Assessment of aerial photographs and multi-spectral scanner imagery for measuring mountain pine beetle damage

Pacific and Yukon Region — Information Report BC-X-333

P. Gimbarzevsky, A.F. Dawson and G.A. Van Sickle

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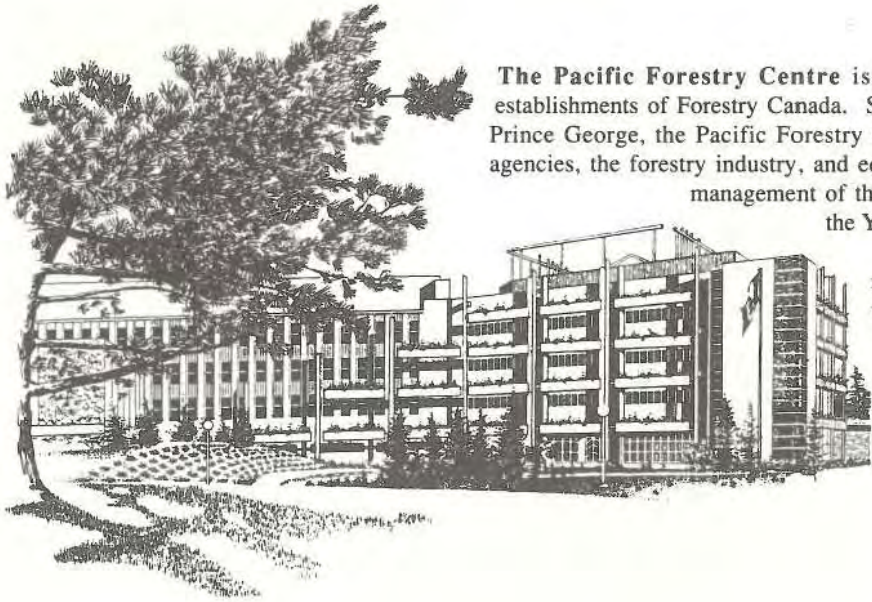

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The Pacific Forestry Centre undertakes research in response to the needs of the various managers of the forest resource. The results of this research are distributed in the form of scientific and technical reports and other publications.

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Cover: *conventional format (23 cm x 23 cm) color infrared aerial transparency. This photo was taken from an altitude of 9450 m above sea level, and the approximate scale is 1:56 000. This image was one of those used to assess mountain pine beetle damage near Gun Lake in British Columbia.*

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Contents

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Abstract

A survey of mountain pine beetle infestation in a 370-km^2 demonstration area was initiated as part of a damage appraisal program conducted by the Forest Insect and Disease Survey of Forestry Canada. The main objective of this study was to investigate the operational use of available remote sensing techniques for identification of beetle-killed forest stands, mapping their areal extent, and measurement of tree damage. Survey procedures involved the mapping of infested stands, acquisition of imagery, image analysis, and compilation of volume losses. The acquired imagery consisted of conventional normal color and color infrared aerial photography at scales of 1:56 000, 1:19 000, and 1:8000, supplementary 70-mm color photography of 32 4-ha photo plots at a scale of 1:6000, and 90 stereo pairs at an average scale of 1:1000, a series of 35-mm oblique color slides, and multi-spectral scanner digital data (airborne and satellite). The high-altitude (scale 1:56 000) color infrared aerial photography was used as a main sensor in a stereoscopic analysis of forest conditions. Infestations were delineated on color infrared transparencies and superimposed on 1:20 000 British Columbia Ministry of Forests cover type maps. The size of damaged areas was determined directly from the map for each of some 300 affected cover types. The intensity of infestation and volume losses were compiled from the analysis of photo plots and ground sampling data, and tabulated by map sheets and cover types. A total area mapped as damaged was 4673 ha, with an estimated volume loss of over 453 000 m^3 of lodgepole pine, averaging 97 m^3/ha. Damage maps were also compiled from digitally processed multi-spectral scanner imagery. They showed the infestation patterns generally comparable to those of high-altitude color infrared aerial photography, but the damaged areas appeared considerably larger. It was not possible to separate different levels of damage intensity on multi-spectral scanner imagery and a proper interpretation of forest conditions required frequent reference to conventional aerial photography. The procedures described in this report are illustrated with numerous color stereograms, oblique photographs, and multi-spectral scanner imagery.

Résumé

Une étude de l'infestation par le dendroctone du pin ponderosa d'une zone de démonstration de 370 km^2 a été effectuée dans le cadre d'un programme d'évaluation des dommages mené par le Relevé des insectes et des maladies des arbres de Forêts Canada. Le principal objectif de l'étude était de déterminer les possibilités d'utilisation des techniques disponibles de télédétection pour repérer les peuplements ravagés par l'insecte, pour cartographier leur étendue et pour mesurer les dommages subis par les arbres. Ces techniques comprenaient la cartograhie des peuplements infestés, l'acquisition d'images, l'analyse d'images et la compilation des pertes volumiques. L'imagerie acquise se composait de photographies aériennes standard en couleurs naturelles et infrarouges couleurs à échelles de 1/56 000, de 1/19 000 et de 1/8000, de photographies en couleurs 70 mm supplémentaires de 32 photoparcelles de 4 ha à échelle de 1/6000, de 90 stéréogrammes à échelle moyenne de 1/1000, d'une série de diapositives en couleurs obliques 35 mm, ainsi que de données numériques (aériennes et spatiales) de balayeur multispectral. Les photographies aériennes infrarouges couleurs de haute altitude (1/56 000) ont servi de base à une analyse stéréoscopique de l'état des forêts. Les infestations ont été délimitées sur des transparents infrarouges couleurs puis superposées sur des cartes 1/20 000 des types de couvert du ministère des Forêts de la Colombie-Britannique. L'étendue des zones ravagées a été déterminée directement à partir des cartes pour chacun des quelque 300 types de couvert atteints. L'intensité des infestations et les pertes volumiques ont été établies par analyse des photoparcelles et de données d'échantillonnage de terrain, puis calculées par feuilles et par type de couvert. La région ravagée cartographiée faisait au total 4673 ha; les pertes volumiques évaluées sont de plus de 453 000 m^3 pour le pin tordu, soit une moyenne de 97 m^3/ha. Des cartes d'endommagement ont aussi été compilées à partir de l'imagerie numérique d'un balayeur multispectral. Elles révèlent des infestations assez identiques à celles des photographies aériennes infrarouges couleurs de haute altitude, mais les zones endommagées semblent être beaucoup plus grandes. L'imagerie multispectrale n'a pas permis de faire la distinction entre les divers degrés d'endommagement; pour bien interpréter l'état des forêts, il a fallu consulter fréquemment des photographies aériennes ordinaires. Les techniques décrites dans le rapport sont illustrées de nombreux stéréogrammes, photographies obliques et l'images de balayeur multispectral, tous en couleurs.

1. Introduction

In western Canada, the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the prime enemy of pine forests. Since the mid-1970s this insect has been epidemic in British Columbia and has caused a large depletion of commercial timber. Aerial surveys conducted annually by the Forest Insect and Disease Survey of Forestry Canada indicate that in 1982 mountain pine beetle infestations occurred on over 290 000 ha and estimated volume losses were in excess of 15.7 million m^3 (Wood and Van Sickle 1983). More recent information on these infestations is provided by Wood *et al.* (1987).

Procedures available for appraisal of damage caused by the mountain pine beetle include direct visual observation, aerial photography, and multi-spectral scanner (MSS) imagery. Forest damage is manifested by changes in the morphology and physiology of living trees, and these changes alter the normal spectral reflectance pattern (Murtha 1972). Symptoms of damage are observable on color photographs because there is a discoloration of the normal green foliage to yellow, then red, then as the dead foliage fades and drops trees appear grey. This change of color is most obvious on large-scale photographs, where individual discolored trees may be recognized and counted. On small-scale photographs the presence of discolored trees within the forest canopy is revealed as a color pattern; this pattern is often very subtle, particularly with normal color film at high altitudes.

Direct visual observation is the oldest survey method. It involves the use of low-flying aircraft from which observers create a sketch-map of beetle-infested stands (Backman *et al.* 1978). With this method, forest stands that contain beetle-killed trees, aside from being delineated on topographic maps, are also described in terms of estimated damage intensity by percentage of host species attacked. Aerial sketch-maps, if complemented by 70-mm color photography, provide a quick overview of beetle-infested areas. Sketch-mapping remains the primary method for assessment of mountain pine beetle damage in British Columbia (Harris and Dawson 1979) and in Washington State (Backman *et al.* 1978).

Aerial photography, using color and color infrared film, is the most common sensor used in operational surveys of mountain pine beetle infestations. Several camera formats, scales, and image analysis techniques are presently used in the surveys of beetle-killed pine trees. In addition to conventional format (23 cm x 23 cm) and small-format (35 mm and 70 mm) aerial cameras, the panoramic (optical bar) camera and large-format (23 cm x 46 cm) frame camera have been successfully used, often in combination with other photographic systems, to obtain the required coverage and scale (Gimbarzevsky 1984). In most cases, interpretation methods are based on a visual examination of contact or enlarged color transparencies and prints, under 2X to 10X stereoscopic magnification. Although there is considerable experience with these various photographic systems, there has been little documentation of the differences and usefulness of various types of film and various photographic scales. A key objective of this study was to assess several photographic scales and film types used in photographic remote sensing today. Another objective was to determine if mountain pine beetle damage can be mapped from digital multi-spectral scanner (MSS) imagery.

There have been several previous tests to determine if it is possible to discriminate between healthy and beetle-killed forest stands using data from satellite and airborne multi-spectral scanners. These tests involved visual photographic techniques generated from digital tapes, and a computer-assisted analysis of digital data. Heller *et al.* (1974) reported that mountain pine beetle infestations could not be detected from Landsat data. However, Hall *et al.* (1974) were able to map three mortality classes of beetle-killed lodgepole pine from enlarged Landsat color composites. Buchman and Hall (1975) distinguished two damage classes (light and heavy) using machine-assisted analysis of digital tapes, and three damage classes (heavy, medium, and light) using visual interpretation of Landsat color composites enlarged to a scale of 1:80 000. This study presented the opportunity to complement previous tests by carrying out direct comparisons of visual observations (from ground checks and sketch-mapping from low-flying aircraft), a variety of film types and scales of aerial photography, and MSS imagery, all from the same study area.

1.1 Previous related work

Assessment of forest damage preceded most other forestry uses of remote sensing. The earliest records of aerial surveys to map insect damage in Canada date to the 1920s (Craig 1920). Some 50 years later, the Canadian Forestry Service produced a comprehensive guide to the recognition of forest damage on aerial photographs (Murtha 1972). The latter publication provided a framework for systematic interpretation of various types of tree damage on color and color infrared aerial photographs. It also assisted in the development of survey procedures for mapping the intensity of insect and disease infestations.

The successful application of remote sensing techniques for assessment of insect damage depends largely upon its operational efficiency and cost. There have been recent improvements in equipment, film, and interpretation techniques that provide a wide selection of survey designs. Recent advances in this field have been described by McHail *et al.* (1984), Mussakovski (1984), and Nixon *et al.* (1984).

Small-scale photography has been used to evaluate mountain pine beetle infestations. Although high-altitude photographic systems provide acceptable survey results for extensive areas of infestation, they have several disadvantages, such as high acquisition cost, unconventional film size, and a changing scale from the nadir point. Ciesla (1974) described the use of 1:126 000 color infrared aerial photographs for mapping color patterns of damaged forest stands; trees recently attacked by bark beetles registered as beige or yellow, and trees from which dead foliage had dropped registered as grey or grey-green. Harris (1972, 1974) reported that moderately light to severe damage caused by several forest pests, including the mountain pine beetle, was visible on normal color aerial photographs at scales of 1:50 000 to 1:160 000. Ciesla (1977) successfully used both color and color infrared films to estimate numbers of beetle-killed pine at scales as small as 1:174 000. Camera systems used for high-altitude aerial photography have been used in recent experiments by Ciesla and Klein (1978), Dillman (1982), Dillman *et al.* (1979, 1981), Klein (1982), Klein *et al.* (1982) and other investigators, with the goal of improving mountain pine beetle surveys in the western United States.

Color and color infrared large-scale photographs (1:6000 to 1:1000) have been used in multi-stage surveys for sampling damage intensity within infested areas that have been previously delineated on small and medium-scale photographs or by aerial sketch-mapping. Klein *et al.* (1978) reported a standard error of 8.2% for the estimated number of lodgepole pine trees killed by mountain pine beetle obtained from analyses of 1:6000 color aerial photographs on a pilot project in Idaho. In an estimate of ponderosa pine mortality in the Black Hills of South Dakota and Wyoming, Hostetler and Young (1979) used 1:6000 color photography for sampling the two most severe damage classes that had been sketch-mapped in a multi-stage survey. On the 1226 km^2 area sampled, there was a standard error of 4.2% for the estimate of the number of trees killed, and 7.2% for the estimate of volume loss. In British Columbia, Harris *et al.* (1982, 1983) used 1:5000 and 1:6000 normal color aerial photography for assessment of mountain pine beetle damage in the Flathead River Valley and near Gold Bridge-Clinton. The areas were sketch-mapped and beetle-killed pine were counted on photo-plots and correlated with ground sub-plots. Sampling error was 18.5% for the tree count and 38.9% for tree volume for the former area and 15% and 17% for the latter area.

For early detection of mountain pine beetle infestations, Hobbs (1983) analyzed four scales (1:1000, 1:2000, 1:3000 and 1:4000) of 70-mm color infrared positive transparencies. Analyses involved both visual and densitometric techniques. The distinction of healthy from attacked trees was achieved with an overall accuracy of 89% at a scale of 1:1000, 83% at 1:2000, 91% at 1:3000, and 85% at 1:4000.

1.2 Study area

The study area (Figure 1) was a 370-km^2 section in the Gun Lake area of the Bridge River valley of south-central British Columbia (NTS map 92-J/15) located in the Chilcotin Range of the Coast Mountains (Holland 1976). Located on a steep-sided valley that widens at the town of Goldbridge, the area contains pure and mixed stands of lodgepole pine that have been infested by the mountain pine beetle since 1974.

The history of mountain pine beetle infestations in the study area was extracted from aerial sketch-maps prepared by personnel of the Forest Insect and Disease Survey of Forestry Canada. The current outbreak is thought to have begun in 1974 and data mapped from 1976 to 1981 reveal a progressive annual increase in area of stands with dead lodgepole pine: 1700 ha in 1976; 2100 ha in 1977; 3000 ha in 1978; 3600 ha in 1979; 10 000 ha in 1980; and 19 700 ha in 1981 (Figure 2). Figure 2 was used as a guide to estimate the relative attack age and the proportion of recently killed lodgepole pine that might be expected in any given part of the study area. Areas attacked in 1979 and 1980 (mapped in 1980 and 1981) were classed as recent mortality, where red lodgepole pine was prevalent. Previously attacked areas from 1975 to 1978 (mapped 1976-1979) were classed as old mortality in which grey lodgepole pine was dominant.

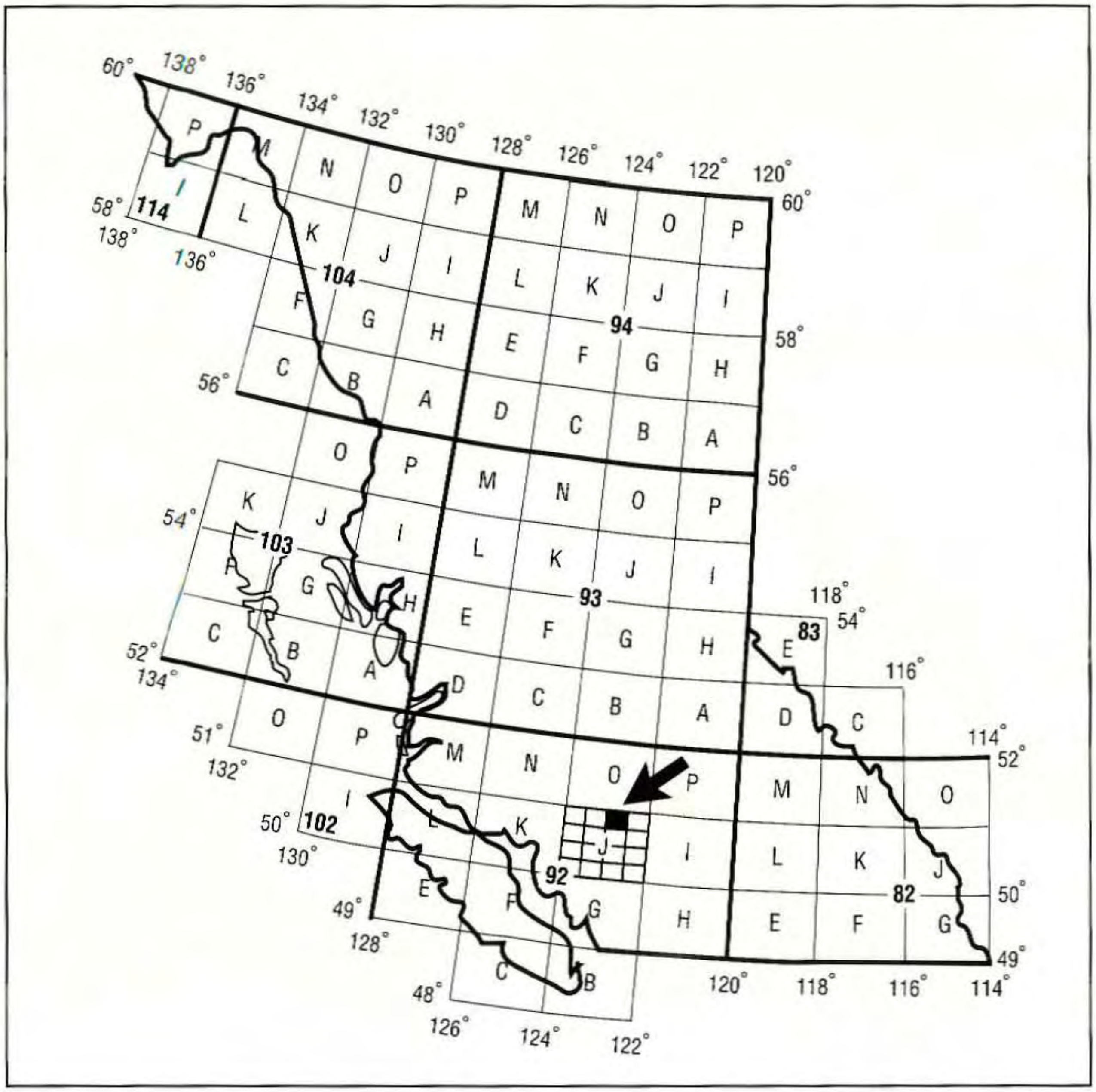

Figure 1. Location of study area

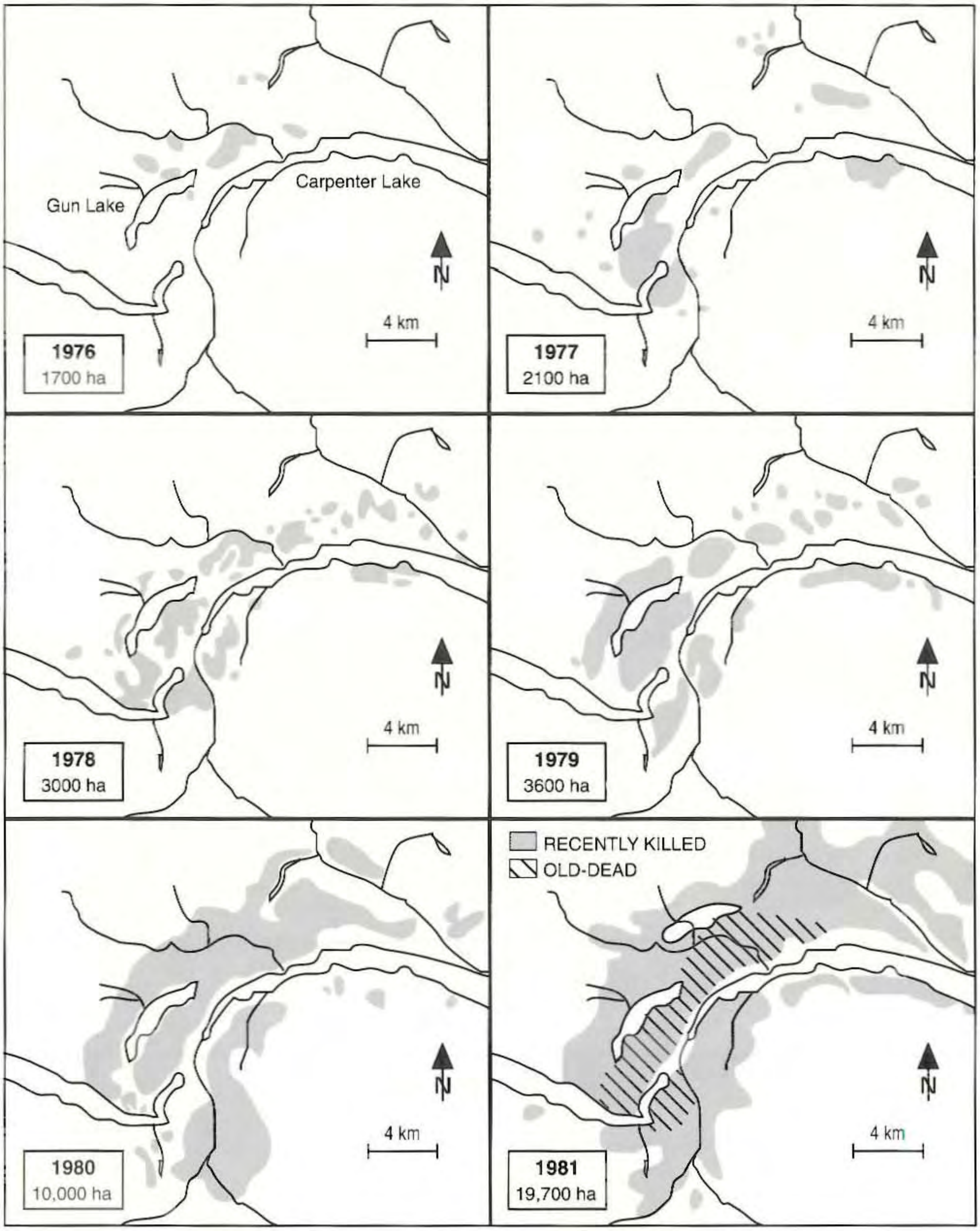

Figure 2. Aerial sketch mapping of mountain pine beetle infestations from 1976 to 1981

2. Methods

This study involved both remote sensing techniques and field observations, and included the following four major tasks: mapping of beetle-infested areas; the acquisition of imagery; image analysis; and compilation of damage losses.

2.1 Acquisition of imagery

Several types of imagery were used in this study: conventional aerial photography (23 cm x 23 cm) involving two kinds of film (normal color and color infrared) and three different scales; supplementary 70-mm aerial photography; oblique 35-mm color slides; and MSS imagery.

2.1.1 Conventional aerial photography

In cooperation with the Canada Centre for Remote Sensing (CCRS), coverage by color and color infrared aerial photography of conventional format (23 cm x 23 cm) and from an airborne 11-channel multi-spectral scanner was obtained on 11 and 12 August 1981. Two RC10 aerial cameras, with 152.12-mm lens cones and loaded with Aerocolor negative film (Type 2445) and Aerochrome infrared film (Type 2443) were exposed simultaneously along the pre-selected flight lines from three altitudes: 9450 m, 3810 m, and 2130 m above sea level. This provided imagery for the same area at the approximate scales of 1:56 000, 1:19 000, and 1:8000. The infrared color film was processed to positive transparencies, while normal color prints were obtained from the Aerocolor negatives.

Color transparencies and prints were analyzed under stereoscopic magnification that ranged from 2X to 8X. Transparencies were viewed by transmitted light on a light table and paper prints were viewed by reflected light. The color infrared film, as a rule, was processed to a positive and duplicate transparencies were produced for stereoscopic analysis. Theoretically, a transparent reproduction records the full range of useful densities from the original film, but in practice the relative amounts of different colors are often altered and the restoration of exact color balance requires complex readjustment with correction filters.

2.1.2 Supplementary 70-mm aerial photography

The supplementary large-scale photography for analysis of photo-plots was obtained in August and October 1981. Within the area sketch-mapped as damaged, 32 4-ha photo-plots established on a 2 km x 2 km grid were photographed from fixed-wing aircraft in August 1981 with a hand-held Hasselblad 70-mm camera using Kodak Vericolor II color negative film. Three or more frames were exposed to provide stereoscopic coverage of each 4-ha plot at an approximate scale of 1:6000 (Harris *et al.* 1983) (Figure 3).

In cooperation with the British Columbia Ministry of Forests, approximately 90 large-scale (1:1000) stereo-pairs were obtained with a 70-mm twin-camera system flown in October 1981. Two rolls of normal color film were processed to positive transparencies and separated into sets of left and right frames for stereoscopic viewing (Figure 4).

2.1.3 Oblique 35-mm color slides

A series of oblique 35-mm color slides were taken during the reconnaissance overflights to document damage levels and capture well defined landmarks that could be correlated with features on vertical photographs (Figure 5).

2.1.4 Multi-spectral scanner (MSS) imagery

The 11-channel airborne scanner was flown simultaneously with the RC10 two-camera system and MSS data were recorded on digital tapes (CCRS Tape No. AR0512-1119, Reels 1 to 16). Shortly after the flight was completed, the Canada Centre for Remote Sensing supplied a set of channel 9 reproductions on thermal sensitive silver-based paper showing the actual area that was covered by the photographic and MSS systems at each of three flight altitudes. The low-altitude (2130 m ASL) MSS printouts were used immediately for the selection of plots to be photographed by the 70-mm twin-camera system.

In addition to the airborne MSS imagery, the original Landsat data of 16 August 1981, on computer compatible tape, were also obtained for the study area.

2.2 Image analysis

2.2.1 Development of damage detection criteria

For development of damage detection criteria from color patterns, the 70-mm supplementary photography of photo-plots, oblique color slides taken during reconnaissance flights, aerial sketch maps, and ground observations all provided valuable aids for verification of interpreted stand conditions.

Figure 3. Example of supplementary photography taken with a hand-held 70-mm camera with 0.25-ha ground sub-plot located

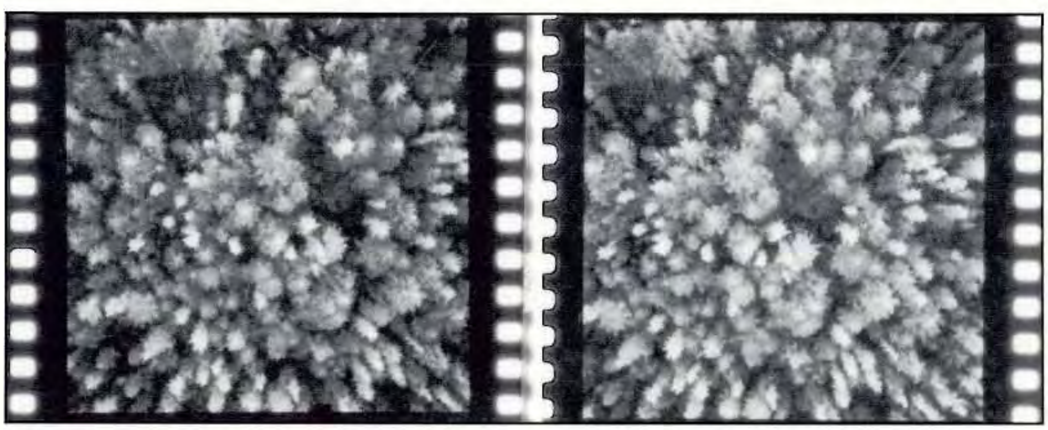

Figure 4. Contact prints of left and right stereo strips of photo plots taken with the B.C. Ministry of Forests 70-mm "Twin camera system"

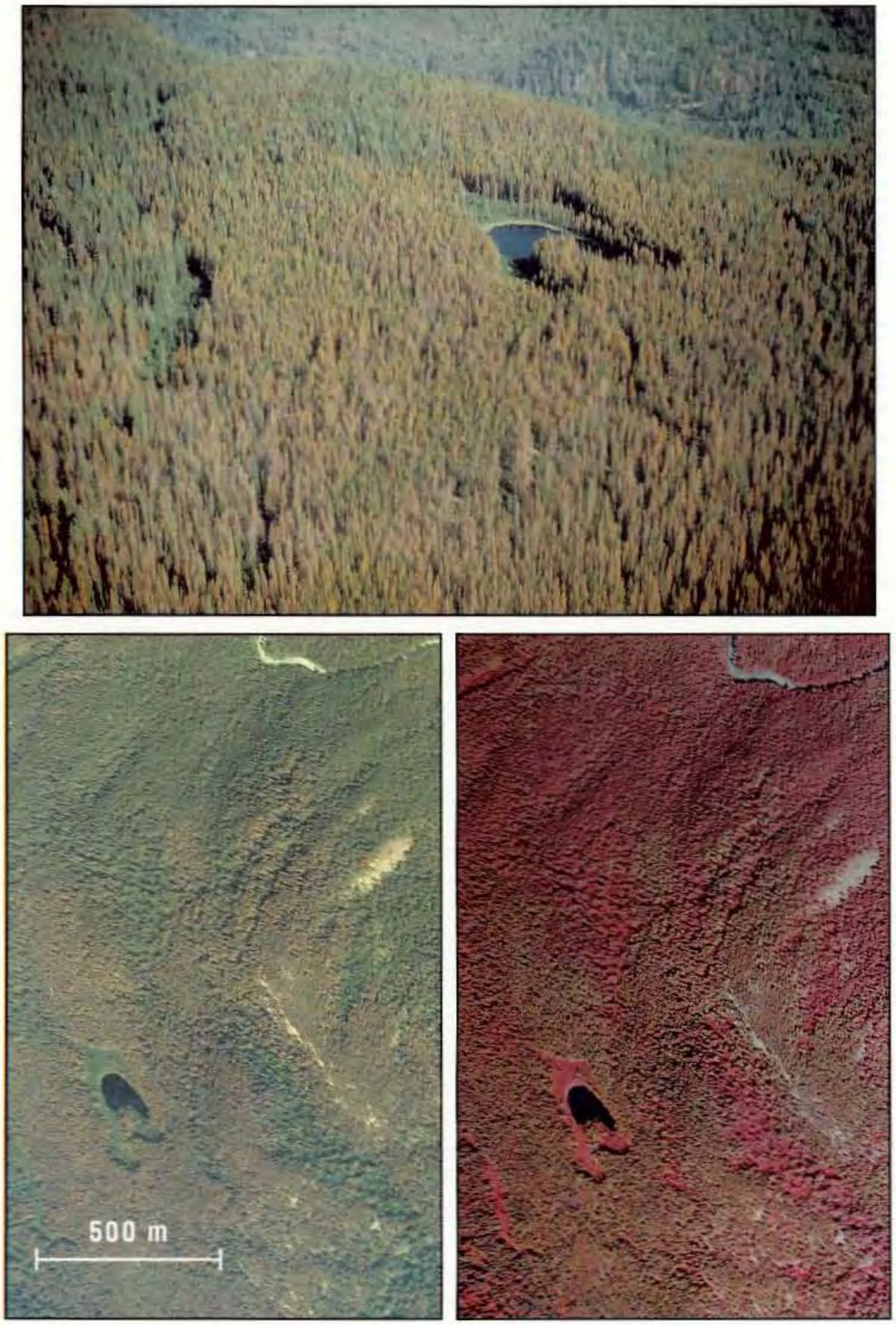

Figure 5. Examples of mountain pine beetle infestations on (top) oblique 35 mm color slide and (bottom) medium-scale (1:19 000) vertical photographs of same area: normal color (left), color infrared (right).

As the usefulness of such data depends on a knowledge of their exact position within the area being analyzed, the location of 70-mm large-scale stereo-pairs, oblique views, and available ground observation sites were pinpointed on 1:8000 and 1:19 000 prints to supply the photo interpreter with readily available reference material.

Figure 6 shows examples of 1:56 000 stereograms, constructed from normal color and color infrared high-altitude (9450 m ASL) photographs. A single 23 cm x 23 cm print at this scale covers an area of about 165 km^2, and 1 cm^2 on the photograph represents more than 30 ha on the ground. The area that may be viewed in three dimensions on these two stereograms is 20 km^2, or 2000 ha.

The medium-scale photography (1:19 000) shown in Figures 7 and 8 was flown along the approximate center of the small-scale (1:56 000) coverage. It covers a strip about 4300 m wide, or about 11% of the area covered at a scale of 1:56 000. The discoloration patterns outlined at locations 1, 2 and 3 in these figures (damage over 50%, less than 25%, and no damage) are well defined on the color infrared prints and less distinct but visible on normal color prints. This scale permits a delineation of damaged areas by estimating the proportion of discolored tree density in the affected stands.

The stereograms in Figures 9 and 10 were constructed from large-scale (1:8000) prints and cover a strip about 1800 m wide along the flight line of the medium-scale (1:19 000) photography. At a scale of 1:8000, a photo area of 1 cm^2 represents about 0.64 ha on the ground and a single 23 cm x 23 cm print covers less than 340 ha. At this scale, individual discolored trees within the forest canopy can be identified easily with both types of photography. When viewed under stereoscopic magnification, the number of discolored trees within a forest type may be estimated and used as a guide for interpretation of color patterns on smaller scale photographs.

The extra-large-scale photography shown in Figure 11 is a stereogram constructed from 70-mm normal color prints, enlarged 2.1 times from the original transparencies which were at a scale of 1:1067 (Figure 4). A single 70-mm frame at this scale covers only about 3000 m^2, one-half of which can be viewed stereoscopically. A 500-m^2 circular sampling plot (photo plot 2-1), with a radius of 12.6 m, is identified by the white circle in Figure 11. Each of the 44 trees on the plot were individually measured, analyzed and classified using transparencies under 8X stereoscopic magnification. According to the forest cover type map, the plot is located in a mature lodgepole pine type that included 19% Douglas-fir and spruce. Stem density exceeded 800 stems per ha and average stand height was 25 m.

2.2.2 Delineation of damaged forest types on aerial photographs

The high-altitude (1:56 000) photography, which provided complete coverage of the study area, was the main sensor for delineation of beetle-infested forest types. Infestation areas identified under 2X stereoscopic magnification were outlined directly on a clear acetate overlay placed over 23 cm x 23 cm color infrared film.

2.2.3 Estimation of damage intensity from photo-plots

A total of 602 photo plots were used to obtain data, involving 512 plots (0.25 ha) at a scale of 1:6000 and 90 plots from large-scale 70-mm stereo-pairs. Thirteen 0.25-ha plots were sampled on the ground to check the accuracy of photo interpretations, to provide the tree volume data, and to obtain other information such as general characteristics of damaged trees, their actual size from direct measurements, or specific ground conditions, none of which could be obtained directly from photographs. On the average, one photo-plot was sampled per 56 ha of the study area. In addition, the 1:8000 normal color and color infrared conventional photography permitted a detailed stereoscopic examination of about 4000 ha of the study area and provided data equivalent to that which could have been obtained from an additional 1000 sampling plots.

After pinpointing the exact location of photo-plots on large-scale (1:8000) conventional photographs, the flying height and scale were determined for each 70-mm stereo pair. The 25 engraved crosses spaced 10 mm apart on the camera reseau plate of the twin-camera system formed a grid on each exposure for calculation of exact flying height and scale. The photo scale of the 90 plots varied from 1:542 to 1:1170, with an average of about 1:1000. At a scale of 1:1000, 1 mm on the photograph represents 1 m on the ground.

As outlined below, two methods (conventional and photogrammetric) were used for quantification of damage from the analysis of photo-plots.

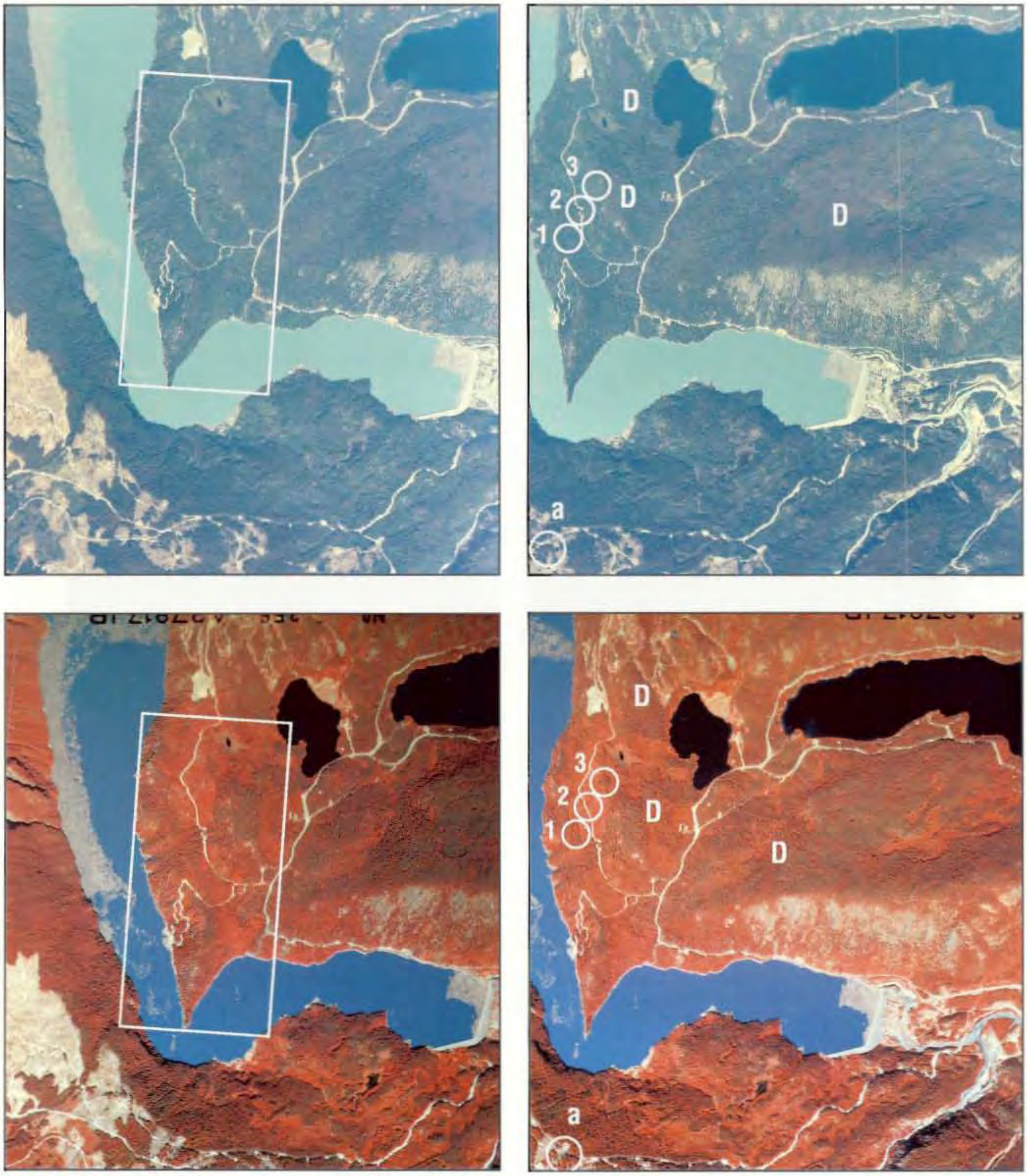

Figure 6. Color patterns of beetle-infested forest types. Stereograms were prepared from small-scale (1:56 000) aerial photographs: top – normal color (A37818, prints 355-356); bottom – color infrared (A37817 IR, prints 355-356). D = damaged areas; 1 = damage intensity over 50%, 2 = damage less than 25%, 3 = no damage (Rectangle defines Figs. 7 and 8).

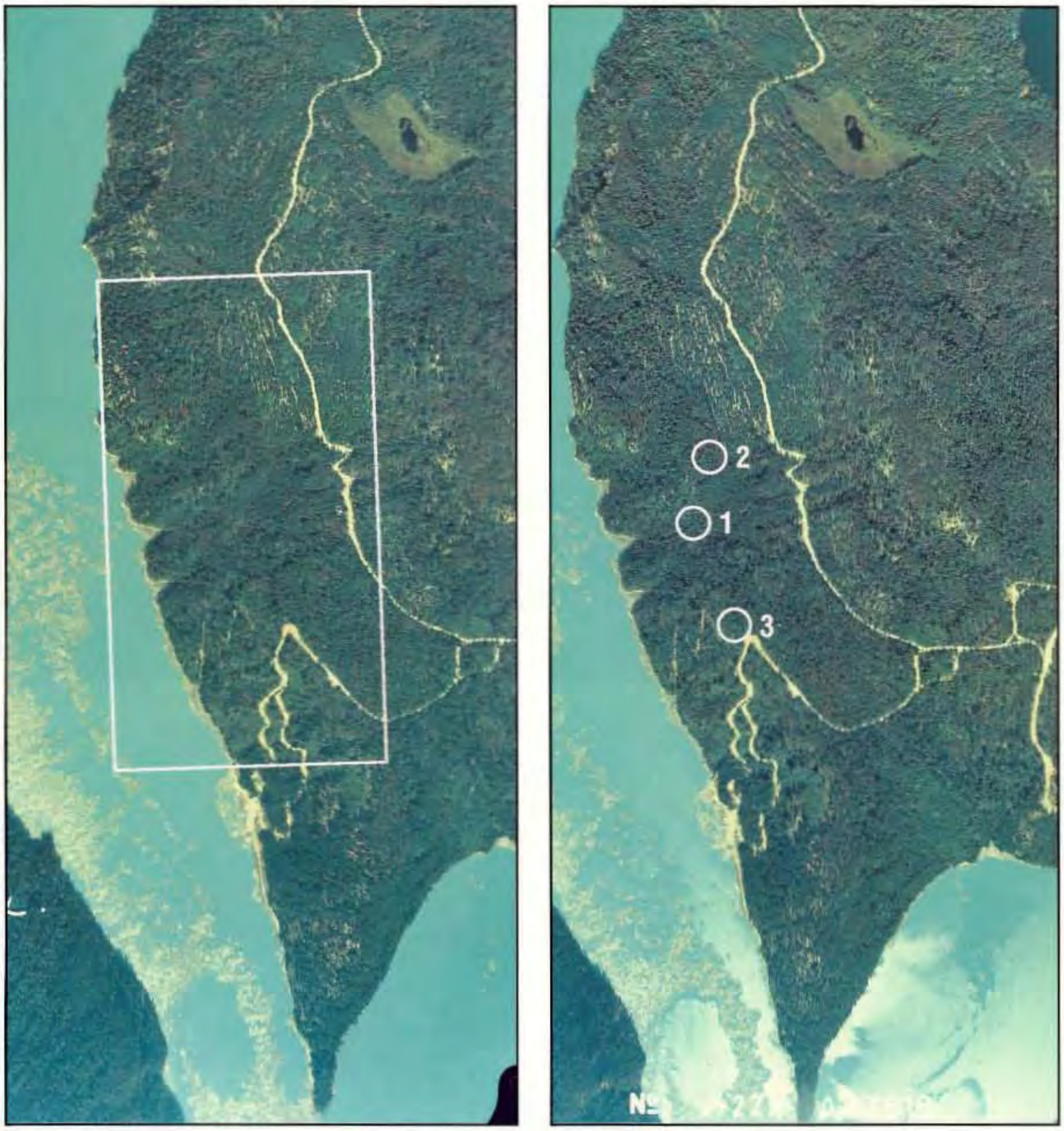

Figure 7. Color patterns of beetle-infested forest types. This stereogram was prepared from medium-scale (1:19 000) normal color aerial photographs (A37816, prints 224-225). 1 = damage intensity over 50%, 2 = damage less than 25%, 3 = no damage (Rectangle defines Figs. 9 and 10).

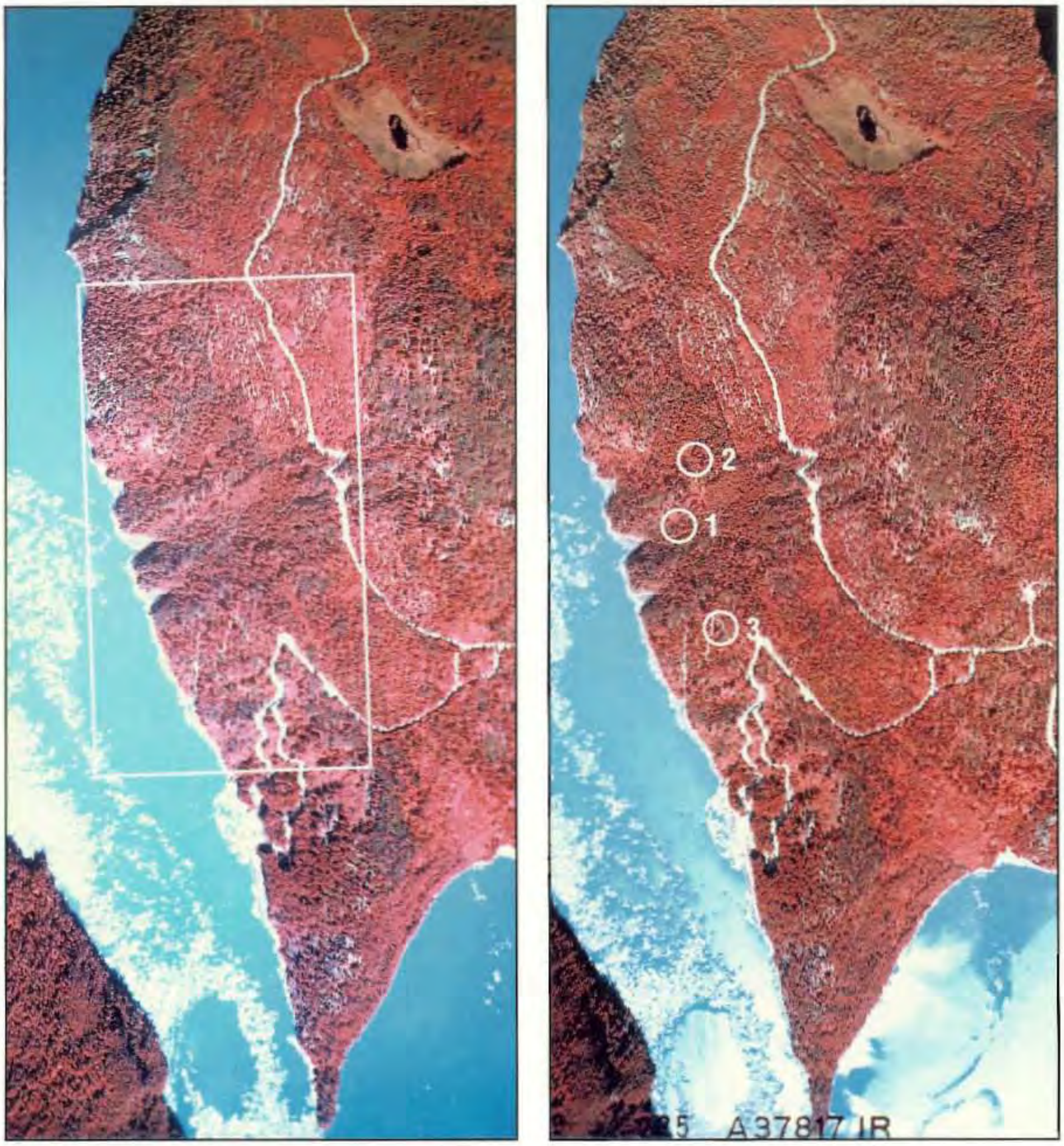

Figure 8. Color patterns of beetle-infested forest types. This stereogram was prepared from medium scale (1:19 000) color infrared aerial photographs (A37817 IR, prints 224-225). 1 = damage intensity over 50%, 2 = damage less than 25%, 3 = no damage (Rectangle defines Figs. 9 and 10).

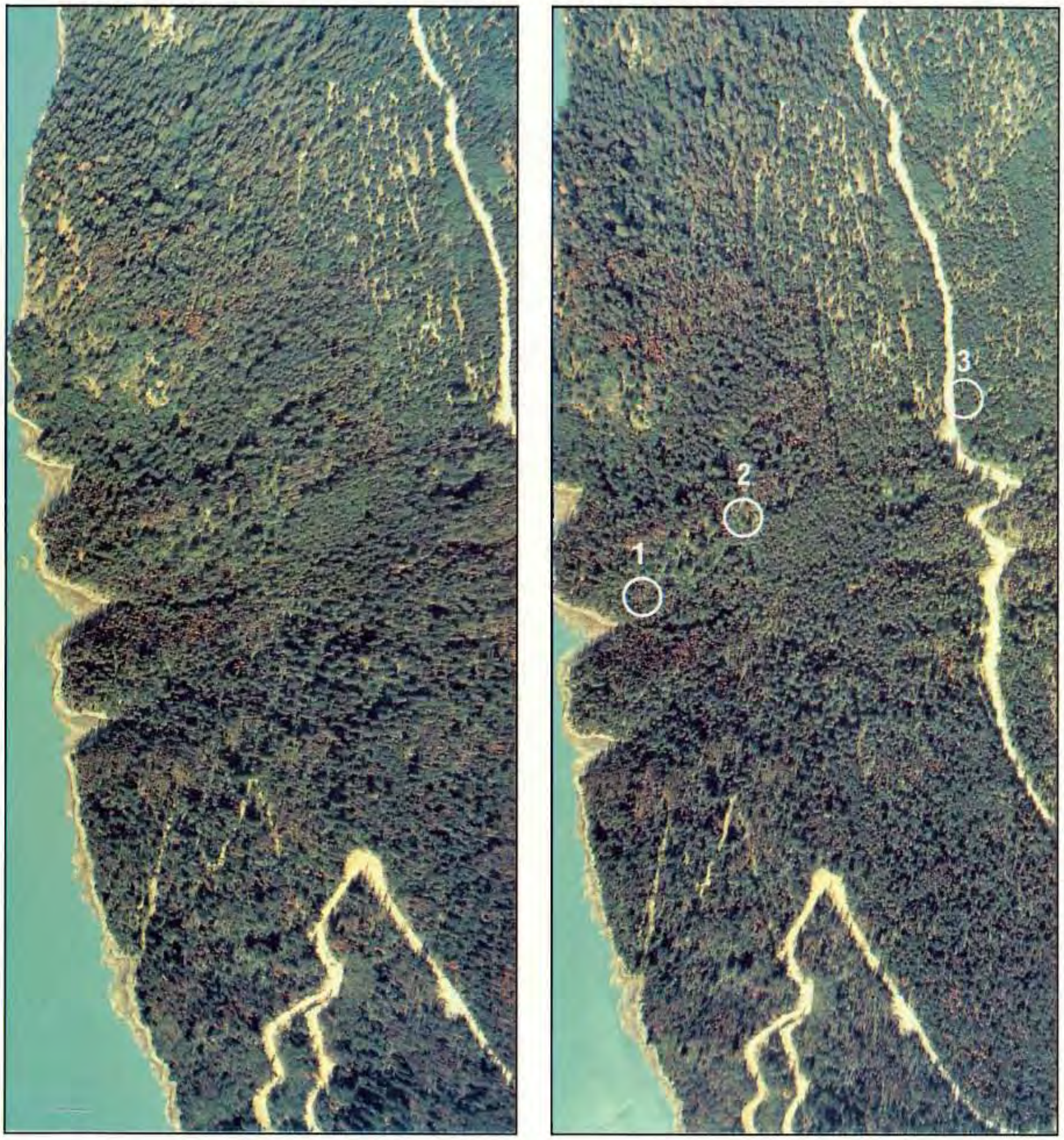

Figure 9. Color patterns of beetle-infested forest types - a stereogram prepared from large-scale (1:8000) normal color aerial photographs (A37818, prints 247-248). 1 = damage intensity over 50%, 2 = damage less than 25%, 3 = no damage

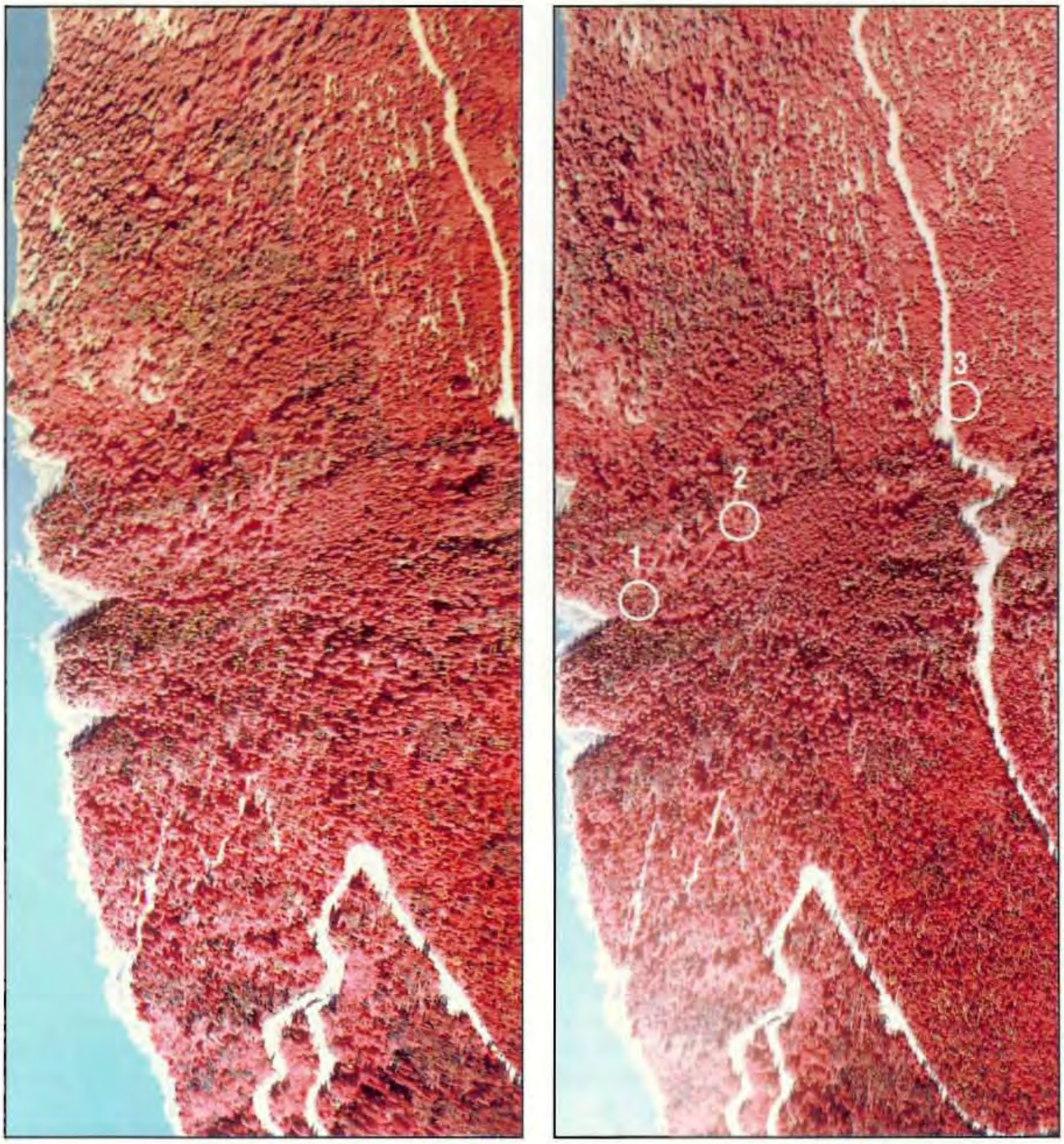

Figure 10. Color patterns of beetle-infested forest types - a stereogram prepared from large-scale (1:8000) color infrared aerial photographs (A37817 IR, prints 247-248). 1 = damage intensity over 50%, 2 = damage less than 25%, 3 = no damage

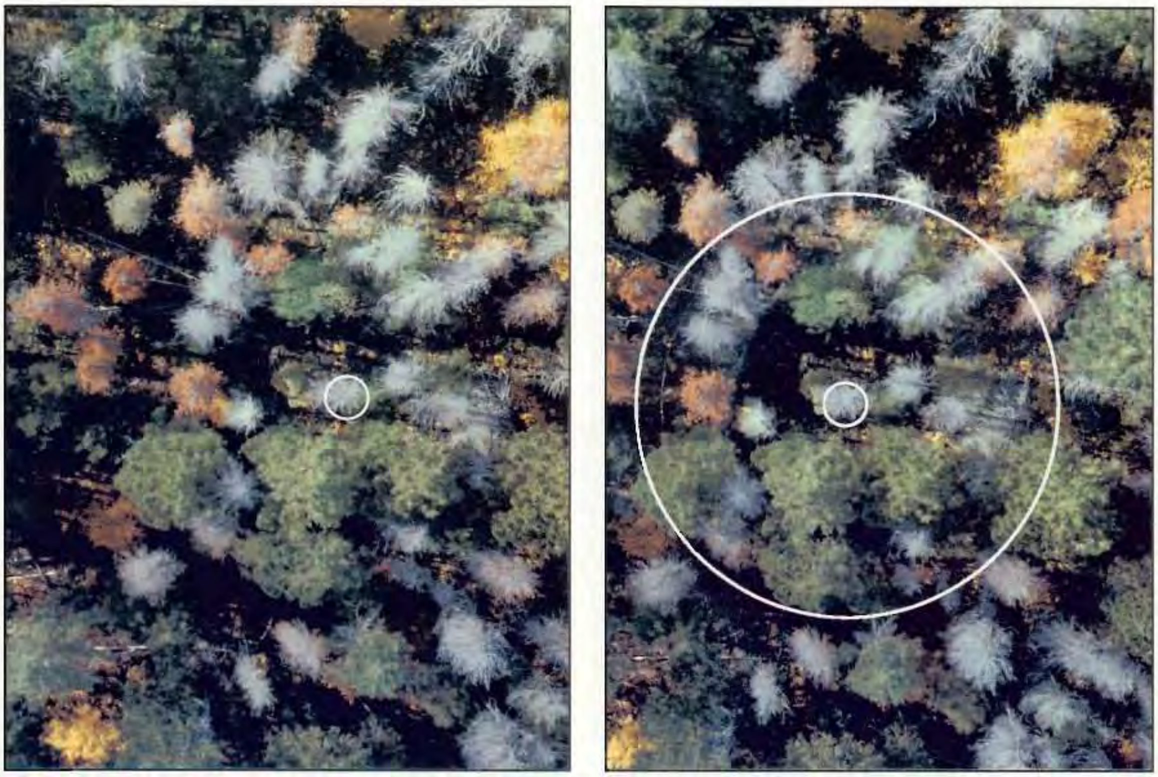

Figure 11. Large scale (1:1067) 70-mm color aerial photographs, enlarged 2.1 times (frames #622-Left and #622-Right) with 500 m^2 circular sample photo plot.

2.2.3.1 Conventional method

In the conventional analysis, all 70-mm supplementary color prints (32 photo-plots) and large-scale color transparencies (90 stereo pairs) were viewed under 2X stereoscopic magnification and all trees observed within the stereogram were analyzed individually. Each tree was classified by species and according to three photo-color classes: green (living); red (dying trees with reddish foliage); and grey (trees without foliage, mostly dead). The numbers of green, red and grey trees identified on 1:6000 color prints of 32 4-ha photo plots were adjusted according to ground sampling of 13 sub-plots of 0.25 ha. The ground measurements also provided the necessary volumetric data. Figure 3 is a sample stereopair of enlarged 70-mm color photographs taken with a hand-held camera illustrating a supplementary plot S-17, where 60 pine trees were identified as dead, while on the ground sub-plot 80 dead trees were counted and measured. All 90 color stereopairs taken with the 70-mm twin-camera system were analyzed in a similar way (Figure 11). In this example, there are 73 lodgepole pine trees of which 17 were green, 9 were red, and 47 were grey. Based on this count, the proportion of dead or dying trees in this 2000 m^2 sample area is 77%, compared with an estimate of 71% for the 500-m^2 when compiled by a photogrammetric method. Because the photo-plot data are used to express stand structure on a per hectare basis, calculation of exact scale of sampling photography is of crucial importance.

2.2.3.2 Photogrammetric method

The 90 stereopairs of large-scale color transparencies were analyzed and measured photogrammetrically, using the British Columbia Ministry of Forests "Photo Plot Sampling Program" with the stereocord system. This system consists of a Zeiss stereocord digital photogrammetric plotter, a Hewlett-Packard 9825 programmable calculator, an electronic interface, and photo measurement and editing software on executable tape cartridges (British Columbia Ministry of Forests 1981). After orienting the stereomodel, the exact flying height was determined from the photo base, the focal length of the camera (100.59 mm), and the distance between the two cameras (6.10 m). The photo scale was calculated from the flying height and focal length of the camera (H:f).

A circular plot was selected in the center of the right-hand photograph of a stereopair (Figure 11), and its size and radius determined. Each tree on the plot was viewed under 8X stereoscopic magnification, classified, measured, and listed in consecutive order on the printout tape. The printout provided data for each tree (a consecutive number, X and Y coordinates from the plot center, height, crown diameter, and vigour class), a volume summary by species, and tree class on a per plot and per hectare basis. Photogrammetric analysis is relatively simple and the printout remains a permanent record, which permits a quick check of any tree data from the coordinates provided for each tree on the plot.

2.2.4 Analysis of multi-spectral scanner (MSS) imagery

To determine if mountain pine beetle infestations can be mapped from digital MSS imagery, airborne and Landsat data were analyzed and compared with the conventional photo interpretation results outlined above.

2.2.4.1 Airborne MSS

Airborne MSS imagery was flown simultaneously with the conventional aerial photography, using a Daedalus/MDDA DS1260 system, modified for the Canada Centre for Remote Sensing as an 11-band imager. This imager is a rotating mirror scanner with an 85.9° swath width orthogonal to the flight direction. The 2.5 milliradian instantaneous field of view is sampled and digitally recorded to 8 bits at 716 pixels per scan line (Zwick *et al.* 1980). The 11-band data were reduced to JSC-formatted computer compatible tapes and used to produce color composite slides for visual analysis and computer-assisted interpretation of digital imagery. The 11 bands were assigned to the following regions of the spectrum: 1 and 2 - violet; 3 - blue; 4 - green; 5 - yellow; 6 - orange; 7 - red; 8, 9 and 10 - infrared; 11 - thermal infrared.

From each band of the airborne MSS tapes, black and white transparencies were obtained on the ARIES digital system at the Petawawa National Forestry Institute. For preparation of color composite images, a Spectral Data Corporation color additive viewer was used. With this instrument, up to four different bands can be viewed simultaneously, each band projected through one of the three color filters (red, blue, and green) and one clear filter, to form a color image.

After preliminary experimentation, bands 1, 2, 5 and 8 were found to be unsuitable because of poor resolution and lack of contrast. The remaining bands – 3 or 4 (blue or green), 6 or 7 (orange or red), 9 or 10 (mid infrared or far infrared) and band 11 (thermal infrared) – were used in various combinations to produce color composite imagery. From the color composite viewer screen, color photographs were taken of several projected combinations of bands and filters. From the selected color composite prints that showed damaged stands the best, damage maps were prepared and compared with those made from conventional interpretation of aerial photographs. Examples of two combinations are shown in Figures 12.

The best combinations of spectral band and color filter for showing stands infested with mountain pine beetle by means of airborne MSS color composite imagery are shown in Table 1. For the medium-scale (3810 m ASL) imagery, superior combinations were those that combined bands 9 or 10 and band 11 with green-red or red-green filters with or without bands 3, 4, 6 or 7 with a blue filter. The combination of bands 7, 9 and 11 viewed through blue, green and red filters (Figure 12, top) simulated natural colors, with killed pine appearing red-brown in color and healthy pine as green or blue-green. The example shown on the bottom of Figure 12 reversed this: areas of beetle-killed trees appeared as blue-grey-green and healthy coniferous stands appeared red to brown.

Digital analysis of several scenes permitted better discrimination of tonal characteristics, but also required continuous reference to aerial photographs to correctly classify the significance of color patterns. Examples of digital imagery are given for high and medium altitude and for color enhancement in Figure 13 with infested areas appearing reddish brown.

2.2.4.2 Landsat MSS

The Landsat MSS data were recorded on 16 August 1981; they are available in the original computer compatible tape format and on a digitally corrected quadrangle. Both tapes were digitally processed with the Pacific Forestry Centre image analysis system and compared with results obtained from aerial photographs and airborne MSS imagery. Because of strong relief differences, it was difficult to use either a supervised or unsupervised classification technique for mapping the

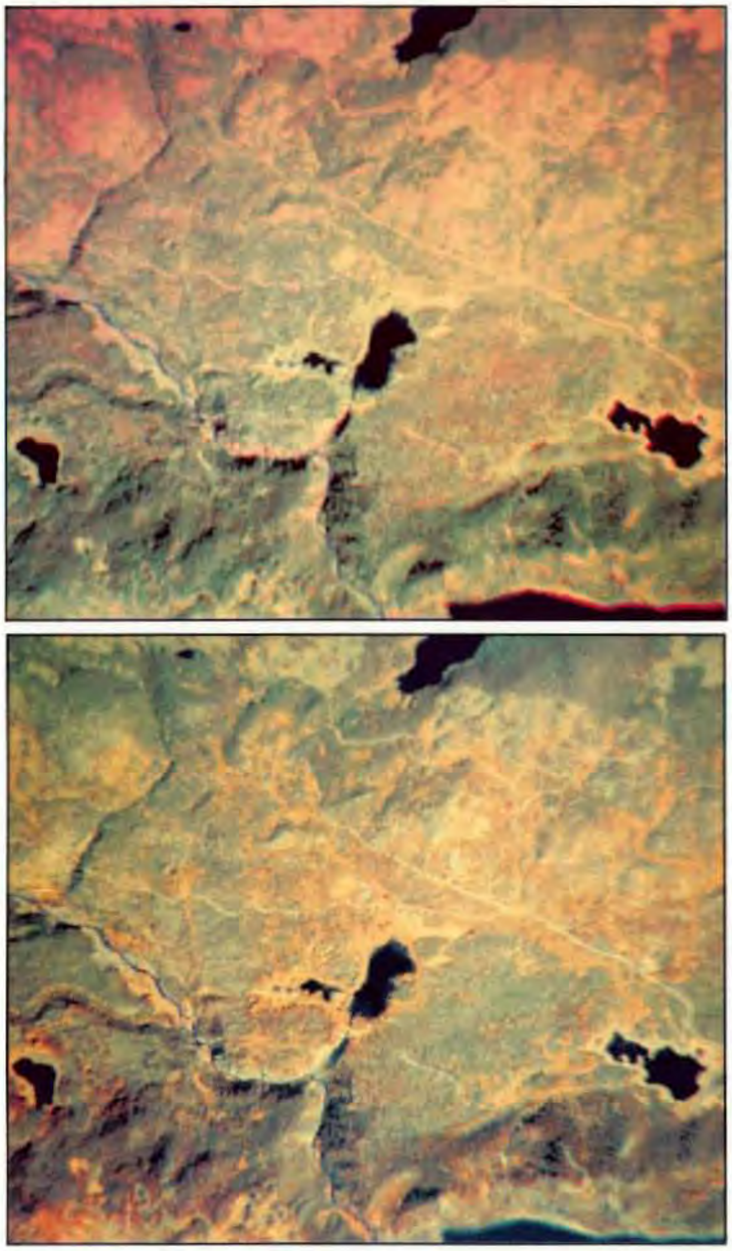

Figure 12. Color composite of medium-altitude (3810 m ASL) airborne MSS imagery produced by using a combination of bands 7, 9, and 11 and viewed through blue, green and red filters (top) and bands 4, 9, and 11, viewed through blue, red and green filters (bottom)

Table 1. Best filter color combinations for depicting mountain pine beetle-killed lodgepole pine stands from color additive viewer airborne MSS color composites

MSS Band			
3 or 4	6 or 7	9 or 10	11
blue	-	green	red
-	blue	green	red
-	-	green	red
blue	-	red	green
-	blue	red	green
-	-	red	green
green	-	red	blue
-	green	red	blue
-	red	green	blue
green	blue	red	-
-	green	red	-
green	-	red	-

infestation areas. However, a digital enhancement method based on the transformation of principal components during digital image processing provided results comparable to those of the high-altitude airborne imagery. Figure 14 is an example of a color composite of original Landsat data with bands 5, 6 and 7 as green, red and blue, resembling a color infrared photograph. The same bands, when enhanced on digitally corrected computer compatible tape, show the infestation areas in green (Figure 15), similar to the medium-altitude airborne MSS color composite in Figure 12 (bottom) and the high-altitude color additive viewer composite of airborne MSS channels 4, 10 and 11 with blue, red, and green filters shown in Figure 16.

One of the advantages of Landsat imagery is its extensive coverage, which permits rapid analysis of a larger area than is possible with high-altitude airborne MSS. However, the use of Landsat imagery for detection of infested areas and a meaningful assessment of pine beetle damage requires frequent reference to conventional aerial photographs to modify the color patterns.


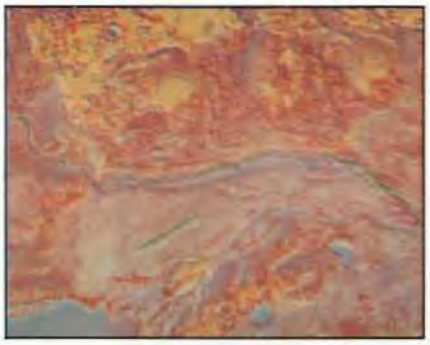
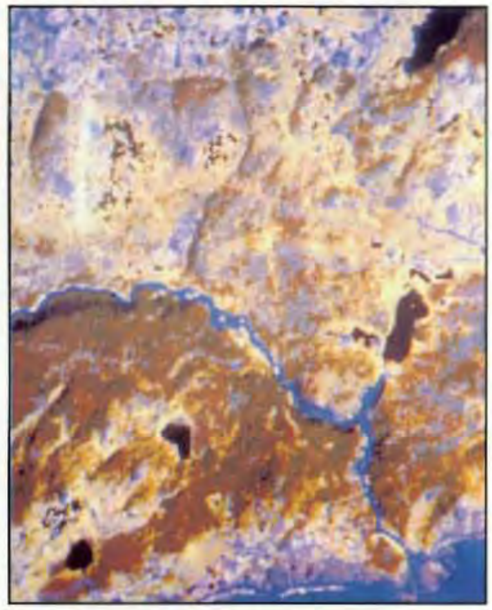

Figure 13. Digitally processed airborne MSS imagery.
Left – Principal components - MSS imagery taken from 9450 m ASL
Center – Principal components - MSS imagery taken from 3810 m ASL
Right – Color enhancement of MSS imagery taken from 9450 m ASL

3. Mapping of forest damage

In this study, existing provincial forest cover maps were used as a base for presentation of the damage survey data. These maps, entitled Forest Cover Series, were compiled for the study area in 1977 from 1964 and 1975 aerial photographs. At a scale of 1:20 000, there are eight quadrangles of the Forest Cover Series on a single 1:50 000 National Topographic Series map sheet. Complete coverage of the study area required five forest cover maps.

The boundaries of infestation areas delineated on photographs were transferred directly to the corresponding map sheets as separate map units superimposed over the original cover types. Planimetric features, cover type details, and the 2000-m UTM grid on the base maps provided adequate control for matching scales of the photography with the base maps.

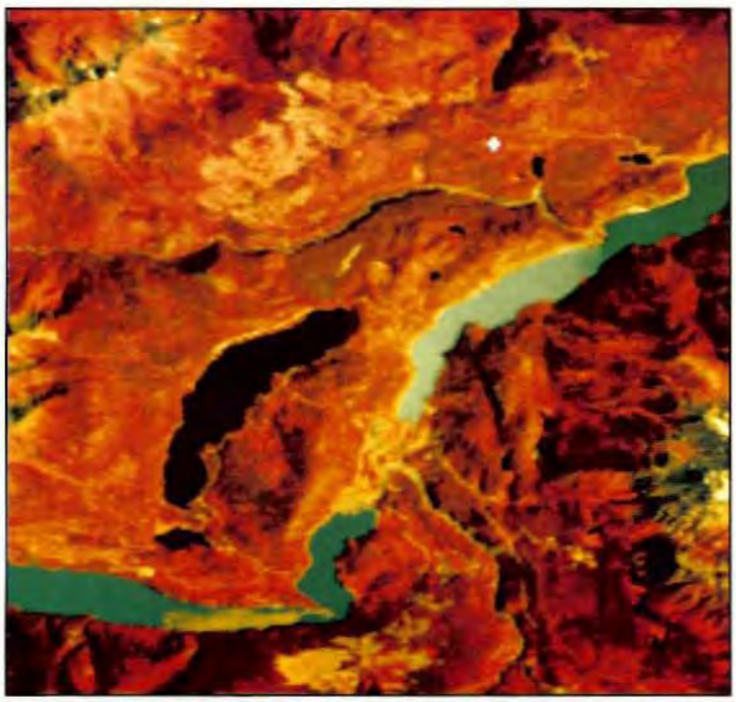

Figure 14. Digital enhancement of Landsat imagery - Color composite of bands 5, 6, and 7, with Linear FM and channel reduction

3.1 Compilation of losses

The intensity of beetle damage was compiled from analysis of large-scale photo-plots and the ground data of 13 sub-plots. Based on the number of killed pine (red and grey trees) in proportion to all conifer species within a stand, the intensity of beetle-kill was originally rated as light, moderate, or severe. Because

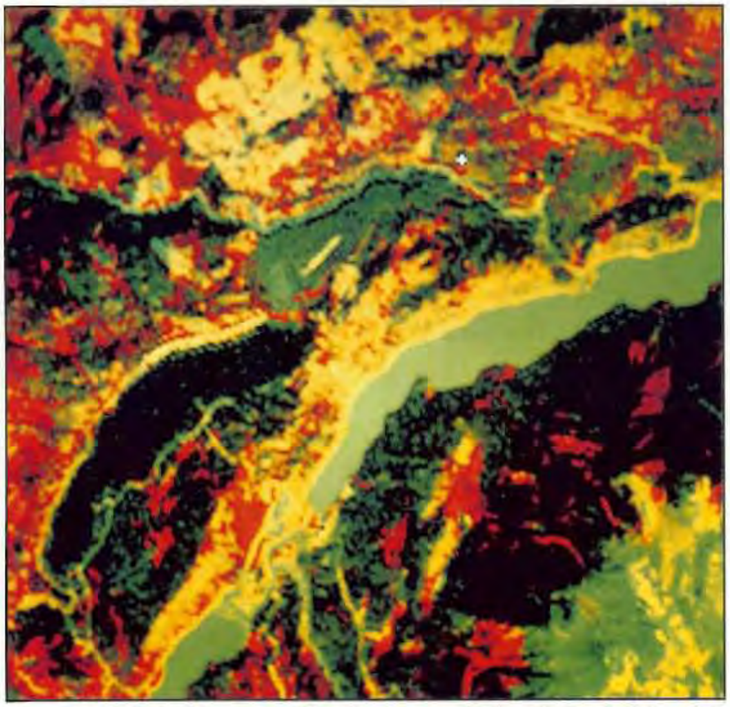

Figure 15. Digital enhancement of Landsat imagery in Fig. 14 - bands 5, 6, and 7 original data on DICS tape

there was very little damage rated light, this category was later included with the moderate category, and the infested stands were grouped into two general classes: moderate - stands with dead lodgepole pine averaging less than 40% of total conifer stems; and severe - stands with dead lodgepole pine averaging more than 40% of total conifer stems in the stand. Losses were compiled from 1:20 000 forest cover type maps updated with the beetle infestation data interpreted from aerial photographs. Based on the intensity of damage, the relative age of infestation, the discoloration patterns on aerial photographs, and the ratio of red to grey trees on photo plots and ground sub-plots, the infested cover types were further grouped geographically into eight map units (Figure 17). The average percent volume of dead lodgepole pine to total lodgepole pine volume and the average volume per hectare of dead lodgepole pine were calculated from photo-plot and ground data for each geographic unit in the moderate and severe damage classes, as summarized in Table 2.

Figure 16. Color composite imagery produced from band-filter combinations on color additive viewer from high-altitude (9450 m ASL) airborne MSS - a combination of bands 4, 10 and 11, projected through blue, red, and green filters, respectively.

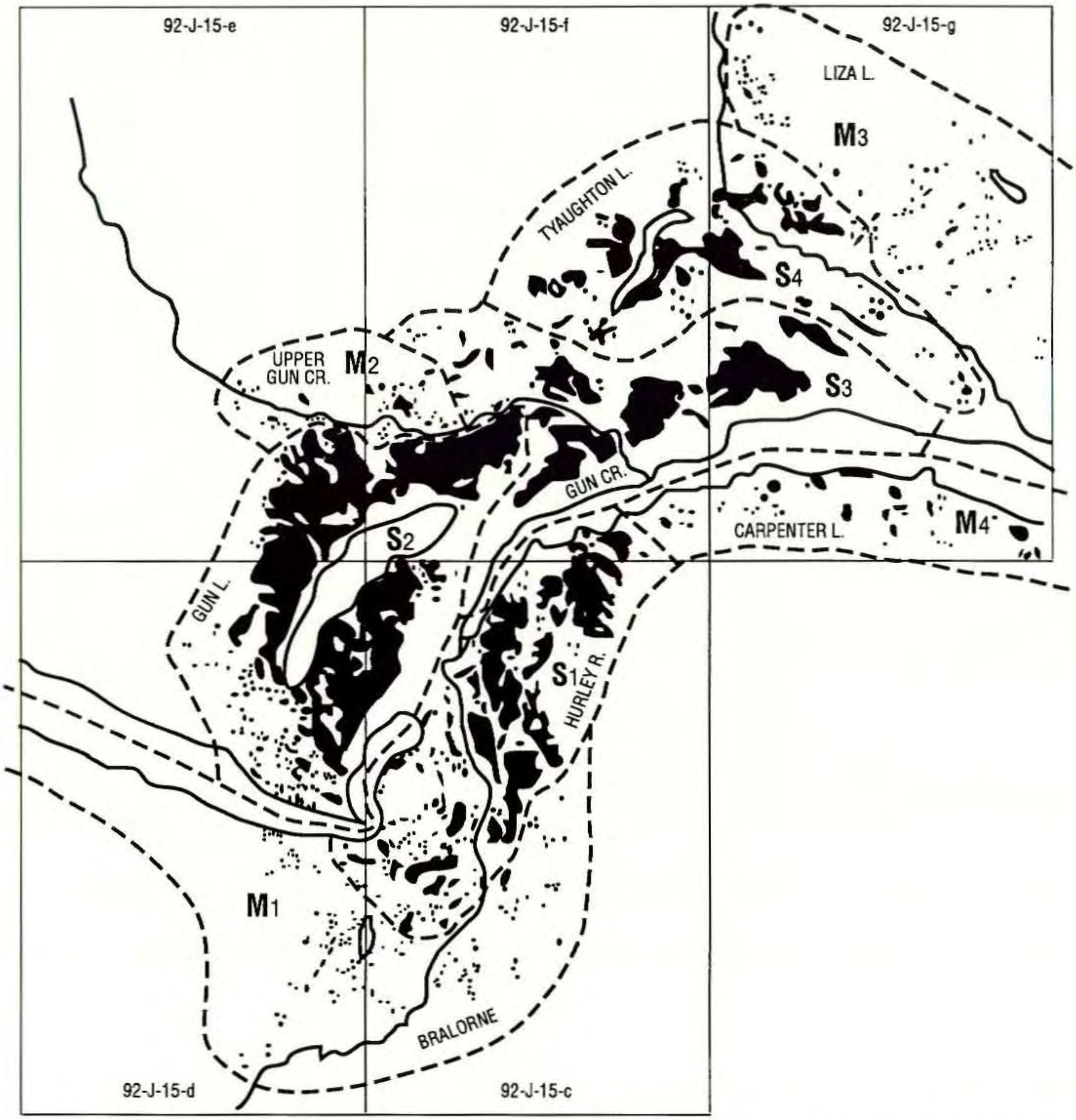

Figure 17. Map of study area showing damage intensity levels – Moderate (M) and Severe (S) – by eight broad geographic units (see Table 2 for explanation)

Table 2. Geographic characteristics of moderately and severely damaged areas (see Figure 17)

Moderately and severely damaged areas	Location	Map sheets	Elevation (m)	Area (ha)	Dead trees (%)	Dead lodgepole pine	
						(%)	m^3/ha
M1	Bralorne (Southern portion of study area; both sides of Hurley River)	92-J/15-c 92-J/15-d	700-2100	7030	15	13	18
M2	Upper Gun Creek	92-J/15-c 92-J/15-f	1000-2000	1480	15	12	30
M3	Liza Lake (NE part of study area)	92-J/15-g	1200-1600	3700	16	14	16
M4	Carpenter Lake	92-J/15-f 92-J/15-g	651-1700	2960	21	30	28
S1	Hurley River (South of Downton Lake)	92-J/15-c 92-J/15-d 92-J/15-f	650-1500	4810	43	65	144
S2	Gun Lake (Area surrounding Gun Lake)	92-J/15-c 92-J/15-d 92-J/15-e	887-1600	6660	51	77	185
S3	Gun Creek	92-J/15-c 92-J/15-f 92-J/15-g	650-1750	5180	35	58	66
S4	Tyaughton Lake	92-J/15-f 92-J/15-g	1000-2000	5180	59	75	106

All forest cover types within map units delineated as damaged were listed on a compilation form and the area of the damaged portion of a type was determined and entered in column 4 of Table 3. From the British Columbia Ministry of Forests' "Map Volume Statements," data on total lodgepole pine volume in the type, area (ha), and average lodgepole pine volume for each type were entered into columns 1, 2 and 3, respectively. Total lodgepole pine volume in the infested portion of the type was obtained by multiplying the lodgepole pine volume/ha (column 3) by the area shown in column 4. The average percentage of lodgepole pine volume killed and the average volume per hectare of lodgepole pine killed, determined previously for the eight geographic units, were entered into columns 6 and 9, respectively, and used for the calculation of mortality. Two methods were used for compilation of volume losses, one based on percentage of killed pine (column 7) and the other based on the average volume per hectare of dead pine (column 10).

3.2 Results

Several stereograms in this report illustrate discoloration patterns in stands infested with mountain pine beetle. These stereograms, when viewed as a series, provide a comparison of color patterns of beetle infestations as they appear on normal color and color infrared photographs at four scales: 1:56 000; 1:19 000; 1:8000; and extra-large, varying from 1:6000 to 1:1000. The discoloration patterns, visible with difficulty on the normal color 1:56 000 stereogram (Figure 6, top), are better defined on the color infrared print at the same scale (Figure 6, bottom). Areas marked *a*, 1 and 2 in Figure 6 are locations of large scale photo-plots. In the case of locations *a* and 1, approximately 50% of the trees were discolored and in location 2 less than 25% were discolored. These areas are only 3 to 5 ha in area and they represent small portions of damaged forest types.

As indicated in Figure 6, with normal color prints at a scale of 1:56 000, discoloration is influenced by color of the background and loss of detail from haze, which is better penetrated by infrared wavelengths. The intensity of color patterns is influenced by the density of discolored trees within the stand, which may be estimated from aerial observations, from larger-scale photography, or from photo-plots.

Based on mapping from 1:56 000 photographs, infestations were evident in about 300 different map units of forest cover types. About 66% (3095 ha) occurred in mature cover types and 34% (1578 ha) in immature cover types. Infested areas ranged from 1 ha to over 100 ha, averaging 15.6 ha. The average area of infestation was similar in mature cover types (16.5 ha) and in immature cover types (14.1 ha). The infested area represented about 22% of all mature and immature forest cover types. Based on the count of damaged trees and their average volume derived from an analysis of data from photo plots and ground sub-plots, it was estimated that over 1.2 million lodgepole pine trees were killed by the mountain pine beetle between 1975 and 1981, with a volume loss of over 453 000 m^3, averaging 97 m^3/ha. By maturity classes, 341 524 m^3 occurred in the mature cover types (average 110.3 m^3/ha), and 111 582 m^3 occurred in immature forest cover types (average 70.7 m^3/ha). About 60% of the lodgepole pine killed were old dead trees, which appeared grey on normal color photographs, and 40% were recently killed (red trees on normal color photographs). Ground sub-plot counts also indicated that about 21% of green lodgepole pine trees were attacked in 1981 and would turn red in 1982.

4. Discussion

Infestations of mountain pine beetle in the study area have been sketch-mapped annually by the Forest Insect and Disease Survey since 1976 (Figure 2). Aerial sketch-mapping is a relatively simple, inexpensive, and quick way to estimate stand damage and to provide forest managers with current information on the general location and intensity of insect infestations. Although sketch-maps provide information faster and at less cost than aerial photography, an inherent problem of sketch-mapping is a tendency to overestimate the size of infestation areas. The infestation area estimated from sketch-maps (19 700 ha) was four times larger than the 4674 ha mapped from the 1:56 000 color infrared photographs.

The sketch-mapping data obtained in 1980-81 of the same general area (Harris *et al.* 1983) was also used for a simplified multi-stage sampling study in which 60 polygons were sketched on 1:6000 color photographs to portray beetle-infested areas. From the count of damaged trees on 33 4-ha plots, adjusted with the aid of fifteen 0.25-ha ground samples, the estimated mortality was 4.3 million lodgepole pine trees, or nearly 1.6 million m^3 of volume losses. These figures are 3.5 times higher than the results from photographic interpretation presented in this report.

The partial coverage by medium and large

Table 3. Example of a damage compilation form used for lodgepole pine killed by the mountain pine beetle in the area covered by British Columbia Ministry of Forests map sheet 92-J/15-f (Yalakom)

Forest type	Map area and volume			Area with pine killed (ha)	Pine vol. in area killed (m^3)	Avg % pine vol. killed	Method 1		Method 2	
	Pine vol. (m^3) (1)	Type area (ha) (2)	Pine vol./ha (3) (1)/(2)	(4)	(5) 3)x(4)	(6)	Vol. pine killed (m^3) (7) (5)x(6)/100	Vol./ha pine killed (8) (7)/(4)	Avg vol./ha pine killed (9)	Vol. pine killed (m^3) (10) (4)x(9) <(5)
PL 523-P	9030	83	109	9	981	58	569	63	66	594
PL 524-P	4720	95.5	49	86	4214	77	3245	38	185	4214
PL 533-M	4260	20	213	20	4260	58	2471	124	66	1320
PL 624-P	300	6	50	6	300	58	174	29	66	300
PL 631-G}				12	3300	12	396	33	30	360
PL 631-G}	67 070	244.3	275	13	3575	63	2288	176	144	1872
PL 631-G}				10	2750	58	1595	160	66	660
PL 631-M	3840	14	274	14	3840	58	2227	159	66	924
PL 633-G	3830	18	213	4	852	75	639	160	106	424
PL 831-G	1900	8	238	4	952	58	552	138	66	264
PL(F)522-P	760	8	95	8	760	75	570	71	106	760
PL(F)524-P	540	11	49	11	540	64	346	31	144	540
PL(F)531-G	52.5		274	71	19 454	75	14,590	205	106	7526
PL(F)531-M			275	24	6600	75	4950	206	106	2544
PL(F)533-G			213	1	213	58	124	124	66	66
PL(F)533-M			213	20	4260	58	2471	124	66	1320
PL(F)624-P			49	36	1764	77	1358	38	185	1764
PL(F)631-G			274	1	274	30	82	82	28	28
PL(F)631-M}			274	132	36 168	77	27,849	211	185	24 420
PL(F)631-M}				56	15 344	58	8900	159	66	8904

photographic scales, and the supplementary 70-mm photography, provided essential data for photo interpretation and quantification of damage losses. The identification of damaged stands was based on stereoscopic analysis of color patterns, deductive evaluation of discoloration in the forest canopy, and diagnostic photo-characteristics of beetle infestations. Because of the difficulty in discriminating tonal differences on high-altitude normal color prints, color infrared transparencies were used for this purpose.

Discoloration patterns can be identified on color infrared film, but are usually missed on the smaller scales of normal color prints. For a comparison of color patterns, between normal color and color infrared images, an undamaged, young pine-fir stand is shown at location 3 in Figure 6. In summary, the high altitude (1:56 000) aerial photography covers the entire study area but, as indicated by comparisons of the stereograms, only color infrared photography was suitable for mapping of damaged stands.

The haze penetration characteristics of infrared film permit high-altitude color infrared photography to be used for discrimination of discrete color patterns and detection of infestations. While the discoloration patterns are relatively well defined on both types of film at the medium scale (1:19 000; Figure 5), with high-altitude photographs (1:56 000; Figure 6, top) they are far less distinct on normal color prints than on color infrared prints. The advantages of larger scale are demonstrated by the low-altitude oblique photograph in Figure 5 in which the discoloration patterns of the forested area surrounding a small lake are quite unmistakable.

At scales of 1:19 000 and 1:8000, normal color photography is often preferred by photo interpreters because the discoloration of affected trees appears more natural than on color infrared photography (Figures 7 to 10). The abundance of hues and colors on the color infrared photographs requires a full understanding of infrared principles to relate these artificial colors to ground conditions.

Analysis of the airborne and satellite MSS imagery was not found to be suitable for detection of damaged forest stands, mainly because proper interpretation of this imagery is complicated and time-consuming. It also requires support from conventional aerial photography or ground surveys.

A comparison of beetle infestations mapped from the MSS imagery using the color additive viewer and from corresponding scales of aerial photography is provided by Figure 18. Although the maps appear generally similar, the MSS composites show more damaged area than aerial photographs. Furthermore, many uninfested locations that are clearly visible as such on the photographs have a color similar to that of damaged stands on the MSS imagery. Also, some tonal characteristics that are very distinct on aerial photographs are not visible on MSS composites; for example, patches of straw-colored ponderosa pine could be readily separated from red stands of lodgepole pine on small-scale color infrared film and on both types of photography at a medium scale, but not on the MSS imagery. Likewise, on the MSS imagery it was not generally possible to discriminate between different intensities of damage or between recent and older beetle-killed stands; for example, much of the upper part of the MSS composite shown in Figure 16 suggests beetle damage, although only limited beetle-kill may be seen on aerial photographs of the same area. Similarly, lodgepole pine stands that are under physiological stress on relatively dry sites, and which have thinner brown-green crowns, appear on MSS as beetle-killed trees. Such uninfested trees can be distinguished from infested trees on color photographs.

Significant factors in the quantification of losses are the size of infested stands and the volume per hectare of damaged trees. Precision in estimation of these factors depends largely upon the scale, type, and quality of aerial photography and the method of image analysis. Photographic scale is particularly critical in the analysis of large-scale photography, where data derived from photo-plots within the appropriate forest type often present a serious problem, particularly in pinpointing the large-scale 70-mm stereoframes on smaller-scale conventional photographs.

The identification and counting of damaged trees was carried out on 70-mm stereoscopic color prints and transparencies, at approximate scales of 1:1000 and 1:6000, and was repeated on the 1:8000 scale conventional (23 cm x 23 cm) photographs. While the 1:1000 stereo-pairs permitted the recognition and counting of almost all trees, the limitations due to decreasing scale were noticeable in the analysis of 0.25-ha photo-plots on 1:6000 scale stereo-triplets. In the latter case, the counts had to be adjusted with the aid of ground-verified sub-plots, using a ground sub-plot/photo-plot ratio, which averaged 1.19 for the red trees, 3.23 for the grey trees, and 1.60 for the total number of counted trees. The tree count on the photo-plot shown in Figure 3, for example, was 60 dead lodgepole pine (32 red and 28 grey); ground sampling of the same plot revealed

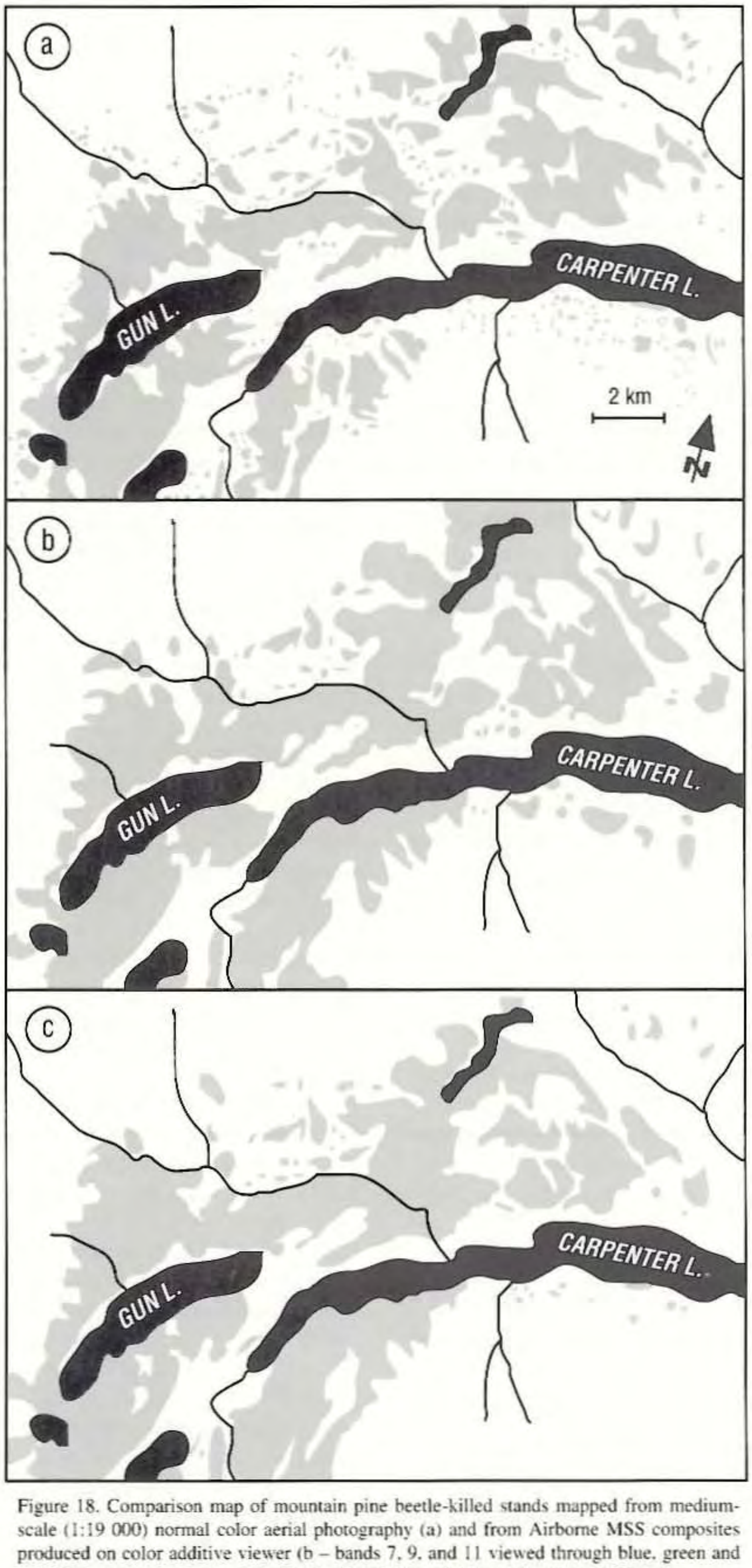

Figure 18. Comparison map of mountain pine beetle-killed stands mapped from medium-scale (1:19 000) normal color aerial photography (a) and from Airborne MSS composites produced on color additive viewer (b – bands 7, 9, and 11 viewed through blue, green and red filters, respectively; c – same bands viewed through blue, red and green filters)

80 dead trees (38 red and 42 grey). For comparison, the counts were repeated on the 1:8000 scale conventional (23 cm x 23 cm) color prints and, as summarized in Table 4, the average difference between these two scales was about 5%.

The photogrammetric method of photo-plot analysis was found to be relatively fast and consistent. It also provided a computer printout of the analyzed data, summarized by tree classes and volume. A comparison of this method with conventional tree counts is shown in Table 5. Generally, the ratio of red to grey lodgepole pine was greater for the photogrammetric method, probably because many trees that had retained some dead foliage were classified as red instead of grey. For the photogrammetric method, the estimated number and volume of trees varied considerably, primarily because photo-sample trees were larger than those on the ground sub-plots. Also, the small plot size (average 0.04 ha) may have resulted in an over-estimation of tree densities when extrapolated to a per hectare basis.

The estimated cost of surveying the 370-km^2 study area was about $18,000, or near $50/$km^2$. Itemized expenses shown in Table 6 indicate that the acquisition of conventional and 70-mm supplementary photography, digital MSS data and base maps accounted for 23% of the expenditures and field expenses accounted for about 19%. The remaining 58% of the total cost was for image analysis, compilation of damage data, and tabulation of results. The following items were not included in these figures: large-scale 70-mm color photography and photogrammetric analysis of 90 photo-plots (provided by the British Columbia Ministry of Forests); hard copies of airborne MSS imagery for preparation of color composites on the color additive viewer (provided by the Petawawa National Forestry Institute); and digital analysis of MSS data, which was done with the assistance of staff of the computer unit at the Pacific Forestry Centre. In addition, conventional color and color infrared aerial photography and MSS imagery was provided by the Canada Centre for Remote Sensing at a special research price of about $2500. At commercial rates, the cost of such imagery would be four to five times higher.

Seven-band thematic mapper imagery is now available, which has improved spatial resolution, spectral separation, geometric fidelity, and radiometric accuracy. It is likely that this imagery would be more successful for the assessment of insect damage. However, the cost of such data is considerably higher than present MSS imagery.

5. Conclusions and recommendations

This study provided an opportunity to investigate the operational use of remote sensing survey techniques for assessment of forest stands infested by mountain pine beetle. The stereoscopic illustrations in this report demonstrate that beetle-infested forest stands and damaged trees can be detected, classified, and measured on aerial photographs when exposed on an appropriate film at a suitable scale. Aerial photography provided adequate damage appraisal data compatible with operational levels of forest inventory. In contrast to the information provided by aerial photography, the MSS imagery and the traditional aerial sketch-maps, while useful in a reconnaissance survey for delineation of broad infestation patterns, did not provide the essential data required for an operational forest inventory.

This demonstration survey led to the following conclusions and recommendations:

1. Traditional direct aerial observation of forest conditions is a relatively simple, rapid, and inexpensive method to compile an overview of infestation patterns and to pinpoint specific areas for detailed investigation. In this study, for example, available sketch-maps provided valuable information for initial planning and for analysis of aerial photographs. The usefulness of aerial sketch-mapping data could probably be improved by adding a hand-held camera and a portable sound recorder or a video system to document the overflight observations for future analysis.

2. Multi-spectral scanner images from airborne and satellite sources were inferior to color aerial photography for outlining beetle-killed forest stands, since more area appeared to be infested by beetles on the MSS imagery than was actually the case. Also, it was difficult to discriminate between intensities or infestation ages without resorting to aerial photographs.

3. The color aerial photography used in this survey was found to be the most efficient, practical, and reliable sensor for appraisal of beetle-infested stands. The small-scale color infrared and medium-scale normal color and color infrared conventional photographs permitted systemic mapping of damaged stands, while the large-scale color photography and supplementary stereo-pairs of photo-plots provided adequate mensuration data for compilation of damage losses.

4. Two types of color film - the normal color, or Aerocolor Negative Type 2445, and Aerochrome

Table 4. Density of lodgepole pine and total conifer species determined from airphoto plots compared to counts made on 1:8000 color aerial photographs, Lines 1 and 3.

Attack category	Location	Conifer stems/ha				Percentage of total conifers that are dead lodgepole pine		
		Dead lodgepole pine						
		Red	Grey	Total	Total conifers	Red	Grey	Total
Severe-recent attack	Line 1 photo plots	192	32	224	425	45	8	53
	Line 1 1:8000 imagery	188	32	220	507	37	6	43
	Line 3 photo plots	164	29	193	402	41	7	48
	Line 3 1:8000 imagery	123	36	159	346	35	10	46
	Avg	167	32	199	420	40	8	48
Moderate-recent attack	Line 1 photo plots	24	4	28	179	13	2	15
	Line 1 1:8000 imagery	51	22	73	317	16	7	23
	Line 3 photo plots	29	9	38	280	10	3	13
	Line 3 1:8000 imagery	18	7	53	321	14	2	16
	Avg	38	10	48	274	14	4	18
Severe-old attack	Line 1 photo plots	45	65	110	286	16	23	39
	Line 1 1:8000 imagery	19	96	115	358	5	27	32
	Line 3 photo plots	115	118	233	550	21	21	42
	Line 3 1:8000 imagery	54	106	160	369	15	29	44
	Avg	58	96	154	301	15	25	40
Moderate-old attack	Line 1 photo plots	-	-	-	-	-	-	-
	Line 1 1:8000 imagery	27	68	95	541	5	13	18
	Line 3 photo plots	29	70	99	389	8	18	26
	Line 3 1:8000 imagery	26	34	60	323	8	11	19
	Avg	27	57	84	418	6	14	20

Table 5. Comparison of estimated number and volume of mountain pine beetle-killed lodgepole pine, healthy lodgepole pine, and other conifer species using British Columbia Ministry of Forests stereochord measurements from helicopter boom plots and airphoto plot and ground subplot data

	Using BCMF helicopter boom plots A	Using airphoto plots and ground subplots B	% Difference (B - A) / A x 100
	number of trees		
Lodgepole pine			
Red	1 079 150	570 650	-47
Grey	768 400	819 250	7
Total dead	1 847 550	1 389 900	-25
Green	1 819 300	1 700 650	-7
Total	3 666 850	3 090 550	-16
Douglas-fir	1 022 650	1 101 750	8
Ponderosa pine	50 850	79 100	56
Spruce	118 650	519 800	338
All conifers	4 859 000	4 791 200	-1
	volume (m^3)		
Lodgepole pine			
Red	544 265	265 510	-53
Grey	323 180	245 775	-24
Total dead	877 445	502 285	-43
Green	420 925	323 180	-23
Total	1 298 370	825 465	-36
Douglas-fir	1 224 130	352 560	-72
Ponderosa pine	12 430	7345	-41
Spruce	54 805	213 005	289
All conifers	2 609 735	1 398 375	-46

Table 6. Estimated costs for damage survey (370 km^2 area).

1.	Cost of imagery			
	a. Conventional aerial photography:			
	- Film (2443 and 2445) and processing	$755.40		
	- Reproductions (Transparencies and prints)	$733.00		
	- Aircraft mileage @ $18.50/mile	$1010.40		$2498.80
	b. Digital MSS imagery:			
	- magnetic tape, dry-silver MSS prints	$43.80		
	- Landsat Computer Compatible Tape	$200.00		
	- color prints MSS imagery	$176.00		$419.80
	c. Supplementary 70 mm and 35 mm photography:			
	- color film, processing and printing	$525.00		
	- aircraft rental (3 hrs. @ $250)	$750.00		$1275.00
2.	Cost of field work:			
	a. Collection of ground data (20 days)	$1600.00		
	b. Field expenses	$1300.00		
	c. Vehicle fuel	$450.00		$3350.00
3.	Cost of image analysis, mapping and data compilation.			
	a. Preliminary work (14 days)	$1100.00		
	b. Photo interpretation	$2600.00		
	c. Analysis of photo plots	$4300.00		
	d. Mapping and data compilation	$2400.00		
	e. Base maps reproductions, B & W photographs	$90.00		$10 490.00
TOTAL COST:				$18 033.60
1.	Cost of imagery:	$4193.60	(23%)	or $11.33/km^2
2.	Cost of field work:	$3350.00	(19%)	or $ 9.05/km^2
3.	Cost of image analysis, mapping and compilation:	$10 490.00	(58%)	or $28.35/km^2
		$18 033.60	(100%)	$48.74/km^2

Infrared Type 2443 - were found useful for the detection of beetle infestations.

Aerocolor Negative Type 2445 film is a high speed, fine-grained, general purpose color film which allows rapid production of color (or black and white) prints and transparencies. Because of poor haze penetration when this film is exposed from high altitudes and because of difficulties in discerning discoloration patterns on 1:56 000 scale stereoscopic prints, normal color small-scale photography is not recommended for the assessment of beetle-infested stands. However, at medium (1:19 000) and large (1:8000) scales, normal color photography was as good as, or even better than, color infrared film for discrimination of damage intensities.

Aerochrome Infrared Type 2443 film is a false color reversal film in which the three emulsion layers are sensitive to green, red and infrared radiation (instead of the usual blue, green and red for normal rendition of the visible spectrum). While actual tones of exposed film vary with image saturation, generally objects that reflect green appear blue, red objects appear green, and those that reflect infrared wavelengths, such as chlorophyll in vegetation, appear red. The high contrast, sensitivity to near infrared wavelengths, and good color differentiation between objects of similar brightness but different spectral reflectances are factors that make this film particularly suitable for assessment of damaged vegetation. Also, because it suffers less degradation from scattering, non-image forming, short-wave radiation than normal color film, color infrared film is strongly recommended for high-altitude photography. Some disadvantages of color infrared film include a slow effective speed, limited exposure latitude, poor shadow penetration, and more "edge fall off" than normal color film. Also, it costs about 62% more than normal color film.

5. For stereoscopic analysis of extensive areas, photo interpreters generally prefer good quality color prints instead of transparencies because the required color reproductions may be made to a specified color saturation. Furthermore, classification data can be placed directly on the paper print during the analysis, and plotting of interpreted details to a map may be done with simpler equipment than is the case with transparencies. Because the exactness of color balance may be controlled more easily on a negative original, it is recommended that the feasibility of processing color infrared film to a negative, instead of the customary transparency, should be examined. Use of a negative instead of a transparency will allow production not only of color infrared prints but also of inexpensive black and white copies by using subtractive filters to enhance the selected ranges of the spectrum. Filtration during printing can broaden the exposure latitude and provide greater scope for correcting any errors in exposure and color balance. This processing technique has been successfully used for the detection of root rot damage (Gimbarzevsky 1983), and has been tested by the Ontario Centre for Remote Sensing (V. Zsilinszky, Director, Ontario Centre for Remote Sensing, personal communication, 1983).

6. The 70-mm large-scale vertical and oblique color photography provided the essential data for proper interpretation of discoloration patterns, determination of damage intensity levels, and quantification of damage losses. The oblique color slides taken during overflights were indispensable aids for stratification of forest cover on small-scale aerial photographs and for identification of beetle-infested forest types. This supplementary photography greatly reduced the amount of field work by enabling rapid verification of interpretation from photographs. It also allowed counts and measurements of affected trees with a precision equal to that of ground sampling.

7. A cartographic presentation of infested stands on existing forest inventory maps provided an adequate base for determination of damaged areas and for compilation of losses within approximately 300 beetle-infested forest stands. Modified cover type maps that display superimposed beetle-infested areas may be used for rapid updating of forest inventory data.

8. The accuracy with which infested stands could be identified on small and medium-scale aerial photographs and the precision with which damaged trees could be counted on large-scale stereo-pairs of photoplots were adequate for purposes of operational levels of forest inventory.

9. The actual costs of the survey were recorded where possible. In general, image analyses and data collection and compilation, requiring about 160 person-days, accounted for almost three-quarters of the total cost. The remaining 25% of the cost involved direct expenses, mainly for the imagery. Some expenditures associated with the experimentation with two types and four scales of photography could be eliminated if the methods outlined here were applied operationally. Further efforts to reduce costs should focus on simplification of the image analysis and photo measurement procedures. For example, a video recorder system used during the flight for sampling photography would be an effective alternative to the time-consuming work of pinpointing the exact location of

photo plots within corresponding forest types. Also, photogrammetric measurement of photo-plots on a digital plotter would speed up compilation and thereby reduce its cost.

10. Additional work should include the following: aerial video recording of infested areas should be undertaken and video tapes should be integrated with other survey data; recent MSS products, particularly the Multi-spectral Linear and Panchromatic Array imagery obtained by the Thematic Mapper (TM) and the SPOT systems, should be used to assess forest damage; operational uses of recent microcomputer-based instruments for rapid analysis and quantification of survey data should be evaluated.

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References

Backman, B.; Gregg, T.; Johnsey, R. 1978. Washington State Forest Insect Survey: combining aerial sketch map and remote sensing techniques. Pages 445-463 *in* Proceedings of the Symposium on Remote Sensing for Vegetation Damage Assessment. February 14-16, 1978. Seattle, Washington.

British Columbia Ministry of Forests. 1981. Stereocord Handbook. Forest cover map series. Map sheets 92J/15-c, -d, -e, -f, and -g. Inventory Branch, Victoria. 60 p.

Buchman, N.; Hall, R.C. 1975. Comparison of digital and visual evaluation of LANDSAT-1 imagery for detection and monitoring of forest insect infestations. Pages 34-37 *in* Proceedings of the workshop for environmental applications of multispectral imagery. November 11-13, 1975. Fort Belvoir, Virginia. U.S. Army Topographic Laboratory.

Ciesla, W.M. 1974. Forest insect damage from high-altitude color-IR photos. Photogramm. Eng. 40:683-689.

Ciesla, W.M. 1977. Color vs. color-IR photos for forest insect surveys. Pages 31-42 *in* Proceedings of the sixth biennial workshop on aerial color photography in plant sciences and related fields. August 9-11, 1977. Fort Collins, Colorado. American Society of Photogrammetry.

Ciesla, W.M.; Klein, W.H. 1978. Inventory of bark beetle mortality in coniferous forests with color and color-IR photography. Proceedings of the international symposium on remote sensing for observation and inventory of earth resources and the endangered environment. G. Hildebrandt and H.J. Boehnel, Eds. July 2-8, 1978. Freiburg, Federal Republic of Germany. International Archives of Photogrammetry 22:2001-2011.

Craig, R.D. 1920. An aerial survey of forests in northern Ontario. Can. For. Magazine 16(11):516-518.

Dillman, R.D. 1982. Estimating mountain pine beetle-killed ponderosa pine over the front range of Colorado with high altitude panoramic photography. Phot. Eng. and Rem. Sens. 48:741-747.

Dillman, R.D.; Eav, B.C.; Prill, J.C. 1979. Evaluation of high altitude imagery for assessment of mountain pine beetle. Pages 165-177 *in* Proceedings of the seventh biennial workshop on aerial color photography in the plant sciences and related fields. May 15-17, 1979. University of California, Davis, California. American Society of Photogrammetry.

Dillman, R.D.; Shen, S.S.; Eav, B.C.; White, W.B. 1981. Operational test of panoramic aerial photography for estimating annual mortality of ponderosa pine caused by mountain bark beetle. Nationwide Forestry Application Program. U.S.D.A. Forest Service, Houston, Texas. 22 p. + Appendix.

Gimbarzevsky, P. 1983. Remote sensing of slope failure on the Queen Charlotte Islands. Proceedings of the RNFRF symposium on the application of remote sensing to resource management. May 22-27, 1983. Seattle, Washington. ASP. 8 p + illustrations.

Gimbarzevsky, P. 1984. Remote sensing in forest damage detection and appraisal: a selected annotated bibliography. Can. For. Serv. Pac. For. Res. Cent., Victoria. Inf. Rep. BC-X-25. 55 p.

Hall, R.C.; Wert, S.L.; Koeber, T.W. 1974. Application of ERTS-1 imagery and underflight photography in the detection and monitoring of forest infestations in the Sierra Nevada mountains of California. Natural Resources Corporation. 44 p.

Harris, J.W.E. 1972. High-level photography for forest insect damage surveillance in British Columbia. Pages 145-148 *in* Dennis White, editor. Proceedings of the first Canadian symposium on remote sensing, Feb. 1972 Ottawa. Department of Energy, Mines and Resources, Ottawa.

Harris, J.W.E. 1974. Small-scale imagery in forest pest surveys in British Columbia. Can. Surv. 28:126-127.

Harris, J.W.E.; Dawson, A.F. 1979. Evaluation of aerial forest pest damage survey techniques in British Columbia. Can. For. Serv. Pac. For. Res. Cent., Victoria. Inf. Rep. BC-X-198. 22 p.

Harris, J.W.E.; Dawson, A.F.; Brown, R.G. 1982. Evaluation of mountain pine beetle damage using aerial photography, Flathead River, B.C. Can. For. Serv. Pac. For. Res. Cent. Victoria, Inf. Rep. BC-X-228. 10 p.

Harris, J.W.E.; Dawson, A.F.; Brown, R.G. 1983. Evaluation of mountain pine beetle damage using aerial photography taken with a hand-held 70 mm camera, Gold Bridge-Clinton, B.C. 1981. Can. For. Serv. Pac. For. Res. Cent., Victoria. Inf. Rep. BC-X-245. 15 p.

Heller, R.C.; Aldrich, R.C.; Driscoll, R.S.; Francis, R.E.; Weber, F.P. 1974. Evaluation of ERTS-1 data for inventory of forest and range-land detection of forest stress. U.S.D.A. For. Serv. Res. Paper PSW-112. 276 p.

Hobbs, A.J. 1983. Effects of air-photo scale on early detection of mountain pine beetle infestation. M.Sc. Thesis. University of British Columbia, Vancouver. 137 p.

Holland, S.S. 1976. Landforms of British Columbia. A physiographic outline. B.C. Dept. of Mines and Petroleum Resources, Victoria, B.C. Bulletin 48. 138 p. + foldout map.

Hostetler, B.B.; Young, R. 1979. Estimation procedures for determining annual tree mortality caused by the mountain pine beetle (*Dendroctonus ponderosae*). U.S.D.A. Forest Service, Mountain Region, For. Insect and Disease Management, State and Private Forestry, Lakewood, Colorado. Tech. Rep. R2-20. 25 p.

Klein, W.H. 1982. Estimating bark beetle-killed lodgepole pine with high altitude panoramic photography. Photogramm. Eng. Rem. Sens. 48:733-737.

Klein, W.H.; Bennett, D.D.; Young, R.W. 1978. Multiphase airphoto assessment for annual losses caused by the mountain pine beetle in lodgepole pine. Pages 355-367 in Proceedings of the symposium on remote sensing for vegetation damage assessment. February 14-16, 1978. Seattle, Washington. American Society of Photogrammetry.

Klein, W.H.; Bennett, D.D.; Young, R.W. 1982. Evaluation of panoramic reconnaissance aerial photography for measuring annual mortality of lodgepole pine caused by mountain pine beetle. U.S.D.A. For. Serv., Methods Application Group, Forest Insect and Disease Management, Davis, California. Rep. 80-2. 21 p.

McHail, R.R.; Kreckel, K.H.; Fiammi, M.A. 1984. The RMSTM Resource Management System, description and applications. Pages 147-150 *in* G.J. Edwards, editor. Proceedings of the ninth biennial workshop on color aerial photography in the plant sciences and related fields. November 15-19, 1983, Orlando, Florida. American Society of Photogrammetry.

Murtha, P.A. 1972. A guide to air photo interpretation of forest damage in Canada. Can. For. Serv., Ottawa. Pub. No. 1292. 65 p.

Mussakovski, R.S. 1984. Application of video remote sensing to resource surveys and environmental monitoring. Pages 91-99 *in* K.P.B. Thomson and F. Bonn, editors. Proceedings of the eighth Canadian symposium on remote sensing. May 3-6, 1983, Montreal. Ontario Centre for Remote Sensing.

Nixon, P.R.; Escobar, D.E.; Bowen, R.L.; Richardson, A.J. 1984. Video color infrared imagery: a future natural resource management tool. Pages 159-165 *in* Proceedings of the ninth biennial workshop on color aerial photography in the plant sciences and related fields. American Society of Photogrammetry.

Wood, C.S.; Van Sickle, G.A. 1983. Forest insect and disease conditions, British Columbia and Yukon, 1982. Can. For. Serv. Pac. For. Res. Cent., Victoria. Inf. Rep. BC-X-239. 31 p.

Wood, C.S.; Van Sickle, G.A.; Humble, L.M. 1987. Forest insect and disease conditions - British Columbia and Yukon, 1987. Can. For. Serv. Pac. For. Cent., Victoria. Inf. Rep. BC-X-296. 40 p.

Zwick, H.H.; McColl, W.D.; Edel, H.R. 1980. The CCRS DS1260 multi-spectral scanner (MSS). Pages 643-648 *in* Proceedings of the sixth Canadian symposium on remote sensing. May 21-23, 1980. Halifax, N.S. Canadian Centre for Remote Sensing, Ottawa.