APPLICATION OF ERTS-1 IMAGERY & UNDERFLIGHT PHOTOGRAPHY IN THE DETECTION AND MONITORING OF FOREST INSECT INFECTATIONS IN THE SIERRA NEVADA MOUNTAINS OF CALIFORNIA

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May 31, 1974

Draft Copy of Type III Final Report

Period June 21, 1972 - May 31, 1974

Prepared for

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland 20771

NRM Natural Resources Management Corporation
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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NRM-III		
4. Title and Subtitle APPLICATION OF ERTS-1 IMAGERY & UNDERFLIGHT PHOTOGRAPHY IN THE DETECTION & MONITORING OF FOREST INSECT INFESTATIONS IN THE SIERRA NEVADA MTS. OF CALIFORNIA		5. Report Date May 31, 1974
		6. Performing Organization Code
7. Author(s) Dr. Ralph C. Hall, S. Wert & Dr. T.W. Koerber		8. Performing Organization Report No. NRM-III
9. Performing Organization Name and Address NATURAL RESOURCES MANAGEMENT CORP. P. O. Drawer 1247 Eureka, Ca. 95501 (707)442-1735		10. Work Unit No.
		11. Contract or Grant No. NAS5-21770
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered TYPE-III Final Report 6-21-72 to 5-31-74
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Analysis of ERTS-1 imagery with underflight aerial photo support including U-2, in the Sierra Nevada Mountains of California indicates promising possibilities of detecting and monitoring forest insect outbreaks visually with some mechanical support utilizing the VP-8 Image Analyzer. Visually, it is possible at a scale of 1:1,000,000 to discriminate between large areas of damaged and undamaged forests; timbered and non-timbered areas; pasture land and cultivated fields; desert and riparian vegetation. At a scale of 1:80,000 it is possible to distinguish among three classes of tree mortality; defoliated and undefoliated areas; non-host mixed conifers; and mountain meadows, rock domes, lakes, and glaciers. Machine tests showed significant differences in image densities among various bands and mortality areas.

17. Key Words (Selected by Author(s))	18. Distribution Statement		
Ecology-Epidemiology-Forestry-Entomology-Interpretation Technique-Development (Forest Insect)			
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

Figure 2. Technical Report Standard Title Page

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PREFACE

(a) OBJECTIVE

The overall objective of this study was to develop space data acquisition methodology which would permit rapid, accurate and comprehensive detection and monitoring of forest insect infestations and other causes of physiological stress and morbidity in vegetative ecosystems through the use of ERTS-1 imagery both alone and supplemented by underflight photography. When fully developed, this methodology would eliminate the present need for expensive, patchwork aerial and ground surveys, would provide a continuously up-dated basis for operational programs of control and salvage, and would permit frequent evaluation of economic and ecological impact of existing and impending infestations as a basis for determining broad research and control strategies.

(b) SCOPE OF WORK

The test site selected was in the Sierra Nevada Mountains of California with the principal target area centered in the Yosemite National Park, representing some of the most rugged mountainous terrain in the West. Extensive ground truth data, representing all degrees of insect damage from none to very heavy in a generally pure stand of lodgepole pine, were collected to serve as a basis for evaluating the effectiveness of ERTS-1 imagery both alone and in combination with underflight photography in detecting varying degrees of forest insect damage. Most of the evaluation was done visually. Some machine evaluation was done with the VP-8 Image Analyzer.

(c) CONCLUSIONS

ERTS-1 imagery (color composites of Bands 4, 5, and 7 at the scale of 1:1,000,000) is not adequate, unsupported, for the identification and close evaluation of forest insect damage. However, it appears to discriminate sufficiently between normal and very abnormal conditions in a fairly homogeneous forest to assist in the detection of heavy insect outbreaks.

Enhanced color composites of ERTS imagery enlarged to 1:80,000 and visually interpreted, permit detection of heavy defoliation and light, medium, and heavy mortality with a reasonably high degree of reliability.

Close mapping and evaluation of damage still require underflight support, for which NASA U-2 imagery should be adequate in most cases, especially if enlarged to 1:18,500 scale.

Visual interpretation at scales of 1:18,500 or more requires highly skilled interpreters.

Machine interpretation, using the VP-8 Image Analyzer, permits a higher degree of discrimination and probably more rapid and consistent work; and appears to hold considerable promise for outbreak detection.

(d) RECOMMENDATIONS

It is recommended that (a) further research be conducted to improve the resolution of ERTS imagery; (b) further research be done in the enhancement of ERTS color composites for visual interpretation; (c) further study and development of machine interpretation systems be undertaken.

1. INTRODUCTION

In the general field of pest management, early detection and monitoring of insect outbreaks are of paramount importance in the protection and management of our natural resources. Once an insect pest reaches outbreak proportions, suppression measures become very costly and, even if effective, are applied only after the host crop has been severely damaged. This is particularly true of forest insect outbreaks in remote areas.

The U.S. Forest Service has estimated that insects alone cause losses of 10 billion board feet annually, equal to about half the volume of wood used in all residential construction in the U.S. The value of this insect-killed timber is more than 250 million dollars on the stump. In California alone, annual insect losses amount to 1.5 billion board feet valued at 35 million dollars.

Since the demand for wood is expected to exceed the supply by 1990, at the present level of forest management practice, early detection and control of insect outbreak and the prompt salvage of dead timber are vital to the economy.

In California, the U.S. Forest Service conducts annual aerial detection surveys on 18 National Forests totaling about 20 million acres, and the California Division of Forestry covers the 10 million acres of state and private forest lands. Infestations are observed from low flying aircraft, noted on a map in their approximate location, and later evaluated on the ground if the infestation appears to be of a serious nature. Such surveys are expensive and difficult to coordinate on a broad scale. Although millions of dollars are spent annually for the purpose, much of the U.S.--and most of the world--forest and wildland areas receive little or no surveillance.

The overall objective of this study was to develop space data acquisition methodology which would permit rapid, accurate and comprehensive detection and monitoring of forest insect infestations and other causes of physiological stress in forest stands. This methodology would employ the use of ERTS-1 imagery alone or supplemented by underflight sample photography; and when fully developed would eliminate the present need for expensive, patchwork aerial and ground surveys, would provide a continuously up-dated basis for operational programs of insect control and timber salvage, and would permit frequent evaluation of the economic and ecological impact of infestations as a basis for determining broad research and control strategies.

The immediate aims were to determine the effectiveness of ERTS-1 imagery in depicting outbreaks of the lodgepole needle miner (Recurvaria milleri Busck.) and the mountain pine beetle (Dendroctonus ponderosae Hopk.) in the lodgepole pine forests of the Yosemite National Park area of the Sierra Nevada mountains, and to develop procedures for visually delineating the areas of infestations, rating the intensity of attack, and evaluating damage to the forest.

Defoliation of lodgepole pine by the needle miner and tree mortality caused by mountain pine beetle are readily detected by eye both on the ground and from aircraft. Aerial color photos were used successfully in 1968 to detect and evaluate outbreaks of the mountain pine beetle in sugar and ponderosa pine in Shasta County, California, and to detect a small outbreak of the mountain pine beetle in lodgepole pine at South Lake Tahoe during the summer of 1970. The effectiveness of Ektachrome infra-red photography in evaluating browse plant defoliation by insects was demonstrated by the senior author in Oregon in 1967.

In the present study, ERTS-1 imagery was used, supplemented by U-2 high altitude aerial photography, middle altitude (1:18,500) color infrared aerial photography, and low level (1:5,000) color and color infrared photography. Multi-stage sampling and ground-truth data collection were relied on to provide hard information.

In addition to visual interpretation by a number of observers and correlation of the imagery listed above, machine interpretation was performed on ERTS-1 imagery using the VP-8 Image Analyzer.

Completion of field and laboratory exercises was seriously delayed by failure to receive NASA-supplied imagery on schedule.

2. THE RESEARCH TEAM

The following contractor, sub-contractor, and cooperator personnel participates in the research:

Natural Resources Management Corporation (Contractor):

Dr. Ralph C. Hall, Principal Investigator
Dr. B. H. Wilford, Assistant
Dr. W. O. Thomas Jr., Test Site Coordinator
Thomas E. Berry, Photo Interpreter
William Dann, Technician

Earth Satellite Corporation (sub-contractor):

Dr. Robin Welch, Underflight Photography and Photo Interpreter Testing
Dr. Phillip G. Langley, Multi-stage Sampling
Stephen Wert, Photo Interpretation
Stephen Daus, Photo Interpretation

U.S. Forest Services (Cooperator)

Dr. Thomas W. Koerber, Research Entomologist, Ground Truth and Biological Data on Needle Miner
Ralph McFarland, Chief Photographer, Pacific Southwest Forest, Range Experiment Station, Imagery Enhancement
Robert W. Gustafson, Forest Pest Branch, Region Six, U.S.F.S., aerial observation and imagery checks by helicopter.

3. THE TEST SITE

The test site (Figure 1 and 2) selected was in the Sierra Nevada Mountains of California, for which the Pacific Southwest Forest and Range Experiment Station had long standing research evidence of the existence of heavy damage by the mountain pine beetle and where an outbreak of the lodgepole needle miner was expected to develop during the course of the study.

The area is centered in the Yosemite National Park and represents some of the most rugged mountainous terrain in the West, with elevations ranging from about 7,500 to more than 12,000 feet, and with subalpine coniferous forests in which lodgepole pine is the dominant tree species.

Because of the wide range in sizes of the infested timber blocks, it was expected that the test site would offer an opportunity to determine the smallest area of infestation consistently identifiable from (a) ERTS-1 imagery, (b) conventional aerial photography, and (c) a combination of both.

4. PEST CHARACTERISTICS

The two dominant pest species in forests of the test site were the lodgepole needle miner and the mountain pine beetle.

The lodgepole needle miner is one of the most destructive defoliators of some of California's most scenic mountain forests. The caterpillars of this inconspicuous moth feed within the pine needles (Figure 3) and have a two-year life cycle, with maximum damage and discoloration of the needles occurring at the end of the second year. In the early stages of larval development the infested needles change from dark green to a light lemon color, which turns to light brown by the end of the season, and to dark brown tinged with red by the fall of the second season. The changing color of the infested foliage is usually the first symptom of damage noted.

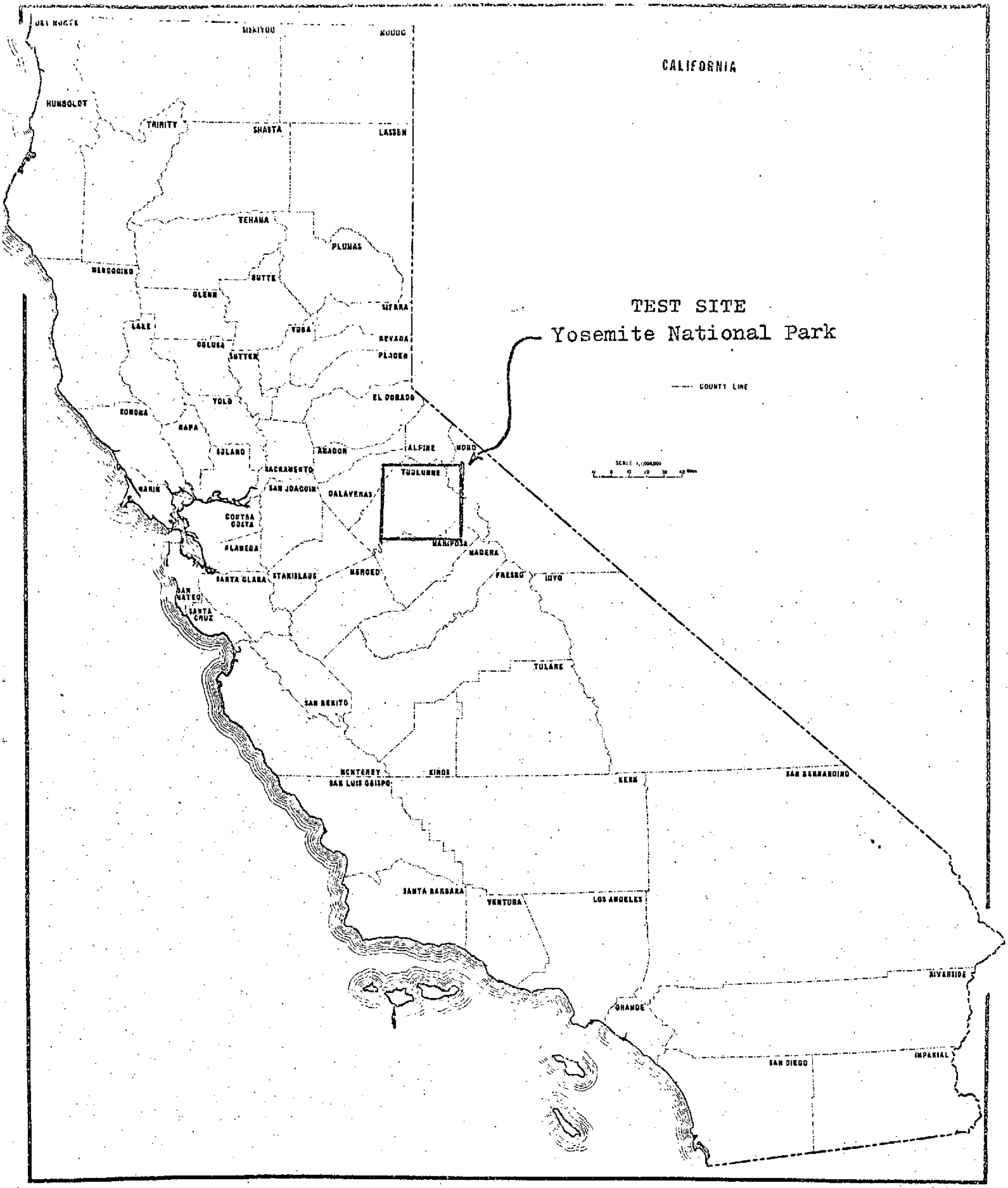
CALIFORNIA
TEST SITE
Yosemite National Park
COUNTY LINE
HUMBOLDT
TRINITY
SHASTA
LASSEN
TEHAMA
PLUMAS
BUTTE
GLENN
SIERRA
LAKE
YUBA
NEVADA
COLUSA
SUTTER
PLACER
YOLO
EL DORADO
SONOMA
NAPA
SOLANO
AMADOR
ALPINE
MONO
SACRAMENTO
TUOLUMNE
MARIN
SAN JOAQUIN
CALAVERAS
CONTRA COSTA
ALAMEDA
MARIPOSA
MADERA
STANISLAUS
MERCED
SANTA CLARA
FRESNO
INYO
SAN MATEO
SANTA CRUZ
TULARE
SAN BENITO
MONTEREY
KINGS
SAN LUIS OBISPO
KERN
SAN BERNARDINO
SANTA BARBARA
VENTURA
LOS ANGELES
RIVERSIDE
ORANGE
SAN DIEGO
IMPERIAL

Figure 1

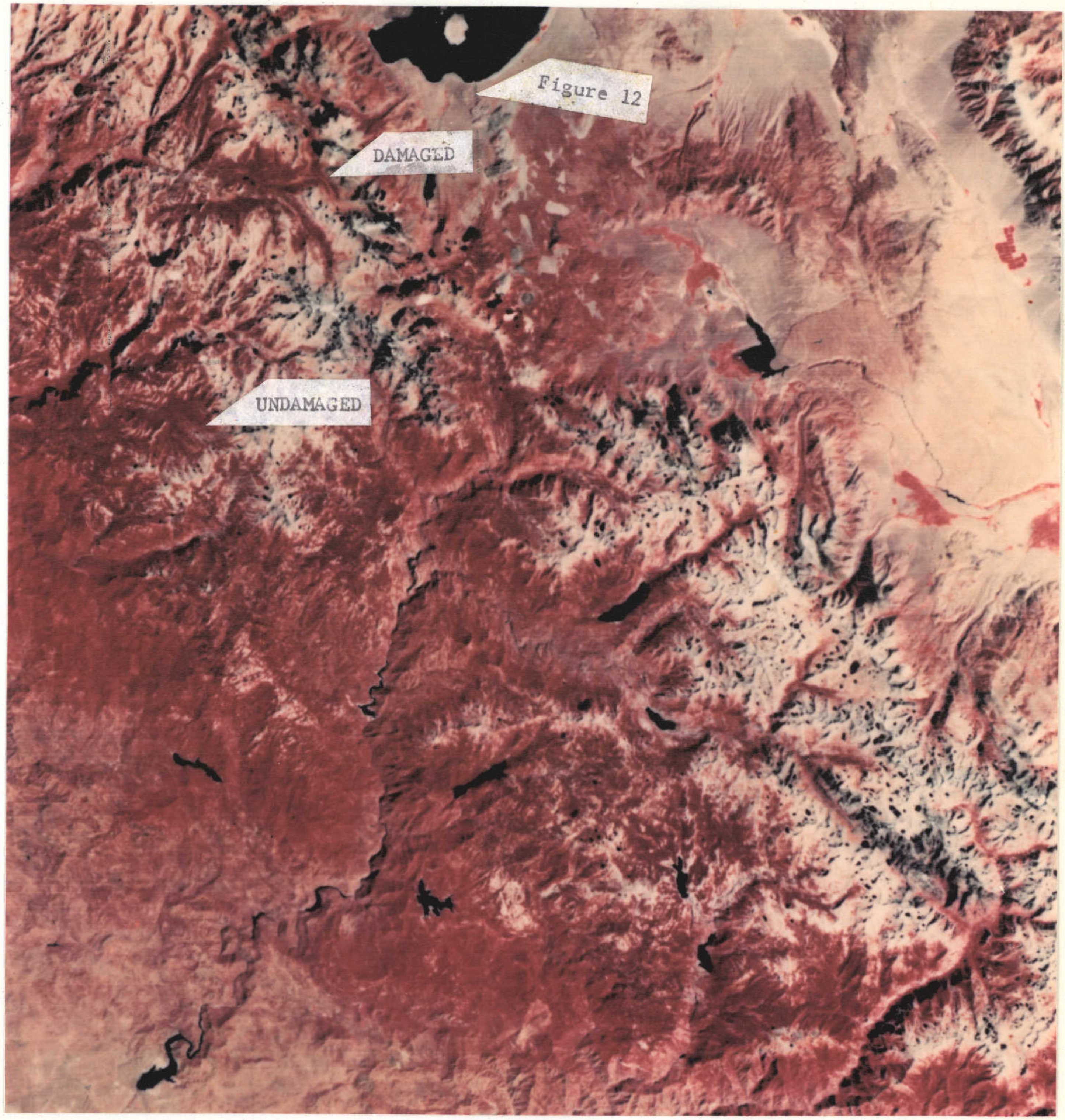

Figure 2

A Kodachrome II copy of a color compositive transparency supplied by NASA, frame #1055-18055, 16 September, 1972. Mono Lake, upper center, with insect damaged forest, milk chocolate brown, southwest from Mono Lake. Undamaged forest, cherry red. Crest of the Sierra Mountains running diagonally from northwest corner to southeast corner. Timbered area in a parallel band to the west, generally cherry red, farther to the west, a band of pasture land, generally lavender, with agriculture land in the extreme southwest corner. Immediately to the east of the Sierra Crest desert land, lemon yellow, with riparian vegetation along streams, and patches of agriculture land, blood red. White Mountains, diagonally in northeast corner.

Figure 3

An extensive area of lodgepole pine in the Virginia Canyon area, which was heavily defoliated by the lodgepole needle miner during the summer of 1973. Note the belt of non-host green trees, predominantly mountain hemlock, in the upper right hand corner. Insert, upper left corner, illustrates the mining of the needles by the lodgepole needle miner. Kodachrome II from the helicopter, 31 July, 1973.

The mountain pine beetle is one of the most destructive bark beetles in the West, particularly in lodgepole pine. The adult beetle deposits its eggs in galleries under the bark of the host tree, and the larvae then enlarge these tunnels. Trees already weakened by defoliation or other physiological or pathological stress are particularly susceptible to attack. The color change in the foliage of trees attacked by the beetle follows the same pattern as in the case of the needle miner, except that the discoloration cycle occurs within a single year and reds, rather than browns, predominate. (Figure 4)

5. IMAGERY AVAILABLE

The imagery available for this study included the following:

ERTS-1 Imagery, Bands 4, 5, 6, and 7
- 16 September 1972, E-1055-18055 (Figure 2)
- 13 June 1973, E-1325-18063
- 11 September 1973 E-1415-18051

U-2 Underflight Photography (NASA)
- April, May, June, 1972 - 70 mm Vinten System A & B
- 27 July 1972 - RC-10 Aerchrome IR, 9 x 9
- 29 June 1973 - A-1 (vertical only), 9 X 18, HR-732

Conventional aerial photography (subcontractor)
- July, 1972 - Ektachrome Color - IR @ 1:18,500 of the entire target area, 9 x 9
- July, 1972 & 1973 - Ektachrome Color and Color IR @ 1:5,000 of 16 selected sample areas, 9 x 9

35mm, hand-held, from helicopter
- Various times throughout project - Ektachrome and Kodachrome. (Figures 3 and 4)

In addition, ground shots were taken of various phases of the project at different times, using 35mm Ektachrome and Kodachrome.

Figure 4

An area of lodgepole pine in the Cathedral Lake Area, where practically all of the mature trees have been killed by the combination of the needle miner and the mountain pine beetle. This is an example of a newly formed "Ghost Forest." Note the white rocks and understory of grasses and reproduction of lodgepole pine trees which are replacing the older dead trees. Insert in upper left corner illustrates the work of the mountain pine beetle, in the mature and pupal stages, under the bark of a lodgepole pine tree. Kodachrome II, 19 September, 1972.

6. PROCEDURE

Office procedures included photo-interpretation of both conventional and U-2 aerial photography, and ERTS-1 imagery. Most of the interpretation was visual, although a limited amount of ERTS-1 interpretation was by means of the VP-8 Image Analyzer. Other office procedures included the analysis of ground truth data gathered on the mortality plots and defoliated areas.

Field procedures included collection of data from twenty-seven sample plots, three each on nine mortality study areas, the locations of which are shown by numbers on Figure 5. In addition, various types of imagery were carried into the field and compared with conditions on the ground, both on foot and by helicopter, principally to delineate areas of needle miner defoliation.

6.1. Aerial Photo Interpretation and Stratification of Damage Areas.

The first step involved interpretation of the 1:18,500 scale photos so as to (a) delineate areas of needle miner defoliation; and (b) stratify the entire target area into light, medium, and heavy classes of tree mortality resulting from the combined effects of needle miner and bark beetle infestation.

The second step was to divide each of the 1:5,000 photos (both color and color-IR) into sample plots 4 to 10 acres in size, each of which was then examined visually to determine the number of freshly faded trees, and the number of older dead trees.

The third step was to select, at random, three of these sample plots in each of the nine mortality study areas for field examination. Sample plot corners were marked on the photos for subsequent location in the field.

Figure 5

Location of Mortality Study Areas, Numbered 2, 3, 4, 5, 6, 9, 10, 12, 13, and 16; and Defoliation Study Areas Numbered 1, 7, 8, 11, 14, and 15. Yosemite National Park, 1972-73.

6.2. Collection of Ground Truth Data

Ground truth data collected included tree mortality, defoliation, and vegetation changes resulting from insect damage of the lodgepole pine overstory.

6.2.1 Tree Mortality Data

Tree mortality data were gathered on the ground on each of the predetermined, randomly selected sample plots outlined on 1:5,000 photos as described above.

The corners of each sample plot were located on the ground by matching with the previously marked photos. Field crews, varying from three to six men, then ran string around the sample plot boundaries and measured and tallied all of the trees, including live undamaged, live damaged, dead standing, and down trees, over 10" in diameter at breast height (dbh), by species, dbh (in 2" classes), height, and condition.

6.2.2. Defoliation Data

Defoliation data were gathered by Dr. Thomas Koerber by taking branch tips at about mid-crown from a number of randomly selected trees in six areas of infestation, the locations of which are shown in Figure 5. These were analyzed in the laboratory for total number of needles, number and percent of needles mined, and oven-dry weight of needles per sample tip.

6.2.3. Vegetation Change Data

Dr. Koerber collected vegetation samples from a series of four plots, each containing 9.6 square feet, in each of two locations: one where no upperstory defoliation had occurred, and one where heavy defoliation and tree mortality occurred about 1960. Samples included the complete ground cover, composed of grasses, sedges, forbs, brush, and sedums, which was oven dried. The results were expressed in pounds of each type of vegetation per acre for each location.

6.3. Analysis of Ground Truth Data

The ground truth data analyzed included tree measurements and classifications from 27 sample plots on nine mortality study areas; needle miner defoliation data (oven-dry weight of branch tips) from six areas of infestation; and vegetation sample weights from two dissimilar areas.

6.3.1. Mortality Data

The distribution of lodgepole pine by dbh class, including both live and dead trees, is shown for all mortality study areas combined in Table 1:

Table 1

DISTRIBUTION OF LODGEPOLE PINE TREES BY DIAMETER CLASS
MORTALITY STUDY AREAS, YOSEMITE NATIONAL PARK, 1972-73

Diameter Breast Height Inches	Average No. of Trees Per Acre	Diameter Breast Height Inches	Average No. of Trees Per Acre
10	9.0	34	1.0
12	10.0	36	1.0
14	8.0	38	1.0
16	6.0	40	0.6
18	7.0	42	0.4
20	7.0	44	0.3
22	6.0	46	0.2
24	6.0	48	0.2
26	5.0	50	0.1
28	3.0	52	0.1
30	3.0	56	0.1
32	3.0	60	0.1
		Total	78.0

The occurence of other tree species in mixture with the lodgepole pine on individual mortality study areas is shown in Table 2. In order of their frequency of occurrence, these species were: Mountain hemlock, *Tsuga mertensiana* (Bong.) Carr; Western white pine, *Pinus monticola* Dougl.; California red fir, *Abies magnifica* A. Murr.; and Limber pine, *Pinus flexilis* James.

Table 2

OCCURRENCE OF TREE SPECIES OTHER THAN LODGEPOLE PINE MORTALITY STUDY AREAS, YOSEMITE NATIONAL PARK, 1972-73

Study Area	Damage Class	Percent of Total Number of Trees, Other Than Lodgepole Pine
Lyell-10	Light	6%
Tioga Pass-9	"	6%
Dana Fork-16	"	$<$1%
Dog Lake-6	Medium	$<$1%
Dingley-4	"	2%
Delaney-5	"	8%
Cathedral-12	Heavy	8%
Connes-2	"	10%
Youngs Lake-3	"	9%
Average		6%

Results of the analysis of mortality data are shown in Table 3, for areas described as having light, medium, and heavy damage.

In sample plots classed as having light damage, 2% to 39% of the trees, containing 3% to 39% of the volume, were dead. In mortality study areas classified as having light damage, the mortality (average of three sample plots) was 4% to 30% of the number of trees, containing 7% to 35% of the stand volume.

In sample plots classed as having medium damage, 25% to 64% of the trees, containing 37% to 78% of the stand volume, were dead. In mortality study areas classed as having medium damage, the mortality (average of three sample plots) was 28% to 59% of the number of trees, containing 41% to 73% of the stand volume.

In sample plots classed as having heavy damage, 70% to 83% of the trees, containing 80% to 92% of the volume, were dead. In mortality study areas classed as having heavy damage, 73% to 80% of the trees, containing 81% to 88% of the volume, were dead.

Table 3

INDIVIDUAL SAMPLE PLOT GROUND TRUTH MORTALITY SURVEY
YOSEMITE NATIONAL PARK - SEPTEMBER-OCTOBER, 1972 & JULY 1973
(Lodgepole Pine Only)

Study Area	Sample Plot	Trees Per Acre Live	Trees Per Acre Dead	Trees Per Acre Total	% Dead	Volume Per Acre, Mbm Live	Volume Per Acre, Mbm Dead	Volume Per Acre, Mbm Total	% Dead
LYELL-10 (light dam.)	B-1	102	31	133	23%	29	10	31	26%
	B-6	70	46	116	39%	18	12	30	39%
	B-5	92	36	128	38%	25	13	38	34%
Ave.		88	38	126	30%	24	12	33	35%
TIOGA PASS-9 (light dam.)	B-9	46	8	54	15%	30	6	36	17%
	B-10	70	6	76	8%	40	5	45	12%
	B-8	52	2	54	4%	20	1	21	4%
Ave.		56	5	61	8%	30	4	34	12%
DANA FORK-16 (light dam.)	B-1	107	4	111	4%	27	2	29	6%
	C-7	96	7	103	7%	28	4	32	12%
	C-10	146	3	149	2%	34	1	35	3%
Ave.		116	5	121	4%	28	2	30	7%
DOG LAKE-6 (medium dam.)	D-4	62	28	90	31%	18	14	32	43%
	D-6	44	16	60	26%	15	11	26	41%
	D-8	54	17	71	25%	18	11	29	37%
Ave.		54	20	74	28%	17	12	29	41%
DINGLEY-4 (medium dam.)	C-7	39	36	75	48%	12	23	35	64%
	D-5	37	24	61	40%	12	19	31	60%
	D-9	25	32	57	55%	8	17	25	69%
Ave.		31	31	62	50%	11	20	31	65%
DELANEY-5 (medium dam.)	B-1	44	57	101	56%	13	26	39	67%
	B-3	39	69	108	64%	9	32	41	78%
	D-9	33	40	73	55%	6	16	22	69%
Ave.		39	55	94	59%	9	24	33	73%
CATHEDRAL-12 (heavy dam.)	A-6	16	49	65	75%	5	24	29	82%
	B-7	15	39	54	72%	5	19	24	80%
	D-2	18	52	70	75%	6	25	31	82%
Ave.		16	46	62	74%	5	22	27	81%
CONNES-2 (heavy dam.)	2-A	29	116	145	80%	6	27	33	81%
	2-C	34	66	100	66%	3	16	19	83%
	2-B	31	73	104	70%	3	15	18	83%
Ave.		31	85	116	73%	4	19	23	83%
YOUNGLAKE-3 (heavy dam.)	3-A	14	71	85	83%	2	29	31	92%
	3-C	24	61	85	71%	4	19	23	83%
	3-B	22	114	136	83%	5	39	44	88%
Ave.		20	82	102	80%	4	29	33	88%
AVERAGE ALL AREAS									
Light		86	16	102	16%	28	6	34	18%
Medium		40	36	76	47%	12	19	31	61%
Heavy		22	71	93	76%	4	23	27	85%
Ave.		49	41	90	46%	15	16	31	56%

Average for the three classes of damage were: light, 16% of the trees and 18% of the volume dead; medium, 47% of the trees and 61% of the volume dead; heavy, 76% of the trees and 85% of the volume dead.

The statistical significance of the results shown in Table 3 is:

Analysis of Variance From
Table 3

Light vs Medium -	Trees	$F = 21.6 < 1\%$
	Volume	$F = 40.2 < 1\%$
Medium vs Heavy -	Trees	$F = 35.5 < 1\%$
	Volume	$F = 24.5 < 1\%$

The percentage of mortality is consistently lower in number of trees than in volume, indicating that the smaller trees are less susceptible to combined needle miner and bark beetle attack.

This relationship between tree size and susceptibility to damage is further shown in Table 4, for one mortality study area in each damage class.

From Table 4 it may be noted that in each damage class (light, medium, and heavy) the susceptibility of trees increases as tree size increases. This relationship is also shown in Figure 6.

Because the mortality study areas and sample plots were classified as to damage (light, medium, and heavy) on aerial photographs prior to field checking, there obviously is a high degree of correlation between photo-interpretive classification and ground truth.

Table 4

RELATIONSHIP BETWEEN TREE SIZE & SUSCEPTIBILITY TO INSECT DAMAGE

THREE MORTALITY STUDY AREAS
YOSEMITE NATIONAL PARK - 1972-73

NUMBER OF TREES PER ACRE

	TIOGA PASS - LIGHT				DINGLEY - MEDIUM				CATHEDRAL - HEAVY			
DBH	LIVE	DEAD	TOTAL	% DEAD	LIVE	DEAD	TOTAL	% DEAD	LIVE	DEAD	TOTAL	% DEAD
10	8	.1	8.1	1%	8	1	9	12%	4	3	7	31%
12	7	.3	7.3	4%	8	2	10	21%	5	5	10	38%
14	5	.4	5.4	8%	4	2	6	34%	3	6	9	62%
16	4	.3	4.3	7%	4	3	7	43%	2	6	8	70%
18	5	.4	5.4	7%	4	3	7	45%	1	7	8	76%
20	5	.4	5.4	11%	3	4	7	56%	1	6	7	74%
22	5	.4	5.4	9%	3	3	6	48%	1	5	6	71%
24	5	.4	5.4	8%	2	3	5	58%	1	4	5	75%
26	5	.2	5.2	5%	2	3	5	56%	.6	3	3.6	84%
28	4	.4	4.4	8%	1	1	2	59%	.3	2	2.3	90%
30	3	.3	3.3	10%	1	2	3	67%	.3	2	2.3	84%
32	2	.3	2.3	15%	1	2	3	77%	.3	2	2.3	87%
34	2	.2	2.2	9%	.2	.6	.8	74%	.1	1	1.1	91%
36	2	.2	2.2	13%	.1	.7	.8	85%		.5	.5	100%
38	1	.2	1.2	20%	.2	.6	.8	70%		.6	.6	100%
40	1	.2	1.2	27%	.1	.5	.6	91%		.3	.3	100%
42	.3	.1	.4	22%	.1	.3	.5	86%		.3	.3	100%
44	.2	.1	.3	33%	.1	.2	.3	71%		.2	.2	100%
46	.2	.1	.3	33%	.1	.1	.2	67%		.1	.1	100%
48	.1	.1	.2	50%	.1	.1	.2	75%		.1	.1	100%
50	.1	.1	.2	50%		.1	.1	100%		.1	.1	100%
52										.1	.1	100%
54												
56	.1	.1	.2	50%								
58												
60												
Tot.	65.0	5.3	70.3	8%	42.0	32.2	74.2	43%	19.6	54.4	74.0	74%

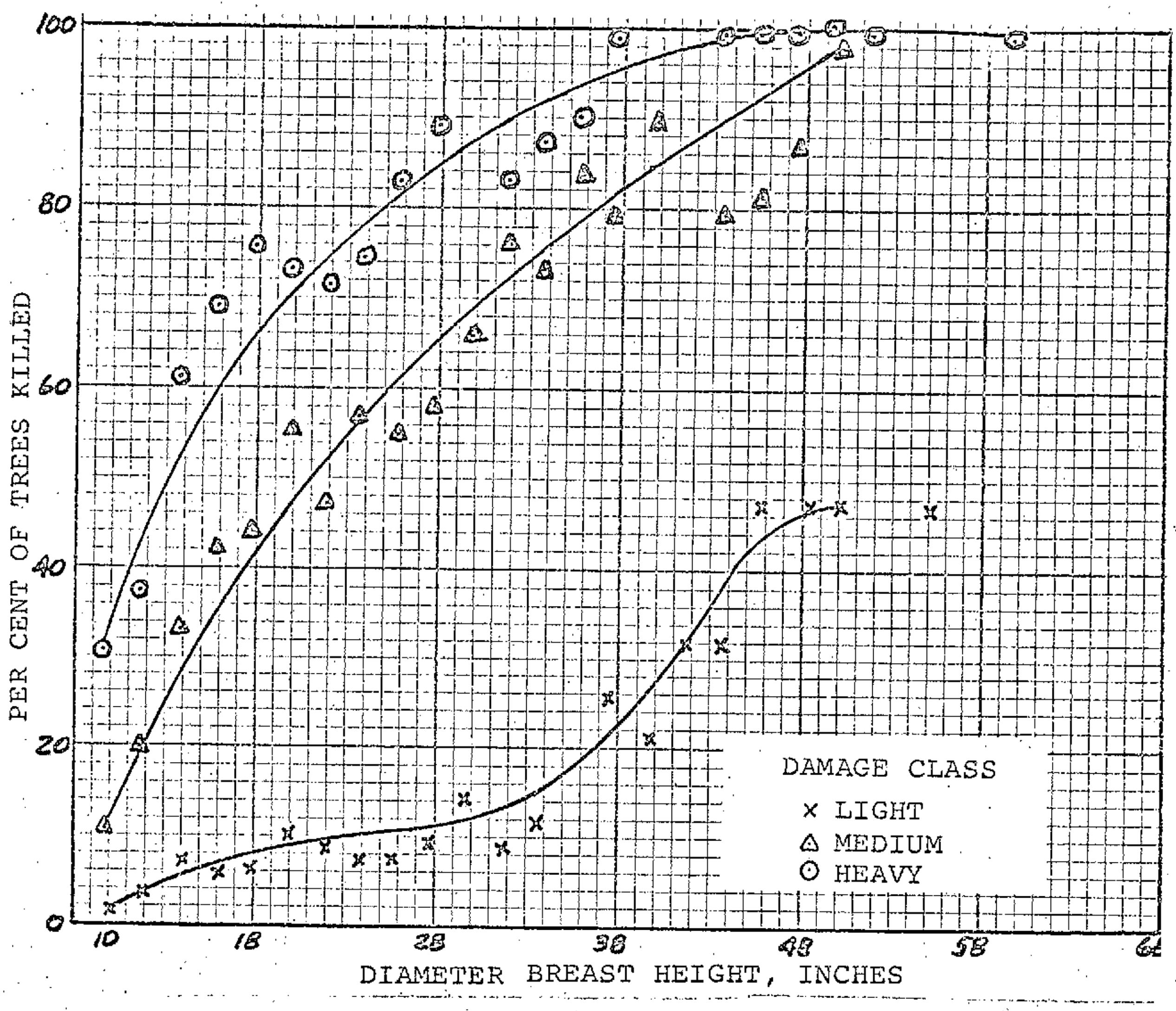

Figure 6

Relationship of Tree Mortality to Diameter
Lodgepole Pine only, Mortality Study Areas,
Yosemite National Park, 1972-73

6.3.2. Defoliation Data

An analysis of the study of oven-dry weights of needles per tip, for two heavily damaged areas (Lyell Fork-11 and Virginia Canyon-1) and one very lightly damaged area (Tenaya Gap), is shown in Table 5:

Table 5

COMPARISON OF OVEN DRY WEIGHT OF NEEDLE TIPS
HEAVY DAMAGE vs VERY LIGHT DAMAGE AREAS
LODGEPOLE PINE, THREE DEFOLIATION STUDY AREAS,
YOSEMITE NATIONAL PARK, 1973

	Oven Dry Weight per Tip, Grams		
Sample Number	Lyell Fork Heavy	Virginia Canyon Heavy	Tenaya Gap Very Light
1	2.09	2.05	11.54
2	3.67	1.76	7.22
3	2.47	4.21	6.78
4	2.22	3.29	5.17
5	2.50	2.66	10.31
6	1.17	3.39	7.77
7	1.21	3.37	9.68
8	2.59	1.90	8.13
9	3.65	3.66	10.85
10	1.18	2.39	8.92
Ave.	2.28	2.87	8.64

Statistical Significance

Lyell Fork vs Virginia Canyon (both heavy defoliation)

$F = 1.2 > 5\%$

Lyell Fork & Virginia Canyon vs Tenaya Gap (very light)

$F = 83.6 < 1\%$

The data show that the very lightly damaged area had three times as much foliage as the heavily damaged areas.

An analysis of the numbers and per cent of needles damaged was made of samples collected from a heavily damaged area (Lyell Fork-11) and from a very lightly damaged stand in the same area (Lyell Fork-Check), with the results shown in Table 6:

Table 6

COMPARISON OF DAMAGE TO LODGEPOLE NEEDLES
BY THE LODGEPOLE NEEDLE MINER,
HEAVY vs VERY LIGHT DEFOLIATION
YOSEMITE NATIONAL PARK, 1973

Area	Defoliation	Tip Number	Number Damaged Needles	Number Undamaged Needles	Total Number Needles	% Damage
LYELL FORK - 11	Heavy	1	86	0	86	100%
		2	190	36	226	84%
		3	82	13	95	86%
		4	92	24	116	79%
		5	108	11	119	91%
		6	41	0	41	100%
		7	61	19	80	76%
		8	136	53	189	72%
		9	106	10	116	91%
		10	135	0	135	100%
		Ave.	104	17	121	86%
LYELL FORK - Check	Light	1	3	466	469	1%
		2	5	258	263	2%
		3	3	263	266	1%
		4	9	297	306	3%
		5	10	237	247	4%
		6	7	417	424	2%
		7	2	313	315	1%
		8	18	400	418	4%
		9	1	302	303	0.3%
		10	1	342	343	0.3%
		Ave.	6	330	336	2%

Statistical Significance

Lyell Fork - Heavy vs Lyell Fork - Light (number damaged needles)

$F = 52.7 < 1\%$

In the area of heavy defoliation the damaged needles ranged from 72% to 100% of the total number of needles, and averaged 86%. In the lightly defoliated area the damaged needles ranged from 0.3% to 4% and averaged 2%.

The needle complement per tip ranges from 41 to 226 needles, and averages 121 needles in the heavily damaged area. In the lightly damaged area the range is from 247 to 469, with an average of 336 needles per tip, or three times as many needles as in the heavily damaged area.

The difference in foliage density affects the appearance of the stands on the imagery. Since the damage classification was made on the photographs prior to the field study, the close correlation between field and photointerpretive results shows that photo-interpretive damage classification is quite accurate.

6.3.3. Changes in Lesser Vegetation

There is a significant increase in the abundance (weight) of total vegetation under damaged stands, as shown in Figure 7. The grasses and sedges increase greatly in bulk, whereas the forbs (broadleaf plants) decline slightly.

The average weight of grasses was 131 pounds per acre under the undamaged lodgepole pine stand, compared with 827 pounds under the heavily damaged stand. The average weight of sedges was 113 pounds per acre under the undamaged stand, versus 462 pounds under the heavily damaged stands. The weight of the forbs was 58 pounds per acre under the lightly damaged stand, versus only 24 pounds under heavy damage.

Total weight of lesser vegetation under undamaged stands was 302 pounds per acre, versus 1,313 pounds under the lodgepole stand which was heavily defoliated about 1960.

To the extent that the lesser vegetation has different image signatures than the conifer overstory--particularly as the former dries out and changes color with the advance of dry weather--these changes are discernible on aerial photography.

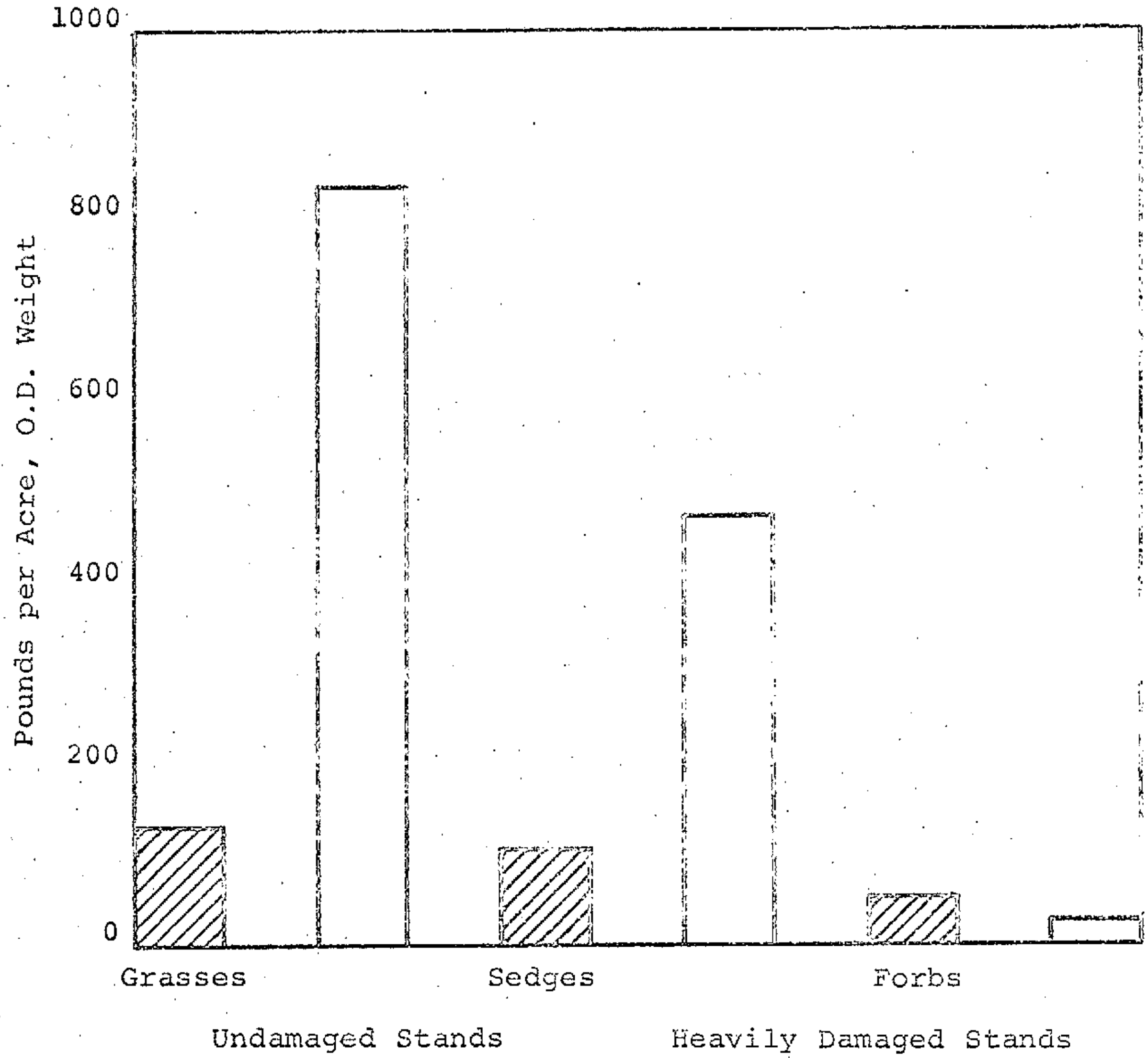

Figure 7

CHANGES IN WEIGHTS OF LESSER VEGETATION
FOLLOWING HEAVY INSECT DAMAGE TO
LODGEPOLE PINE STANDS, YOSEMITE NATIONAL PARK, 1960-73

7. INTERPRETATION OF IMAGERY

ERTS-1 imagery (both normal, and enhanced by three procedures), U-2 underflight photography, conventional aerial photography, and hand-held 35mm aerial and ground photography, were interpreted visually. In addition, ERTS-1 imagery was interpreted with the VP-8 Image Analyzer.

7.1. Conventional Aerial Photography

IKtachrome color and color-IR photographs, at scales of 1:5,000 and 1:18,500, were taken during the summers of 1972 and 1973. Color IR gave greater signature contrasts between healthy and infested timber stands than did color, at both scales.

7.1.1. Aerial Photography at 1:5,000 Scale

The ground locations of the sample areas used for field data collection were plotted on the 1:5,000 scale aerial photographs. An experienced photointerpreter made counts, within these sample plots, of all trees 8 inches and larger in diameter at breast height. These were segregated into two inch diameter classes and classified into the following groups: living, which included all non-host species; green infested, which were trees currently attacked by the mountain pine beetle but which had shown no evidence of crown fading; fresh fades, which were trees that had been killed by the mountain pine beetle the previous year and had red foliage; and older dead trees, which included trees killed more than one year, with varying color phases from dark brown to grey.

Analysis of this data showed a high correlation of photointerpretation counts to field data counts of dead trees. A much lower correlation existed however for recently faded trees and for faded plus green infested trees. This analysis is summarized below and in figures 8 and 9.

PI vs Dead Trees	$r = .875$
PI vs Faded Trees	$r = .561$
PI vs Faded and Green infested	$r = .433$

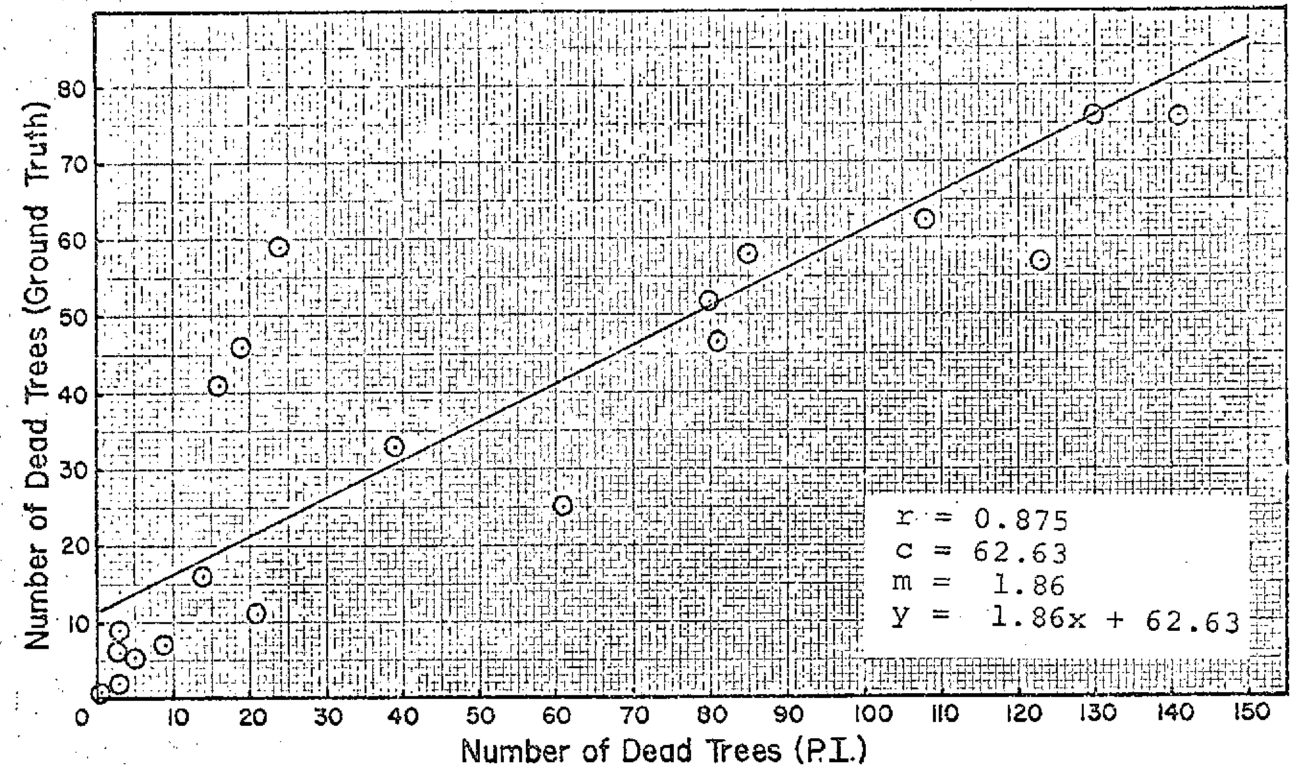

Figure 8

COMPARISON OF PHOTOINTERPRETER'S COUNT
WITH FIELD COUNT OF DEAD TREES.
YOSEMITE PARK, 1973

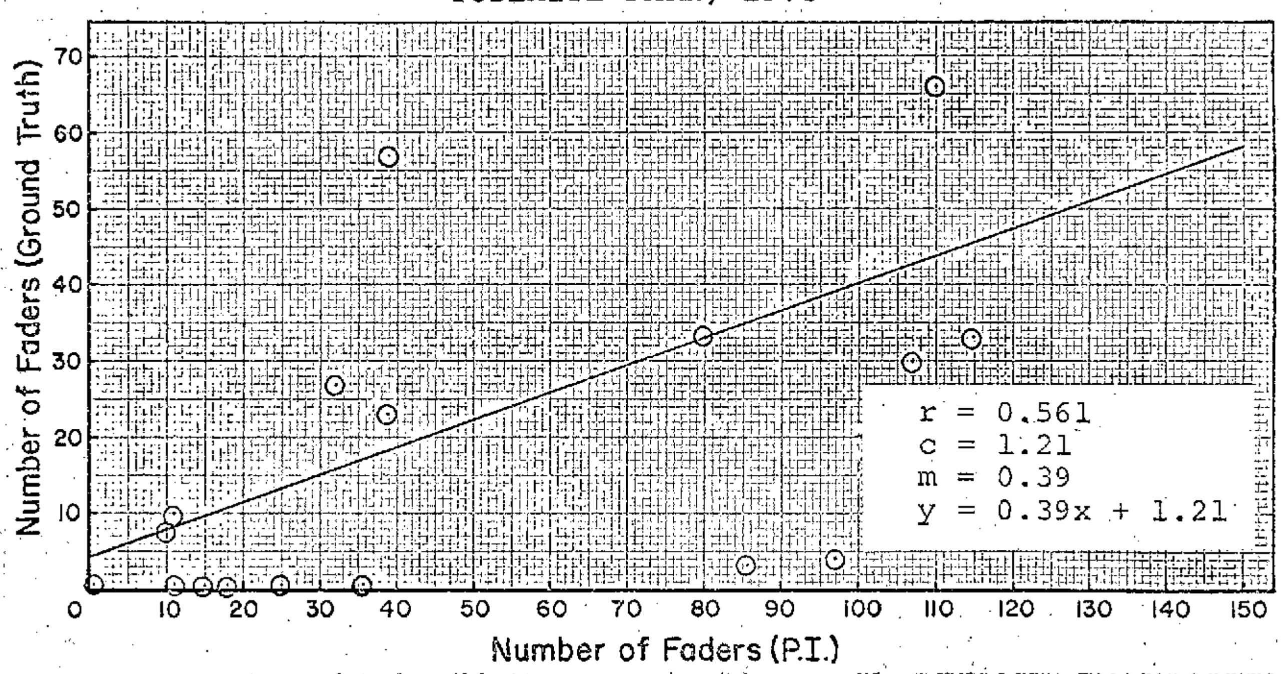

Figure 9

COMPARISON OF PHOTOINTERPRETER'S COUNT
WITH FIELD COUNT OF FADED TREES
YOSEMITE PARK, 1973

indicating that with this scale and type of photography experience and local familiarity are not of great importance in identifying dead trees.

It appeared that practically all dead trees over 20 inches in diameter were counted, but that many dead trees under 20 inches were missed.

It was possible to delineate precisely both mortality and defoliation as light, medium, and heavy; to delineate forest types; and to identify individual trees by species with a high degree of accuracy.

Other features, such as roads, trails, buildings, small streams, meadows, lakes, rock outcrops, glaciers, small snow patches, and vegetation types within timbered areas, could also be identified with great accuracy.

7.1.2. Aerial Photography at 1:18,500 scale

Ektachrome color-infrared photos, taken in 1972, were interpreted visually using an ordinary mirror stereoscope, to successfully stratify the infested areas into light, medium, and heavy mortality classes, and to delineate the areas of defoliation.

Infestation and mortality characteristics could be identified as to timber stands, and counts of individual faded or dead trees were possible, although resolution and accuracy were not as good as with the 1:5,000 scale photos.

7.2. Helicopter 35mm Kodachrome Photography

The use of a hand-held 35mm camera in the helicopter proved valuable in defining precisely the boundaries betwen damage classes, and between defoliated and non-defoliated stands (Figure 3), and helped to refine the boundaries initially established by use of conventional aerial photography, U-2 imagery, and ERTS-1 imagery.

7.3. U-2 Underflight Imagery, 1:30,000 scale

The U-2 underflight support included 70mm imagery produced by the Vinten System A and B (April, May, and June, 1972); RC-10 Aerchrome Infrared, 9 x 9 format (July, 1972); and HR-732, 9 x 18 format, A-1 (June, 1973). Interpretation was limited to the RC-10 and HR-732 products.

7.3.1. U-2 Imagery, RC-10

This coverage, at 1:30,000, was included in scenes obtained from investigators in two other projects. The cameras were set for the average scene for all projects, including mainly urban and agricultural land, and the imagery proved to be rather dense at the elevations of the target area for the subject study.

When enlarged to 1:18,500 scale it gave eventually the same information as was obtained from conventional aerial photography (7.1.2.), (Figure 10), except that it did not permit identification of individual faded or dead trees.

7.3.2. U-2 Imagery, HR-732, A-1

The overall quality and resolution of this imagery was excellent, (Figure 11). Interpretation was visual, using a filmstrip viewer equipped with an enlarging mirror stereoscope.

The location of each of six sampling areas, and plots therein, of the field sample was transferred from the 1:5,000 imagery to this film. The photo-interpreter then made estimates of the numbers of dead standing trees within each sample plot on both the 1:5,000 scale photos and the 1:30,000 HR-732 photos.

The correlation between estimates at these scales was high (r =.851), using the generalized formula:

$$\text{Est.} = \left(\frac{1}{m} \sum^{m} \frac{V_i}{P_i}\right) \cdot C_2$$ where V_i = ground count, P_i = photo count, C_2 = count from HR-732 frame.

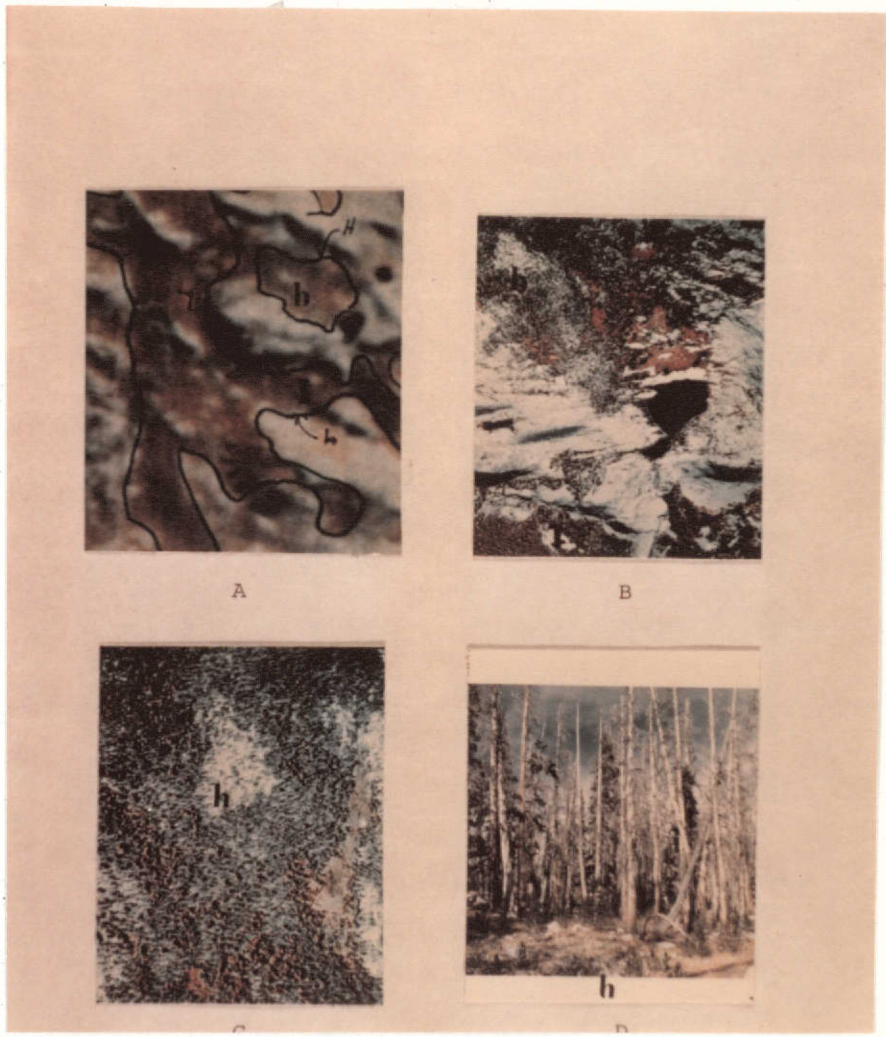

Figure 10

Comparison between light and heavy damage in the Cathedral Lakes area. A, ERTS-1 color composite 1, light damage - H, heavy damage; B, U-2, color IR, 1:30,000, upper portion heavy damage, lower portion light damage; C, U-2, color IR, enlarged to 1:18,500, Salmon colored trees are non-host mostly mountain hemlock; D, Kodachrome II, ground shot of heavy damage. Symbol "h" indicates the same area on each print.

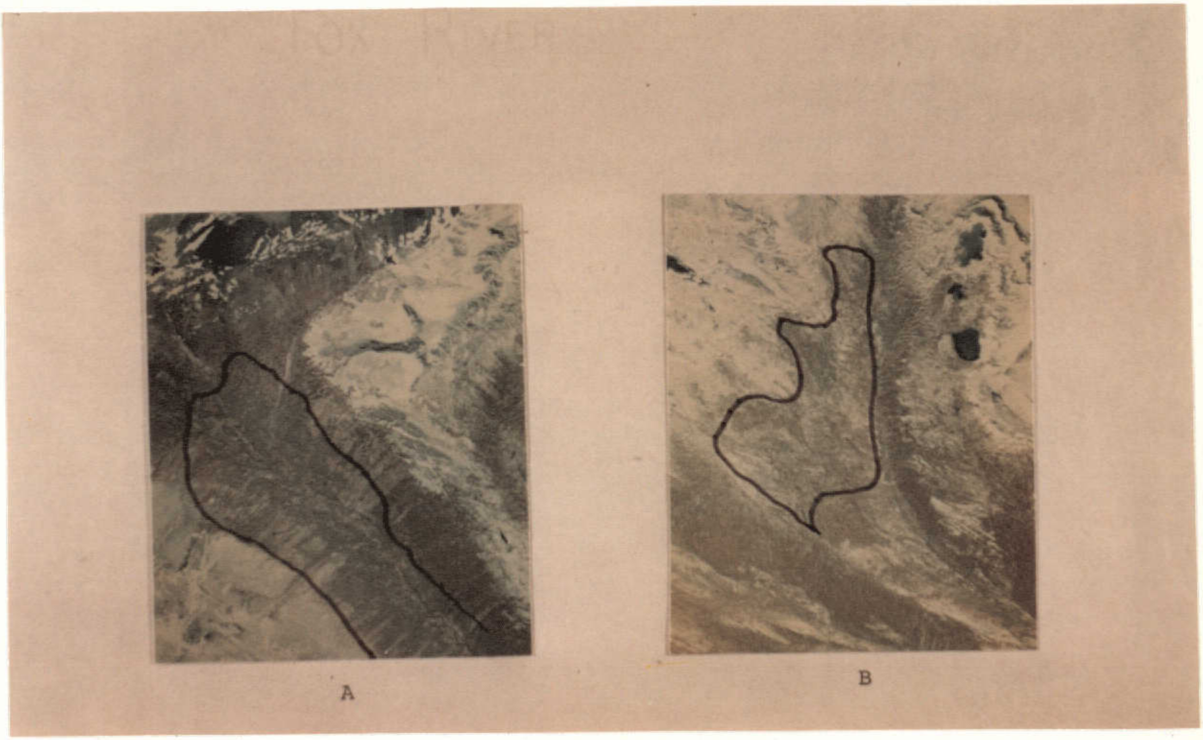

Figure 11

U-2 imagery, HR-732, 1:30,000, A-1, showing (A) heavy defoliation within the black line, Virginia Canyon area; and (B) heavy mortality within the black line, Youngs Lake area.

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The results of correlation analysis by study areas, were:

Area Number	Estimated Number of Dead Trees, HR-732 photos
4	23,793
5	25,387
6	10,933
9	690
10	17,397
16	5,715

7.4. ERTS-1 Imagery Enhancement and Interpretation

ERTS-1 imagery was interpreted visually both at the original scale of 1:1,000,000 and at the enlarged scale of 1:80,000 following imagery enhancement; and by machine, using the VP-8 Image Analyzer.

7.4.1. ERTS-1 Imagery Enhancement

Various enhancement techniques were tested on ERTS-1 imagery, including:

(a) use of 12-S Digitol color additive viewer with MSS bands 4, 5, and 7;

(b) copying color composite negatives through the internegative route, using commercial photographic firms;

(c) copying color composite positives, using Kodachrome II film with an electronic flash to produce slides from which enlarged color prints were made. (Figure 12)

In case (c), the work was done by Mr. Ralph McFarland of the Pacific Southwest Forest and Range Experiment Station. Enlargements of the original 1:1,000,000 scale were made to a maximum of 1:80,000. Enlargement beyond the latter scale resulted in loss of significant detail.

Of the three procedures, (c) gave by far the best resolution of imagery at each scale.

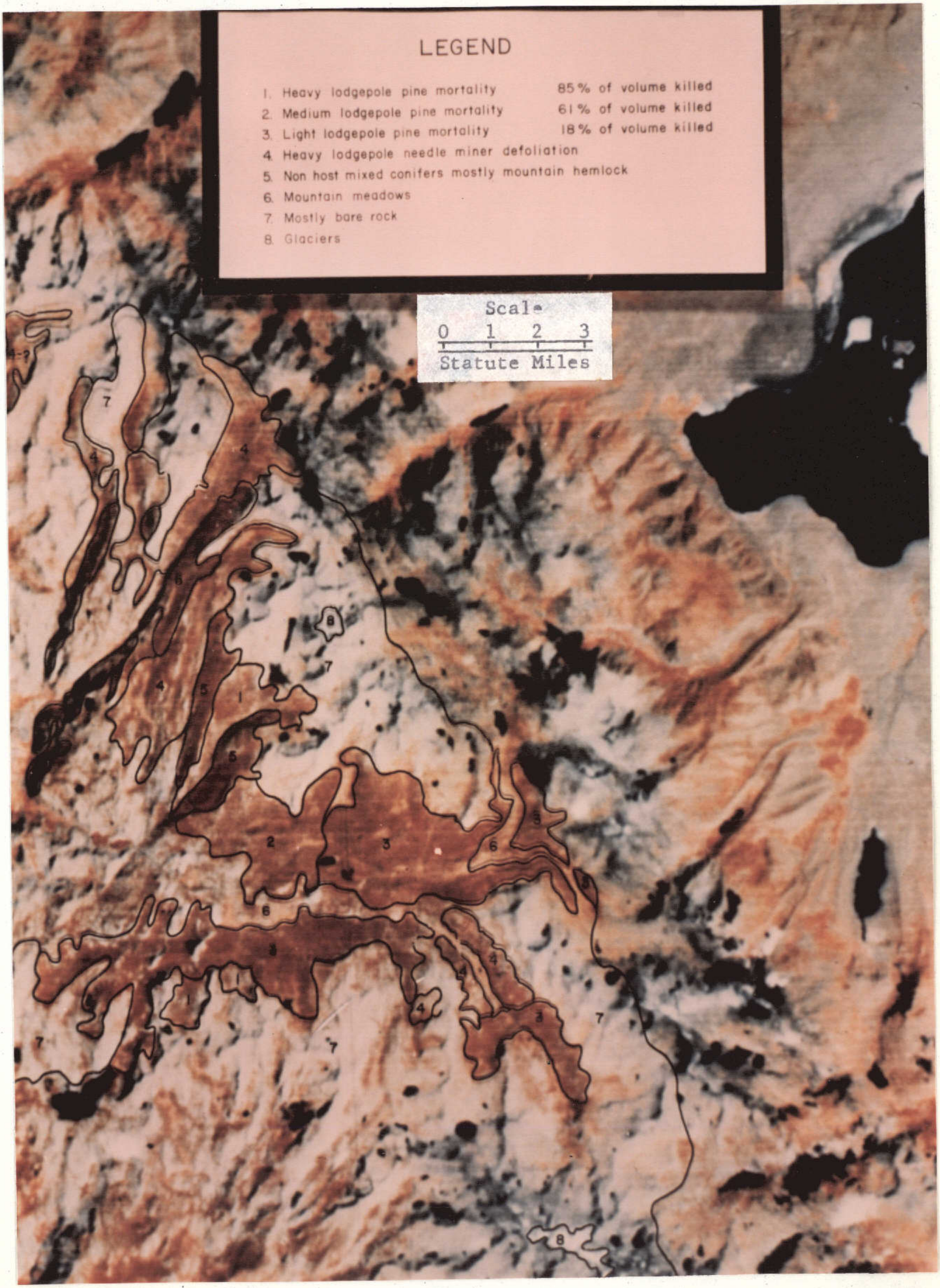

Figure 12

Delineation of damaged and defoliated areas together with other significant features. Enlargement of ERTS-1 frame #1055-18055, 16 September, 1972.

7.4.2. Color Classification System

The Munsell Book of Color Classification was used as the standard by which to classify the colors visible to the eye on ERTS-1 imagery. Applied to damage classes and geological features, they are:

Table 7

COLOR CLASSIFICATION

Classification or Feature	Color by Eye	Munsell Color Code
Scale 1:1,000,000 (Figure 2)		
Light mortality	Cherry red	5R - 5-8
Heavy mortality	Chocolate brown	10RP- 4-4
Meadows	Light yellow	10YR- 8-8
Lakes	Dark blue	10B - 2-4
Rock Dome Shadows	Black	10B - 2-1
Scale 1:80,000 (Figure 10)		
Light mortality	Blood red	5R - 6-4
Medium mortality	Chocolate brown	10R - 5-4
Heavy mortality	Moldy yellow	5R - 4-8
Heavy defoliation	Deep yellow	10YR- 6-4
Non-host conifers	Dark brown	5R - 4-3
Meadows	Light yellow	10R - 8-8
Bare rock	Light blue	5B - 7-4
Glaciers	White	5B -8-1

7.4.3. Visual Interpretation of ERTS-1 at 1:1,000,000

By visual interpretation alone, it was possible from all three sets of imagery (16 September, 1972, 13 June, 1973, and 11 September, 1973) to distinguish timbered from non-timbered areas and to identify agricultural land, pasture land, desert, mountain meadows, riparian vegetation, rock domes, and old burned areas in forest and brushland (Figure 2).

Within timbered areas, it was possible to discriminate broadly between areas with little or no insect damage and those with extensive and heavy damage.

7.4.4. Visual Interpretation of Enhanced ERTS-1 Imagery

Using imagery enlarged to 1:80,000 scale by the McFarland procedure (7.4.1.), it was possible visually to identify the geologic and vegetative conditions listed in 7.4.3.

In addition it was possible to delineate three classes of forest insect damage (tree mortality) in lodgepole pine--light, medium, and heavy--and to distinguish between areas of heavy defoliation and that of light or no defoliation by the needle miner (Figure 12).

When the 16 September, 1972 imagery was visually compared with that of 11 September, 1973, no significant changes in forest or other vegetation could be detected.

The 13 June, 1973 imagery was not received until May, 1974. Enlargements from it were color-defective, and no conclusions could be drawn from its use at this scale.

7.4.5. Machine Interpretation of ERTS-1 Imagery at 1:1,000,000

ERTS-1 image #1397-18053, dated 8 August, 1972, was selected for machine interpretation because it was cloud- and snow-free and corresponded most closely in time with the field data collection period. On this image, three locations were designated, including one each of light, medium, and heavy mortality. The area and extent of each location was delineated directly on each of Bands 4, 5, 6, and 7 by reference to 1:18,500 and 1:5,000 photos.

At random points within each mortality class location, the VP-8 Image Analyzer was used to measure image density, resulting in a population of image density readings for each mortality class.

These readings were tested for variance comparing image densities for light, medium, and heavy mortality classes for each of Bands 4, 5, and 6. When compared with the tabled values of $F^{2}_{57} = 3.17$ @ 5% significance level and $F^{2}_{57} = 5.01$ @ 1% level, Band 5 showed the greatest discrimination among mortality classes

F calculated = 71.871); Band 4 showed a high degree of discrimination (F = 48.706); and Band 6 showed little discrimination (F = 1.134). (Figure 13)

When density readings from two areas of heavy mortality were compared with the tabled values of F for each of Bands 4, 5, and 6, it was found that the values were very close in Band 5 (F = 0.578), close in Band 4 (F = 2.580), and reasonably close in Band 6 (F = 4.565.

When density readings from each of the three bands were compared within each mortality class, it was found that for areas of light and medium mortality there is a strong difference among density readings for Bands 4, 5, and 6; but that for areas of heavy mortality, there is very little difference in density readings among Bands 4, 5, and 6.

When density readings for heavily defoliated and non-defoliated stands were tested for variance in Bands 4, 5, and 7, the differences were found to be highly significant in each case, as shown in Table 8:

Table 8

F-TEST FOR SIGNIFICANT VARIANCE AMONG POPULATIONS OF IMAGE DENSITY READINGS FROM DEFOLIATED AREAS

Test Area	Calculated "F" Value for Equality of Variance (1) vs (2) vs (3) vs (4)		
	Band 4	Band 5	Band 7
(1) Lyell Cr. (Heavy)	Calculated	Calculated	Calculated
(2) Cold Cr. (Light)	F^{3}_{76} = 12.81	F^{3}_{76} = 15.81	F^{3}_{76} = 5.62
(3) Virginia Cr. (Heavy)	Table Value	Table Value	Table Value
(4) Dana Mdw. (None)	F^{3}_{76} = 2.72	F^{3}_{76} = 2.72	F^{3}_{76} = 2.72

Heavy defoliation:	Bands 4 vs 5 vs 7, F^{2}_{57} = 59.70	Table Value F^{2}_{57} = 3.16
No defoliation:	Bands 4 vs 5 vs 7, F^{2}_{57} = 81.64	

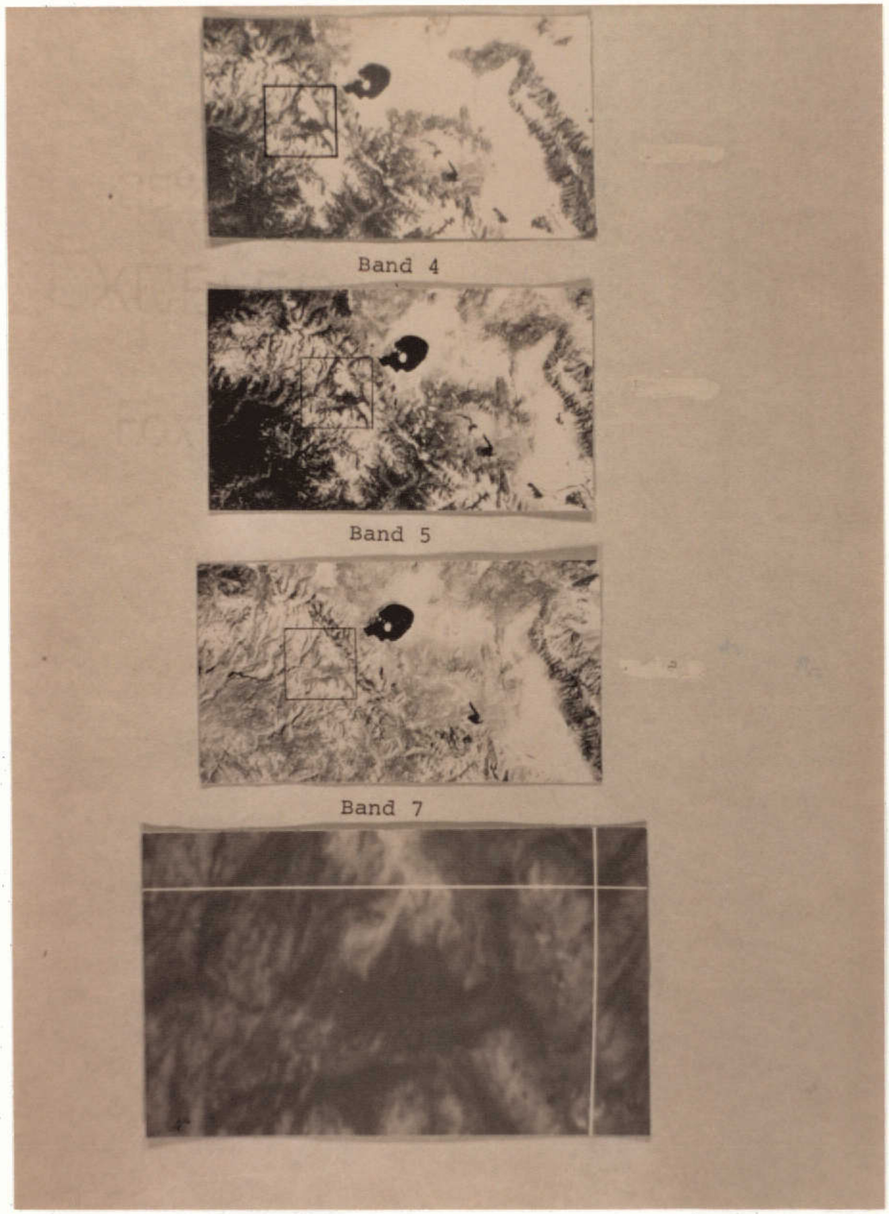

Figure 13

Images from Bands 4, 5, and 7, showing in square outline the general test area and (below) an enlargement of a portion of the study area.

When the Students "t" test was applied to heavy vs light or no defoliation, within each of Bands 4, 5, and 7, the results were significant at the 5% level in all but one case, as shown in Table 9:

Table 9

STUDENTS "t" TEST VALUES FOR DIFFERENCES AMONG MEANS OF POPULATIONS OF IMAGE DENSITY READINGS FROM DEFOLIATED AREAS

Test Area	Band 4	Band 5	Band 7
(1) Lyell Cr. (Heavy) (2) Cold Cr. (Light)	1 vs 2 t_{38}=4.43	1 vs 2 t_{38}=2.64	1 vs 2 t_{38}=3.46
(3) Virginia Cr. (Heavy)	1 vs 3 t_{38}=0.85	1 vs 3 t_{38}=4.30	1 vs 3 t_{38}=2.49
(4) Dana Mdw. (None)	1 vs 4 t_{38}=5.51	1 vs 4 t_{38}=5.50	1 vs 4 t_{38}=2.52
Table Value Students t_{38} @ 5% = 1.68			

In a second step, density-sliced images were produced by analyzing each of the ERTS-1 band images separately on the VP-8 Image Analyzer. These images were then color-enhanced electronically for each density level within a given mortality class. Examples of these enhanced images and the bands they represent are shown in Figure 14. Subtle density differences among the mortality classes and within defoliated areas were enhanced by density slicing, which accentuates the difference between the reds in healthy vegetation and the light green to off-white where healthy tree foliage is lacking.

Figure 14

Illustrations of density-sliced images produced separately by the VP-8 Image Analyzer and color-enhanced electronically, MSS Bands 4, 5, and 6.

7.5. Changes In Vegetative Image As A Result of Insect Damage

Significant changes in the images of vegetation are brought about as a result of damage by insects, and changes vary with the type and species of insects involved. In our study the two principal insect species, as pointed out previously, were the mountain pine beetle and the lodgepole needle miner.

7.5.1. The Mountain Pine Beetle

Attack by the mountain pine beetle causes a tree to die. The first change in image is a change in color of the foliage from green to lemon yellow which usually persists for about a month and then changes to red which persists for about one year. During the second year the color changes to a dark brown and, depending on the frequency and intensity of storms, the needle compliment may be greatly reduced. In the third year practically all of the needles will have fallen and at about ten years most all of the twigs and branches and most of the bark will have fallen, leaving a bare snag. Figure 4. A dead tree then means a hole in the tree canopy and the extent of the openings depend on the percentage of the trees and volume of timber killed. Volume of timber killed is a better measure of the opening up of the canopy, since the large trees would represent larger openings.

Based upon our classification of mortality areas into light, medium, and heavy, Figures 10 and 15, the results of our ground truth samples showed that 18% of the volume was killed in the light areas compared to 61% in the medium, and 85% in the heavy areas. Table 3. We would expect, in the heavy areas particularly, that the true image would be made up of the following components: (a) mostly gray tree trunks; (b) a high percentage of ground vegetation, particularly grasses and sedges, Table 7; (c) bare rock outcrops; and (d) a small percentage of non-host, green trees. Table 4 and Figures 3 and 4.

Figure 15

Medium damage near Dog Lake #6. Symbol "b" represents the same area in each photo. A, ERTS color composite; B, U-2, color IR, enlarged to 1:18,500; C, Kodachrome II.

7.5.2. The Lodgepole Needle Miner

There is considerable difference in the change of image in areas defoliated by the lodgepole needle miner compared to that in the mortality areas. The principal change is that the color of the needles which when mined change from green to brown. Figure 3 and 16. However, there is also a significant reduction in needle compliment as may be noted from Tables 5 and 6. On the basis of oven dried weight of the needles, those on the undefoliated trees are about three times heavier than on the heavy defoliated areas. On the basis of number of needles per tip, there are about three times as many needles on the undefoliated areas as there are on the heavy defoliated areas.

On a visual basis, from ERTS imagery the heavy defoliated areas are quite similar in color tones to the heavy mortality areas which was unexpected, because there is considerable difference in the two classes of areas from both the U-2 and conventional aerial photo coverage. Figure 11.

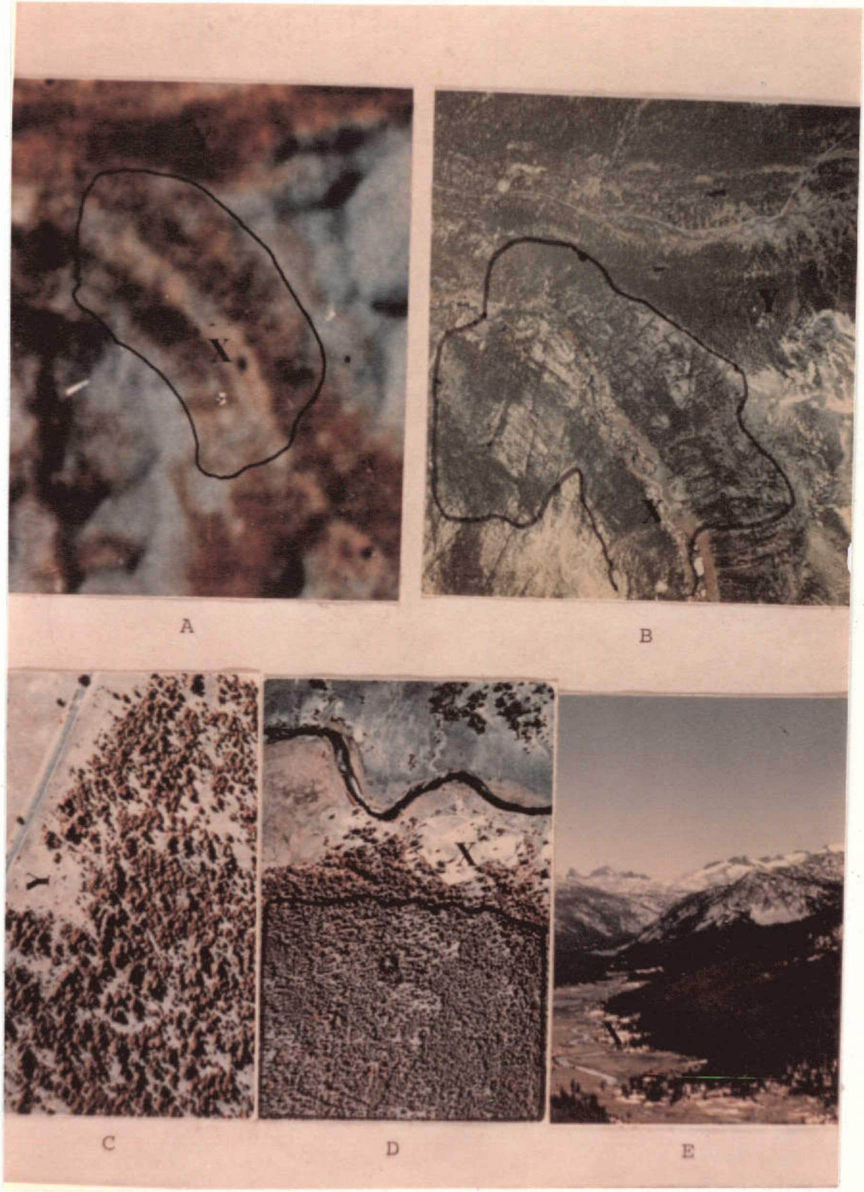

Figure 16

Needle miner defoliation, Lyell Fork #11. A, ERTS color composite; B, U-2, A-1, at 1:30,000; C, Color IR, 1:5,000; D, Color IR, 1:18,500; E, Kodachrome II. Areas outlined in black on A and B are heavily defoliated; C has no defoliation. Brown areas in E are heavily defoliated; D area above black line Salmon Color light defoliation, area below black line, green, heavy defoliation.

8. RESULTS

Defoliation of lodgepole pine by the needle miner insect reduces the volume and density of tree foliage, causes changes in the foliage color, and promotes greater growth of lesser vegetation. All of these result in differences in color, tone, and image density which are readily discernible in conventional color and color infrared photography at scales of 1:5,000 and 1:18,500, and in U-2 imagery at 1:30,000 and 1:18,500.

At the 1:5,000 scale, defoliation can be categorized as light, medium, and heavy, and individual affected trees can be distinguished. At the 1:18,500 scale, both with conventional aircraft photography and enlarged (original 1:30,000) U-2 photography, it is possible to discriminate between heavily defoliated and lightly or non-defoliated stands.

At the 1:30,000 scale, using NASA U-2 photography, HR-732 film, it was also possible to identify areas of heavy defoliation.

Applying visual interpretation to ERTS-1 imagery, enhanced by McFarland's process to 1:80,000, it was possible to distinguish between heavily defoliated and lightly or non-defoliated stands.

When, as is usually the case, defoliation by the needle miner is accompanied or followed by bark beetle attack, or when bark beetles alone attack in force, the death of the host trees follows. The mortality may range from light to total. As it proceeds, foliage density and color and the character of the lesser vegetation change radically, and are much more readily discernible on aerial photography and ERTS-1 imagery than are changes associated with the needle miner alone.

At the 1:5,000 scale, using both color and color infrared, it is possible to delineate mortality classes with great accuracy; to distinguish healthy, infested, and dead trees; and to count dead and fading trees with a high degree of correlation between photo evidence and ground truth, and with close correlation among different observers.

At the 1:18,500 scale in both color and color infrared, mortality can be stratified and delineated accurately by three severity classes; numbers of dead and dying trees can be estimated with good accuracy; and there is reasonably close agreement among interpreters.

NASA U-2 imagery, HR-732 film, enlarged from 1:30,000 to 1:18,500 gave substantially the same results as the 1:18,500 photos from conventional aircraft. At 1:30,000, it was possible to distinguish light, medium, and heavy mortality classes, and to estimate numbers of dead and dying trees with fair accuracy.

ERTS-1 imagery, color composite, enlarged to 1:80,000 and interpreted visually, permitted discrimination broadly among the three classes of mortality--light, medium, and heavy--but did not permit identification of individual trees or estimates of numbers dead and dying.

ERTS-1 imagery, color composite, 1:1,000,000, visually interpreted, permitted discrimination between undamaged stands and broad areas of heavy mortality.

ERTS-1 imagery, interpreted by means of the VP-8 Image Analyzer, permitted discrimination among three classes of mortality, and between non- or lightly defoliated and heavily defoliated stands, on the basis of image density. The use of density-slicing enhanced both image density and color values.

9. EXTENDABILITY OF TECHNIQUES DEVELOPED

We find ourselves with the unanswered question as to the practical usefulness of ERTS imagery under limited or no ground truth conditions, since this phase of the problem was not studied. The general concensus of our team is that it might be practical but would need a special study before any conclusions could be drawn.

In the body of our report we discussed our use of the Munsell color code scheme as a possible standard for various photographic images of tree mortality, defoliation and other features identified. This scheme was developed in the early stages of the investigation when we were led to believe that the ERTS photographic process could be standardized with little or no variability in color images. However our experience with color images received was that there was considerable variability from frame to frame, which indicates that our color coding scheme was not too reliable.

To the extent that ERTS digital data is not subject to the same problems found in the photographic process and appears to be more consistent from frame to frame, it is our feeling that digital data would be much more useful in detecting insect infestation over unknown areas than interpretation of photographic data. We also would expect that the digital data would be much more useful in monitoring insect outbreaks. However we did not use digital data in our study and can only theorize on its applicability. We had provided for the use of digital data in our original proposal but this phase of the study was eliminated from our final contract.

10. CONCLUSIONS

ERTS-1 imagery (color composites of Bands 4, 5, and 7 at the scale of 1:1,000,000) is not adequate, unsupported, for the identification and close evaluation of forest insect damage. However, it appears to discriminate sufficiently between normal and very abnormal conditions in a fairly homogeneous forest to assist in the detection of heavy insect outbreaks.

Enhanced color composites of ERTS imagery enlarged to 1:80,000 and visually interpreted, permit detection of heavy defoliation and light, medium, and heavy mortality with a reasonably high degree of reliability.

Close mapping and evaluation of damage still require underflight support, for which NASA U-2 imagery should be adequate in most cases, especially if enlarged to 1:18,500 scale.

Visual interpretation at scales of 1:18,500 or more requires highly skilled interpreters.

Machine interpretation, using the VP-8 Image Analyzer, permits a higher degree of discrimination and probably more rapid and consistent work; and appears to hold considerable promise for outbreak detection.

11. RECOMMENDATIONS

It is recommended that (a) further research be conducted to improve the resolution of ERTS imagery; (b) further research be done in the enhancement of ERTS color composites for visual interpretation; (c) further study and development of machine interpretation systems be undertaken.