consequently, we designed a study aimed not only at detecting discolored vegetation from aircraft, but also at the previsual detection of ponderosa pine trees (Pinus ponderosa, Laws.) being attacked by the Black Hills beetle (Dendroctonus ponderosae, Hopk.).

LOCATION OF STUDY AREA

The Black Hills, in western South Dakota and eastern Wyoming, rise to 2,200 meters (7,250 feet) from the surrounding flat to rolling plains, at about 1,100 meters (3,500 feet). Ponderosa pine is the principal commercial tree. It occurs primarily above 1,200 meters (4,000 feet). The total sawtimber volume in the Black Hills is estimated to be 2.3 billion board feet.

A serious epidemic of the Black Hills bark beetle has been under way since 1960 (Fig. 1). A study area about 1.6 by 5 kilometers (1 by 3 miles) was selected northwest of Rapid City, South Dakota (Fig. 2). In areas where no control efforts were exerted, beetle populations from the outbreak were continuing to kill trees in large numbers. Groups of several hundred trees were infested annually, whole hillsides of timber were destroyed, and the total infestation ran to many thousands of trees killed each year.

COLLECTION OF GROUND AND AIRBORNE DATA

Whenever a remote sensing study is undertaken, we need to make a great many ground observations to correlate with data from the airborne platform. Usually as we learn more about the characteristics of our target areas, less ground work is needed, and we can extrapolate our airborne data over wider areas. Both ground and airborne data were measured on and over the Black Hills study site, from August 1965 through August 1969. Most ground data were monitored continuously during the tree growing season, while the aerial imagery was collected intermittently.

GROUND DATA COLLECTION

Biological observations which involve ecological, physiological, and meteorological interactions must be made over a time continuum. Since one of our objectives is to detect loss of tree vigor before visual symptoms occur, we are interested in the rate at which stress changes take place. To capture these changes, we measured beetle populations, numbers of infested trees, foliage color, foliage internal temperatures, needle moisture tensions, transpiration, solar radiation, soil moisture, air temperature, humidity, and wind velocity.

Most of these data are needed to compute the total energy budget which affects tree growth. For example, the data permit one to explain why trees under moisture stress may produce higher temperatures at one time of the day but not at another--even under similar sunlight conditions. One can then deduce how thermal imagery may differentiate less vigorous trees from healthy ones in one time period and not in another.

Another objective is to learn which sensors provide us with reliable evidence of past stress in the event previsual detection fails. For aerial photography, what scales, films, and filters are optimum? We know that during a bark beetle epidemic, trees likely to be attacked in the future are more likely to be related to past stressed trees. There is ample evidence that beetles tend to attack trees in clusters and usually near the site of older attacked trees. Aerial photography is particularly helpful in locating the older stressed trees, and thus we can direct our attention to these areas.

Finally, we want to learn what sizes of infestations can be detected from high-flying aircraft or even satellites. Thus, we may be able to relate known infestation sizes (groups of discolored, killed trees) to the expected and actual resolution of the Earth Resources Technology Satellite (ERTS).

Visual Determination of Tree Decline

Once a tree is attacked by beetles, the success or failure of the attack may be in doubt to the observer--even when close ground examination is continued. One manifestation of heavy attack is the presence of pitch tubes on the outer bark. 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 to look for 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. Blue stain is discovered by making small hacks into the wood with an axe. The time required to kill a tree and the likelihood that an 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.

The rate of foliage discoloration was followed in two ways: (1) by taking 35 mm. color photographs on the ground of 10 selected dying trees at weekly intervals from May 1 to August 30, 1967, and (2) by having one person with full color perception check all infested and healthy trees on four occasions: May, June, July, and August in both 1967 and 1968. Tree colors were identified by the Munsell color notation system described by Nickerson (7). 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 are mounted on hue cards with holes punched between the chips to aid 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 (8) to discriminate between grades of cotton and by Heller et al. (4) to identify northern tree species.

By relying on one observer we reduced subjective bias and permitted quantification of the color attributes. Furthermore, we hoped to compare the ground observer's Munsell notations with ground and aerial photographs of the trees.

To assess the accuracy of photo interpretation, one must know the locations and sizes of the dying groups of pine trees, how many trees in each group, and their foliage color. Over our selected study area (1.6 by 5 kilometers) we made ground visits to over 260 known and suspected infestation centers (Fig. 3).

Biophysical Measurements taken on Healthy and Infested Trees

A great many techniques were developed and improved over the course of this study. Most methods for previsual detection are discussed in detail by Weber (10) and Heller (5), but a brief description follows:

Spectral reflectance of healthy, newly infested, and discolored foliage was measured by the Bureau of Standards, U. S. Department of Commerce, using General Electric, Cary Model 14, and Cary White Model 90 recording spectrophotometers.[2] A Beckman DK-2 recording spectrophotometer was also used in later studies. Reflectance was recorded from 0.35 to 22.22 micrometers.

Internal needle temperatures of the healthy and dying pine trees were recorded continuously by means of copper-constantan thermocouples inserted into the

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[2] Mention of commercial products does not imply endorsement by the U. S. Department of Agriculture.

pine needles. Thus, we could follow the heat patterns between healthy and infested trees as they differed by time of day and by solar conditions.

Apparent (emitted) temperatures were monitored by aiming a Barnes PRT-5 (precision radiation thermometer) at healthy and insect-attacked trees from a high tower (Fig. 4). Net and total radiation thermometers are now being used in a related study (9) from tower-supported moving tramways suspended above the trees (Fig. 5). Thus, solar radiation and emitted foliage temperatures can be monitored continuously.

Relative transpiration was determined by measuring the differential sap flow between healthy and affected trees (Fig. 6).

Needle moisture tension, a measure of the tightly bound water within needles, was determined by a hydrostatic pressure bomb. Stressed foliage has less water than healthy, and by inserting the coniferous needles into a pressure bomb the amount of gas pressure required to force out the water can be related to the vigor of the tree (Fig. 7). Stressed trees require more gas pressure than healthy trees and this difference is an early indicator of stress.

Soil moisture data were collected at first with a Colman soil moisture meter, but later by a neutron probe (Fig. 8). This device measures the differential bombardment of neutrons from a nuclear source through moist and dry soils to a detector. It is important that we know soil moisture levels so that we may relate changes in transpiration rates to sap flow, solar radiation, or to soil moisture.

Wind velocity and direction are also recorded so that we may know whether excessive heat loss of foliage may be ascribed to high wind speed.

In the early stages of the study, most of the data were collected independently on separate recording instruments and analyzed separately--a slow, tedious process. In 1970, we used a data logger and the moving tramway described by Wear and Weber (9) to collect up to 38 channels of data, digitize it, and store it on magnetic tape (Fig. 9). This system permits rapid access to the data and is in computer-compatible form. It saves up to one year in the analysis of the energy budget data. I would recommend continuous ground data recording of this kind if your funding will permit it.

AIRBORNE DATA COLLECTION

Aerial Photography

Color films (both natural and false color) have generally been more useful than panchromatic or black-and-white infrared emulsions for locating and accurately mapping discolored coniferous trees. In using color films, we wanted to determine (1) whether infrared color film could serve as a previsual sensor and (2) the smallest scale and best film for detecting discolored groups of beetle-infested pine trees.

To answer the first objective, we obtained very large-scale (1:1,584) photographs over known green infested trees for a two-year period. We used two KB-8 70 mm. aerial cameras equipped with 150 mm. Schneider Xenotar lenses (Fig. 10) and extremely high-speed shutters (up to 1/4,000 second). These cameras were triggered simultaneously at 0.5-second intervals for stereo overlap. Anscochrome D/200 normal color film (with a Wratten 1A filter) was used in one camera and Kodak Ektachrome Infrared film (with a Wratten 12 filter) in the other. The photographs were taken at five time periods: in October just after the trees were attacked by the beetle, the following May after snow had left the ground and the trees began growing, and in June, July, and August almost one year after attack and when foliage color progressed from green to green-yellow, yellow, and finally yellow-red.

To determine the smallest infestation size in meters (or feet) that we could resolve, we used high-altitude photography by our own Forest Service aircraft and NASA's RB-57. Tables 1 and 2 summarize the photographic combinations, taken in July and August 1969, of the large study area (1.6 by 5 kilometers). August is usually the month in the Black Hills when maximum color contrast occurs between old-killed trees, newly dying trees, and healthy green trees. Consequently, this is the one seasonal period when likelihood of detection would be greatest and resolution could be measured most accurately on film.

Optical-Mechanical Scanning Imagery

You have already been introduced into the operation and capabilities of optical scanning instruments in your earlier session on Sensors. In 1966 and 1967, we tested infrared line scanners adapted by Stanley Hirsch for fire detection and fire mapping purposes. The instruments were designated as HRB Singer Reconofax 11 and Texas Instrument RS-7; they were primarily designed to pick up high-energy returns from forest fires. We learned a great deal about interpreting single channels of line scan imagery from these tests but could not detect dying trees. The infrared fire scanner was not designed to detect the subtle temperature differences (2° to 6° C.) occurring between healthy and infested trees.

In 1968 and 1969, the University of Michigan multispectral line scanner was flown over our instrumented test sites. It used the discrete channels shown in Table 3. Data were collected at four time periods (early morning, midmorning, early afternoon, and late afternoon) in May 1968 and July 1969. These periods coincided with maximum changes in tree metabolic activity as determined from our field measurements. We used handy-talky radios for ground-to-air communications, primarily to inform the operator of the thermal scanner about the range of apparent temperatures in ground targets. This information permits him to adjust his temperature-controlled reference plates on the thermal line scanner.

Interpretation of Aerial Photos

The 70 mm. color and color infrared transparencies were viewed over a balanced white light source by several unbiased interpreters with 2.25X magnification lens stereoscopes. On photographic scales smaller than 1:63,360, a Bausch and Lomb stereomicroscope was used to discriminate the healthy green from the discolored infested trees (Fig. 11). To test the previsual capabilities of color and false-color film, we built a special Munsell color comparator (4) (Fig. 12) to assign colors to the dying trees in connection with the film tests taken at very large scale (1:1,584). The Munsell film colors in the comparator permitted an interpreter to compare foliage colors on the aerial photos with Munsell colors. In turn, these Munsell notations were compared with those taken of the identical trees on the ground.

The 210 mm. format color and false-color transparencies resulting from the RB-57 flight were examined over our viewing tables with Old Delft stereoscopes (Fig. 13). The interpretations of suspected infestations were plotted on templates and the trees counted within each discolored group. In turn, these interpretations were compared with the known ground conditions on the study area. Thus we could draw conclusions on the limits of resolution at various scales.

Multispectral Processing

0.4 to 1.0 micrometer

The processing equipment at the University of Michigan's Infrared and Optics Laboratory (IROL) reflects an advanced technology in the field of multispectral image processing. The details of the multispectral discrimination technique, which employs a tape-loop training device, are described by Hasell et al. 1968 (2). In effect, we are trying to exploit the energy return from our targets in very narrow segments of the electromagnetic spectrum; some segments, or wavebands, contribute more than others. The analog and digital computers connected with the electrical signal outputs are programmed to select those wavebands which, when combined, best identify the targets we are interested in. The targets for which we furnished ground information and wished positive separation were: healthy pines, nonfaded-infested pines, faded (discolored) infested pines, and old-killed pines with few or no needles.

To locate training examples on the scanning imagery, the operator needs a good aerial photograph (color or black-and-white) showing the images in their proper spatial orientation. Next, analog printouts of each waveband are made on 70 mm. film strips which preserve the shape and pattern relationship of the original scanner imagery. These printouts (analogs) are useful to a new investigator who may be unfamiliar with each waveband response. Of more interest are the combined wavelength printouts which are made on individual transparent film strips only of the targets of interest. Through the use of special color diapositive material, these combined waveband printouts can be coded in color. Then, each color-coded strip and its respective recognition spots are placed over the analog of the original imagery to re-establish spatial orientation with respect to the "ground truth." Color prints can be made of this packet of templates. The prints show the tree condition classes of interest, and each class is recognized as a different color spot (Fig. 14).

Reflective IR and Thermal Processing

1.0 to 13.5 micrometers

On the Infrared and Optics Laboratory (IROL) scanner, because there is not perfect registration of all five channels of reflective and thermal infrared imagery to satisfy requirements for multiple-channel processing, some infrared channels are processed individually. There are several techniques for displaying the thermal responses of the target temperatures on the infrared imagery. Two of the most effective are: (1) combining two channels of reflective infrared with the 4.5 to 5.5 micrometer thermal channel and then varying voltage levels to produce reliable signatures of the targets and (2) using the 8.5 to 13.5 micrometer channel and producing a series of color printouts which represent targets of equal temperature (Fig. 15). This latter technique, known as thermal contouring, capitalizes on the fact that the calibration plates in the scanner are set to include the range of temperatures of the ground targets. Targets of higher or lower temperatures can be overlooked.

ANALYSIS AND RESULTS

Let us first consider the application of aerial color photography to stress detection--including previsual possibilities, comparison of color and false-color film, and the effect of smaller scales on detection accuracies. Next, the results on previsual detection with multispectral scanners and processors.

AERIAL PHOTOGRAPHY

In general, we have learned a great deal about the biological and physical changes in pine trees as they begin to die and how these changes are reflected in the photographic image. The visual and photographic color changes which show up on the ground and on large-scale aerial transparencies (1:1,600) vary with the length of time since the stress (beetle attack) was imposed.

Visual Determination of Tree Decline

The visual comparisons of foliage color made by one ground observer with the prepunched Munsell hue charts are shown in Figure 16. At a glance one can see the shift in hue of the dying trees (sample size 209) as the season progressed from May through August. For example, in May about 75 percent of the infested trees were green-yellow, whereas in August the same percentage of trees were yellow-red. The greatest shift from the normally healthy green-yellow (5 GY and 2.5 GY) foliage to off-green foliage (2.5 GY and 10 Y) seems to take place during the fall following attack until the next May.

About 10 to 15 percent of the healthy trees in May, June, and August have a slightly yellow hue (2.5 GY) which is similar to early fading of infested trees. In July, the healthy trees appeared greener; this is probably a result of new needle growth and dropping of old (dead) needles.

When foliage is healthy, it is fairly dark--the average Munsell value (lightness or darkness) being 5 and the chroma (color strength) 4 to 6. When the tree loses vigor it becomes lighter (the Munsell value goes up to 6 and 7). The ground observer also noted during May and June that infested trees appeared lighter and more silvery than healthy trees while both still had the same hue. As infested foliage changes to yellow, the trees become still lighter and the Munsell value becomes 7 to 8 with little change in chroma. The chromas increase appreciably as the foliage becomes drier later in the summer and tends toward the orange or yellow-reds (7.5 YR and 5 YR). It is at this stage in late July, August, and September that the infested trees have their highest reflectivity in the visible spectrum. Note that even in August about 12 percent of the infested trees have the same hues as healthy trees. These trees may either not die, and consequently not change color, or may succumb, and discolor in September and October. The ground inspection in October revealed that 17 percent of the infested trees did not die or change color.

Munsell readings made from the ground of 10 sample infested trees are compared with Munsell readings made from ground color photos and with aerial color photos in the discussion of photo interpretation results.

Ground readings of infested trees were made one year later (1968) of an entirely different population of trees, but it was interesting to note that the August foliage colors were nearly identical to the 1967 August readings. The use of Munsell cards in the field is a reliable indicator of early and late stress symptoms and can be used in similar studies of vegetative stress.

Munsell notations vary by the three methods in which they were used, namely: (1) by ground comparison of the Munsell charts with the 10 sample trees in the field, (2) by comparison of the aerial photo images with Munsell transparencies,[3] and (3) by comparison of the 35 mm. color photos taken of the same 10 trees on the ground with Munsell transparencies. The hue comparisons made from the 10 representative trees are shown graphically in Figure 17. There is good agreement between the ground observations and those made of the identical aerial photo images; they are not over one hue apart at any time period. Note that the aerial photos detected an earlier changeover from the GY (green-yellow) hues to the Y (yellow) hues as compared with the ground observations. The ground photography did not correlate at all well with either the aerial transparencies or the visual ground Munsell comparisons of foliage. We advise against using ground color photography if very accurate comparisons are to be relied upon.

Infrared Color versus Normal Color Film for Stress Detection

In coniferous timber, our studies over a three-year period have shown that photo interpreters can distinguish discolored pines as well on normal color film

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[3] A special viewer, developed and described in a previous study (4), permits an interpreter to select Munsell color chips by transmitted light while viewing 70 mm. transparencies stereoscopically, also by transmitted light.

as on false-color film (Fig. 18) in the Black Hills (5). Even at very small scales (1:174,000) no differences in interpretation accuracies could be ascribed to films (Fig. 19). At no time did either normal color film nor false-color film detect stressed pine trees before the foliage discolored. In other words, infrared color film cannot be used as a previsual sensor of stress for ponderosa pine. Probable reasons are described in detail by Knipling (6) and Heller (5).

Infrared color film does show advantages for other forest applications, particularly when coniferous and hardwood species are difficult to distinguish, or when atmospheric haze is unfavorable. The Wratten 12 or 15 yellow filter, always used with infrared color film, absorbs blue light and permits better atmospheric penetration. Under severe haze, infrared color film should always be used.

Detection Success of Finding Various Sizes of Discolored Infestations on Aerial Photographs

How small a discolored spot (infestation) can we detect on small-scale aerial photography? You will recall that we hope to relate known infestation sizes with resolution capabilities of sensors used on very high-flying aircraft (above 15,000 meters) or satellites (ERTS, Skylab, etc.).

The large study area (1.6 by 5 kilometers) was found to have a distribution of infestations and trees grouped into the following size classes:

Size Class (number of discolored trees per infestation)	Average Largest Dimension (meters) m.	(ft.)	Number of Infestations	Percent of Total
1 - 3	5	(16)	109	52
4 - 10	13	(43)	49	23
11 - 20	24	(80)	27	13
21 - 50	45	(149)	16	8
51 - 100	53	(175)	3	1
100+	122	(403)	7	3
			211	100

Our results are shown in Figures 19, 20, and 21. Figure 19 compares interpretation success on two films (color and color infrared) by seven scales, and with two seasonal differences. Again, we see very little difference between the two films; a "t" test showed no significant differences. As might be expected, detection success fell off as the scales and images became smaller. July photography, taken before all stressed trees became discolored, was significantly poorer than August photography.

Figure 20 indicates that small infestations, 1-3 trees (5 m.), are not likely to be detected at acceptable accuracies when scales are smaller than 1:31,680. However, infestations of 4 to 10 trees (13 m.) can be detected at scales around 1:100,000 with an accuracy of about 20 percent. Not good but still detectable.

Figure 21 again compares the two color films (color and false color) but by infestation size in meters. Again, as infestation size (or resolution size) becomes large, detection success improves; however, detection success is acceptable only on the larger infestations (over 30 m. in size and more than 20 trees) when scales are as small as 1:174,000. For determining stress in the early stages of an epidemic, it is apparent that we will need good resolution capabilities--probably 5 meters (16 feet). For discovery of stress in very remote areas or in developing countries, we may be able to detect discolored timber with resolution capabilities of 30-50 meters (100-200 feet). Based on the expected resolution (100 meters) of the two ERTS sensors--the return-beam vidicon and the 4-channel line scanner--it seems unlikely that we will be able to detect any but the largest discolored areas. Resolution and sensor capabilities of Skylab I and II sound more promising. For stress detection, perhaps ERTS data will prove most helpful in learning how to use the mass of data most effectively.

PREVISUAL DETECTION WITH MULTISPECTRAL SCANNERS

I should emphasize that our studies with multispectral scanners are still experimental and not ready for application. The results are encouraging, and we should expect more improvements with better sensors and automatic processors. Line scanning is readily adaptable to automatic combining and processing of waveband data. Automatic data processing is a necessity for handling the great mass of data which will pour out from ERTS.

The "ground truth" data collected continuously through the growing season permitted us to learn the optimum conditions for sensing with the Infrared and Optics Laboratory (IROL) multispectral scanner. We learned, for example, that needle temperatures of both healthy and stressed ponderosa pine trees reached ambient air temperatures after sundown; therefore, thermal sensing for stress would be useless at night.

Figure 22 represents the ground conditions that existed at the instrumented test site in May 1968. Note particularly the first three graphs which reflect the respiratory conditions of the stressed and healthy trees. Inhibition of transpiration in stressed trees is probably the main factor which permits us to sense temperature differences. The dying tree still transpires, but at a reduced rate, because of stomata and needle desiccation (Fig. 23) and because of reduced sap flow. Needle and foliage temperatures--measured with thermocouples and radiation thermometers--at the time of the flight (1530 hours) showed a 5° C. emission temperature difference. This difference is detectable on the IROL thermal scanner. Such basic physiological information is needed to predict when thermal or spectral differences should occur. It also permits the investigator to specify what kind of sensor is required to detect targets on the ground.

Multispectral Processing

The spectral processing and recognition computer (SPARC) at the IROL could discriminate the four target signatures for which training samples were established, namely healthy pines, nonfaded infested pines, faded infested pines, and old-killed pines. The combination of wavebands which best identified these targets are shown in Table 4.

Four analog printouts are shown in Figure 14; the target identifications show as dark spots on the darker analog print of the area. A color slide of this scene has been prepared which shows these black spots in color; the color code is: green for healthy trees, amber for nonfaded infested trees, red for faded infested trees, and blue for old-killed trees. The level of accuracy of correctly identifying the nonfaded trees is low, and the rate of making commission errors in this class quite high.

A digital processing program has been developed by the Laboratory for Agricultural Remote Sensing (LARS) at Purdue University, Lafayette, Indiana, which uses the Michigan IROL multispectral scanner data. This program was tried from the same analog tapes taken over our test site to test Purdue's digital method of computer processing and readout. Figure 24 is a representation of their output. For this trial, we were unable to identify green infested trees. The faded infested trees showed up very well, but the training sample for old dead trees must have been incorrect because it grossly overstated this target by about 5 times.

Thermal Processing

Improvements in thermal processing methods in 1969 and 1970 provided us with more evidence that previsual detection is possible. Figure 15 is a thermal contour map; targets of equal temperature can be depicted in separate colors, but the gray tones represented in this illustration are not as easily deciphered as the color print. Nevertheless, this technique was successful in identifying the discolored trees over a wide area (2 by 5 kilometers). The dying green trees are distinguishable from the healthy green trees in many cases; however, there are still too many other objects that have the same temperature range as the stressed trees and hence appear as the targets we wish to recognize.

CONCLUSIONS

Stress induced on forest vegetation is best detected when symptoms exhibit foliage discoloration. At our present state of the art, color or false-color photography is still our most efficient sensor. There are many examples of successful programs using one or more scales of aerial color photography to detect and locate efficiently areas of affected timber. Some of these examples of multistage aerial photography include air pollution injury to ponderosa pine near Los Angeles, bark beetle epidemics in California, South Dakota, Washington, and Southeast United States, hardwood diebacks in Northeast United States, and spruce-fir defoliators in Northern United States. We must remember that one of the stages of any stress-detection program includes limited ground sampling to identify causal agents and to make the correlation between the photographic images.

Because aerial color photography has high resolution, is inexpensive, and is readily available to most user agencies, I predict it will continue to be one of our most useful sensors for stress detection for some time to come.

Multispectral scanners are still research tools for stress detection. Because the causal agent, such as air pollution or Dutch elm disease (Ceratocystis ulmi [Buism.] C. Moreau), often affects single trees and produces subtle foliar symptoms, we require sensing systems with high resolution capabilities. Most available scanners do not have good enough resolution to separate individual tree crowns when flown from aircraft at altitudes above 1,500 meters. Our ground studies indicate that when a multispectral scanner and ground processor, with perfect spatial registration in wavebands from 0.38 to 13.5 micrometers, is available, we will be more successful in previsual detection.

The ERTS program will be a useful exercise in learning how to handle large masses of data. Because of the low resolution capability of the 4-waveband scanner and the 3-band return-beam vidicon (RBV), probably only the largest areas of discolored timber will be detected.

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GLOSSARY OF TERMS

Bark beetle infestation (or spot): A single pine tree or group of pine trees which have been successfully attacked by pine bark beetles (Scolytidae, Dendroctonus ponderosae, Hopk.), and this stress causes the foliage to discolor and the tree to die.

Faded pine trees: The result of discoloration of pine foliage caused by bark beetle attack which in turn causes pine needles to change color progressively, from green to yellow to yellow-red.

Pitch tube: An exudation of pitch or resin from the inner bark of the tree.

Previsual detection: Detection of vegetation under stress before visible symptoms (foliage discoloration) occur.

"t" test of significance: A statistical test designed to compare two (or more) groups of experimental data to determine whether they came from the same populations.

Table 1. Film-filter-scale combinations exposed during RB-57 Flight Mission #101 - August 3 and 8, 1969

Film	Filter	Camera	Focal Length	Scale	Format
Color IR (SO 117)	Zeiss "B" (15)	Zeiss	304 mm.	1:55,000	210 mm.
Color (2448)	HF-3	RC-8	152 mm.	1:110,000	210 mm.
Color IR (SO 117)	15	RC-8	152 mm.	1:110,000	210 mm.
Color (SO 368)	2A	Hasselblad	76 mm.	1:220,000	70 mm.
Color (SO 368)	12	Hasselblad	76 mm.	1:220,000	70 mm.
Color IR (SO 180)	15g	Hasselblad	76 mm.	1:220,000	70 mm.
Panchromatic (3400)	58	Hasselblad	76 mm.	1:220,000	70 mm.
Panchromatic (3400)	25A	Hasselblad	76 mm.	1:220,000	70 mm.
Panchromatic IR (SO 246)	89B	Hasselblad	76 mm.	1:220,000	70 mm.

Table 2. Film-filter-scale combination exposed during Aero Commander flight on July 21, 1969, with KB-8 70 mm. camera

Film	Filter	Focal Length	Scale
Color D/200	HF-3	150 mm.	1:7,920
EIR (8443)	12	150 mm.	1:7,920
Color D/200	HF-3	150 mm.	1:15,840
EIR (8443)	12	150 mm.	1:15,840
Color D/200	HF-3	150 mm.	1:31,680
EIR (8443)	12	150 mm.	1:31,680
Color D/200	HF-3	38 mm.	1:63,360
EIR (8443)	12	38 mm.	1:63,360
Color D/200	HF-3	38 mm.	1:120,000
Color D/200	12	38 mm.	1:120,000
EIR (8443)	12	38 mm.	1:120,000
Color D/200	HF-3	38 mm.	1:170,000
EIR (8443)	12	38 mm.	1:170,000

Table 3. Spectrometer channels used for target recognition by University of Michigan aircraft and processing unit and their respective spectral colors

Spectral Color	Wavelength (Micrometers)	Channel Number
Violet	.40 - .44	1
	.44 - .46	2*
Blue	.46 - .48	3
Blue-Green	.48 - .50	4*
Green	.50 - .52	5
	.52 - .55	6
Yellow-Green		
	.55 - .58	7
Yellow		
Yellow-Red	.58 - .62	8
Light Red		
	.62 - .66	9
Deep Red	.66 - .72	10
	.72 - .80	11
Reflective Infrared		
	.80 - 1.0	12
	1.0 - 1.4	13
	1.5 - 1.8	14
	2.0 - 2.6	15
Thermal Infrared	4.5 - 5.5	16
	8.2 - 13.5	17

*Not used in the course of this study.

Table 4. Optimum target recognition channels for detecting stressed pine trees on the Michigan multispectral processor

Target	Wavelength Channels[1]	Threshold Voltage
Healthy trees	1, 6, 7, 8, 9, 10, 11, 12	2.00
Nonfaded infested trees	1, 3, 5, 6, 7, 8, 9, 10, 11, 12	1.75
Faded infested trees	6, 9, 10	2.87
Old-killed trees	1, 3, 9, 10, 11, 12	1.00

[1] Channel numbers refer to specific wavelengths listed in Table 3.

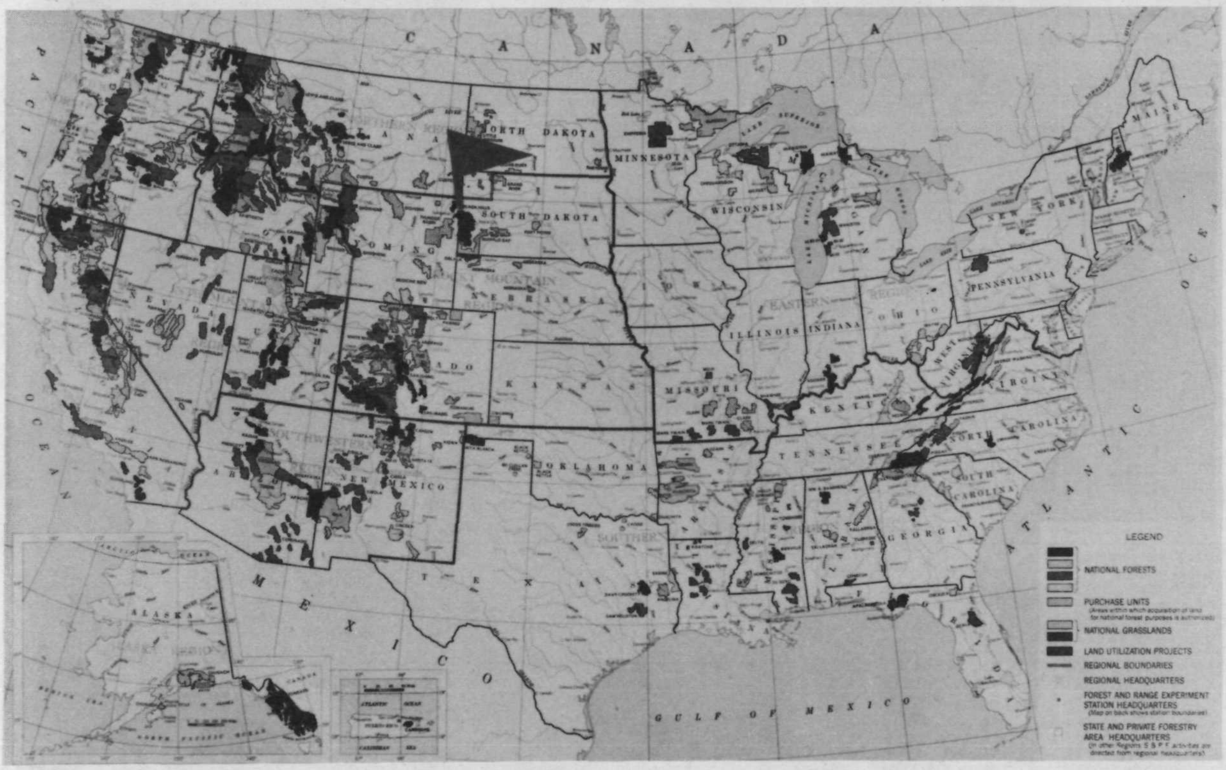

Figure 1. Flag shows location of the Black Hills National Forest near Rapid City, South Dakota. Ponderosa pine (Pinus ponderosa, Laws.) is the principal tree species and is under stress from attack by the Black Hills bark beetle (Dendroctonus ponderosae, Hopk.).

Figure 2. An oblique view of a portion of the study area looking down the drainage where over 3,000 ponderosa pine trees have been killed since 1967. Made from an Ektacolor negative. Whitish trees are most recently killed; light gray trees were killed one year earlier; dark gray images are mostly uninfested healthy trees.

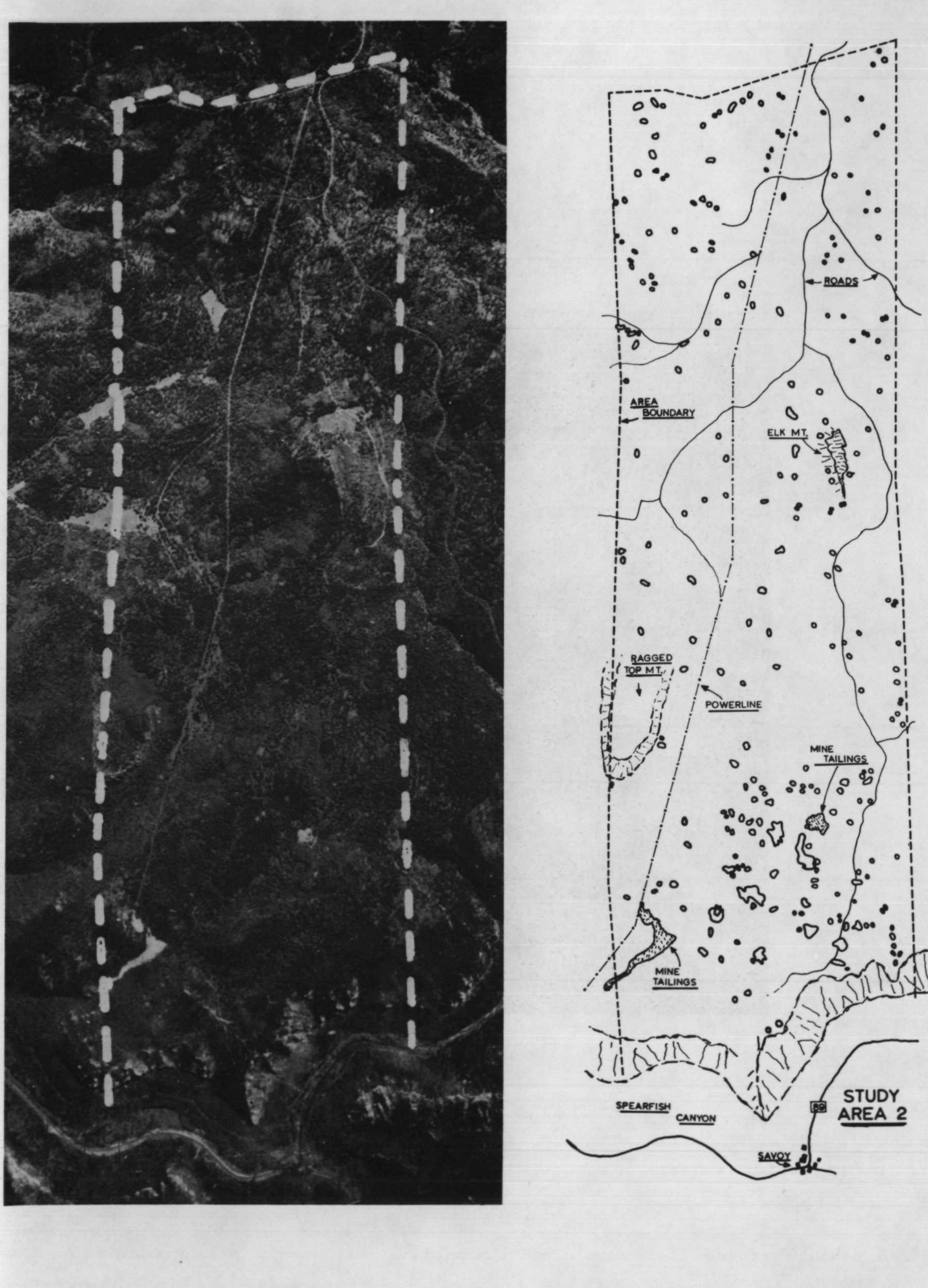

Figure 3. Aerial mosaic, left, of 1.6 by 5 kilometer study area near Savoy, N. D. Right, the 211 infestations are plotted at the same scale.

Figure 4. Measurements of apparent emittance (°C) are taken of healthy and infested trees from a tower overlooking infested and healthy ponderosa pine trees.

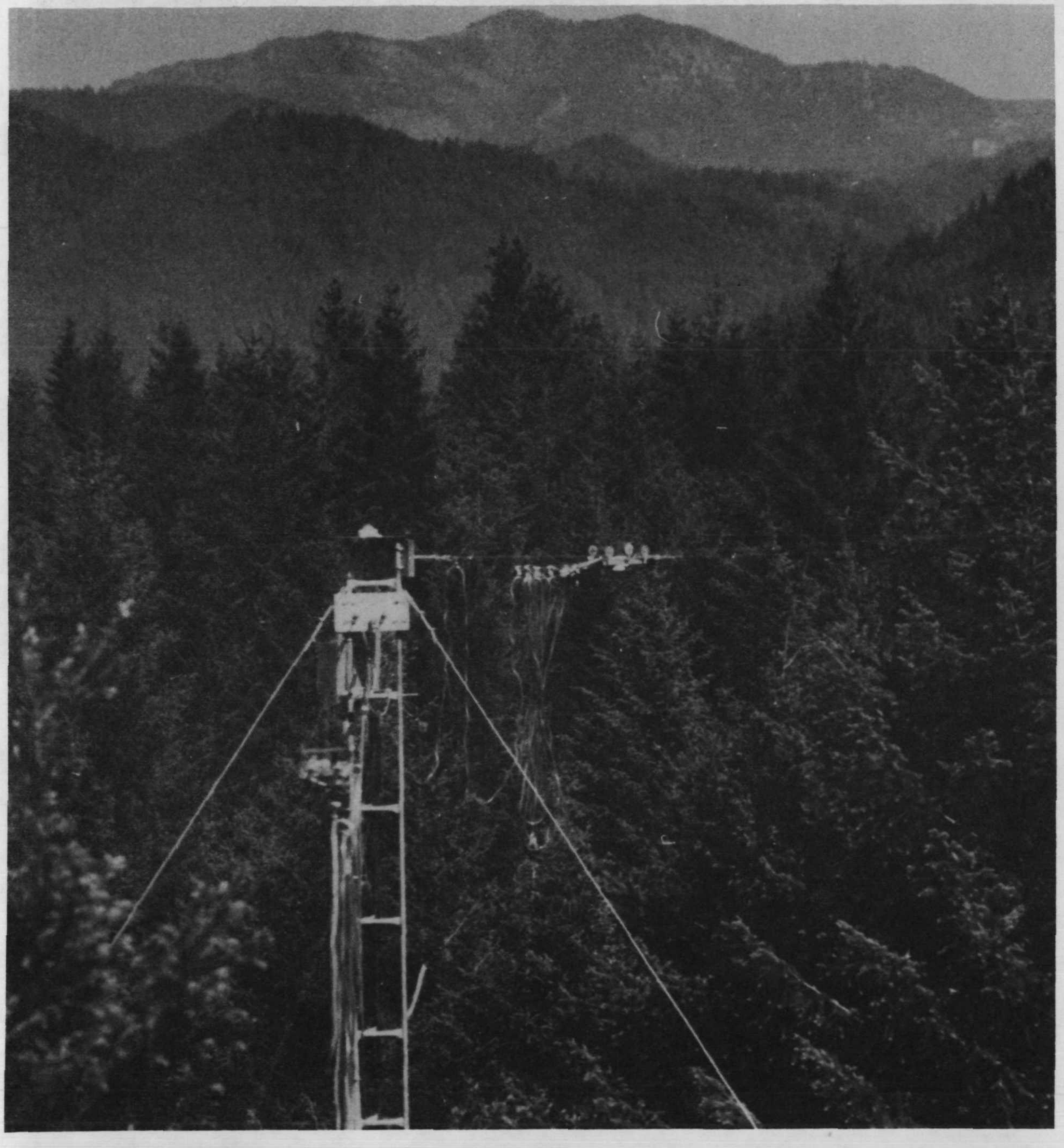

Figure 5. Net and total radiation thermometers are supported on moving tramway system above 30-meter-tall Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) trees. These trees are being monitored for stress induced by Poria weirii root rot.

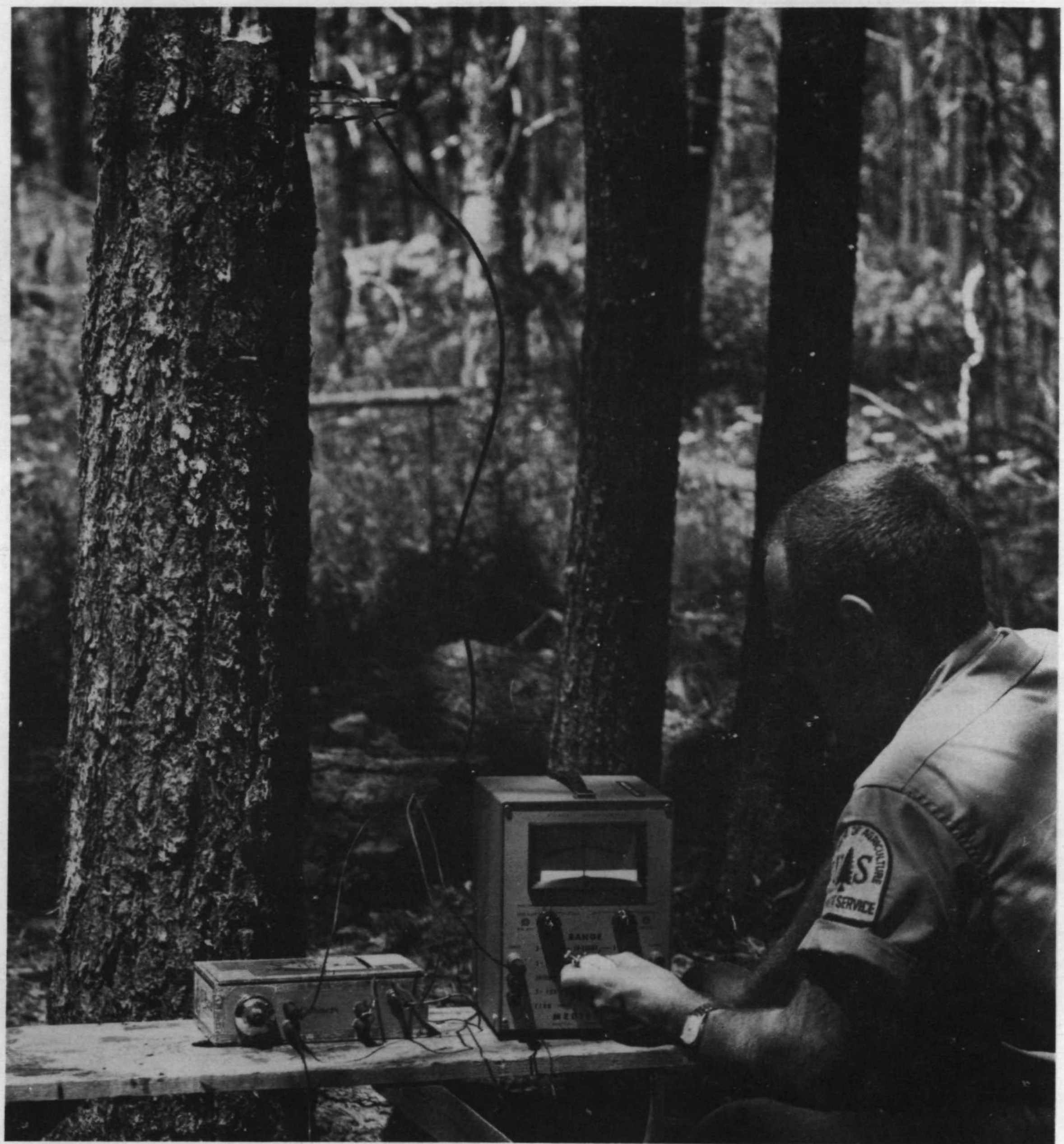

Figure 6. Rate of sap flow is measured by measuring the rate of heat loss from a small, high-energy heat source by means of thermocouples. Sap flow is related to transpiration; normal transpiration of foliage tends to keep foliage cooler than when transpiration is reduced by a stress of some kind.

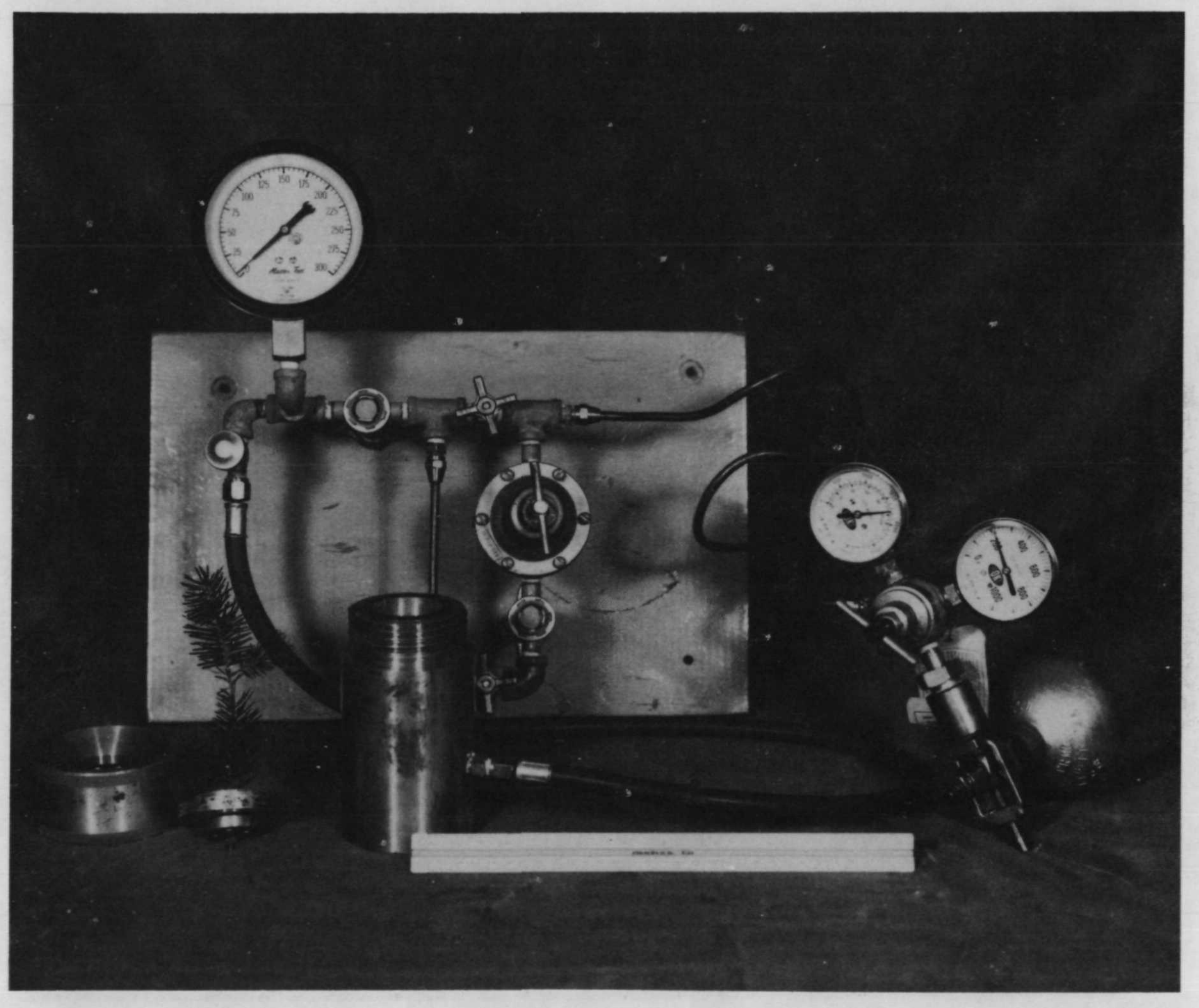

Figure 7. Hydrostatic pressure cell with pressure manifold is taken into field to measure leaf moisture tension. Induced pressures are closely related to moisture stress conditions and general tree vigor. Relatively low pressures are indicative of healthy trees; high pressures are needed to force moisture from stressed twigs.

Figure 8. Neutron probe device is used to measure soil moisture at known depths of the soil.

Figure 9. Field data logger can collect, digitize, and store on magnetic tape up to 38 channels of field data.

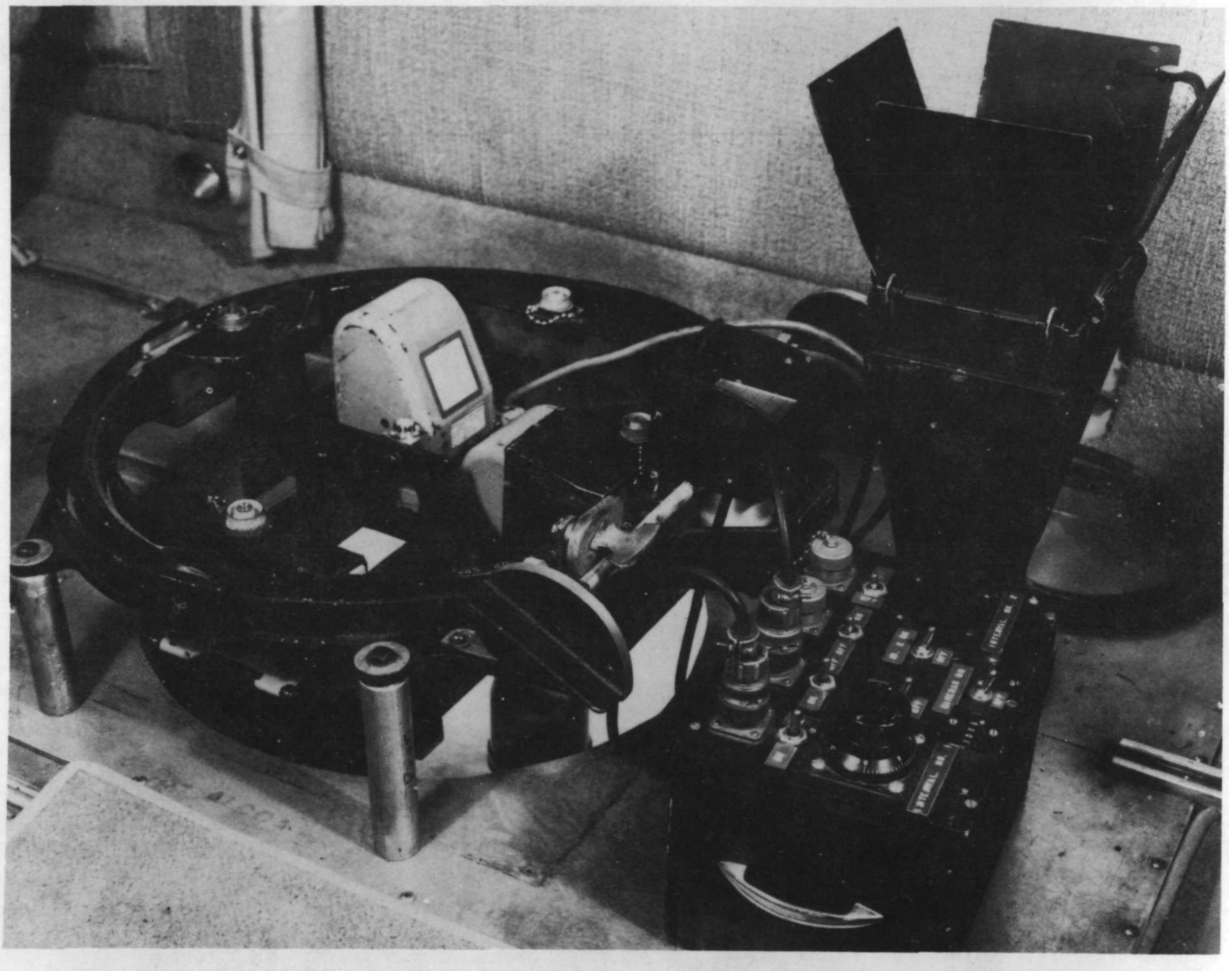

Figure 10. Two 70 mm. Maurer KB-8 cameras were triggered simultaneously from one intervalometer to get identical coverage with color and false-color film. 150 mm. Schneider Xenotar lenses were used from medium altitudes (to 6,000 meters); 38 mm. Zeiss Biogon lenses were used at higher altitudes.

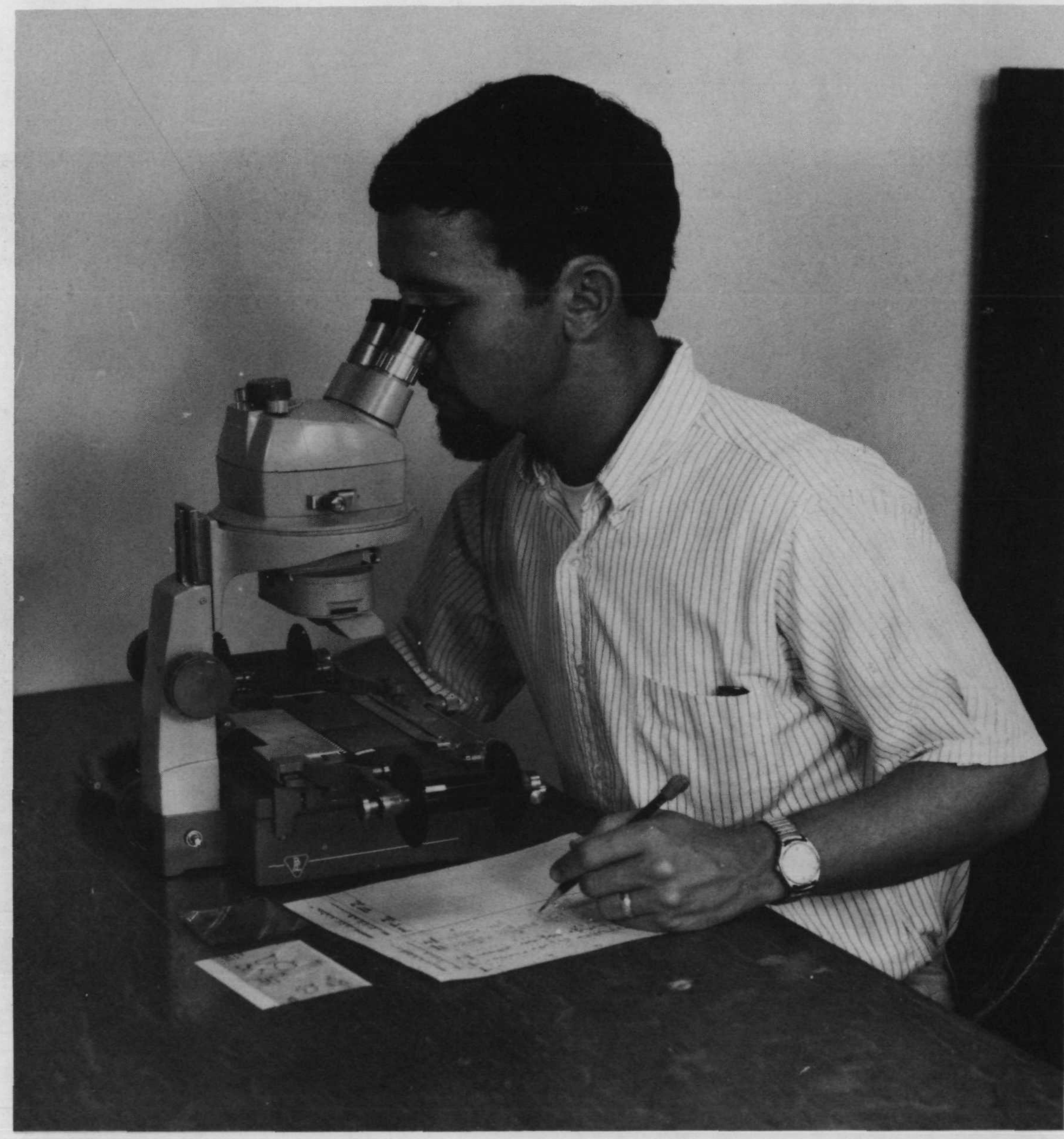

Figure 11. Bausch and Lomb Zoom stereoscope was used to interpret small-scale color and infrared color transparencies (1:116,000 to 1:174,000). Magnifications used by the three photo interpreters varied from 12X to 28X.

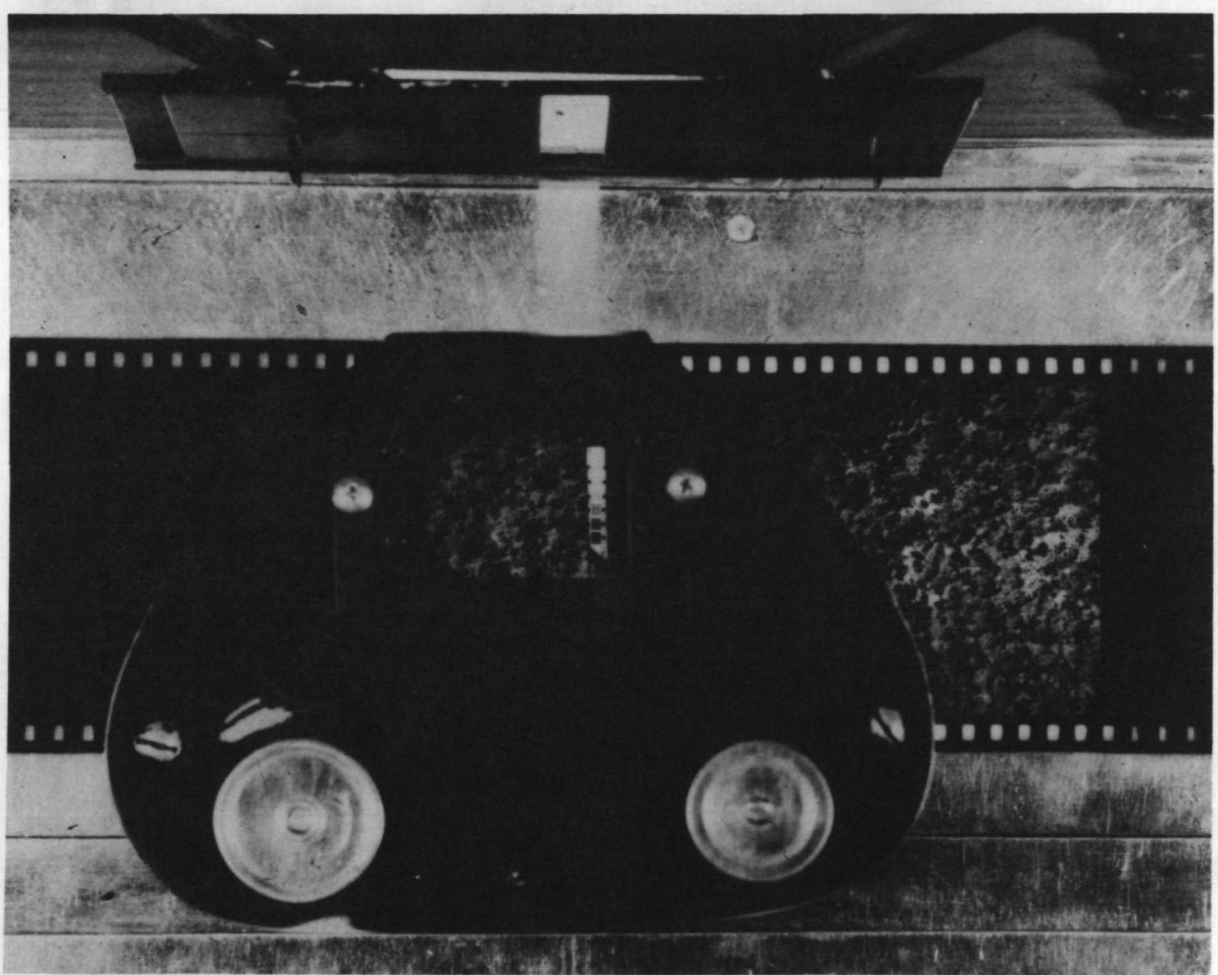

Figure 12. Munsell comparator permits a photo interpreter to compare film transparencies of Munsell charts with images of interest on aerial color photographs. The same light source is used in making this comparison.

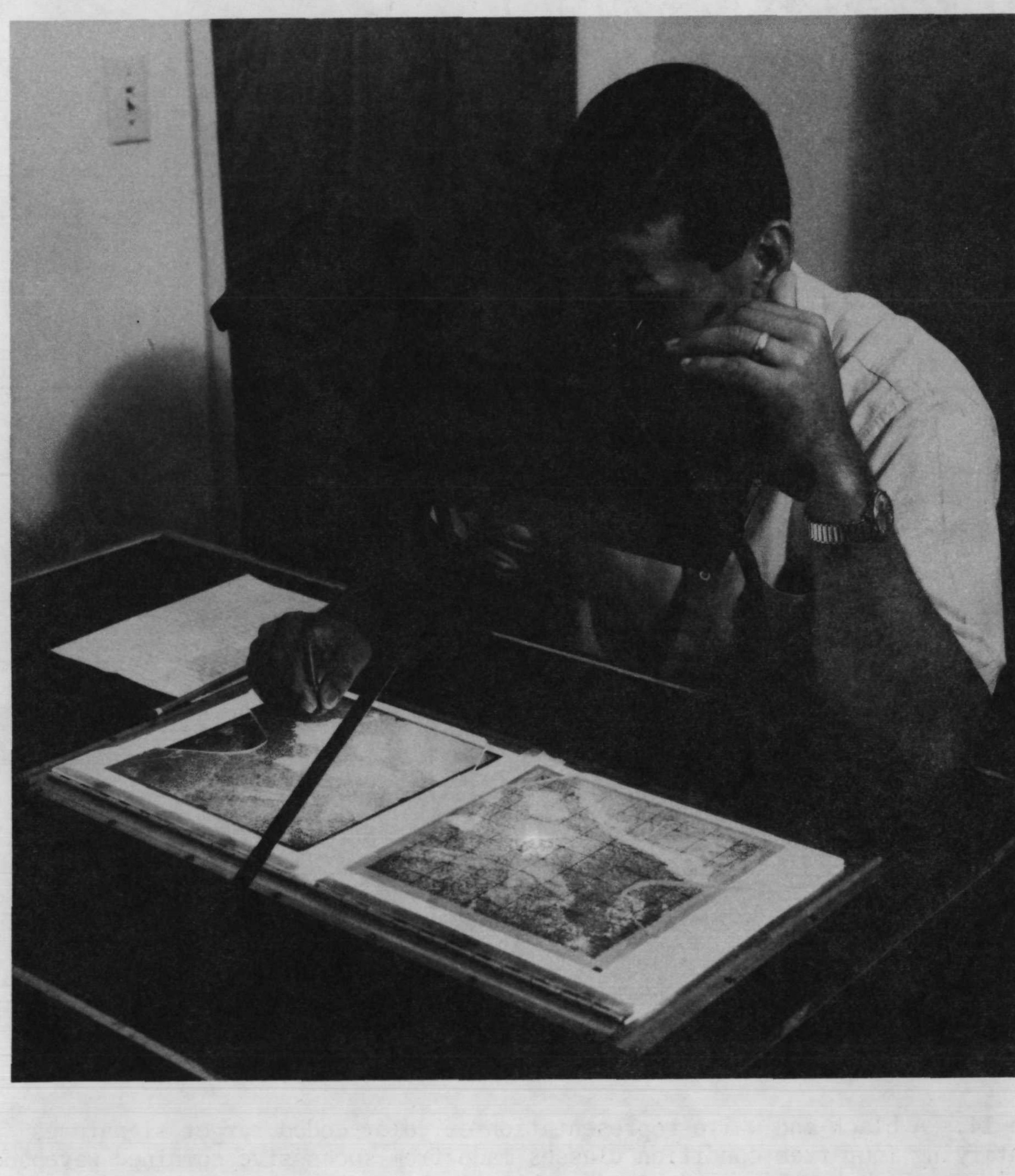

Figure 13. Aerial color and false-color transparencies taken from the RB-57 aircraft (high altitude) were examined with Old Delft scanning stereoscopes at 4.5 magnifications.

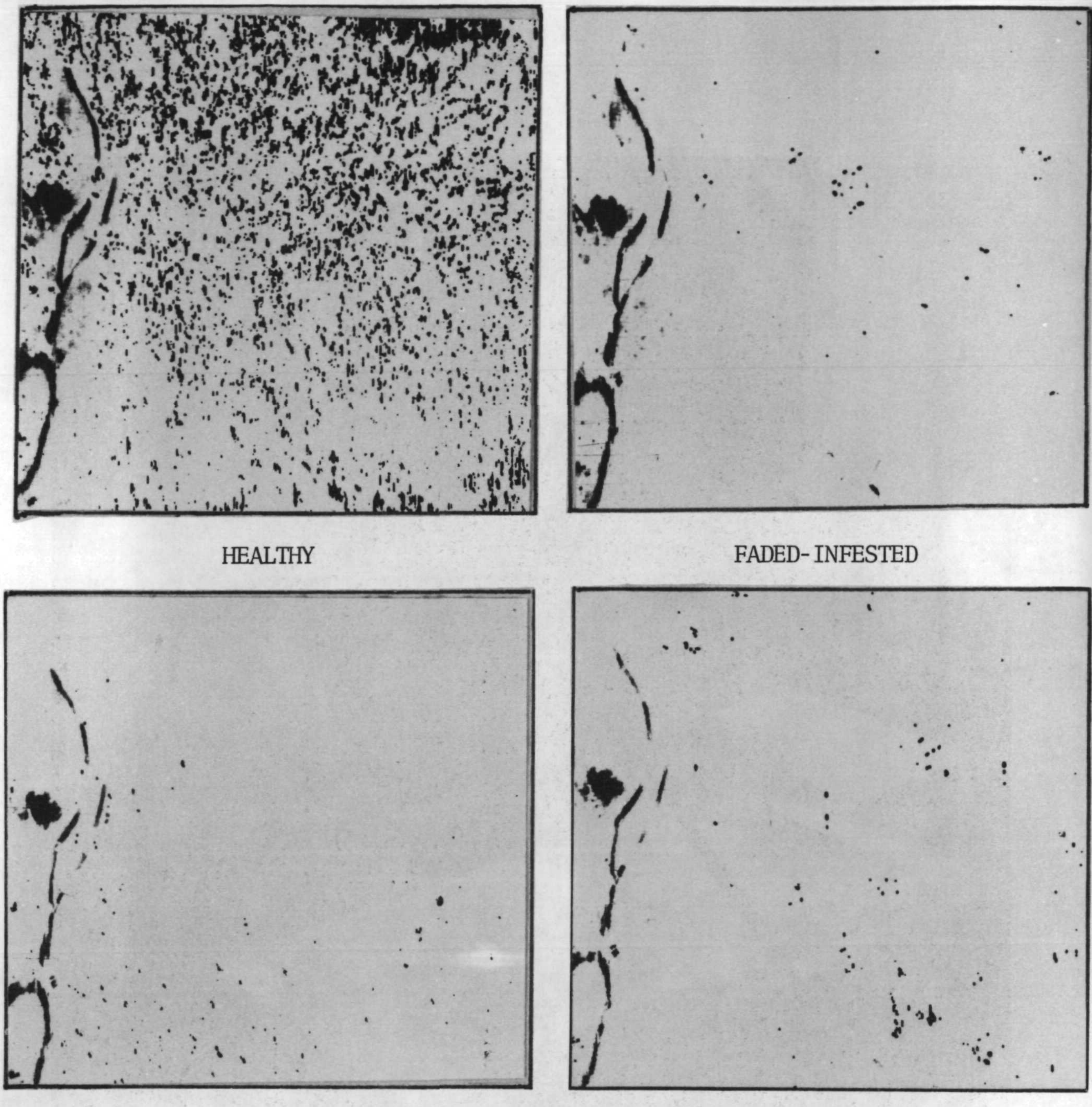

Figure 14. A black-and-white representation of color-coded target signatures identifying four tree condition classes made from successive combined waveband overlays. Each overlay is derived mathematically as the best combination of wavebands which identify a particular target. The multispectral scanner and processor operated in 10 wavebands from 0.40 to 1.0 micrometer.

Figure 15. Upper: A black-and-white representation of a color print made from "temperature contouring" techniques developed at IROL, University of Michigan. Each gray level depicts a particular ground emission target temperature. Objects of equal temperature are more easily distinguished on color prints or transparencies. Lower: Infrared line scan imagery in analog form of upper picture. This imagery covers the study area shown in Figure 3.

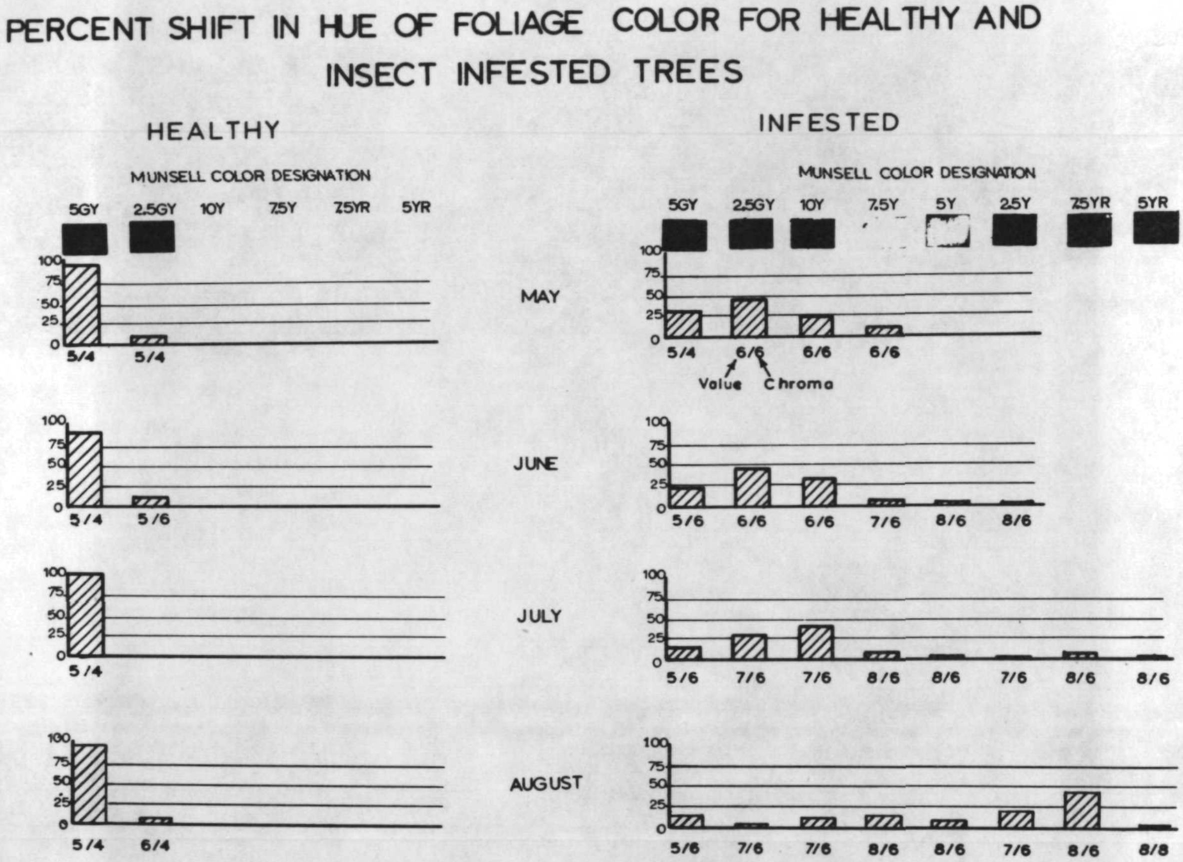

Figure 16. The shift in foliage color of healthy and stressed ponderosa pine trees over a four-month period. Munsell estimates of foliage color were made on the ground for 209 infested and 47 healthy trees in May, June, July, and August 1967. Almost identical readings were obtained in 1968.

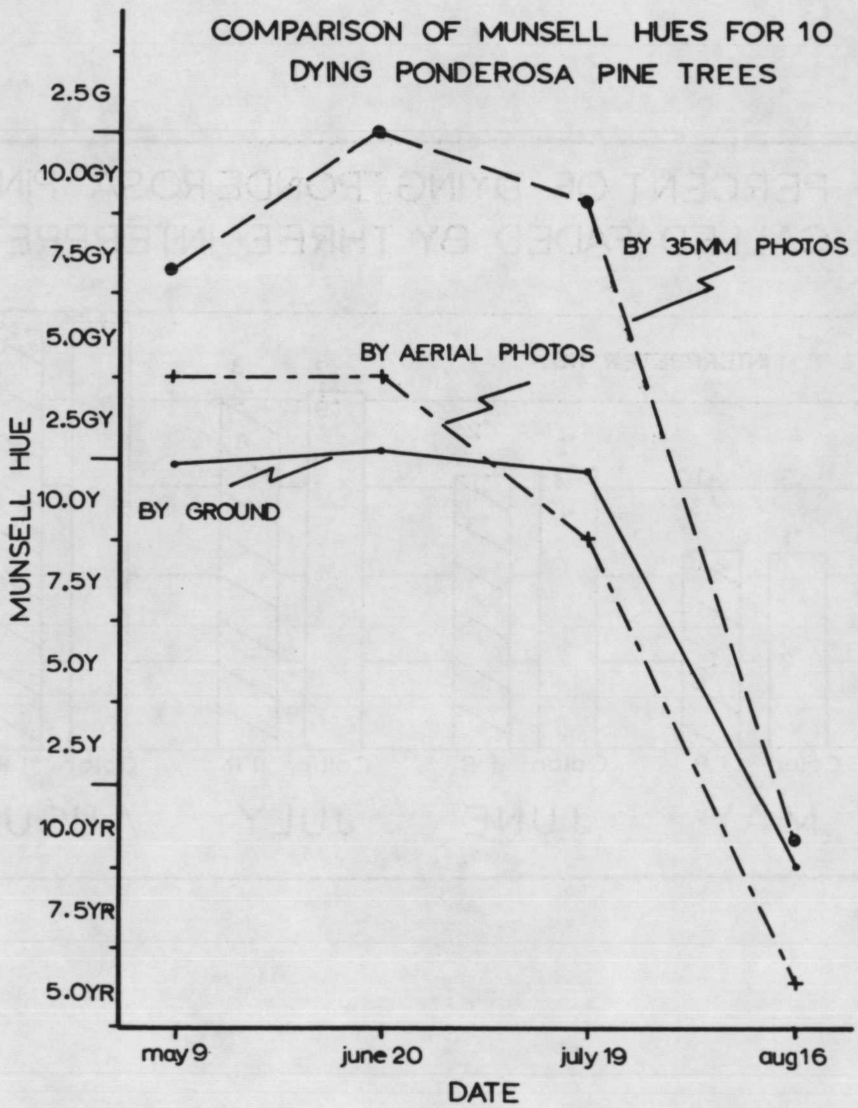

Figure 17. Comparison of Munsell hues of 10 sample trees taken by three methods at four time periods.

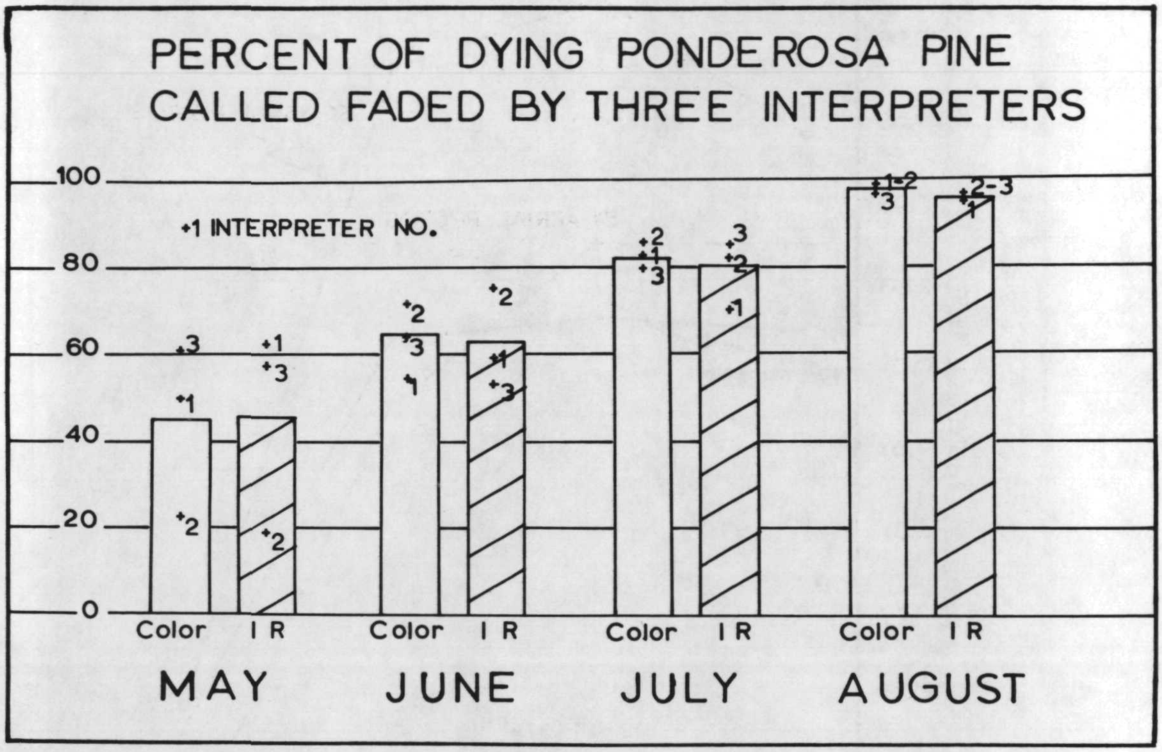

Figure 18. Photo interpretation results from three experienced photo interpreters, using Anscochrome D/200 and Ektachrome Infrared Aero films at 1:1,584 scale. Note the increased ability to detect infested trees as the season progresses, and the greater consistency among interpreters in July and August.

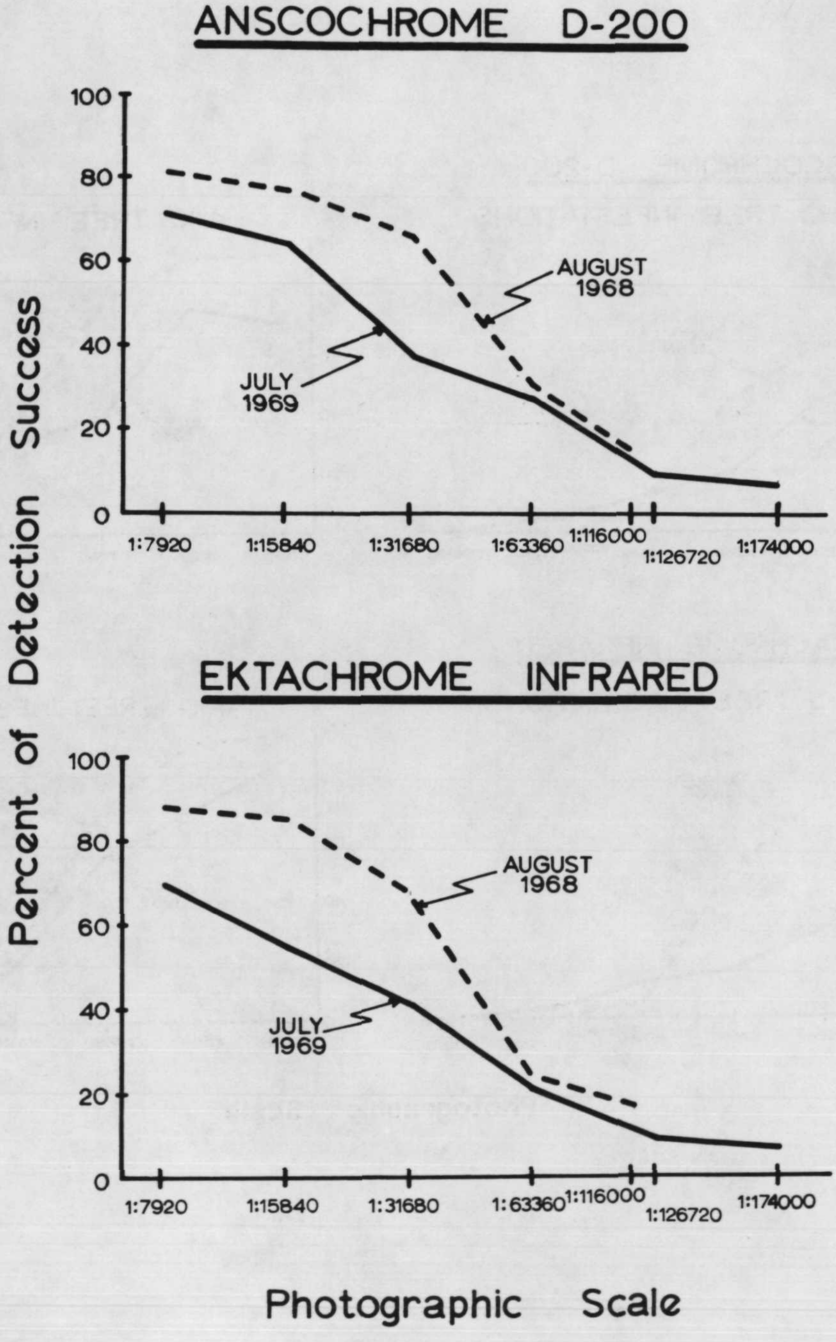

Figure 19. Detection of beetle-attacked trees in 1968 and 1969. The 1968 data represent the mean for three interpreters--the 1969 data for two. Accuracy of photo interpretations is expressed as a percent of the total number of discolored infestations present. Note the significant drop in 1969 detection because maximum discoloration of foliage had not occurred by July 1969.

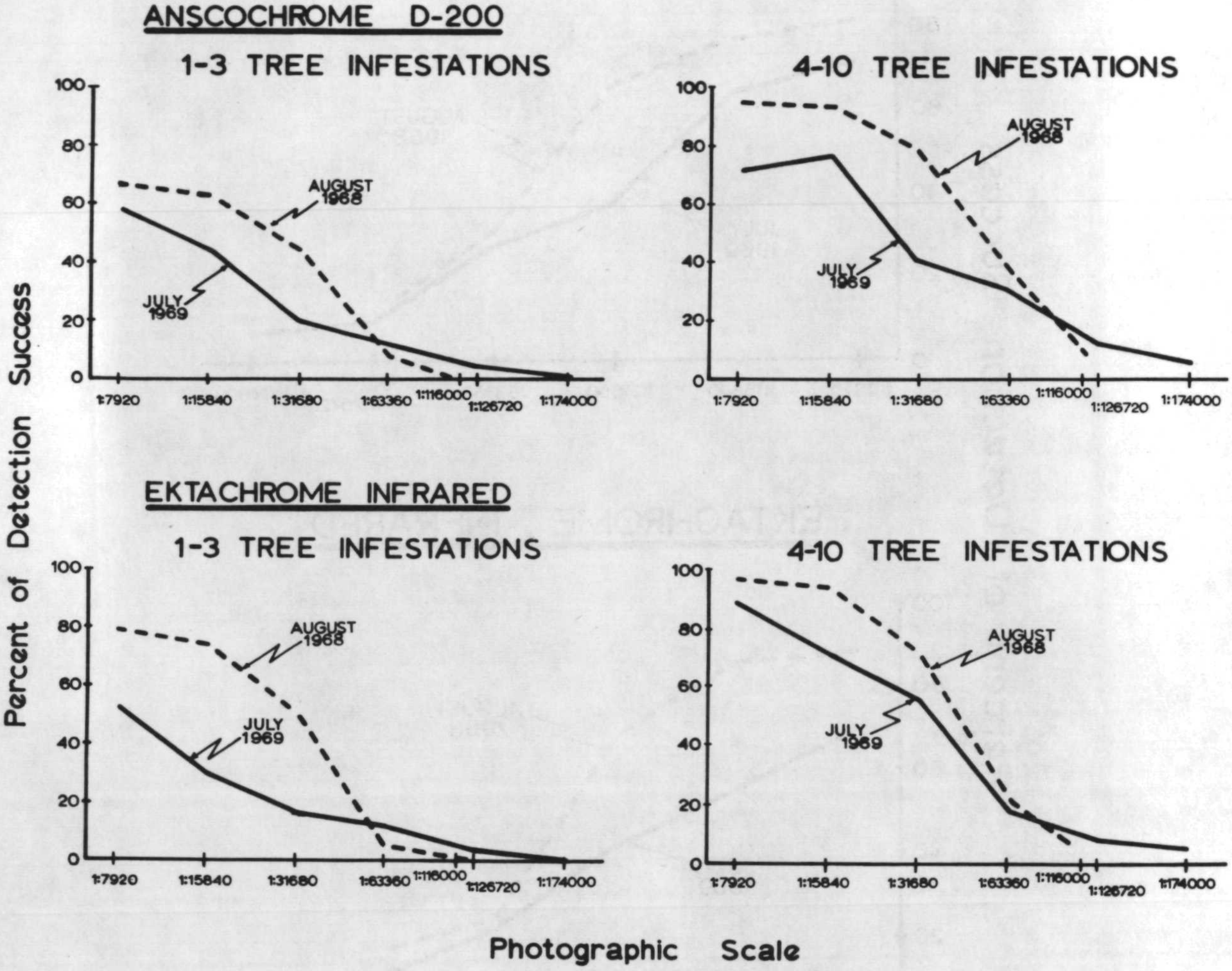

Figure 20. Detection success in August 1968 and July 1969 for small bark beetle infestations. Small infestations are representative of stress conditions showing up early in the cycle of a bark beetle epidemic. Note the similarity in detection success of the two films (color and false color) and also the drop in detection accuracies when photos were taken in July 1969 before maximum foliage discoloration occurred.

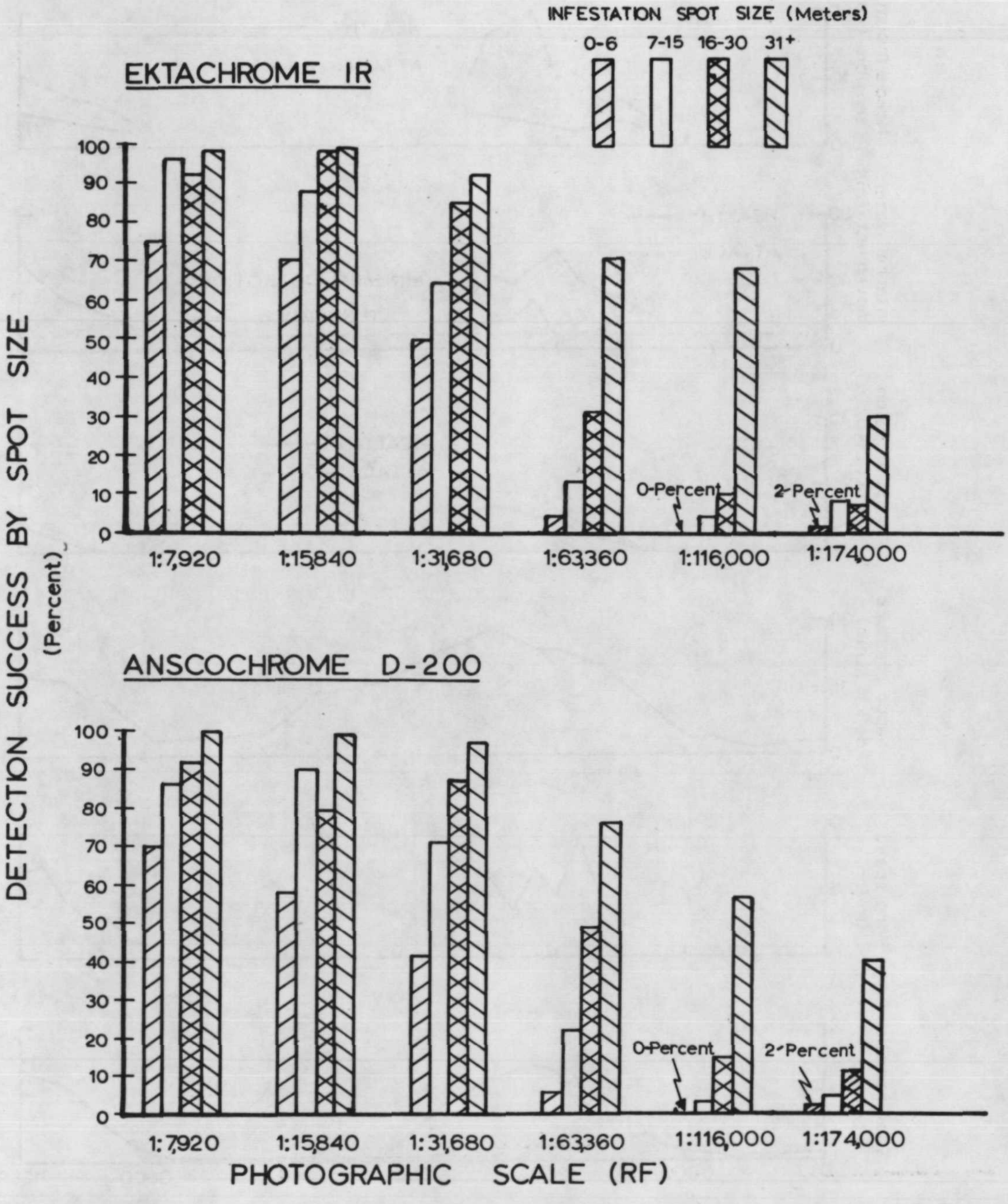

Figure 21. Detection successes (mean of three interpreters) expressed as a percent of 4 infestation size classes, 6 photographic scales, and 2 films. The upper chart is for infrared color film; the bottom chart for color film. Note the high level of detection success on 1:31,680 transparencies even for infestations 7 to 16 meters in diameter (average of 4 to 10 trees). The big drop in detection success occurs at scales smaller than 1:31,680.

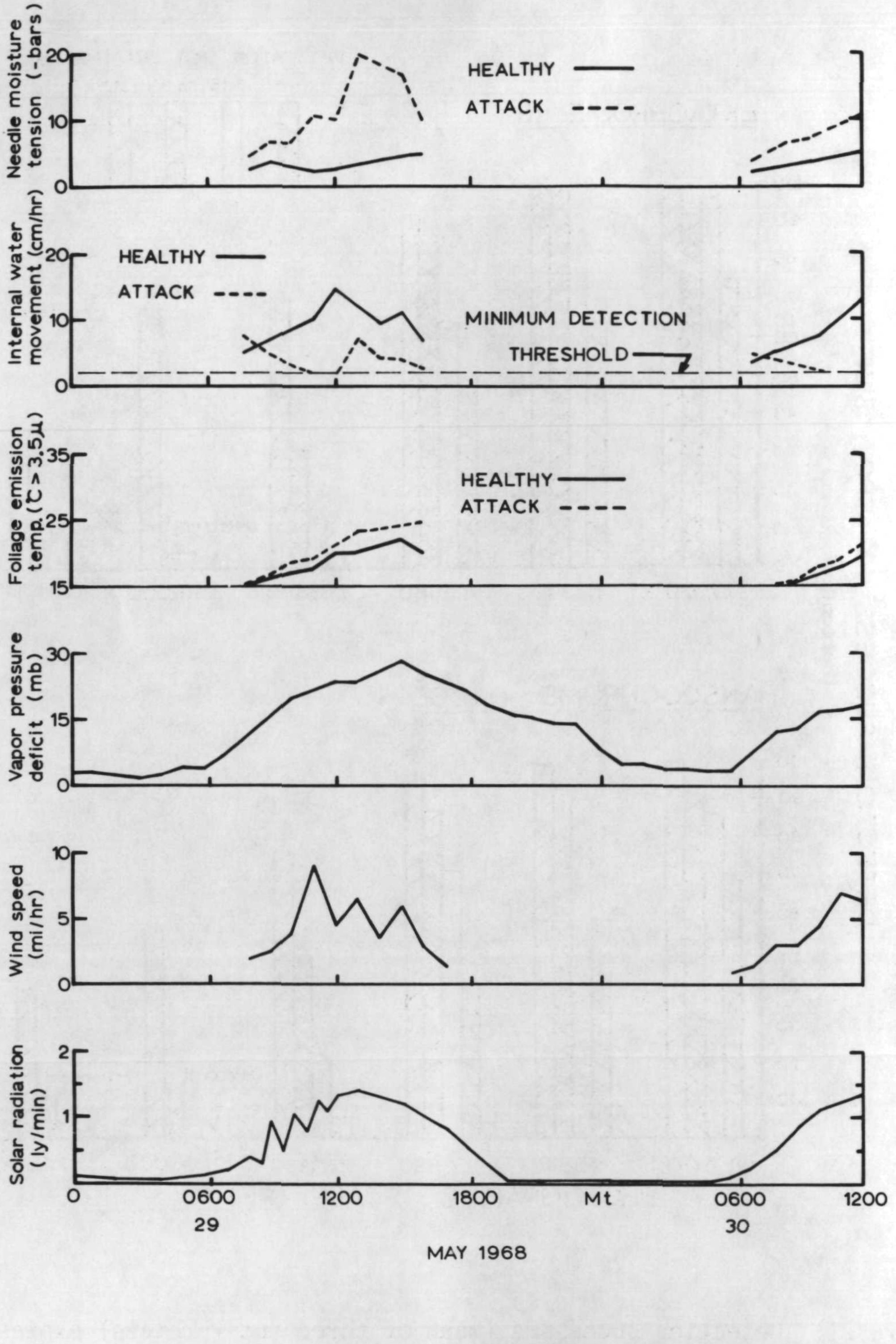

Figure 22. Meteorological and tree physiological data collected at instrumented test site, May 29 and 30, 1968. Sampling intervals cover the period during which overflights were made with the University of Michigan C-47 aircraft equipped with the 17-channel scanner system.

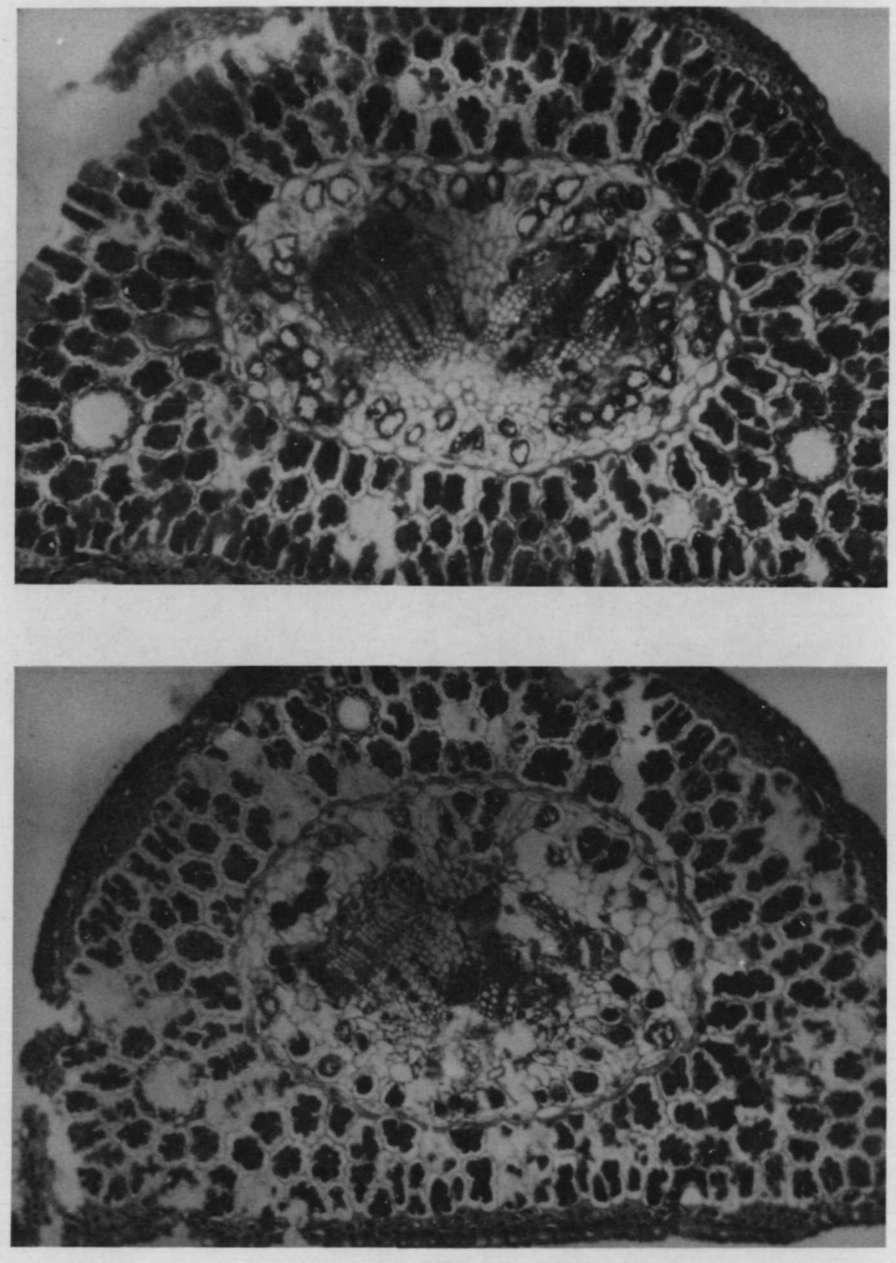

Figure 23. Cross section of needle tissue from ponderosa pine. Upper: from healthy needle; most cell walls are intact and are filled with cytoplasm. Lower: from needle taken from infested tree; many cell walls are broken, vascular bundles, resin canals, and stomata are collapsed, and cytoplasm is absent or shrunken.

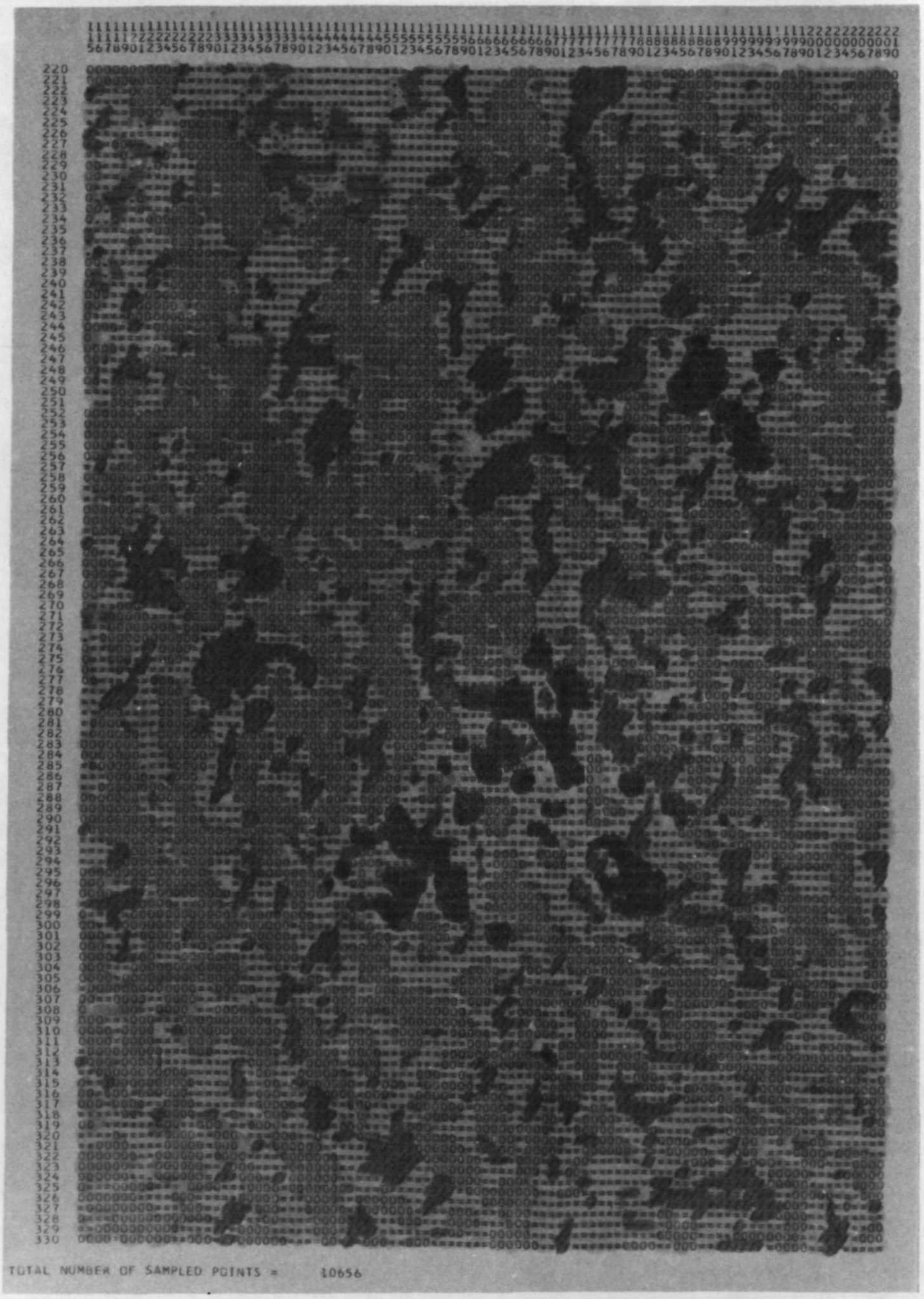

Figure 24. This display printout of the Black Hills test site was made from the Purdue LARSYAA target-recognition program. The various shades of gray and black represent six different condition classes. The discolored pine trees were accurately identified; other targets were not accurately identified.