REMOTE SENSING OF DOUGLAS-FIR TREES NEWLY INFESTED BY BARK BEETLES

by

PETER MICHAEL HALL

B.Sc., The University of Victoria, 1972

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(Department of Forestry, Forest Entomology)

THE UNIVERSITY OF BRITISH COLUMBIA
January 1981

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of ______________________

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date Mar. 12, 1981.

ABSTRACT

Two study plots containing Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) newly infested by Douglas-fir beetle (Dendroctonus pseudotsugae Hopk.) were established and photographed with large-scale (1:1000), colour infrared film on July 29, 1979 - approximately three months after possible insect attack. Ground checking confirmed attacked trees and also showed that at the time of photography all trees had visually green, healthy-appearing foliage. All trees, both attacked and non-attacked in each plot were matched to their photographic images, and visual photo interpretation for damage types and densitometric analysis of the original transparencies were done. For each tree-crown image included, the yellow, magenta and cyan dye layer density measurements were taken and these values plus three ratios derived from them were tested statistically using analysis of variance and stepwise discriminant analysis.

Significant differences were found between the optical density values of the images of healthy and attacked trees. The ratio values had much smaller variances than did the individual dye layer densities and all three ratios showed significant differences between healthy and attacked trees. Stepwise discriminant analysis produced significant separation of damage classes. Two-thirds of the successfully attacked trees were correctly classified and were confirmed by a second ground check in January, 1980.

It is concluded that successfully beetle-attacked trees have a unique spectral signature than can be detected on colour infrared air photos approximately three months after initial attack when the trees still support visually green, healthy-appearing foliage.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

I would like to acknowledge the guidance and constructive criticism received from my thesis committee: Dr. J.A. McLean, Dr. P.A. Murtha and Dr. J. Worrall. I also thank Dr. L.H. McMullen of the Canadian Forestry Service (Pacific Forest Research Centre) for showing me and allowing me to use some of his Douglas-fir beetle research plots. Figures were drafted by N. Holm.

1. INTRODUCTION

1.1 General Impact of Bark Beetles

Bark beetles of the genus Dendroctonus Erichson are extremely important pests. The significance of bark beetle damage in British Columbia was noted as early as 1913 by J.M. Swaine who carried out his survey in response to requests made by forestry personnel in the province (Swaine 1914). These insects, as a group, cause widespread mortality to mature and overmature stands of pine (Pinus L. sp.), spruce (Picea A. Dietr sp.) and Douglas-fir (Pseudotsuga menziesii (Mirb) Franco). Mountain pine beetle (Dendroctonus ponderosae Hopk.) normally attacks standing, living trees and so is a chronic pest of stands of mature lodgepole and ponderosa pine (Pinus contorta var. latifolia Engelm. and P. ponderosa Laws) (Safranyik et al. 1974). Spruce beetle (D. rufipennis (Kirby)) and Douglas-fir beetle (D. pseudotsugae Hopk.) normally breed in windthrow and logging slash (Dyer and Taylor 1971; McMullen 1977). However, when insect population densities are high and tree resistance is low, these insects may attack and kill mature standing trees. Douglas-fir beetle commonly attacks small groups of living, although weakened trees (Walters 1956).

Of these three insect species, the mountain pine beetle and the Douglas-fir beetle are chronic pests of British Columbia forests. Each year they inflict substantial losses on the timber resource (Table I). By contrast, spruce beetles rarely kill live trees; however, when an epidemic occurs, the results may be catastrophic. The impact of these insects is great as during epidemics the larger, more commercially valuable trees are killed first.

Table I. Volume Losses (m^3) Caused by Bark Beetles (*Dendroctonus* sp.) in B.C. Forest Regions 1971-75 (Cottrell, *et al*. 1979)

Region	Mountain Pine Beetle*	Douglas-fir Beetle	Spruce Beetle
Vancouver	19,647	807	-
Kamloops	49,282	2,754	175,346
Nelson	98,983	1,152	-
Cariboo	90,747	32,477	-
Prince George	985	191	-
Prince Rupert	52,216	-	-
Total	311,860	37,381	175,346

* includes attack on Lodgepole Pine only

The control of these insects, or the minimization of losses caused by these insects, is dependent on early detection. Promp detection of infested trees allows ample time for management regimes to be implemented, such as logging infested areas or treating single trees to reduce the population of insects in a valuable stand.

1.2 Douglas-fir Beetle Life History

The generalized life cycle of the Douglas-fir beetle is shown in Figure 1 (McMullen 1977). Mature adults emerge from the overwintering sites in the spring when conditions are conducive to beetle flight. Under shaded conditions and mid-range relative humidity spontaneous flight will not occur below 19 to 20^{o}C. However, when exposed to full sunlight, the beetles will fly at 17^{o}C (Atkins and McMullen 1960). Because of this, flight will occur earliest in slash areas, in stand margins and in relatively open stands.

Attacking insects prefer freshly felled or damaged host material over aged material and also prefer horizontal material over vertical material (McMullen and Atkins 1962). Flying insects select suitable host material by the detection of host volatiles including the oleoresin components alpha-pinene, camphene and limonene (Atkins and McMullen 1958; McMullen and Atkins 1962; Rudinsky 1966; Pitman and Vite 1970). Degradation products such as ethyl alcohol have also been shown to be attractive to flying beetles (Pitman et al. 1975). Stressed or damaged standing trees may exude larger quantities of these attractive volatiles, thus explaining why these trees are attacked by flying beetles while nearby healthy trees are ignored.

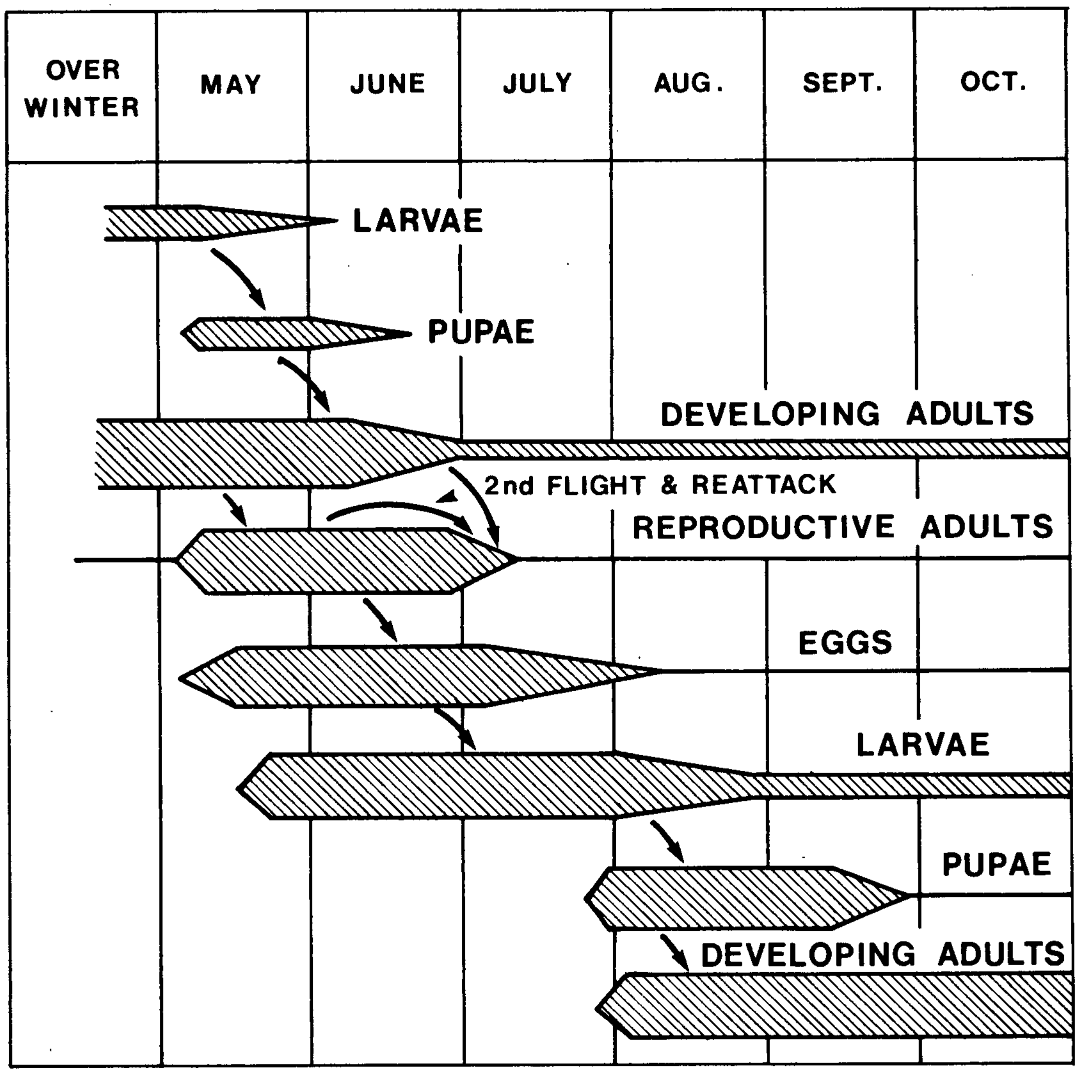


Figure 1: Generalized Life Cycle of the Douglas-fir Beetle (Dendroctonus pseudotsugae Hopk.).

Mass attack of the host is typical of Dendroctonus behaviour (Hopping 1929; Walters 1956; McMullen 1977). The female beetle initiates the egg gallery and produces pheromones for the aggregation of more beetles (Pitman and Vite 1970; Pitman et al. 1975; Dyer and Lawko 1978). The attacking beetles space themselves over the bark surface area by means of sonic stimuli and repellent pheromones (Hedden and Gara 1976; Rudinsky et al. 1976; Ryker et al. 1979). The greatest number of attacks and the greatest proportion of successful attacks on standing trees have been found to be on the upper bole of the tree, half way up the infested height and well above breast height (Furniss 1962). Because of this, estimation of successful attack based on samples taken from breast height may be unreliable as the absence of successful attacks would not necessarily preclude the presence of successful attacks high up the bole. However, evidence of successful attack at breast height indicates a successfully colonized tree.

After successful attack, adult beetles begin construction of the egg gallery at the cambium. The gallery is unbranched and extends vertically. The gallery is approximately 5mm wide and on the average is about 27 cm long. Eggs are laid in individual niches excavated in the side of the gallery. As the eggs hatch, the larvae begin feeding in the cambial region, producing larvael galleries going at right angles to the parent egg gallery, thus girdling the phloem and blocking the translocation of photosynthates down the tree. The larvae pass through several instars and are generally in the last instar or pupal stage in the fall following the attack. They overwinter in these stages and complete their development to become adults capable of flight and attack the next spring. Throughout most of its range, the Douglas-fir beetle has a one-year cycle.

Associated with the Douglas-fir beetle is a symbiotic fungus. It is introduced into the tree by the attacking insects and colonizes the sapwood. Rapid growth of the fungal mycelia blocks resin canals, thereby protecting the burrowing beetle from pitch flow. Pitch flow is the main defence mechanism of the tree and a healthy tree can pitch out the attacking beetle (Rudinsky 1966). This pitching-out process leaves pitch pockets in the wood which can be seen years after the attack (Belluschi et al. 1965). Tree water status affects the resin pressure. In trees under water stress, the resin pressure is reduced and the tree becomes more susceptible to successful insect attack (Rudinsky 1966; Lorio and Hodges 1977). The fungus colonizes the sapwood and may completely block the translocation of water and nutrients up the tree, causing the death of the tree and a foliar colour change.

The rate of foliage colour change is dependent upon weather conditions. The colour progression is from healthy green to pale green to yellow to red to bare branches. The first easily visible colour change (from green to yellow) usually occurs in the spring of the year following the attack. In hot summers, however, the foliage may change colour by the October following attack (Belluschi and Johnson 1969).

Detection and appraisal surveys for the Douglas-fir beetle have been dependent upon this colour change. Aerial surveys are usually conducted in August and numbers of red-topped trees are counted. However, because of the time lag between attack and colour change, the mapping of red-tops represents the mapping of the previous years attack, not the current attack. The time available for treatment and management of the population prior to insect flight is reduced. However, comparison of the number of red-tops to the number of older attacks gives a measure of the rate of spread of the infestation.

1.3 Management Considerations

Management regimes to reduce the hazards of Douglas-fir beetle attack include single tree treatments, trap tree and trap log programs, logging in high risk stands and salvage logging of currently infested stands (Hopping 1921; Walters 1956; Lejeune et al. 1961; McMullen 1977).

Single tree treatments are concerned with killing the brood in infested material prior to the insect flight and attack period. Such treatments include piling and burning infested material, peeling the bark to expose the insects to dessication and spraying infested material with bark penetrating insecticides which include ethylene dibromide and lindane (the gamma-isomer of benzene hexachloride) in fuel oil. These treatments are expensive and, to be successful, infested material must be located and treated before the insects fly to attack new hosts. The benefits derived from such treatments and the costs involved must be considered before such a program is carried out. Costs may be amortized over a period of years if a high-value, high risk stand can be saved until harvest under long-term logging plans.

Trap tree and trap log programs are instituted prior to insect flight. They are designed to absorb the flying population and thereby decrease the numbers of beetles available to infest desirable timber. In trap log programs, host trees are felled within the control area. These felled trees attract and absorb the flying insects. After flight, these logs are treated as above for single tree treatments or removed for processing. An adequate survey of the stand is necessary to establish both the amount of infested material (wind-throw and standing trees) and its location. After the survey, the number of trees to serve as trap logs sufficient to absorb the attacking insects must be selected and felled. These logs must also be located near the brood producing material to prevent dispersal of the insects. Trees between the trap logs and brood material may become attacked thereby reducing the effectiveness of the trap tree program. Trap logs may be baited with synthetic pheromones to increase their attractiveness and effectiveness and they may be sprayed with a contact insecticide which would kill arriving beetles. Whatever the method, insects at the trap log must be killed to decrease the population and reduce the risk of attack to the remaining stand. Standing trap trees may be used similarly to trap logs. Their effectiveness is mostly dependent upon the use of an attractant pheromone. Trap trees must be treated after flight in the same manner as trap logs unless they had previously been protected with insecticide. An effective trap program is dependent upon the locating of brood material far enough in advance of insect flight to establish the trap trees in optimum numbers and location. Detection of brood material prior to foliar colour change would give greater time available for treatment. Harris et al. (1978) have proposed a method for detecting recent wind-throw, the other brood source besides standing trees, by detecting gaps in the forest canopy on aerial photographs.

Logging of high risk stands is equivalent to direct competition with the insects for the timber resource. Risk rating systems have been developed for mountain pine beetle (Safranyik et al. 1974; Amman et al. 1977; Mahoney 1978) and spruce beetle (Schmid and Frye 1976). Similar risk rating systems could be developed for the Douglas-fir beetle. Once stands have been classified as high, medium or low risk, logging priorities may be altered so that high risk, high value stands may be utilized before they become significantly infested by bark beetles. This method of bark beetle management does not require detection of infested trees to the same extent as the above two methods. It does, however, require information about the biology of the insect and the dynamics of the stands. Harvesting by risk is a long-term method of insect control necessitating great changes in current long-range harvesting plans. This type of management may also disrupt other criteria for setting harvesting priorities so that insect damage cannot be the sole reason for harvesting plans.

Salvage logging of already infested stands is a "catch-up" type of management. Its aim is to utilize insect killed timber before significant degradation of wood qualities can occur. When large areas of timber have been killed, as happens with mountain pine beetle infestations, salvage logging produces large clearcuts without greatly reducing the population of insects. Salvage logging should be carried out in such a way as to remove insect populations as well as the most recently killed trees. This requires starting salvage operations at the perimeter of an infestation rather than in the center.

Preservation of desirable stands for long periods of time requires the elimination of small, incipient infestations within the stand. Management of stands for control of Douglas-fir beetle must include aspects of all of the above methods. Early detection is a requirement for such treatments.

1.4 Survey and Detection Methods to Date

Detection surveys for bark beetle activity have been carried out for several years by the Forest Insect and Disease Survey of the Canadian Forestry

Service (McGugan 1956). Detection surveys consist of observations and reports of insect infestations. Their purpose is to reveal the presence of harmful or potentially harmful infestations of forest insects prior to their development into outbreak proportions, at which time the treatment of the infestation is difficult (Orr 1954).

Present Douglas-fir beetle survey methods include aerial sketch-mapping, aerial photography with colour or colour infra-red (CIR) film and some ground checking (Harris and Dawson 1979). In British Columbia these surveys are usually carried out in the fall and numbers of red-tops are counted as they are seen from the air. These red-tops represent trees that have been attacked the previous year and which have no brood remaining in them. Currently infested trees which are still green are not detected (Belluschi and Johnson 1969; Harris and Dawson 1979). To determine the amount of current infestation, ground surveys are carried out in areas where red-tops were detected. These ground surveys are used to calculate the ratio of new infested trees to old infested trees. Obviously, this survey for green attacked trees is expensive. The cost ratio of ground strip cruising to photographic survey is approximately 100:1 (Heller et al. 1959; Wear et al. 1964; Meyer and French 1967; Wert and Roettgering 1968; Klein 1973). Also, only the number of green attacked trees in known infestations is assessed. Isolated infested trees or small incipient infestations are not detected. These present surveys, if conducted annually, yield an historic record of the progress of insect infestations. Also, they indicate areas which have a high likelihood of having current infested trees, based on the presence of an attacking population source.

Surveys would be made more effective if green attacked trees could be detected from the air. Ground surveys would not need to be as extensive and survey flights could be carried out earlier in the season, allowing a greater amount of time for treatments or formulation of management plans.

1.5 Early Detection - Methods and Success to Date

Three general methods have been used in attempting previsual detection: analysis of thermal imagery, analysis of multispectral scanning imagery and analysis of CIR photographs.

Early detection of a foliar colour change which is not detectable through visual means may be termed either extravisual or previsual (Murtha 1978). It is extravisual if a visual change does not occur eventually. This type of damage may be caused by a temporary stress or a general weakening of the tree which does not lead to the death of the tree. The detection is previsual if a further colour change does occur. In the case of detecting green bark beetle infested trees, the trees will eventually die and change colour so that the correct term is previsual.

Previsual detection is based upon the detection of physiologically changed foliage resulting from stress. Stress occurs in beetle attacked trees when the blue-stain fungus has successfully blocked the sapwood, thereby reducing water transport. The results of this stress are the changes in the reflective characteristics of the foliage. Gausman (1977), studying various herbacious plants, determined that near infra-red (NIR) light (700 - 900nm) was reflected by intra-cellular discontinuities including nucleii, crystals and cytoplasm in addition to the cell wall airspace interface which accounts for the major portion of the NIR reflectance. Cellular constituents account for approximately 8% of the reflectance at 800nm (Gausman 1977). These components may change in stressed foliage and produce an increase or a decrease in the amount of reflected NIR (Knipling 1967).

NIR reflectance in conifers is generally less than that for broad leaved species, possibly due to their more compact structure and more contained shadows (Kodak 1971). It has been postulated that the first change in reflectance of a plant under stress is a change in the amount of reflected NIR (Fritz 1967; Murtha 1978). Thomas et al. (1966) showed that in cotton, reflectance of NIR increased with water stress possibly due to an increase in solute concentration within the cell cytoplasm and to changes in the size and shape of cells and intra-cellular spaces. Olson et al. (1970) also reported an increase in NIR reflectance with greater moisture stress (low foliar moisture content) in yellow birch (Betula alleghaniensis Britton), sugar maple (Acer saccharum Marsh) and white ash (Fraxinus americana L.), all of which are broad leaved species. This increase in reflectance was not found in beetle attacked conifers. In these conifers, the NIR reflectance was found to decrease by about 10% (Weber 1965; Heller 1968; Weber and Polcyn 1972). These decreases, however, were not visually detectable on CIR film. The decrease of the NIR reflectance found by Weber (1965) and Heller (1968) was found to occur approximately 45 days after initial attack. Heller (1968) also found no discernible changes in needle structure 2 months after attack. Ten months after attack, after the foliage changed colour, significant changes in morphology occurred (Table II). These changes in morphology probably reflectance. Preliminary changes occurring within 2 months of attack might account for the 10% decrease in NIR reflectance that was found.

Other authors (Benson and Sims 1967; Ciesla et al. 1967; Meyer and French 1967; Ciesla 1977) have also stated that no visual difference between green infested and green healthy trees could be found on colour infra-red photographs although they did state that the colour contrast between old

Table II. Structures of Pine Needles (<u>Pinus ponderosa</u> Laws.) Before and 10 months after Mountain Pine Beetle Attack. (Heller, 1968)

Structure Affected	Normal Needle	Yellow Needle From Infested Pine
Resin Canal	Open	Collapsed or Broken
Vascular Bundles	Most Cells Filled with Cytoplasm	Cytoplasm absent
Stomata	Intact	Broken, Shrunken, Degenerated or Closed
Cytoplasm	Fills Out to Cell Walls	Shrunken from Cell Walls, Frequently Absent
Cell Walls	Normally Thin	Thicker by Comparison

infested trees and green trees and between deciduous and coniferous trees was greater with colour infra-red film. The haze penetration with infra-red film was also much better. Arnberg et al. (1973), working with aerial photography of damage caused by *Ips typographus* (L.), a European bark beetle, found visual differences in green infested trees. They postulated that bark beetle damage to trees is manifested by a change in physiology caused by nutrient deficiency which affects the reflectance properties of the foliage.

Previsual detection using thermal imagery makes use of a thermal line scanner which detects emitted radiation greater than about 2600nm (Fig. 2). This energy band can be detected using a multispectral scanner. Results using these devices have been partially successful. Heller (1968) detected some green infested trees in the spectral range of 1000 to 2600nm (mid infra-red) but the limit of discernible shades of gray often restricted detection of subtle changes in moisture stress. Heller (1968) also noted a 6°C increase in needle temperature in infested trees. This result agreed with the results of Weber (1965) in attacked pines and in Engelmann spruce (*Picea engelmannii* Parry) infested with spruce beetle (Schmid, 1976). Schmid's results were variable, however, and needle temperatures varied according to wind, shading, needle location (east or west aspect) and orientation to the sun. These factors obscured a consistent difference between healthy and infested trees. A decrease in reflected NIR and an increase in foliar temperature in infested trees form the basis for attempts at previsual detection of beetle infested trees.

Later, Heller (1971) detected several green infested pines using a multispectral scanner, but there were also many other objects in the imagery

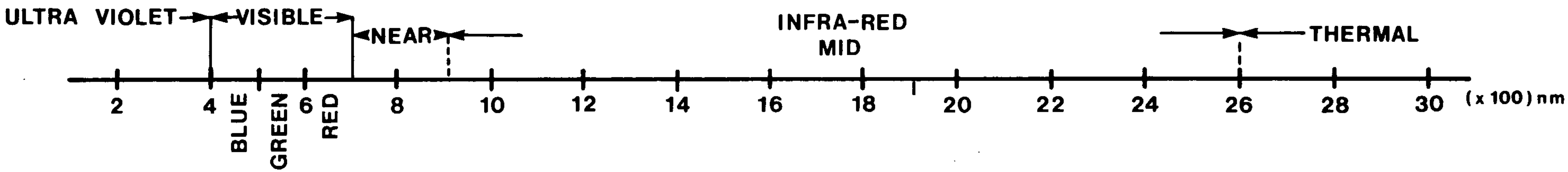


Figure 2: Portion of the Electromagnetic Spectrum Currently Used in Attempts at Previsual Detection.

that had the same temperature range as the target trees. The resolution of such scanners was also not fine enough to distinguish individual trees when the aircraft was flying at over 1500m (Heller, 1971; Weber and Polcyn, 1972). Weber and Polcyn (1972) also had some success with detecting non-faded attacked trees using far infra-red spectral ranges (greater than 900nm). They had difficulties with the resolution of the imagery and stated further that greater success could be achieved by covering the entire band-width in narrow band increments. Other authors (Rohde 1971; Rohde and Olson 1970; Alger et al. 1978) have also had success using sensors sensitive to this spectral region. The main problems associated with thermal line scanners and multispectral scanners have been poor resolution and poor tree species identification. Analysis of photographs avoids these problems.

Most analysis of normal colour and CIR photographs to date has been purely visual interpretation. Most attempts have failed, with the authors stating that no colour change occurs on infra-red film before it shows up in normal colour film (Benson and Sims 1967; Ciesla et al. 1967; Heller 1968 and 1971; Heller and Wear 1969; Brown 1971; Ciesla 1977). Only Arnberg et al. (1973) reported success in visually detecting infested trees on CIR film.

More sophisticated analysis of CIR photographs has led to the detection of stress in plants. Murtha and Hamilton (1969) detected partially and fully girdled trees prior to foliar colour change. The photographs were analyzed using a microdensitometer to measure the densities of the dye layers in the film. They were able to show a decrease in the amount of NIR reflectance in the damaged trees as indicated by dye-layer density changes. This was also shown by Murtha (1968). Analysis of normal colour film by the densitometric technique did not yield similar results. Microdensitometric analysis was used by Lillesand et al. (1978) to detect elm trees (Ulmus americana L.) suffering from Dutch Elm disease. Using discriminant analysis, stressed trees were found to be significantly different from healthy trees. Thus, through the use of densitometric analysis, the 10% decrease in NIR reflectance reported by Weber (1965) and Heller (1968) could possibly be detected on CIR film.

1.6 Densitometry

Microdensitometric analysis of colour infra-red film to detect previsual symptoms of bark beetle attack involves the measurement of the densities of the three dye layers in the film. Colour infra-red film is made up of three dye layers, each sensitive to a different region of the visible and near infra-red spectrum (Fritz 1967). These dyes are: yellow dye forming, magenta dye forming and cyan dye forming layers (Fig. 3). These layers are sensitive to green light (500 - 600nm), red light (600 - 700nm) and near infra-red light (700 - 900nm) respectively. Because all three dye layers are sensitive to blue light (400 - 500nm), a Wratten 12 filter must be used when exposing the film. The Wratten 12 filter is a yellow or minus-blue filter which absorbs blue light. The amount of dye formed in each layer is inversely proportional to the amount of incident light in a specific region of the spectrum (Fritz 1967). Upon development to a positive transparency, the amount of the dye-forming layer not exposed forms a dye in inverse proportion to the amount of incident light in the particular range. The density (the amount) of dye formed is therefore a relative measure of the reflected light in each of the three spectral regions.

These dye layer densities can be measured by using a densitometer

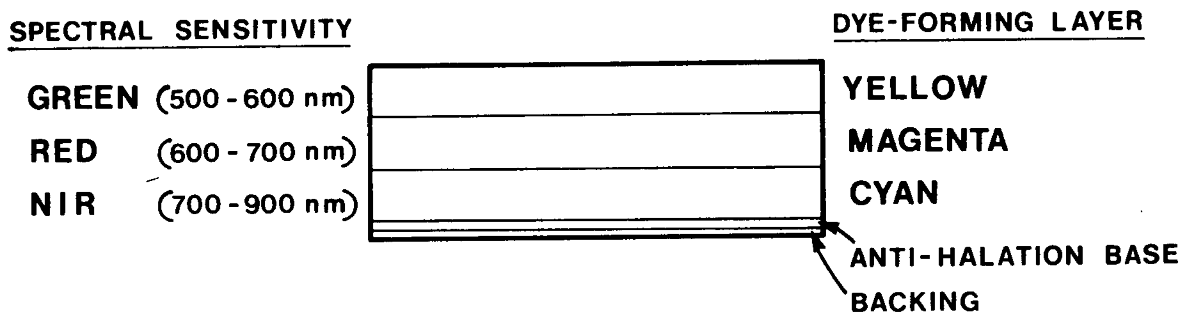


Figure 3: Schematic X-Section of Colour Infrared Film.

which measures the light transmittance at specific spectral regions through a positive transparency. Table III shows the filters required to measure the dye layers. On the transparency, a high density of a dye layer indicates a low reflectance in that specific spectral region. This is shown schematically in Figure 4 (after Murtha, 1978). The diagram shows both the progression of the theoretical reflectance changes in stressed trees and the resultant effect of the reflectances on the film.

1.7 Study Objectives

The objective of this study was to determine if the change in NIR reflectance previously detected by Weber (1965) and Heller (1968) relative to bark beetle attack could be detected on CIR photographs before a visual colour change was noticed. A change in the reflectance alters the amount of dye formed on the transparency. Although no success in detecting green infested trees has been reported, previous workers relied principally on visual interpretation of CIR photographs. The human eye detects density differences of about 0.1 and notes them as tonal changes. Densitometric analysis should be able to detect the differences which would escape visual analysis as differences in density as small as 0.01 are detectable through the use of a microdensitometer. Original transparencies must be used for the densitometric analysis as there is a reduction in the amount of information on duplicates. Densitometric analysis will also quantify differences in dye layer densities allowing statistical analysis of reflectance changes in stressed trees.

Successful detection using photographs will eliminate some of the problems inherent with thermal line-scanning as well as reduce the costs as the equipment and overall costs of photography are less expensive than

Table III. Filters Used to Measure Specific Dye Layers on Colour Infra-red Film on a Densitometer.

Dye Layer To Be Measured	Colour of Filter	Spectral Reflectance Region being Measured
Yellow	Blue	Green (500 - 600nm)
Magenta	Green	Red (600 - 700nm)
Cyan	Red	near infra-red (700 - 900nm)

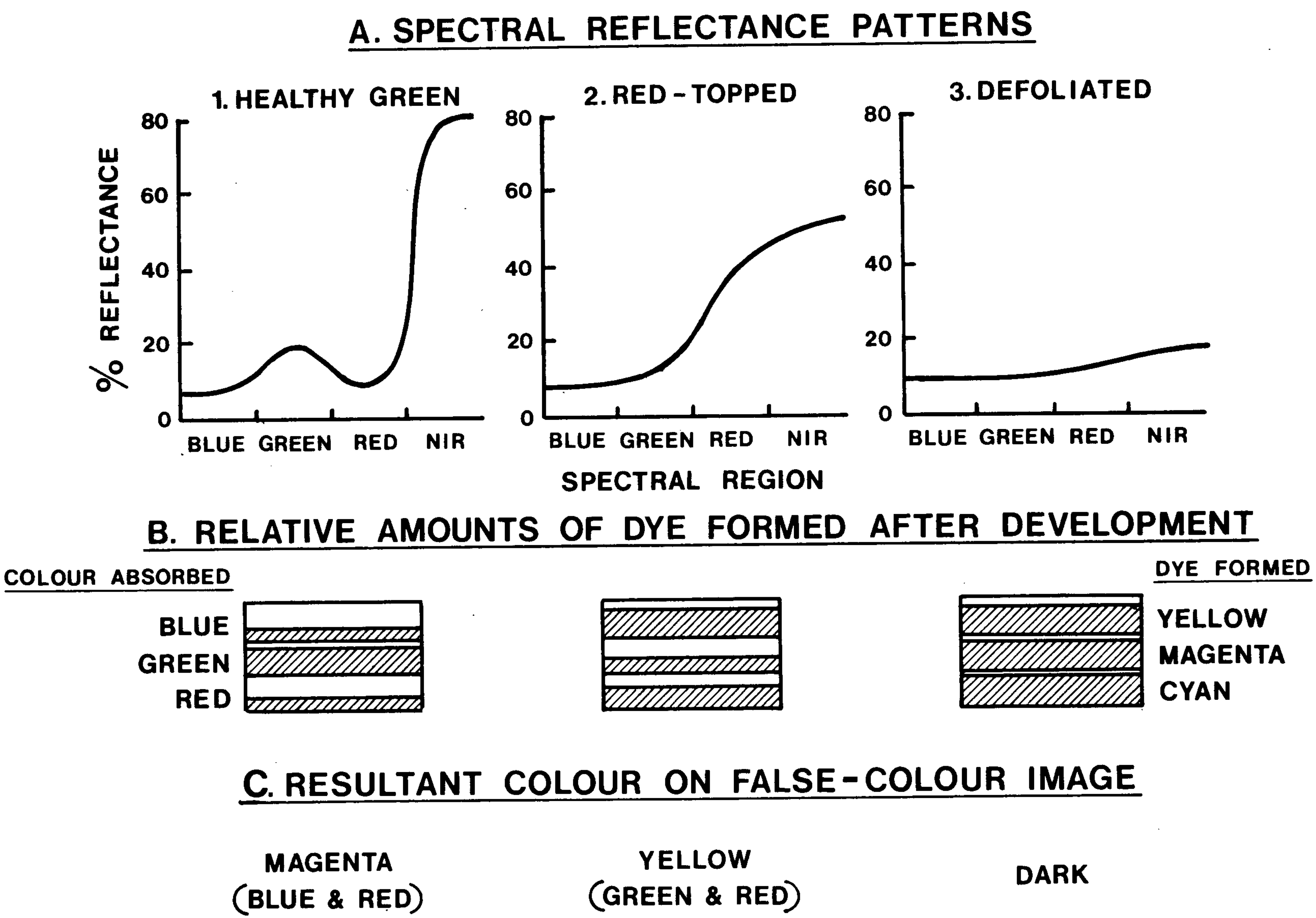


Figure 4: Reflectance Curves of Various Stages of Insect-attacked Trees and the Resultant Effect on Colour Infrared Film.

for thermal imagery. The technology is also more commonly available. Incorporation of this technique into bark beetle damage surveys would reduce the amount of ground cruising required to estimate the spread of known infestations and thereby reduce the costs involved. High risk, high value stands may also be monitored for the occurrence of small incipient infestations. This would allow more time for treatment of the infested trees leading to the extension of the life of the stand.

2. METHODS

2.1 Study Region

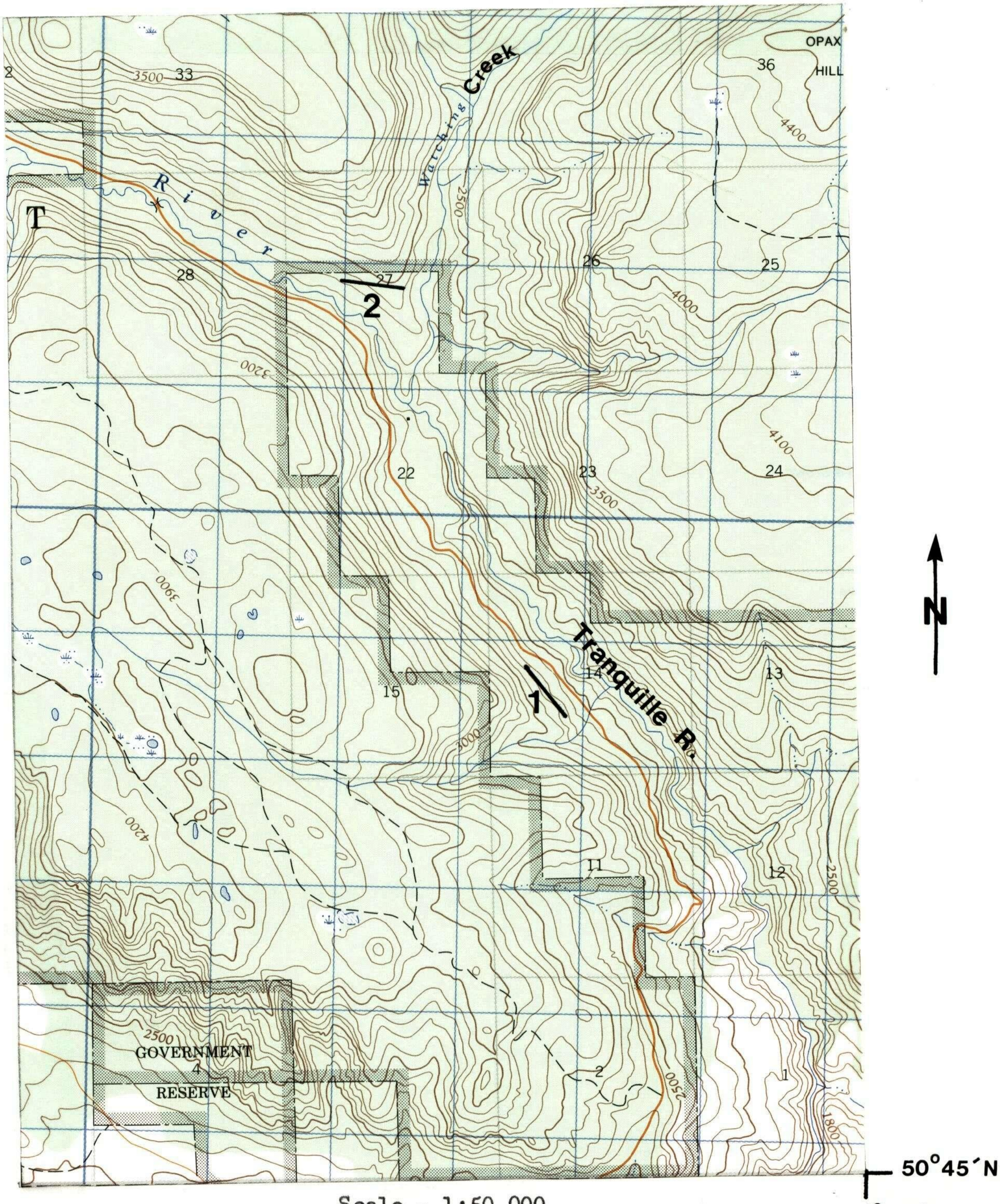
The Tranquille Valley in the Kamloops Forest Region of British Columbia was chosen as the general study area for two reasons. Firstly, the Douglas-fir beetle has been a chronic problem in this region for several years and, secondly, several other remote sensing studies were being carried out in this region by other researchers from the University of British Columbia. This led to a more efficient utilization of the expensive technology used to obtain the CIR photographs. Selection of the actual photo plots was made after ground reconnaissance of the area. The final locations of the study sites are shown in Figure 5.

2.2 Selection and Location of Photo Plots

The criteria for selection of photo plots were as follows: plots must be located in pure, even-aged stands of mature Douglas-fir; trees infested in 1978 must be in the plot or in close proximity to the plot to provide a source of attacking beetles for 1979; there must be some evidence of bark beetle attack (e.g. boring dust on the bole) on some trees with green foliage in the plot; there must be comparable trees with no symptoms of attack to act as checks.

Two such plots were located along the Tranquille River (Fig. 5). The current attacks on trees in these plots may have been artifically induced,

Figure 5. Topographic Map of the Tranquille River Area with the Two Photo Plots Marked.



Scale - 1:50,000

however. Dr. L.H. McMullen[1] had baited standing trees with a synthetic attractant Douglas-fir beetle pheromone prior to beetle flight which occurred in the last week of April, 1979. Therefore, some of the attacked trees may not have been attacked under normal circumstances. These areas, though, were judged to have a high probability of containing some successfully attacked trees.

Plot markers were put in position on July 26. Each marker consisted of a white cotton sheet 260 x 165cm. Markers were placed in an open area at the ends of each plot. White sheets were chosen since they are highly reflective in all wave lengths and would therefore be readily identifiable on aerial photographs. All trees in the plots were ground checked at this time.

Five trees were girdled in plot 2 (Fig. 5) on July 26. These trees were to simulate attacked trees for comparison of their spectral reflectance patterns with healthy trees and with beetle-attacked trees. The would provide further information on reflectance changes following phloem disjunction. The depth of the girdling extended into but did not completely sever the sapwood of each tree.

2.3 Photography

Aerial photography of the plots was carried out on July 29, approximately three months after beetle attack. It was hoped that this time interval would allow sufficient beetle development and reflectance changes to indicate successfully attacked trees on CIR photographs prior to a visual colour change.

The photographic flight was done by Integrated Resource Photography of Vancouver, B.C. Stereo photographs were taken between 18:38 and 18:51

---

1 Dr. L.H. McMullen. Research Scientist, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, B.C. Personal communication.

Greenwich Mean Time or between 11:38 and 11:51 Pacific Daylight Savings Time. Pictures were taken with a Vinten 492 70mm reconnaissance camera with a Leitz f2.0 lens set at f7.5 using a Wratten 12 and a CC20M filter and Kodak Aerochrome IR film. The resultant false-colour transparencies were at a scale of approximately 1:1100. Forty-four stereo pairs provided photo coverage of the two plots.

2.4 Analysis of Photographs

A Macbeth[2] TR-524 Transmission Reflectance Densitometer was used to take density readings on the crowns of trees in the photographs. The transmission head was used and densities of all three dye layers were measured by using the filter selection of either blue, green or red filters to give density measures of the yellow, magenta and cyan dye layers respectively. Only the dominant Douglas-fir were measured in this study as only mature trees were rated as being suitable for beetle attack. Densities were taken from the images of trees with green foliage, red-tops (attacked and killed in 1978), and dead defoliated trees (attacked and killed prior to 1978).

Murtha's (1972) damage classification index was also applied in the visual interpretation of the photographs.

2.4.1 Analysis of Densities

A final ground check was made between January 24 and 27, 1980 to establish which trees in the plots were successfully attacked, attacked but pitched out or unattacked and green. Such trees were identified and matched to their photo images. Successfully attacked trees were those which had evidence of beetle attack and straw-coloured foliage; trees which had pitched-out the

---

[2] Division of Kollmorgen Corporation

attacking insects were those with beetle entrance holes on the bole and green foliage; unattacked and healthy trees were those with no evidence of beetle attack on the bole and green foliage. This ground check was necessary to identify trees positively in each damage class for further statistical analysis to determine if significant differences existed.

The variables derived for each tree were the density readings for each of the three dye layers (yellow, magenta and cyan) and three ratios from these readings (magenta/yellow, cyan/magenta and cyan/yellow). The ratios were used because they gave a measure of the relative reflectance between each of the spectral regions. The use of ratios, therefore, should decrease any variance due to film/plot irregularities such as differences in aspect, slight differences in scale due to changes in altitude or slight irregularities in the film itself.

Histograms and descriptive statistics (mean, sample size, range and standard error of the mean) were computed for each variable in all the damage classes to check normality of the data and to identify oulier values. One-way analysis of variance (ANOVA) for each variable between the three green-appearing damage classes was carried out to detect significant differences. Only the green-appearing damage classes were analyzed by this method as the other two classes (red-topped and old dead) were easily distinguished visually. MIDAS (Fox and Guere 1976), a statistical computer package, was used for the calculation of ANOVA, histograms and descriptive statistics. If ANOVA showed a significant difference between the three damage classes for a variable, an a posteriori least significant range tests of means was carried out using the Student-Newman-Keuls test for unequal sample sizes (Sokal and Rohlf 1969).

Stepwise discriminant analysis was used to obtain a weighted linear combination of the independent variables that would best separate trees into their proper damage classes. The stepwise discriminant analysis package BMD P7M (Jennrich and Sampson 1977) was used for the analysis. All six variables were included so that the best combination could be found although the ratio variables were given priority for selection due to their lower variability and representation of how one spectral region varied with another. Two sets of discriminant analysis were done, one attempted to discriminate between all five damage classes while the other considered only the three green-foliaged classes.

3. RESULTS AND DISCUSSION

3.1 Data Description

Densities of the three dye layers (yellow, magenta and cyan) were measured for trees with green foliage, red-tops (attacked and killed in 1978) and dead defoliated branches (attacked and killed prior to 1978). In all, the three dye layer densities were measured for each of 636 trees.

A ground check made three days prior to the photography showed that both trees with no evidence of attack and trees with fresh boring dust on the bole had green, healthy-appearing foliage. A final ground check was made in January, 1980 to determine which trees in the plots were successfully attacked, attacked but pitched-out, or unattacked and healthy. By this time the foliage of successfully attacked trees had turned a straw colour that was readily apparent from the ground. Unsuccessfully attacked trees were identified as those trees having green foliage and boring dust on the bole. Densitometric measurements of trees in the same damage class did not vary significantly ($p<0.05$) between plots so that the data were pooled in the analysis. A random sample of the healthy trees was selected for comparison with the damaged trees. This was approximately equal in number to the sizes of the other damage classes. All successfully attacked, pitched-out, red-topped and old trees in the plots were included in the analysis (Table IV).

The variables used for the analysis were the densities of the three dye layers and the three ratios of the densities (magenta/yellow, cyan/magenta and cyan/yellow). The first three variables are representative of the reflectance of light in certain wave lengths (Fig. 3). A high density value indicates a low reflectance and *vice versa*. The last three variables are more indicative of reflectance patterns. The ratios also tend to overcome film and localized reflectance irregularities facilitating comparison between different locations and aspects. They may also be more sensitive to differences in reflectance patterns.

Descriptive statistics including sample size, range, mean and standard error of the mean were derived for each variable in each damage class and are detailed in Appendix I and recorded graphically in Figures 6 and 7. Histograms of each variable in each damage class are shown in Appendix II.

The reduction of variance attributable to the ratios as well as overlapping of values is shown in Figures 6 and 7. The confidence intervals for the ratios are much narrower than for the individual dye layers. Differences between damage classes are also indicated in Figures 6 and 7 as the more the intervals overlap, the less is the difference between means. Larger sample sizes would tend to emphasize any differences which exist as the confidence interval decreases with increasing sample sizes.

Generally, two distinct groups of observations were obtained (Fig. 6, 7). One grouping represented the green appearing trees (healthy, pitched-out

Table IV. Number of trees used for each damage class in the analysis of dye layer densities.

Damage class	Number of trees used
Healthy	27
1979 Pitch out	26
1979 Successful attack	15
Red-tops	31
Old dead	27
Total	126

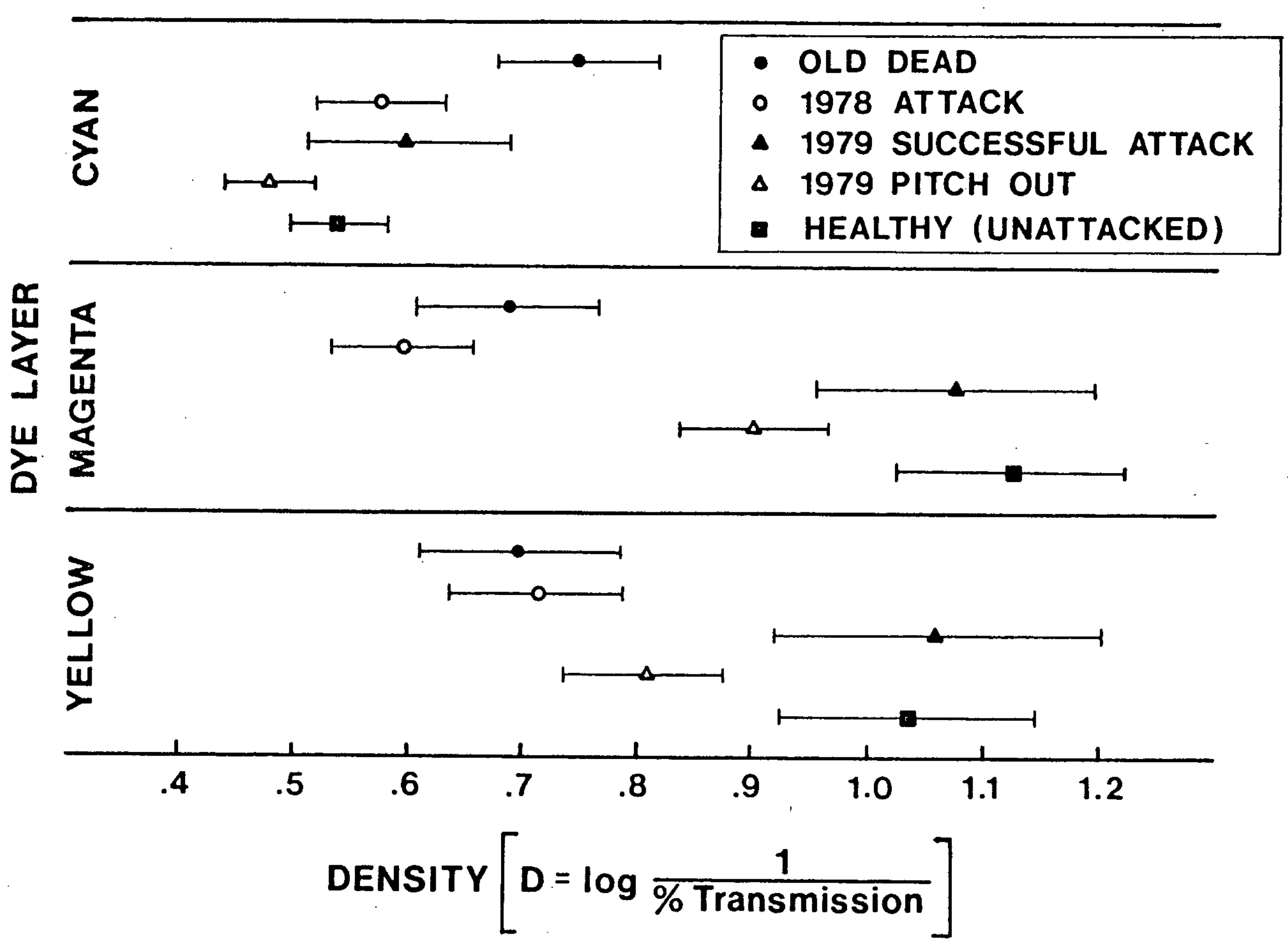


Figure 6: Means and 95% Confidence Intervals of the Individual Dye Layers for the Five Damage Classes.

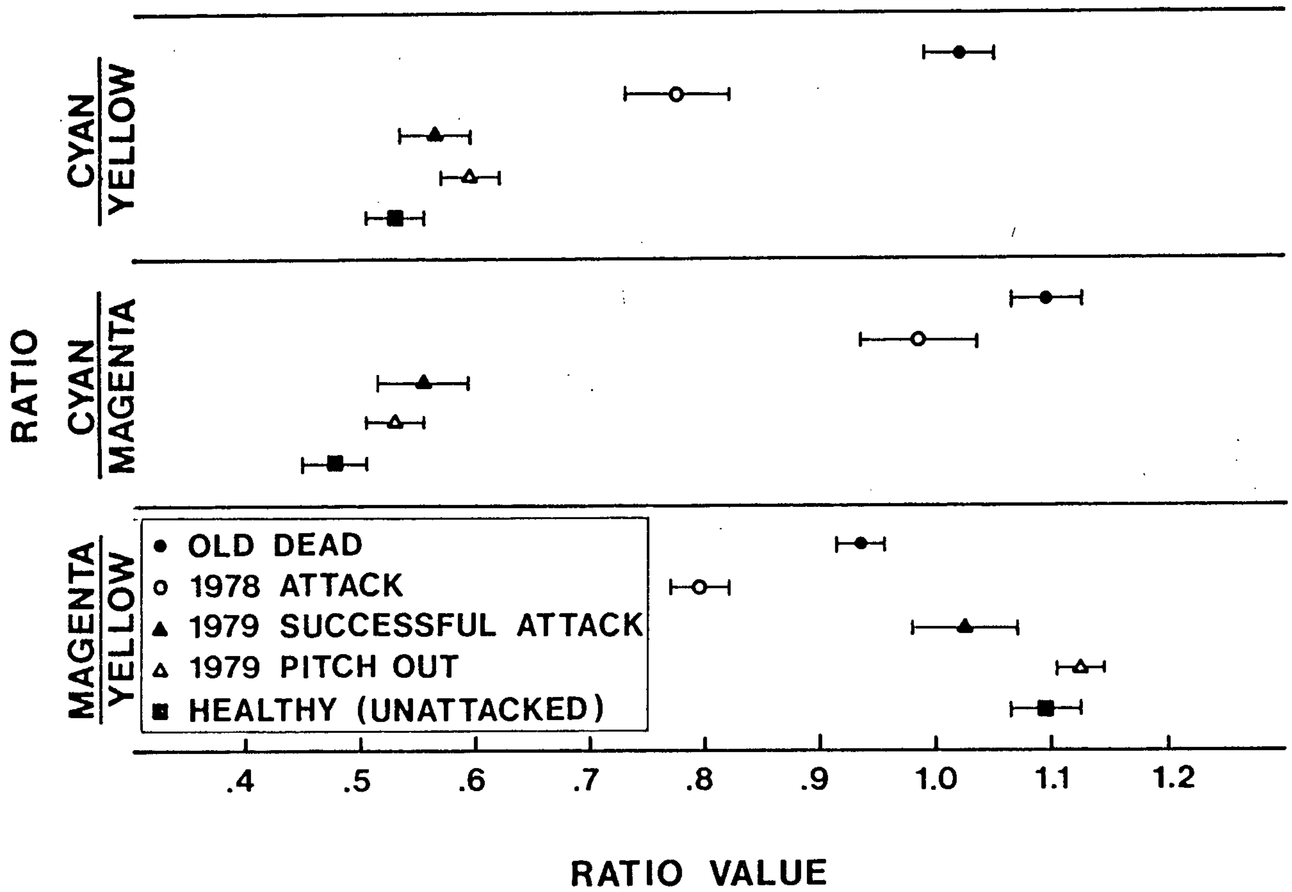


Figure 7: Means and 95% Confidence Intervals of the Ratio Variables for the Five Damage Classes.

and successfully attacked) and the other group the red-topped and old-dead trees. These two groups are also easily distinguishable from each other visually both from the ground and on the colour infra-red photographs (Figs. 8, 9). The three green-appearing classes were not greatly different from each other when visually compared on a photograph except for the slight orange hue of the 1979 successfully attacked trees (Fig. 9). Because the trees killed prior to 1979 were visually distinct and because the purpose of this experiment was to distinguish healthy trees from successfully attacked trees, the remainder of the discussion will deal primarily with the three damage classes which had green foliage.

A damage classification system (Murtha 1972) was applied to the trees in the photographs. In this system trees may be assigned a damage classification index on the basis of morphological or physiological deviations from normal healthy trees. Morphological changes are those which are apparent as changes in shape or form of the trees such as loss of foliage or broken branches. Physiological deviations from healthy trees are expressed as changes in the colour or tone of the foliage of affected trees. Classification of damage may be done with either normal colour or CIR film. Morphological damage is illustrated by old-dead trees (Fig. 8). These trees are given a damage classification of IB, i.e. scattered individuals or small groups of defoliated conifers. Trees that had been dead for one year, or red-tops, are given the classification IIIG, or a conifer with red-brown current and red-brown older foliage. Because all years of foliage are killed at the same time, this damage type indicates a tree killed rapidly in the present season. The pitched-out trees (Fig. 9) appear as a normal, healthy magenta colour and they would not be included in a damage appraisal based on visual photo-

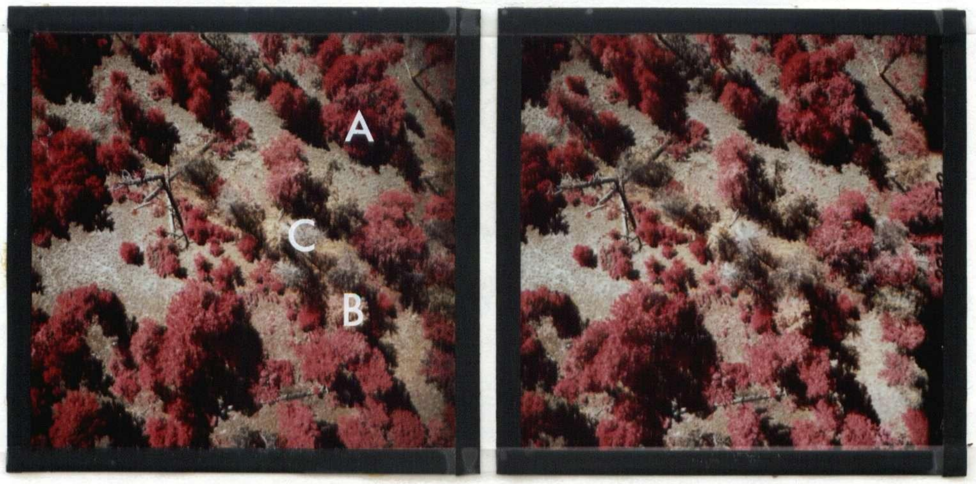


Figure 8: Stereo aerial CIR photos of green, red-topped and old-dead trees. A. Healthy Douglas-fir (magenta tone); B. 1-yr. old dead Douglas-fir with red-brown foliage (yellow tone); C. Old dead, defoliated tree (grey tone).

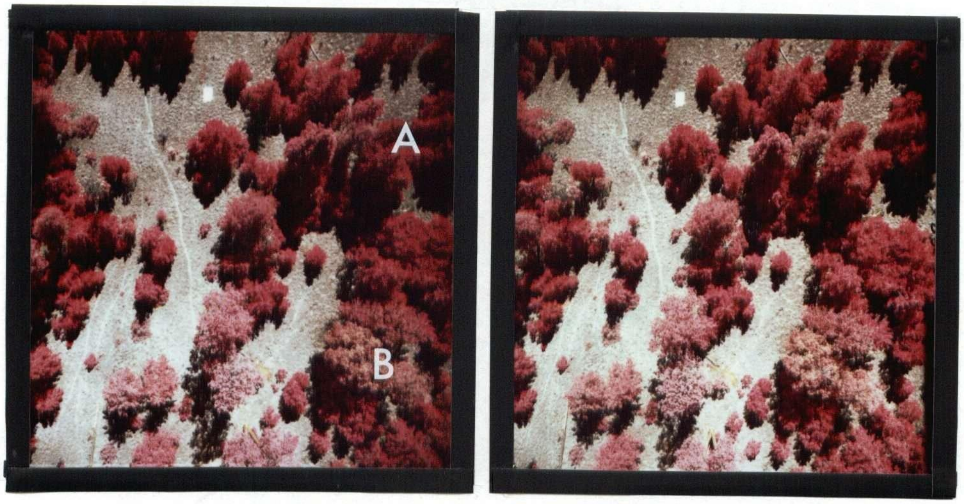


Figure 9: Stereo aerial CIR photos of healthy and successfully attacked trees. A. Healthy Douglas-fir (magenta tone); B. Beetle infested Douglas-fir with green foliage (tan-pink tone).

interpretation methods. The successfully attacked trees shown in Figure 9 exhibit a marked colour change indicating a stress situation. These trees appear as intermediate between the healthy magenta and the yellow colouration of the 1978 attacked trees. As such, they were given the classification of IIIOb or lighter than normal magenta tone. This, however, is not completely descriptive and a further class may have to be added to this classification system to more accurately describe this type of tree. Also, some bare branches are evident in the crown of the successfully attacked tree which is a morphological change so that the classification under the present system, should be IIIOb/IIA. The IIA describes defoliation concentrated in the top part of a conifer.

Damage classification systems for aerial photographs are useful as they permit quantification of differing types of damage occurring in close proximity. Also, some damage classes are indicative of specific causal agents or of a limited group of agents, thereby supplying more information than just a notation that some damage is occurring.

The three green appearing classes were not distinguishable from each other when viewed from the ground four days prior to the photographic mission. They are also not greatly different when seen on the colour infra-red photographs (Fig. 9). Notice, however, the slightly orange colour of the successfully attacked trees (Fig. 9). This colouration was consistent in all successfully attacked trees while the other two classes showed the magenta colour of healthy green foliage. This difference in colour may be explained by comparing the densities of individual dye layers and by comparing their ratio values.

3.2 Statistical Analyses

3.2.1 One-Way Analysis of Variance

As red-topped trees and old-dead trees are readily distinguishable from trees with green foliage on the ground and on CIR photographs, only the successfully attacked, pitched-out and healthy classes were compared by analyses of variance. Each of the six variables (three dye layer densities and three ratios) was tested separately for the three damage classes. The individual class means were compared using the Student-Newman-Keuls test for unequal sample sizes (a least significant range test of means) if the F-value from the analysis of variance was significant at the 95% level (Sokal and Rohlf 1969).

There were significant differences between damage classes for all six variables at the 0.01 level of significance. Results of the tests of means are given in Table V. For the individual dye layer densities the trees which had pitched-out the attacking insects had consistently lower densities which indicated higher reflectance in the green, red and NIR portions of the spectrum. These data confirm the differences indicated upon examination of the confidence intervals around the means (Fig. 6). This general higher reflectance may be indicative of greater vigour and therefore possible greater resistance to insect attack. These trees may not have been attacked naturally; rather, the synthetic aggregating pheromone released in the area (as mentioned previously) may have been responsible for attracting the beetles which initiated these unsuccessful galleries. The trees which pitched-out the attacking beetles may owe their greater vigour to either microsite differences in nutrients, differences in infection by pathogens or age differences.

At the significance level used in the test of means ($p<0.05$) the cyan dye layer density of the images of the pitched-out trees was not significantly different from that of the healthy trees. The same differences were present at the 0.10 level as for the other two dye layers.

Table V. Means of each variable for each of the three damage classes with green-appearing foliage (healthy, pitched-out and successfully attacked).

Damage Class	Dye layer densities			Ratios		
	Yellow	Magenta	Cyan	Magenta/Yellow	Cyan/Yellow	Cyan/Magenta
healthy	1.037[a][1]	1.125[a]	0.536[ab]	1.099[a]	0.526[b]	0.480[b]
pitched-out	0.807[b]	0.900[b]	0.476[b]	1.121[a]	0.591[a]	0.529[a]
successfully attacked	1.061[a]	1.074[a]	0.597[a]	1.022[b]	0.562[a]	0.555[a]

1 Values within a column with different superscripts differ at the 0.05 level of probability (Student-Newman-Keuls test).

The ratio variables best differentiate between successfully attacked trees and healthy trees. As ratios provide a measure of reflectance patterns (i.e. the reflectance in one region as compared to another) and because the ratios have a much smaller range within each class, they provide a more sensitive basis of comparison between classes.

In the two ratios dealing with the cyan dye layer which measures NIR reflectance, the images of the pitched-out trees and successfully attacked trees had higher values than those of the healthy trees. The pitched-out tree images have higher values because although the density of the cyan layer was equal to the cyan layer density of the healthy tree images, the densities of the yellow and magenta layers were lower in the pitched-out tree images. These densities and the ratio values are a result of the generally higher reflectance found in the foliage of pitched-out trees.

The significantly higher cyan/magenta and cyan/yellow ratios in the successfully attacked trees were due to less obvious changes in the reflectance patterns. While the density values of the individual dye layers for the images of successfully attacked trees did not differ significantly from the values for the healthy tree images a change in pattern resulting in differing ratio values was shown (Figs. 6, 7). The mean of the cyan dye layer density was higher than that for the healthy tree images and the confidence limits did not greatly overlap. There was a considerable overlap of densities of the yellow and magenta dye layers between images of successfully attacked and healthy trees. The generally higher cyan layer densities for the images of successfully attacked trees would yield significantly different ratios. This is particularly true if the higher cyan layer densities were from the images of the same trees as the lower values for the yellow and magenta layers. The ratio, therefore, became a measure of the reflectance pattern. The slightly higher cyan layer densities reflect a lowering of the NIR spectral reflectance which is in agreement with the underlying hypothesis tested in this study.

The images of successfully attacked trees had a significantly lower magenta/yellow ratio than either images of healthy trees or pitched-out trees (Table V, Fig. 7). The lowering of the ratio towards a value of 1.0 where the reflectance of the two spectral regions would be equal indicates a change in the normal reflectance of the green and red spectral regions. This may be caused by a decrease in the green reflectance and an increase in the red reflectance. There was no significant difference between healthy and successfully attacked trees in either of the individual dye layers concerned in this ratio (Table V) and their confidence intervals overlap extensively (Fig. 6). However, there must be a consistent relationship to produce significantly differing ratios. This indicates that the higher values of the yellow dye layer (lower green reflectance) were from the same successfully attacked tree images that had a lower magenta dye layer density (higher red reflectance). The ratios represent a measure of reflectance patterns showing how the change in reflectance of one spectral region is related to the change in the reflectance of another.

The shifting of green and red reflectance and the above mentioned slight decreasing of NIR reflectance explain the orangish hue of the images of successfully attacked trees (Fig. 9). The red reflectance increase may have been a result of the chlorophyll beginning to break down, unmasking the reflectance from carotenoids and anthocyanins. This is a preliminary step to the all-red appearing one-year-old attacked trees, producing a colour on CIR film intermediate between the magenta colour of healthy foliage and the yellow colour of red dead foliage. This slight change in green colour was not noticed just prior to the photographic mission, so the visual change must have been slight.

Although the sample sizes in this study were relatively small (Table IV), significant differences in reflectance as measured by film dye layer density were found to exist between healthy and attacked tree images. Finding specific spectral signatures unique to each damage class would allow computer-assisted discrimination between classes based on multispectral data. To determine if this is possible, stepwise discriminant analysis was employed using the generalized spectral data available from film dye layer analysis. Greater discrimination between classes could probably be achieved if a greater number of smaller discrete spectral bands were considered, as is possible with a multispectral scanner. The dye layer densities offer spectral reflectance data in only three broad spectral ranges.

3.2.2 Stepwise Discriminant Analysis

A stepwise discriminant analysis program, BMD P7M, was used to derive the best weighted linear combination of reflectance variables and ratios that would distinguish between the damage classes. Two analyses were done: one discriminating between all five classes and the other discriminating between only the three classes with green foliage. The second analysis was done as the red-topped and old-dead classes are readily separated from each other and other damage classes from the ground and from photographs.

Before any variables were selected in discriminant analysis, F values were calculated that were equivalent to those obtained from one-way analysis of variance for each variable over all the classes concerned. The first variable selected was that which had the highest F value and was therefore the variable which best discriminated between classes. After a variable had been selected, the variance associated with it was removed from the variance/covariance matrix, and the next best discriminating variable as indicated by the highest F value was then included in the discriminant function. This process was repeated until no further variation could be removed.

A classification function using the variables entered with coefficients calculated from known individuals is derived for each class. Each case is tested and allocated to a class by the classification functions. The values of the individual variables for each case are substituted in each of the functions (one classification function for each class). The function which yields the highest value determines which class that case is assigned to. In jack-knife classification, which was used in this study, the functions are re-evaluated excluding the case being considered. Thus each case is considered as an unknown giving a better measure of the power of the discriminant functions. As the class of each case was known, a percentage of correct classification was determined. A U-statistic is calculated for the analysis. A low U value indicates a high degree of successful discrimination. That is, the lower the U-statistic the more powerful the discriminant functions.

Table VI is a summary of the discriminant analysis with the 5 classes: old-dead, red-top, successful attack, pitched-out and unattacked healthy. The first variable entered was the cyan/magenta ratio. This represents the ratio of NIR to red reflectance. As seen from Figure 7 this serves to divide the five classes into two groups: trees without green foliage and trees with green appearing foliage. The low total correct discrimination is due to old-dead and red-topped trees being mutually misclassified and the three green-appearing classes being misclassified among themselves. The next variable, the cyan/yellow dye layer ratio, separated the old-dead from the red-topped

Table VI. Summary of Stepwise Discriminant Analysis of all Five Damage Classes

	Variable					Percent Classified Correct[1]					
Step	Entered	Removed	No. Included	U-Statistic	Approximate F-Statistic	Old Dead	Red Top	Successfully Attacked	Pitched-out	Healthy	Total
1	C/M[2]		1	0.1024	265.276	74.1	41.9	53.3	19.2	70.4	51.6
2	C/Y		2	0.0358	128.428	96.3	80.6	53.3	73.1	63.0	75.4
3	M/Y		3	0.0298	72.763	92.6	83.9	66.7	53.8	44.4	69.0
4	M		4	0.0245	53.468	92.6	83.9	60.0	69.2	48.1	72.2
5	C		5	0.0202	43.627	92.6	83.9	60.0	73.1	51.9	73.8

1 Jack-kinfe classification

2 M = Magenta dye layer (red sensitive)

C = Cyan dye layer (NIR sensitive)

C/M = Cyan to Magenta ratio

C/Y = Cyan to Yellow ratio

M/Y = Magenta to Yellow ratio

trees while still leaving some confusion among the green-appearing classes. The remaining three variables included in the final discriminant function serve primarily to discriminate between the three green-appearing classes. The magenta to yellow dye layer ratio (green to red spectral reflectance ratio) was entered at the third step. As mentioned in the section dealing with one-way analysis of variance, this ratio separated the successfully attacked trees from the other two green categories. With this variable included, 66.7 percent of the successfully attacked trees were assigned to the correct damage class. Discrimination success of the old-dead and red-topped trees remained high and the overall correct classification dropped slightly as there was confusion between the pitched-out and healthy trees. The addition of the final two variables (magenta and cyan dye layer densities) served to increase the discrimination between pitched-out and healthy trees while decreasing the correct classification of successfully attacked trees to 60 percent. This decrease represents the further misclassification of one tree. As the purpose of the analysis was to discriminate between successfully attacked trees and other green-appearing classes the inclusion of the last two variables serves no purpose even though the overall successful discriminations was improved. The classification functions for all five damage classes which gave the best separation of successfully attacked trees are shown in Table VII.

Significant differences based on the discriminant functions were found between all five groups. The greatest differences exist between the discoloured classes and the green-appearing classes. This is consistent with the appearance of the two groups on the photographs (Figs. 8, 9). Significant differences

Table VII Classification functions giving maximum separation of successfully attacked trees (66.7% correctly classified) when all 5 damage classes used in the analysis.

	coefficients for group				
Variable	old-dead	red-tops	successful attack	pitch-out	healthy
M/Y[1]	1193.240	1218.685	1219.694	1265.199	1262.817
C/M	1369.481	1442.803	1361.470	1392.511	1394.387
C/Y	-1256.544	-1368.426	-1327.085	-1356.570	-1368.716
Constant	-666.425	-663.982	-629.865	-678.460	-669.976

1

M/Y = Magenta/Yellow dye layer ratio

C/M = Cyan/Magenta dye layer ratio

C/Y = Cyan/Yellow dye layer ratio

also exist between all three classes with green foliage. The discriminant analysis considers and combines all the information from all included variables between all classes.

A summary of the discriminant analysis for the three green-appearing classes (successfully attacked, pitched-out and healthy) is shown in Table VIII. In this case the first variable selected was the magenta to yellow dye layer ratio. This variable served primarily to correctly classify 66.7 percent of the successfully attacked trees. This was the same maximum separation of successfully attacked trees as was found in the analysis of all five groups. Table IX shows the classification functions using this variable which yielded the 66.7 percent correct classification of successfully attacked trees. The remainder of the trees in the other classes were poorly identified producing an overall successful classification percentage of 45.6. The addition of further variables to the function improved the classification of the other classes while again reducing the correct classification of successfully attacked trees to 60.0 percent. The final overall successful classification was 66.2 percent. F-test comparisons between the three green-foliaged damage classes based on the final three variables included in the discriminant functions showed significant differences between all three groups. The greatest difference was found to be between the successfully attacked trees and the remaining two classes.

Successful discriminant analysis depends upon each class having a unique reflectance pattern. Variation exists within each class. In the case of successfully attacked trees the degree of change in reflectance may depend upon the degree of infection by the beetle/fungus complex. Trees with more attacks

Table VIII. Summary of Stepwise Discriminant Analysis of Three Damage Classes with Green Foliage

Variable						Percent Classified Correct[1]			
Step	Entered	Removed	No. Included	U-Statistic	Approximate F-Statistic	Successfully Attacked	Pitched-Out	Healthy	Total
1	M/Y[2]		1	0.7522	10.706	66.7	53.8	25.9	45.6
2	C/Y		2	0.5868	9.775	60.0	73.1	48.1	60.3
3	M		3	0.5430	7.948	60.0	76.9	51.9	63.2
4	C		4	0.4879	6.691	60.0	80.8	51.9	64.7
5		M/Y	3	0.4940	8.879	60.0	80.8	55.6	66.2

1 Jack-knife classification

2 M = Magenta dye layer (red sensitive)

C = Cyan dye layer (NIR sensitive)

C/Y = Cyan to Yellow ratio

M/Y = Magenta to Yellow ratio

Table IX. Classification functions giving maximum separation of successfully attacked trees (66.7% correctly classified) when only the three green-appearing classes were used in the analysis.

Variable	Coefficients for Group		
	Successful Attack	Pitch-Out	Healthy
M/Y[1]	226.029	247.984	249.993
Constant	-116.599	-140.127	-134.587

1 M/Y = Magenta/Yellow dye layer ratio

may degenerate faster than those trees with few attacks. This may be related to the rate of spread of the blue stain fungus through the sapwood. The more innoculations by attacking beetles the faster the sapwood becomes completely colonized and the faster the reflectance pattern degenerates from the normal pattern. Also, site differences may affect the speed of colonization. Time of attack is probably not a factor as the population of Douglas-fir beetles emerges from the hosts and attacks new trees over a short period of time. Even with this additional possible source of variation, significant differences were found between the groups.

Discriminant analysis of these tree classes has shown differences in reflectance patterns in each of the classes. Discriminant analysis on dye-layer density data shows promise as an aid to damage assessment from aerial photographs or other imagery. It is speculated that measurements from a greater number of narrow spectral regions, as is possible with a multispectral scanner, may provide better separation of damage classes.

3.3 Girdled Trees

The five trees girdled in late July, 1979 prior to the photographic flight were intended to serve as simulated successfully attacked trees although the effect of the fungus was not properly reproduced. Densitometric readings on the foliar reflectance of these artifically stressed trees were to have served as comparisons with readings taken from attacked trees. It was hoped that these trees would provide further infomration on the reflectance changes occurring in stressed trees. Density data were not obtained for these trees since the plot was not covered by the air photos.

These trees were observed during the final ground check in January, 1980. They still had healthy appearing green foliage which was in contrast to the successfully beetle attacked trees whose foliage had changed to a yellow colour. Although the phloem had been severed and the sapwood partially severed, required nutrients were still available to the foliage through the remaining sapwood and these trees may continue to live indefinitely due to root grafting with surrounding healthy Douglas-fir.

The change in foliage colour in the successfully attacked trees indicates that the sapwood had been completely colonized by the blue-staining fungi associated with the Douglas-fir beetle. Death of trees attacked by the Douglas-fir beetle can therefore be attributed primarily to the successful colonization of the sapwood by the fungus. If this is the case, the main role of the insect is that of a vector for the fungus which not only causes the death of the tree but also protects its vector by blocking resin canals, thereby ensuring successful beetle broods to act as vectors in the next year. Because of the importance of the fungus, the rate of foliar colour change may be related to the rate of development of the fungus rather than to the development rate of the beetle larvae. To predict when foliar colour change will occur it will be necessary to determine the biological requirements of the fungus.

Further research should be conducted to determine when reflectance changes occur in relation to the degree of colonization of the sapwood by the fungus. In this study, a slight foliage reflectance change of unknown value occurred approximately three months after initial attack by the beetle and introduction of the fungus. Some changes in reflectance may occur prior to this visual change. Trees could be girdled (completely severing the sapwood) at weekly intervals and a single photographic flight using both colour and CIR films could be made after several such treatments which would include all such treated trees as well as untreated trees. The time progression of reflectance changes could then be determined which would aid in determining when beetle survey flights should be made to detect the first changes in spectral reflectance patterns. Additionally, sets of trees could be girdled to varying depths of the sapwood and then photographed. Analysis of the dye layer densities of these images may give some indication as to the progression of reflectance changes in relation to the amount of active sapwood available for nutrient transport.

4. CONCLUSIONS

The present study demonstrated that Douglas-fir trees successfully attacked by the Douglas-fir beetle could be detected on colour infra-red photographs prior to a visual foliage colour change. Such detection depended upon a change in the amount of reflected NIR light prior to any change in the visual spectral regions. This change in the NIR reflectance produced a change in the density of the cyan dye layer of the film. Slight changes, after the first stages of insect attack, were not apparent visually from the ground, but densitometric analysis of film dye layer densities showed the changes occurring. Departures from the dye layer densities of normal trees signify physiological stress in the trees, possibly caused by the activity of the Douglas-fir beetle/blue stain fungus complex.

Significant differences were found in the dye layer densities between healthy and attacked trees (Table V). The most significant differences were found when ratios of dye layer densities were compared. Ratios have much smaller variances than the single dye layer densities and provide a measure of the reflectance pattern in trees showing how one spectral region interacts with another.

Discriminant analysis determined the optimum combination of variables that correctly classified individual cases to their proper class. This analysis made use of the unique spectral qualities associated with each damage class. Highly successful discrimination was achieved when the classes are vastly different. Such was the case when old-dead and red-topped trees are compared to the green-appearing damage classes. Poorer discrimination occurred when the differences between classes were not so extreme. In such instances a larger number of samples may help to define the classification functions for each class. However, even with the limited number of samples used in this study nearly 67 percent of the successfully attacked trees were classified correctly, indicating that these trees do have a unique spectral signature.

Discriminant analysis shows promise in distinguishing damage types from spectral reflectance data.

In this study the significantly different magenta dye layer to yellow dye layer density ratio (ratio of red to green reflectance) found in the successfully attacked trees indicated that some slight visual colour change had already occurred at the time the photographs were taken. Although the difference was not noted from the ground immediately prior to the photographic mission, this change was possibly an intermediate step between the initial change in NIR reflectance and the visual change apparent in straw-coloured trees. Further experiments should be carried out to determine the earliest possible time after insect attack that differences can be found in the dye layer densities, especially the cyan dye layer which is responsive to NIR reflectance. This time period will probably be variable from year to year depending on the seasonal temperature as it affects the growth and spread of the blue stain fungus. The rate of colonization of the sapwood by the fungus should also be studied under a variety of temperature regimes. Initial photographic detection flights could then be carried out after a pre-determined number of day-degrees since initial beetle attack. Chemical analysis of foliage from healthy and successfully attacked trees should also be carried out to determine the physiological changes occurring which influence the changes in reflectance patterns.

Determination of the smallest photograph scale necessary for the detection of the first reflectance change is also necessary. A scale of 1:1100, as was used in this study, is too large to be practical for insect surveys except as one of the final stages in a multi-stage sampling regime. A small scale is necessary if this technique is to be used in the future for cost effective insect-damage surveys. Larger scales may be used in high-value, high-risk stands where expense of survey is less of a factor.

This technique may never identify all the infested trees in a stand. However, because Douglas-fir beetle infested trees tend to occur in small clumps, the correct identification of one tree will lead to the identification of others when the area is ground checked. This technique should provide starting points for the ground cruises allowing more optimal allocation of resources.

Although this study concerned itself with Douglas-fir beetle detection, all bark beetles of the genus Dendroctonus behave in a similar fashion. Also, all members of this genus which are economically important have associated blue stain fungi. Because of this, this technique may be used in the detection of other bark beetle caused damage. In the case of the mountain pine beetle, detection of newly attacked trees from the air months prior to a foliar colour change would greatly improve the possibility of controlling this insect and avoiding widespread epidemics such as are now in progress in British Columbia.

5. LITERATURE CITED

Alger, L.A., P.J. Egan and H.J. Heikkenen. 1978. Previsual Detection of Stressed Loblolly Pine (Pinus taeda L.). Symp. Rem. Sens. Veg. Dam. Assess.:65-72.

Amman, G.D., M.D. McGregor, D.B. Cahill and W.H. Klein. 1977. Guidelines for Reducing Losses of Lodgepole Pine to the Mountain Pine Beetle in Unmanaged Stands in the Rocky Mountains. U.S.D.A. For. Serv. Gen. Tech. Rept. INT-36. 19pp.

Arnberg, W., L. Wastenson and B. Lekander. 1973. Use of Aerial Photographs for Early Detection of Bark Beetle Infestations of Spruce. Ambio 2: 77-83.

Atkins, M.D. and L.H. McMullen. 1958. Selection of Host Material by the Douglas-fir Beetle. Bi-Mon. Prog. Rept. 14:3.

Atkins, M.D. and L.H. McMullen. 1960. On Certain Factors Influencing Douglas-fir Beetle Populations. Special Paper. Proc. 5th World For. Cong.: 857-859.

Belluschi, P.G., N.E. Johnson and H.J. Heikkenen. 1965. Douglas-fir Defects Caused by the Douglas-fir Beetle. Jour. For. 63:252-256.

Belluschi, P.G. and N.E. Johnson. 1969. The Rate of Crown Fade of Trees Killed by the Douglas-fir Beetle in Southwestern Oregon. Jour. For. 67:30-32.

Benson, M.L. and W.G. Sims. 1967. False-Color Film Fails in Practice. Jour. For. 65:904.

Brown, H.D. 1971 Declining Loblolly Pine Not Reliably Detected with Aerial Color Film. 3rd Bien. Wrkshp. Col. Aer. Photog. in the Plnt. Sci. and Related Fields:246-254.

Ciesla, W.M. 1977. Color vs. Color IR Photos for Forest Insect Surveys. 6th Bien. Wrkshp. Aer. Col. Photog. in the Plnt. Sci. and Related Fields:31-42.

Ciesla, W.M., J.C. Bell Jr. and J.W. Curlin. 1967. Color Photos and the Southern Pine Beetle. Photogram. Eng. 33:883-888.

Cottrell, C.B., L.S. Unger and R.L. Fiddick. 1979. Timber Killed by Insects in British Columbia, 1971-1975. Environ. Can., Can. For. Serv. Rept. BC-X-189. 31pp.

Dyer, E.D.A. and D.W. Taylor. 1971. Spruce Beetle Brood Production in Logging Slash and Windthrown Trees in British Columbia. Environ. Can., Can. For. Serv. Info. Rept. BC-X-62. 18pp.

Dyer, E.D.A. and C.M. Lawko. 1978. Effect of Seudenol on Spruce Beetle and Douglas-fir Beetle Aggregation. Bi-Mon. Res. Notes 34:30-32.

Fox, D.J. and K.E. Guire. 1976. Documentation for MIDAS. 3rd Ed. Statistical Research Laboratory, Univ. of Michigan. 203pp.

Fritz, N.L. 1967. Optimum Methods for Using Infrared-Sensitive Color Films. Photogram. Eng. 33:1128-1138.

Furniss, M.M. 1962. Infestation Patterns of Douglas-fir Beetle in Standing and Windthrown Trees in Southern Idaho. Jour. Econ. Ent. 55:486-491.

Gausman, H.W. 1977. Reflectance of Leaf Components. Rem. Sens. of Envir. 6:1-9.

Harris, J.W.E., A.F. Dawson and R.G. Brown. 1978. Detecting Windthrow, Potential Foci for Bark Beetle Infestation, by Simple Aerial Photographic Techniques. Bi-Mon. Res. Notes 34:29.

Harris, J.W.E. and A.F. Dawson. 1979. Evaluation of Aerial Forest Pest Damage Survey Techniques in British Columbia. Envir. Can., Can. For. Serv. Info. Rept. BC-X-198. 22pp.

Hedden, R.L. and R.I. Gara. 1976. Spatial Attack Pattern of a Western Washington Douglas-fir Beetle Population. For. Sci. 22:100-102.

Heller, R.C. 1968. Previsual Detection of Ponderosa Pine Trees Dying From Bark Beetle Attack. Proc. 5th Symp. Rem. Sens. of Envir.:387-434.

Heller, R.C. 1971. Detection and Characterization of Stress Symptoms in Forest Vegetation. Proc. Int. Wrkshp. Earth Res. Surv. Syst. Vol II: 108-122.

Heller, R.C., R.C. Aldrich and F.W. Bailey. 1959. An Evaluation of Aerial Photography for Detecting Southern Pine Beetle Damage. Photogram. Eng. 25:595-606.

Heller, R.C. and J.F. Wear. 1969. Sampling Forest Insect Epidemics with Color Films. 6th Symp. on Rem. Sens. of the Envir.:1157-1167.

Hopping, R. 1929. The Control of Bark Beetle Outbreaks in British Columbia. Can. Dept. Agric. Ent. Br. Circ. No. 15. 15pp.

Jennrich, R. and P. Sampson. 1977. P7M Stepwise Discriminant Analysis. In BMDP Biomedical Computer Programs, M.B. Brown (Ed.). pp. 711-36.

Klein, W.H. 1973. Beetle-Killed Pine Estimates. Photogram Eng. 39:385-388.

Knipling, E.B. 1967. Physical and Physiological Basis for Differences in Reflectance of Healthy and Diseased Plants. Proc. Wrkshp. on Infrared Col. Photog. in Plnt. Sci. Flo. Dept. Agric., Div. Plant Indus., Winterhaven, Fla. 24pp.

Kodak. 1971. Kodak Data for Aerial Photography. Eastman Kodak Co., Kodak Publ. No. M-29. 80pp.

Lejeune, R.R., L.H. McMullen and M.D. Atkins. 1961. The Influence of Logging on Douglas-fir Beetle Populations. For. Chron. 37:308-314.

Lillesand, T.M., P.D. Manion and B.B. Eav. 1978. Quantification of Urban Tree Stress Through Microdensitometric Analysis of Aerial Photography. St. Univ. New York, Col. Envir. Sci. and For., Syracuse. 57pp.

Lorio, P.L. and J.D. Hodges. 1977. Tree Water Status Affects Induced Southern Pine Beetle Attack and Brood Production. U.S.D.A. For. Serv. Res. Pap. SO-135. 7pp.

Mahoney, R.L. 1978. Lodgepole Pine/Mountain Pine Beetle Risk Classification Methods and Their Application. Proc. Symp. on Theory and Practice of Mountain Pine Beetle Management in Lodgepole Pine Forests:106-113.

Meyer, M.P. and D.W. French. 1967. Detection of Diseased Trees. Photogram. Eng. 37:1035-1040.

McGugan, B.M. 1956. The Canadian Forest Insect Survey. Proc. Tenth Int. Cong. Entomol. 4:219-231.

McMullen, L.H. and M.D. Atkins. 1962. On the Flight and Host Selection of the Douglas-fir Beetle, Dendroctonus pseudotsugae Hopk. (Coleoptera; Scolytidae). Can. Ent. 94:1309-1325.

McMullen, L.H. 1977. Douglas-fir Beetle in British Columbia. Environ. Can., Can. For. Serv. FPL. 14. 6pp.

Murtha, P.A. 1968. Near-Infrared Detection of Simulated Animal Damage on Conifers. Ph.D. Thesis, Cornell Univ. 85pp.

Murtha, P.A. 1972. A Guide to Air Photo Interpretation of Forest Damage in Canada. Envir. Can., Can. For. Serv. Publ. 1292. 62pp.

Murtha, P.A. 1978. Remote Sensing and Vegetation Damage: A Theory for Detection and Assessment. Photogram. Eng. 44:1147-1158.

Murtha, P.A. and L.S. Hamilton. 1969. Detection of Simulated Damage on Conifers Using Near Infrared Film. Jour. For., Nov., 1969:827-829.

Olson, C.E. Jr., W.G. Rohde and J.M. Ward. 1970. Remote Sensing of Changes in Morphology and Physiology of Trees Under Stress. Ann. Prog. Rept. for Earth Resources Survey Prog., Off. of Space Sciences and Applications, NASA. - Remote Sensing Applications in Forestry. 26pp.

Orr, L.W. 1954. The Role of Surveys in Forest Insect Control. Jour. For. 52:250-252.

Pitman, G.B. and J.P. Vite. 1970. Field Response of Dendroctonus pseudotsugae (Coleoptera: Scolytidae) to Synthetic Frontalin. Ann. Ent. Soc. Amer.

Pitman, G.B., R.H. Hedden and R.I. Gara. 1975. Synergistic Effects of Ethyl Alcohol on the Aggregation of Dendroctonus pseudotsugae (Col., Scolytidae) in Response to Pheromones. Z. ang. Ent. 78:203-208.

Rohde, W.G. 1971. Multispectral Enhancement of Disease in Forest Stands 3rd. Bien. Wrkshp. Col. Amer. Photog. in the Plnt. Sci.:131-143.

Rohde, W.G. and C.E. Olson, Jr. 1970. Detecting Tree Moisture Stress. Photogram. Eng. 36:561-566.

Rudinsky, J.A. 1966. Host Selection and Invasion by the Douglas-fir Beetle, Dendroctonus pseudotsugae Hopkins, in Coastal Douglas-fir Forests. Can. Ent. 98:98-111.

Rudinsky, J.A., L.C. Ryker, R.R. Michael, L.M. Libbey and M.E. Morgan. 1976. Sound Production in Scolytidae: Female Sonic Stimulus of Male Pheromone Release in Two Dendroctonus Beetles. J. Insect Physiol. 22(12):1675-1681.

Ryker, L.C., L.M. Libbey and J.A. Rudinsky. 1979. Comparison of Volatile Compounds and Stridulation Emitted by the Douglas-fir Beetle from Idaho and Western Oregon Populations. Envir. Ent. 8:789-798.

Safranyik. L., D.M. Shrimpton, H.W. Whitney. 1974. Management of Lodgepole Pine to Reduce Losses from the Mountain Pine Beetle. Environ. Can., Can. For. Serv. For. Tech. Rept. 1. 24pp.

Schmid, J.M. 1976. Temperatures, Growth, and Fall of Needles on Engelmann Spruce Infested by Spruce Beetles. U.S.D.A. For. Serv. Res. Note RM-331. 4pp.

Schmid, J.M. and R.H. Frye. 1976. Stand Ratings for Spruce Beetles. U.S.D.A. For. Serv. Res. Note RM-309. 4pp.

Sokal, R.R. and F.J. Rohlf. 1969. Biometry. W.H. Freeman and Co., San Francisco. 776pp.

Swaine, J.M. 1914. Forest Insect Conditions in British Columbia. A Preliminary Survey. Can. Dept. Agric. Div. of Entomol. Entomol. Bull. No. 7. 41pp.

Thomas, J.R., V.I. Myers, M.D. Heilman and C.L. Wiegand. 1966. Factors Affecting Light Reflectance of Cotton. Proc. 4th Symp. Rem. Sens. of Environ.:305-312.

Walters, J. 1956. Biology and Control of the Douglas-fir beetle in the Interior of British Columbia. Can. Dept. Agric. For. Biol. Div. Publ. 975. 11pp.

Wear, J.F., R.B. Pope and P.G. Lauterbach. 1964. Estimating Beetle-Killed Douglas-fir by Aerial Photo and Field Plots. Jour. For. 62:309-315.

Weber, F.P. 1965. Exploration of Changes in Reflected and Emitted Radiation Properties for Early Remote Detection of Tree Vigour Decline. M.Sc. Thesis. Univ. of Michigan, Sch. of Nat. Res. 101pp.

Weber, F.P. and F.C. Polcyn. 1972. Remote Sensing to Detect Stress in Forests. Photogram. Eng. 28:163-175.

Wert, S.L. and B. Roettgering. 1968. Douglas-fir Beetle Survey With Colour Photos. Photogram. Eng. 34:1243-1248.

Appendix I. Descriptive Statistics for all six variables in all five damage classes.

Yellow Dye Layer Density (Green Sensitive - 500 - 600nm)

Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.640 - 1.650	1.037	0.0532
1979 pitch-out	26	0.540 - 1.260	0.807	0.0324
1979 attack	15	0.680 - 1.580	1.061	0.0659
1978 attack	31	0.140 - 1.380	0.713	0.0374
old attack	27	0.100 - 1.220	0.696	0.0429
Total	126	0.100 - 1.650	0.840	0.0240

Magenta Dye Layer Density (Red Sensitive - 600 - 700nm)

Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.760 - 1.630	1.125	0.0473
1979 pitch-out	26	0.580 - 1.335	0.900	0.0309
1979 attack	15	0.755 - 1.500	1.074	0.0570
1978 attack	31	0.370 - 1.120	0.592	0.0301
old attack	27	0.390 - 1.100	0.687	0.0382
Total	126	0.370 - 1.630	0.848	0.0256

Cyan Dye Layer Density (NIR sensitive - 700 - 900nm)

Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.370 - 0.740	0.536	0.0216
1979 pitch-out	26	0.360 - 0.705	0.476	0.0199
1979 attack	15	0.380 - 0.895	0.597	0.0394
1978 attack	31	0.370 - 1.120	0.575	0.0272
old attack	27	0.480 - 1.140	0.742	0.0362
Total	126	0.360 - 1.140	0.582	0.0150

Magenta/Yellow Density Ratio (Red reflectance/Green reflectance)

Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.988 - 1.209	1.099	0.0132
1979 pitch-out	26	1.034 - 1.206	1.121	0.0100
1979 attack	15	0.873 - 1.206	1.022	0.0224
1978 attack	31	0.662 - 1.000	0.792	0.0133
old attack	27	0.848 - 1.022	0.935	0.00908
Total	126	0.662 - 1.209	0.984	0.0128

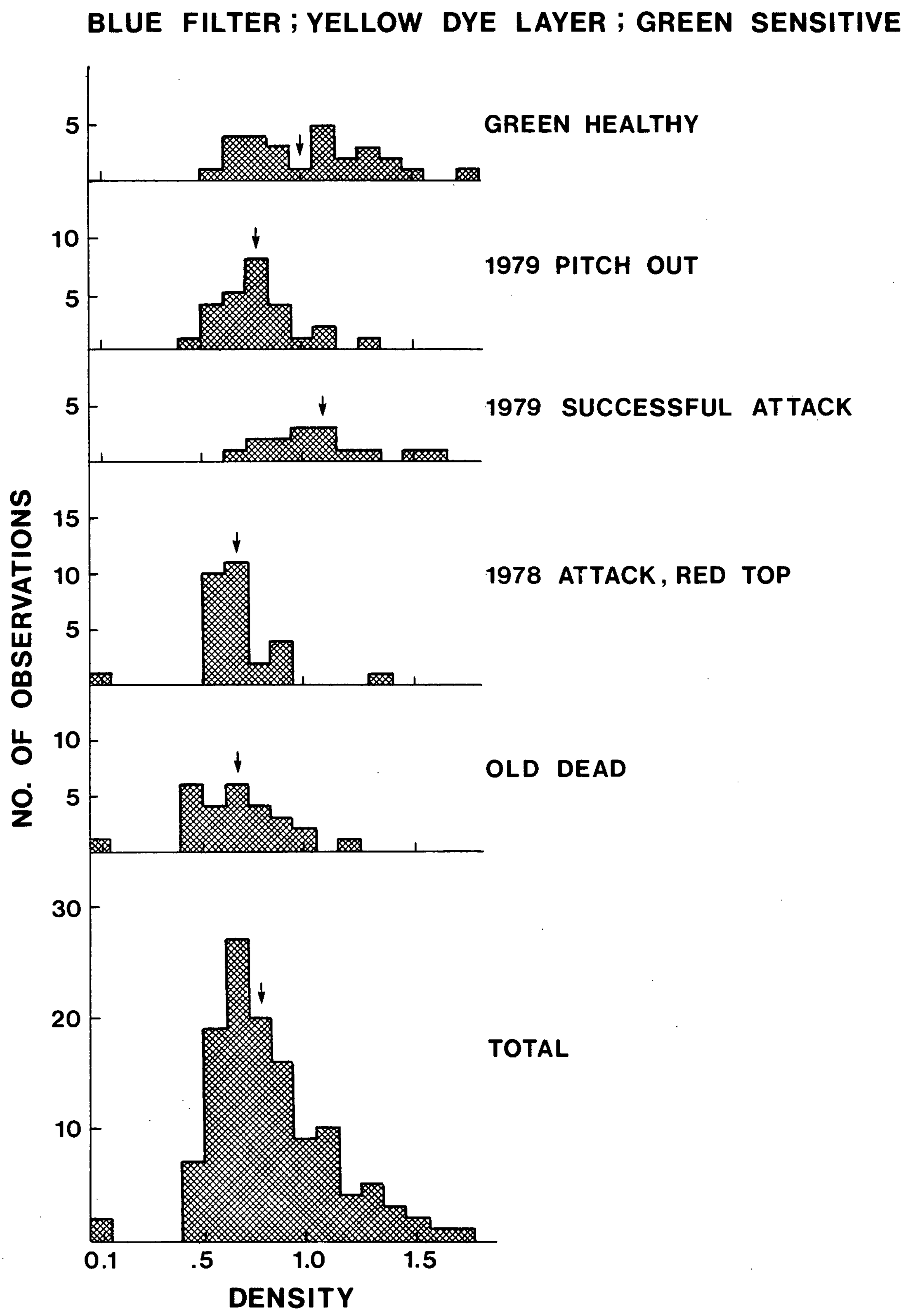
Cyan/Magenta Density Ratio (NIR reflectance/Red reflectance)

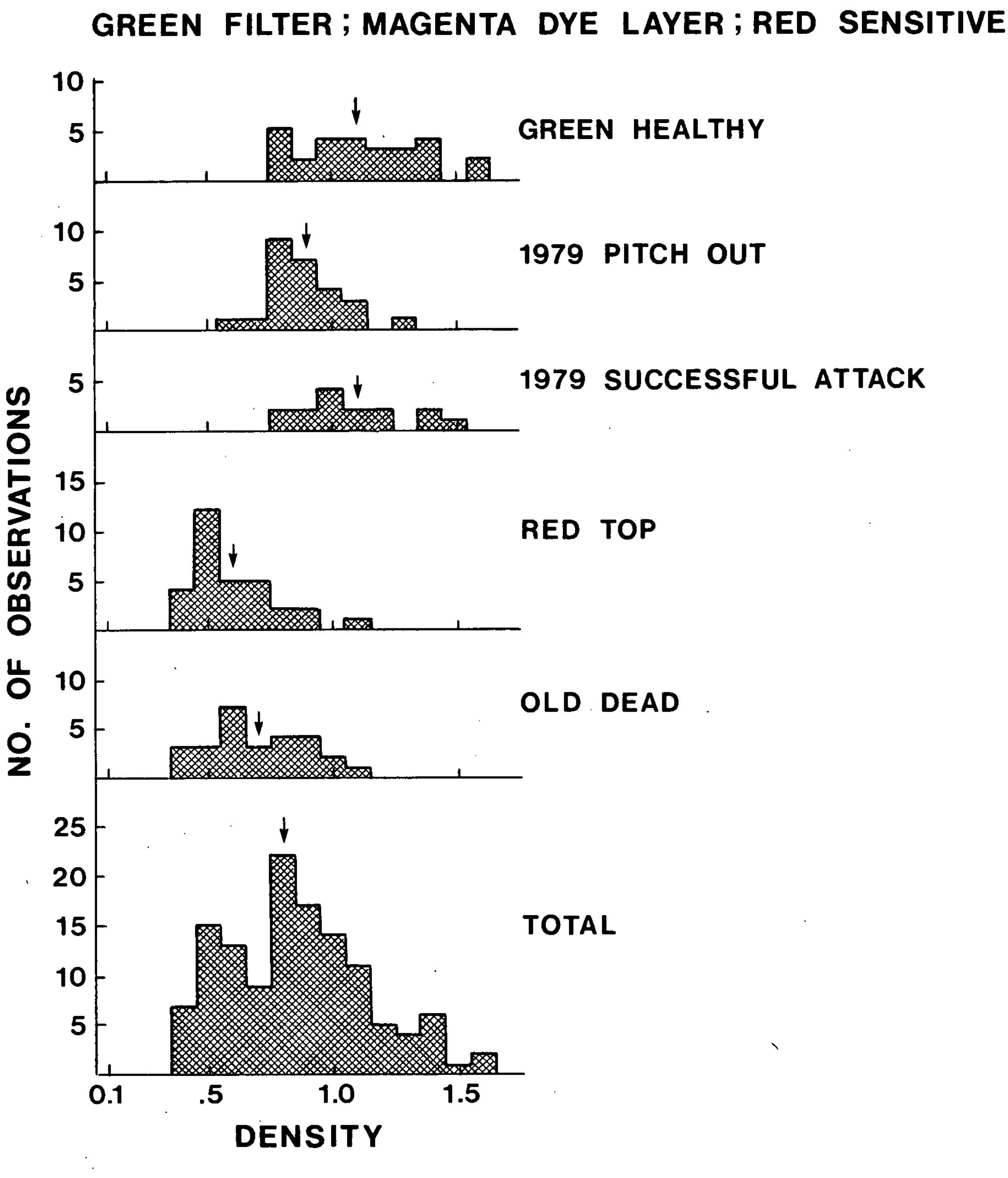
Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.389 - 0.627	0.480	0.0110
1979 pitch-out	26	0.430 - 0.690	0.529	0.0127
1979 attack	15	0.462 - 0.670	0.555	0.0195
1978 attack	31	0.677 - 1.137	0.988	0.0246
old attack	27	0.946 - 1.286	1.093	0.0152
Total	126	0.389 - 1.286	0.756	0.0248

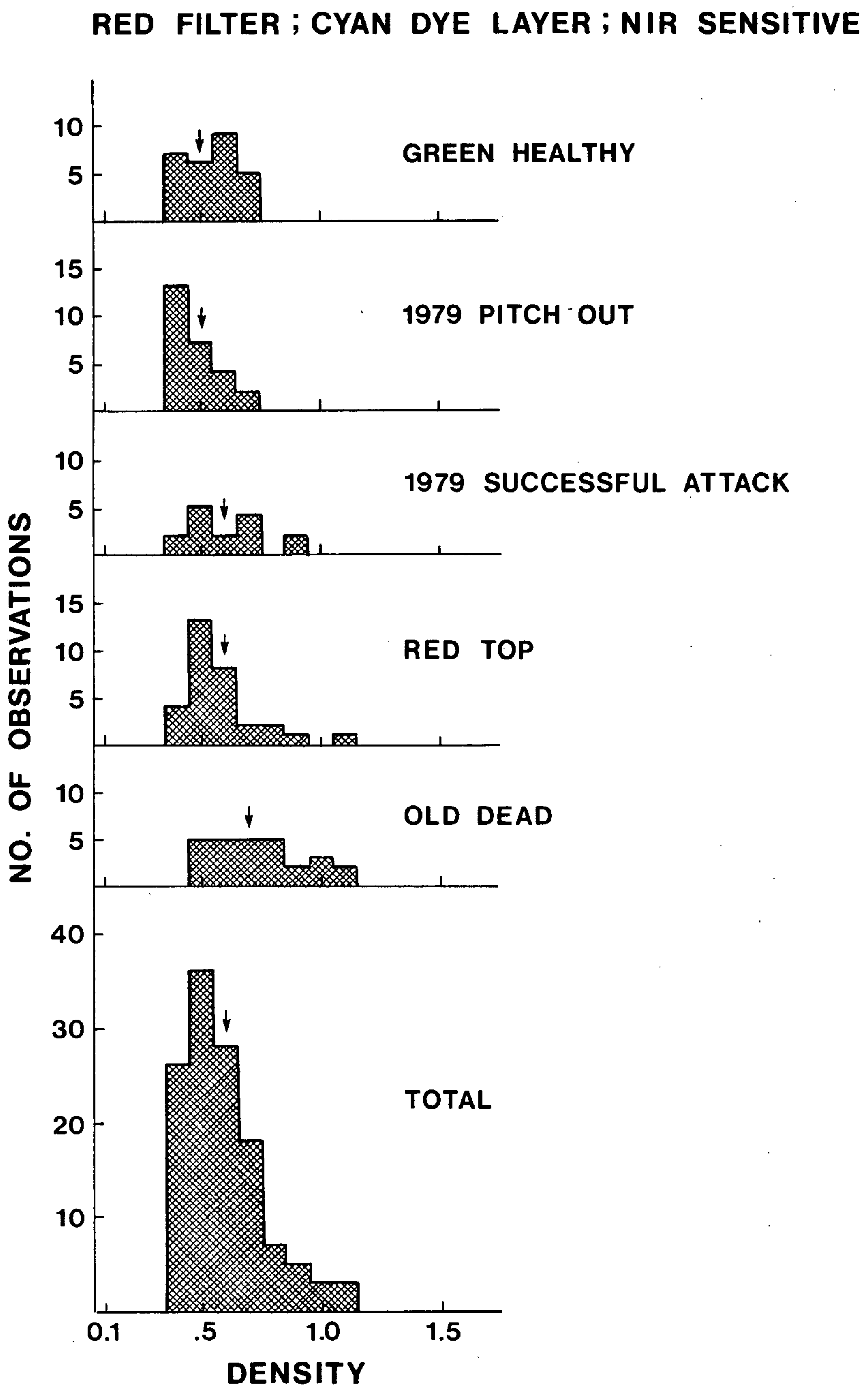
Cyan/Yellow Density Ratio (NIR reflectance/Green reflectance)

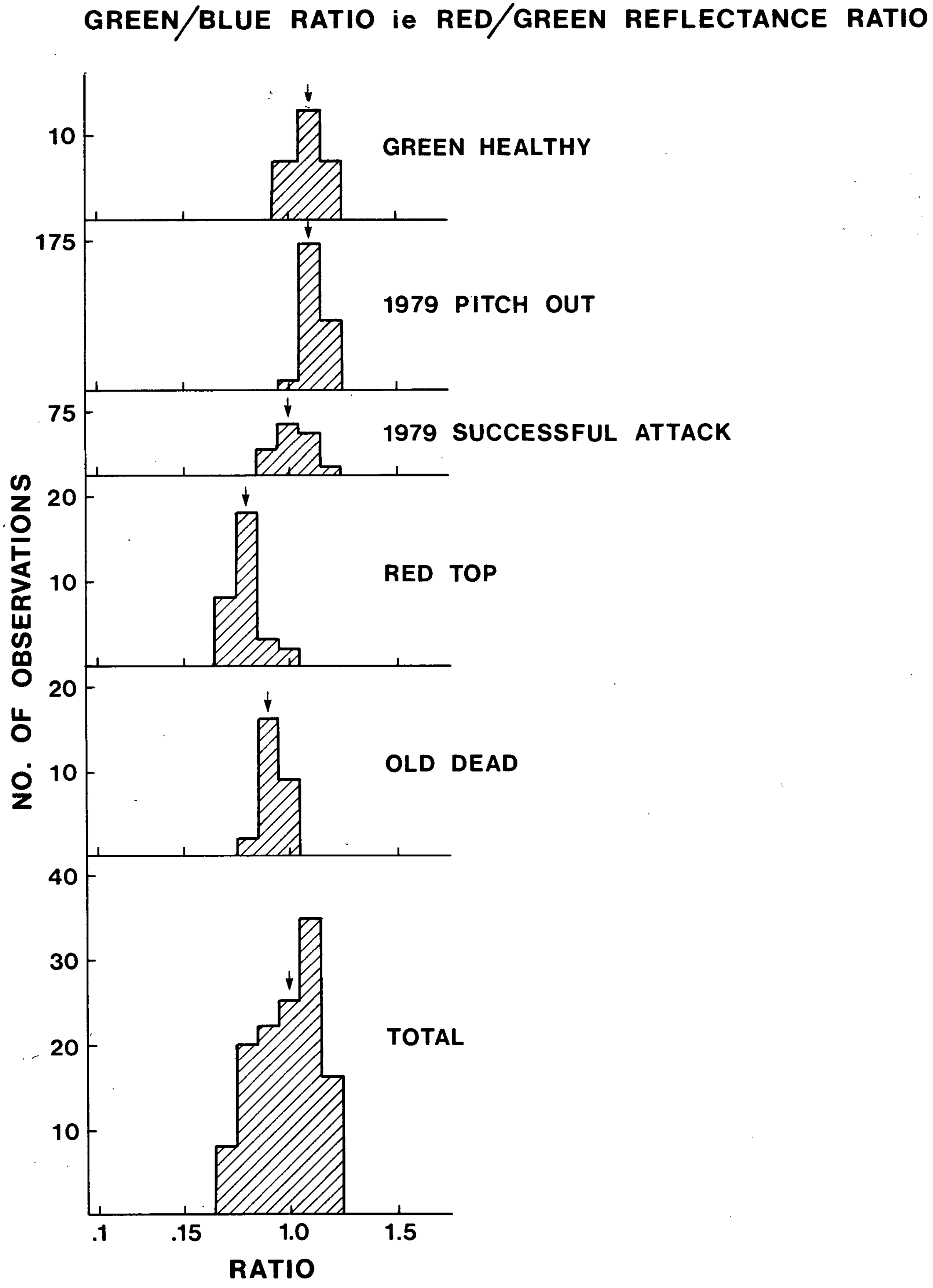
Damage class	n	range	$\bar{x}$	$S\bar{x}$
Healthy green	27	0.416 - 0.673	0.526	0.0116
1979 pitch-out	26	0.512 - 0.741	0.591	0.0109
1979 attack	15	0.485 - 0.639	0.562	0.0124
1978 attack	31	0.538 - 0.964	0.779	0.0200
old attack	27	0.894 - 1.182	1.021	0.0150
Total	126	0.416 - 1.182	0.712	0.0180

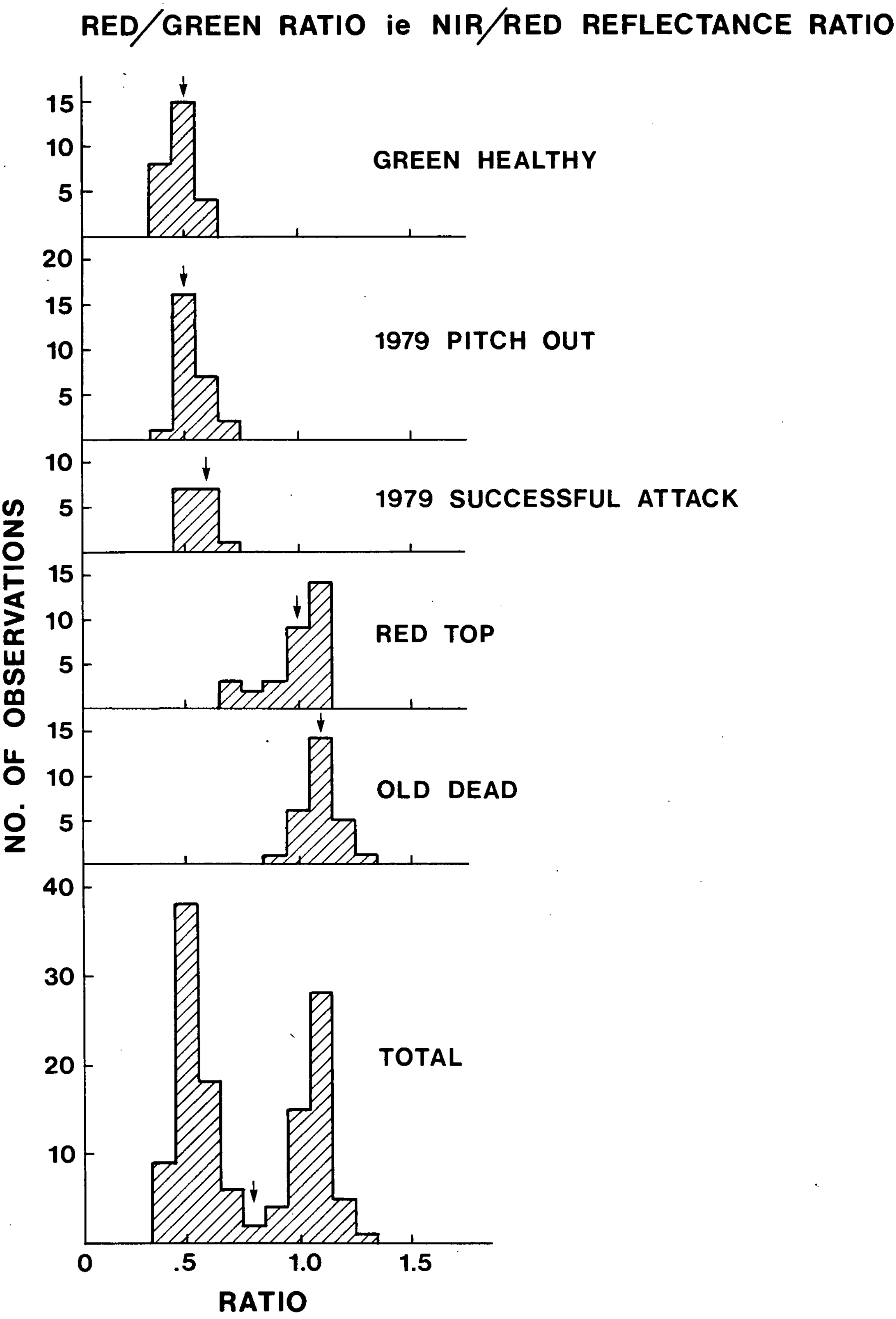
APPENDIX II. Histograms of all six variables in all five damage classes.

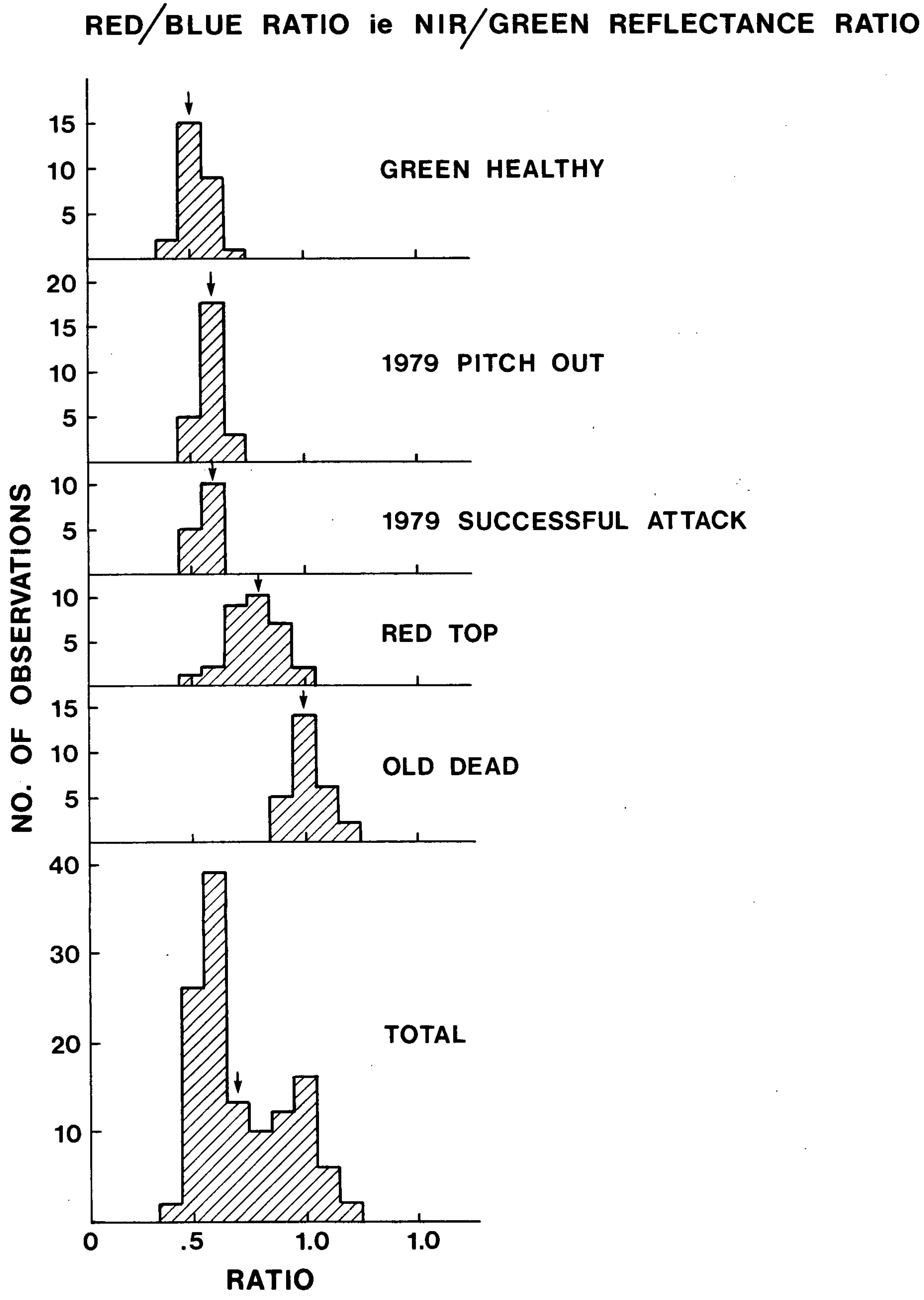

BLUE FILTER ; YELLOW DYE LAYER ; GREEN SENSITIVE
GREEN HEALTHY
1979 PITCH OUT
1979 SUCCESSFUL ATTACK
1978 ATTACK, RED TOP
OLD DEAD
TOTAL
NO. OF OBSERVATIONS
DENSITY
0.1
.5
1.0
1.5
5
10
15
20
30


GREEN FILTER ; MAGENTA DYE LAYER ; RED SENSITIVE
NO. OF OBSERVATIONS
GREEN HEALTHY
1979 PITCH OUT
1979 SUCCESSFUL ATTACK
RED TOP
OLD DEAD
TOTAL
0.1
.5
1.0
1.5
DENSITY


RED FILTER ; CYAN DYE LAYER ; NIR SENSITIVE
GREEN HEALTHY
1979 PITCH OUT
1979 SUCCESSFUL ATTACK
RED TOP
OLD DEAD
TOTAL
NO. OF OBSERVATIONS
5
10
15
20
30
40
0.1
.5
1.0
1.5
DENSITY


GREEN/BLUE RATIO ie RED/GREEN REFLECTANCE RATIO
NO. OF OBSERVATIONS
10
GREEN HEALTHY
175
1979 PITCH OUT
75
1979 SUCCESSFUL ATTACK
20
10
RED TOP
20
10
OLD DEAD
40
30
20
10
TOTAL
.1
.15
1.0
1.5
RATIO


RED/GREEN RATIO ie NIR/RED REFLECTANCE RATIO
NO. OF OBSERVATIONS
GREEN HEALTHY
1979 PITCH OUT
1979 SUCCESSFUL ATTACK
RED TOP
OLD DEAD
TOTAL
0
.5
1.0
1.5
RATIO
5
10
15
20
30
40


RED/BLUE RATIO ie NIR/GREEN REFLECTANCE RATIO
15
10
5
GREEN HEALTHY
20
15
10
5
1979 PITCH OUT
10
5
1979 SUCCESSFUL ATTACK
10
5
RED TOP
15
10
5
OLD DEAD
40
30
20
10
TOTAL
NO. OF OBSERVATIONS
0
.5
1.0
1.0
RATIO