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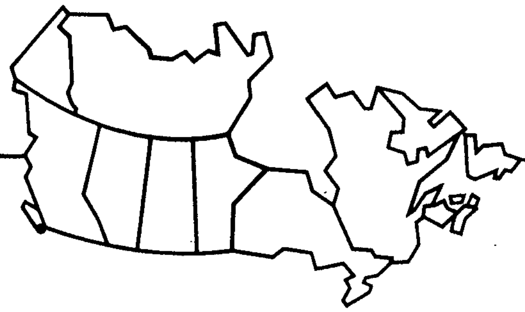

Evaluation of mountain pine beetle damage using aerial photography taken with a hand-held 70-mm camera, Gold Bridge-Clinton, B.C., 1981

J.W.E. Harris, A.F. Dawson and R.G. Brown

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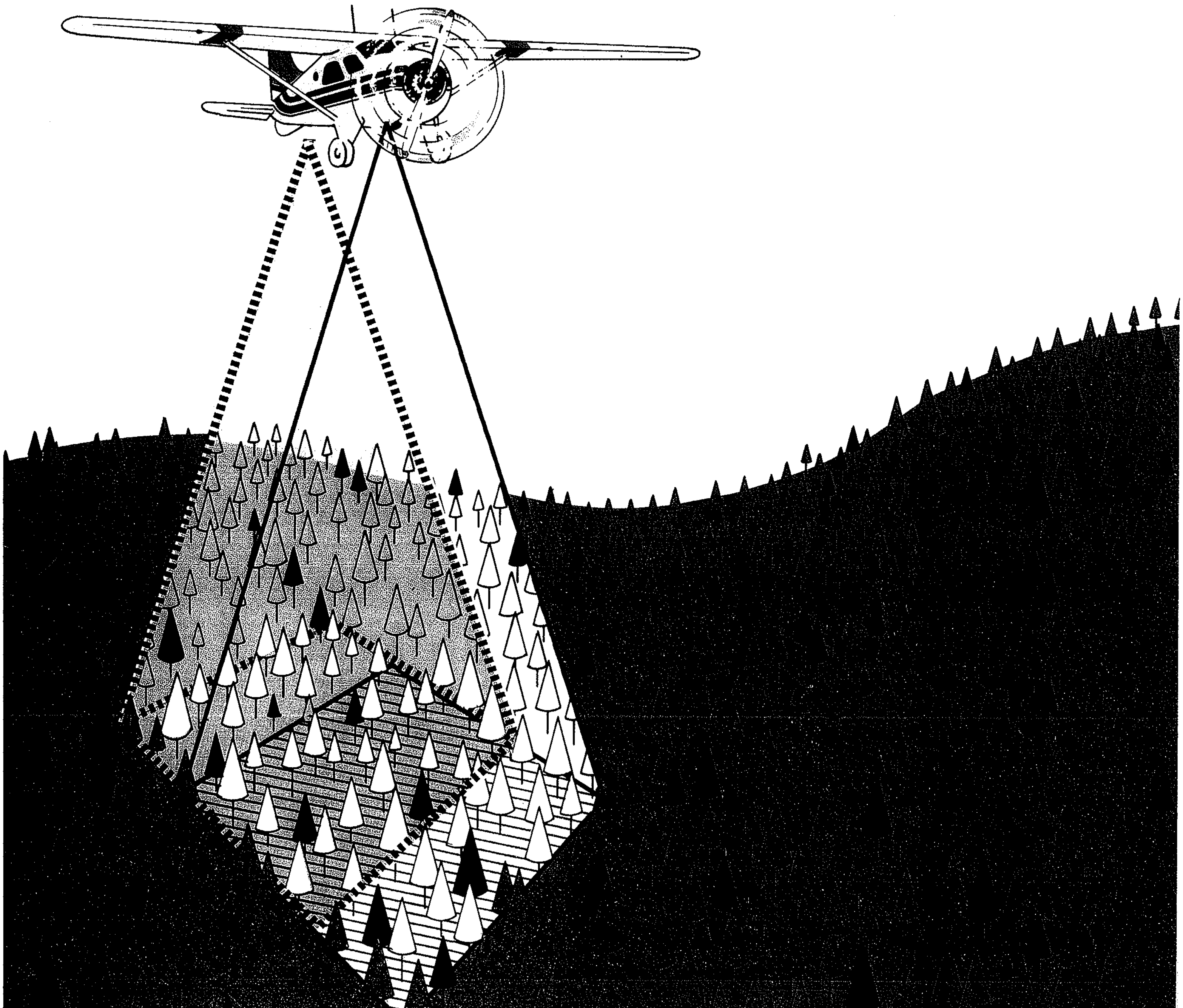

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ABSTRACT

A simplified multistage sampling procedure using large-scale color aerial photography taken with a hand-held 70-mm camera was developed to assess mortality of lodgepole pine *(Pinus contorta)* stands attacked by the mountain pine beetle, *Dendroctonus ponderosae,* in British Columbia. Damaged pine stands were sketch-mapped from the air at two locations, at Gold Bridge in the Bridge River Valley and between Clinton and Dog Creek. Damage was stratified into two intensity levels based on aerial dead-tree count estimates. At each location, 4-ha airphoto plots were established at a scale of 1:6 000 on a grid interval, aiming at one plot per 1000 ha in the light-damage stratum and one plot per 500 ha in the severe-damage stratum. Airphoto plots were subdivided into 16 0.25-ha subplots, and one or two subplots were ground-sampled from selected photo plots.

Beetle-killed pines were counted on the airphoto plots, and ground-to-airphoto ratios of dead-tree counts were calculated for the ground subplots. A "ground-corrected'' average number of dead trees per hectare and an estimated total number of killed trees were then obtained for each stratum. Height-diameter curves were used to determine average dead-tree volumes, which were applied to the estimated total number of killed trees to estimate the total volume loss for each area.

In the two study areas, beetle damage was sketch-mapped on over 48 000 ha. An estimated 6.4 million lodgepole pine were killed, amounting to an estimated volume loss of 2.1 million m^3. Study costs were about 41 cents per hectare.

RESUME

On a mis au point une méthode simplifiée d'échantillonnage en plusieurs Ctapes qui consiste 1 utiliser des photographies aériennes en couleur à grande échelle, prises par un appareil 70 mm portatif, pour évaluer la mortalité dans les peuplements de pin tordu (*Pinus contorta)* de la Colombie-Britannique attaqués par le dendroctone du pin ponderosa *(Dendroctonus ponderosae)*. On a fait des croquis en plan de peuplements endommagds, à Gold Bridge dans la vallde de la rivière Bridge et entre Clinton et le ruisseau Dog. Les dommages ont été stratifiés en deux degrés d'intensité à partir d'une estimation, du haut des airs, du nombre d'arbres morts. Sur la photo de chaque endroit, on a délimité des placettes de 4 ha à l'échelle de 1/6 000 sur un intervalle de quadrillage, à raison d'une placette pour 1 000 ha dans la strate où les dommages Gtaient légers et d'une placette pour 500 ha dans celle où ils Ctaient graves. Ces placettes ont été subdivisées en 16 sous-placettes de 0,25 ha, dont une ou deux ont été echantillonnées sur le terrain après avoir été sélectionnées sur la photo.

Les arbres tués par le dendroctone ont été comptés sur la photo, et le rapport des arbres morts comptés au sol aux arbres morts comptés sur la photo a dtd calculé, pour les sous-placettes. Le nombre moyen corrigd d'arbres morts à l'hectare et le nombre estimatif total des arbres tués ont été ensuite calculés pour chaque strate. À l'aide des courbes du rapport hauteur/diamètre, on a pu déterminer le volume moyen des arbres morts et ainsi estimer le volume total perdu dans chaque région.

Dans les deux régions on a établi des croquis des superficies (plus de 48 000 ha) ravagées par le dendroctone. On estime que 6,4 millions de pins tordus ont été tubs, ce qui correspond à 2,1 millions de mètres cubes. L'étude a coûté 0,41 $/ha.

INTRODUCTION

In 1981, the mountain pine beetle, ***Dendroctonus ponderosae*** Hopkins, continued to be the most serious forest insect problem in British Columbia. More than 158 000 hectares of forest with pine mortality were sketch-mapped during aerial surveys by the Forest Insect and Disease Survey of the Canadian Forestry Service, resulting in an estimated volume loss of over 6.6 million m3 (Fiddick and Van Sickle 1982). Most of the mortality occurred in lodgepole pine ***(Pinus contorta*** Dougl.).

This study was initiated in 1980 to develop a low-cost method for estimating numbers and volume of lodgepole pine killed by the mountain pine beetle in B.C. at a level of accuracy greater than that obtained from sketch-mapping and limited ground observations. In 1980, a simple multistage sampling system using vertical color aerial photography was tested in the Flathead River Valley (Harris ***et al.*** 1982). In 1981, a modification of this system was used at two other locations to evaluate mountain pine beetle damage by means of aerial sketch-mapping, vertical 1:6 000 airphoto plots, and ground subplots.

METHODS

In 1981, several modifications were made to the survey design used in 1980 at the Flathead River Valley (Harris ***et al.*** 1982). For 1980, sketch-map data were obtained in 1979 and left unstratified; for 1981, they were obtained in the current year and stratified into two damage intensity levels to increase precision. Airphoto plot size, 1 ha in 1980, was increased to 4 ha in 1981. Plot locations were selected by constructing a grid for a predetermined number of plots and placing the grid randomly over the damage, rather than locating plots using an arbitrarily-selected grid interval. In the current study a single camera system was used, giving better stereo separation at the scale employed than the fixed-base twin-camera system used in the previous study. In 1980, ground subplots were selected in the field, but in 1981 ground subplots were preselected from airphoto subplots. However, selection of photo plot locations to be ground sampled was based, as in 1980, on proximity to road access. In 1981, tree measurements for volume determination were taken at every ground subplot location, compared to only two subplots in 1980.

Site Description

Two study areas were selected: one in the Bridge River Valley at Gold Bridge, and one at the south edge of the Fraser Plateau between Clinton and Dog Creek. In both areas, pine stands had been attacked by the mountain pine beetle for the previous several years. Lodgepole pine was the primary host and it was the only species sampled in this study.

The Bridge River Valley is relatively confined and steep-sided, but widens at Gold Bridge where most of the damage is concentrated in relatively pure lodgepole pine stands. British Columbia Ministry of Forests (BCMF) inventory data indicate that there are in this area approximately 12 800 ha of immature and 24 500 ha of mature forest types with lodgepole pine as a major species by volume (20% or more of stand volume). In the mature forest types, there are about 3.7 million m^3 of lodgepole pine.

At Clinton-Dog Creek, most of the terrain is flat or gently rolling, with damage scattered over a larger area than at Gold Bridge (2 500 km^2 vs 400 km^2) in pine stands mixed with Douglas-fir or adjacent to open range. In this area there are 20 200 ha of immature and 32 100 ha of mature forest types with lodgepole pine a major species by volume. In the mature forest types, there are about 3.0 million m^3 of lodgepole pine.

Sampling

In early July at both locations, lodgepole pine stands attacked by the mountain pine beetle were sketch-mapped from a fixed-wing aircraft. Damage was delineated on medium-scale 23-cm x 23-cm vertical black-and-white airphotos or mosaics, supplemented by small-scale (approximately 1:60 000) vertical color airphotos and 1:125 000 or 1:250 000 topographic maps. Dead trees were grouped into irregular areas of damage called polygons, which are often defined by forest types and topography, and an ocular estimate of the number of killed lodgepole pine in each polygon was made and recorded. Generally this only included recently-killed (red) trees, but where longer-dead (grey) trees were numerous they were also mapped.

When sketch-mapping was completed, the area of each damage polygon was determined and the average density of killed trees (dead trees/ha) was estimated. Damage polygons for each study area were listed in ascending order of dead-tree density, then divided into two strata (light and severe) based on damage intensity levels.

The number of airphoto plots selected was one per 1000 ha in the light-damage stratum, and one per 500 ha in the severe-damage stratum. The photo plot sampling interval (I, in km) was calculated for each stratum as follows:

$$I = \sqrt{\frac{\text{area of stratum in km}^2}{\text{number of photo plots in stratum}}}$$

A grid with intervals of I km was dropped randomly over each stratum and grid intersection points falling in the stratum became airphoto plot centers. The airphoto plots were marked onto black-and-white vertical airphotos and topographic maps for use in navigation.

Airphoto plots of 4 hectares at a photo scale of 1:6 000 were selected. To maintain scale accuracy, the ground elevation for each airphoto plot, taken from a 1:50 000 topographic map, was added to the required flying height above terrain (480 m) to obtain flying height above sea level. The flying height above sea level was marked onto the navigational airphotos and maps beside each airphoto plot. For each study area, a predetermined flight path was drawn onto the airphotos and maps.

In early August, each photo plot was photographed vertically using a hand-held Hasselblad 500 EL/M 70-mm camera with an 80-mm lens and a film magazine containing 70-mm Kodak Vericolor II color negative film. Photographs were taken through the open cargo hatch of a de Havilland Beaver fixed-wing aircraft. As each photo plot was approached, the pilot was advised by the navigator of the required flying height and the aircraft altimeter reading was recorded for subsequent scale adjustment. At each photo plot, three consecutive frames were taken with an average of 60% overlap (a stereo triplet).

The photographs were processed to standard 13-cm x 13-cm print enlargements. The actual scale of each triplet was determined, and a 4-ha plot outline marked on a clear plastic overlay was centered over the mid-photo of each stereo triplet (Fig. 1). The overlay was divided into 16 0.25-ha subplots on which all red and grey lodgepole pine were counted by subplot and totalled. Then, for each photo plot, counts of red, grey and total dead (red plus grey) trees were converted to a per-hectare basis.

Ground subplots were established in late September or early October using the 13-cm x 13-cm stereo prints of each selected photo plot to locate the subplots. Two 0.25-ha subplots in the light stratum and one subplot in the severe stratum were ground sampled from each photo plot selected. Subplots were outlined with string and subdivided into sections to facilitate tree counting. Lodgepole pine were tallied by 5-cm dbh classes and classified as green-healthy (unattacked), green-attacked, red (recently killed, retaining yellow to reddish foliage), or grey (dead several years with all or most foliage dropped). At each ground subplot, for each dbh class 10-cm or greater, dbh and height were measured and recorded for 1 to 2 trees in order to establish a height-dbh curve.

Calculations

A height-dbh curve was drawn for each subplot, then using BCMF volume tables for lodgepole pine, the average subplot tree volume was obtained, weighted by the number of trees in each dbh class 10-cm or greater. The average tree volume was calculated separately for red and grey trees in each subplot.

The estimated total number and volume of dead lodgepole pine with 10-cm dbh or greater, and the respective sampling errors, were calculated for each study area separately for red and grey trees in each stratum. An estimate of the total number of killed trees ($\hat{T}$) was obtained as follows: the average number of killed trees/ha ($\bar{P}$) was multiplied by the average subplot ground/airphoto count ratio ($\bar{R}$) to obtain a

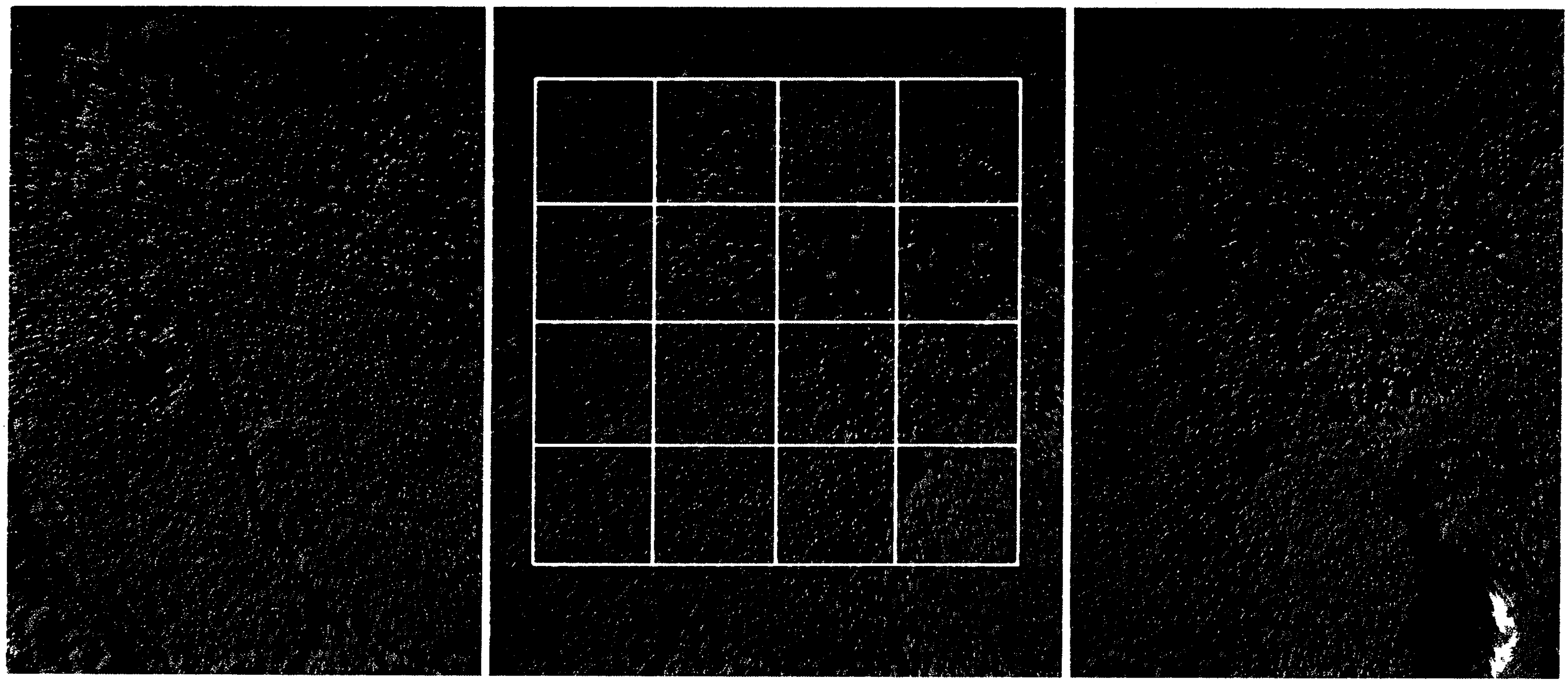

Figure 1. Airphoto plot stereo triplet with overlay of 4-ha plot and 16 0.25-ha subplots.

ground-corrected average number of dead trees/ha ($\bar{G}$) (i.e., $\bar{G} = \bar{P} \times \bar{R}$). This was multiplied by the respective total area of pine mortality (N) to derive the estimated total dead tree count ($\hat{T}$) (i.e., $\hat{T} = \bar{G} \times N$). The variance of $\bar{G}$ was calculated from the variances of $\bar{R}$ and $\bar{P}$ as follows (Freese 1962) (variance of a product, $\bar{R}$ and $\bar{P}$ assumed independent) :

$$S^2_{\bar{G}} = \bar{G}^2 \left(\frac{S^2_{\bar{R}}}{\bar{R}^2} + \frac{S^2_{\bar{P}}}{\bar{P}^2} \right)$$

The standard error of $\hat{T}$ was determined as $S_{\hat{T}} = \sqrt{N^2 \times S^2_{\bar{G}}}$ and the percent sampling error as $(S_{\hat{T}}/\hat{T}) \times 100$.

To estimate the total volume of killed trees ($\hat{V}$), the estimated total number of killed trees ($\hat{T}$) was multiplied by the average tree volume ($\bar{v}$) of all respective ground subplots (i.e., $\hat{V} = \hat{T} \times \bar{v}$). The variance of $\hat{V}$ was calculated from the variances of $\hat{T}$ and Vas follows:

$$S^2_{\hat{V}} = \hat{V}^2 \left(\frac{S^2_{\hat{T}}}{\hat{T}^2} + \frac{S^2_{\bar{v}}}{\bar{v}^2} \right)$$

The sampling error of $\hat{V}$ was determined as $\sqrt{S^2_{\hat{V}}}$ and the percent sampling error as $(S_{\hat{V}}/\hat{V}) \times 100$. The sampling errors for total (red + grey) dead trees and volumes within strata and sampling errors taken over both strata were estimated using standard formulae for the variance of a sum and population total, respectively (Freese 1962).

RESULTS

In the Bridge River Valley, lodgepole pine mortality caused by the mountain pine beetle was sketch-mapped over 21 316 ha in 60 damage polygons and was estimated to have over 390 000 dead trees (Table 1). Over half of the damaged area (58%) was classified as severely damaged, the rest as lightly damaged. At Clinton-Dog Creek, lodgepole pine mortality was sketch-mapped over 27 066 ha in 83 damage polygons and was estimated to have over 164000 dead trees. Unlike the Bridge River Valley, most of the area (77%) was classified as lightly damaged. In both study areas, all damage polygons with 10 or less dead trees/ha were defined as the light stratum, and all those with over 10/ha as the severe stratum.

In the Bridge River area, 26 severe- and 7 light-stratum plots were aerially photographed (Fig. 2). A total count of 18 800 dead trees (red + grey, strata combined) (Table 2) on the airphoto plots gave an average density of 142 dead trees/ha. The ground-corrected average of dead trees/ha was 224. In the Clinton-Dog Creek area, 21 light- and 14 severe-stratum plots were aerially photographed (Fig. 3). A total count of 10007 dead trees (red + grey, strata combined) (Table 2) on the airphoto plots gave an average density of 71 dead trees/ha. The ground-adjusted density of killed trees was 95/ha.

Data collected from ground subplots is summarized in Table 3. At Bridge River, 6 light- and 9 severe-stratum subplots were established (Fig. 2), while at Clinton-Dog Creek, 4 light- and 9 severe-stratum subplots were ground sampled (Fig. 3). The overall ratio of dead trees counted (red + grey, strata combined) on the ground to those counted on airphoto subplots was 1.58:1 for the Bridge River area and 1.34:1 for the Clinton-Dog Creek area. The greatest difference between ground and photo subplot counts in both areas was for grey trees (over 2.4:1) (Table 3), generally because many of these were smaller trees than the red trees (ratio less than 1.2:1) and hidden from view on the airphotos. The overall average dead tree volume was 0.44 m^3 for Bridge River and 0.34 m^3 for Clinton-Dog Creek.

The total number of lodgepole pine (10-cm or greater in dbh) counted on 15 ground subplots at Bridge River was 2 675, with 33% green-healthy, 21% green-attacked, 23% red, and 23% grey. At Clinton-Dog Creek the total number of trees counted was 1917 on 13 ground subplots, with 53% green-healthy, 16% green-attacked, 17% red, and 14%grey.

For the total area attacked at Bridge River (light and severe strata combined), an estimated 4.3 million lodgepole pine (red and grey),

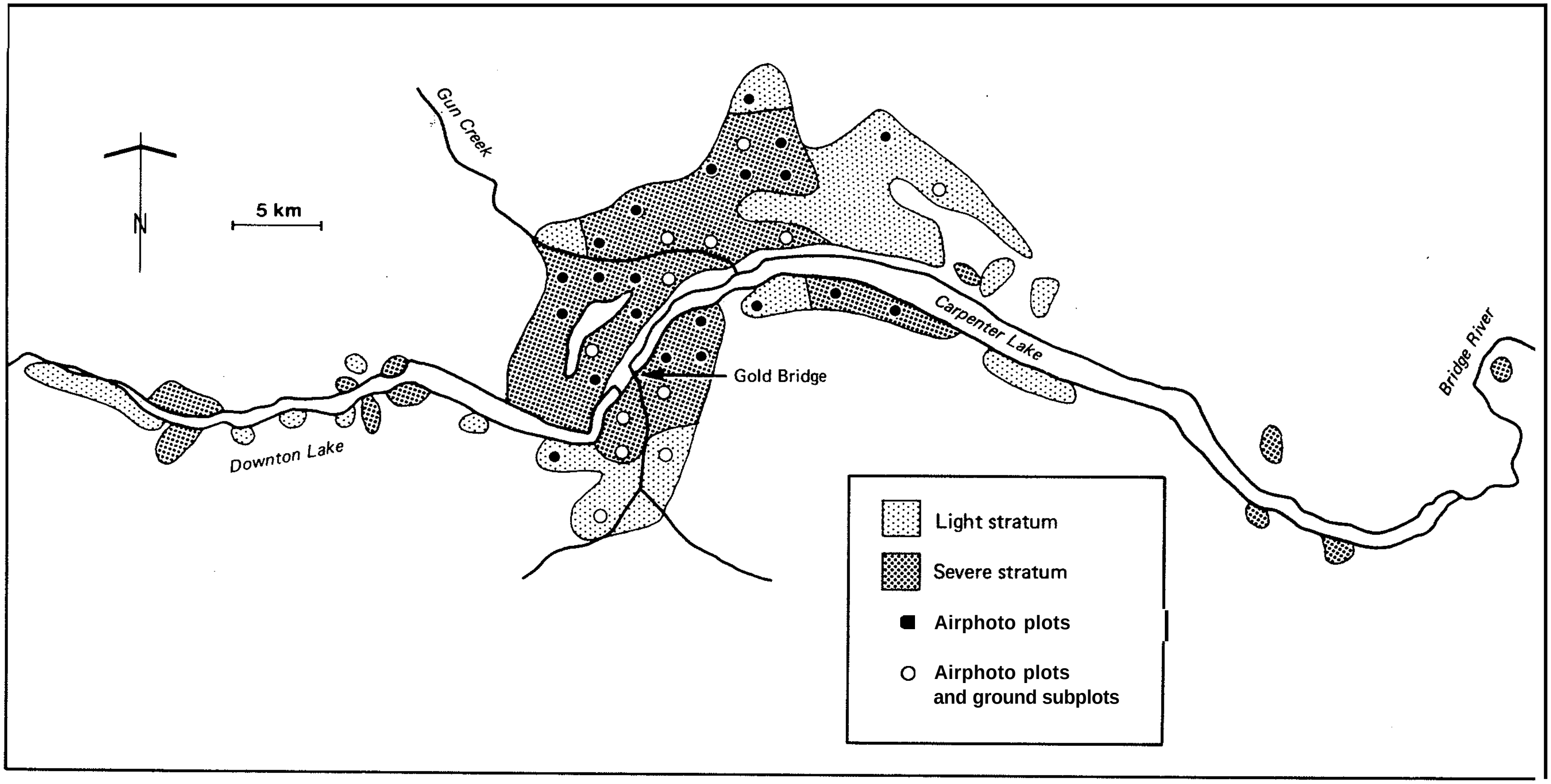

Figure 2. Mountain pine beetle damage sketch-mapped from the air, and location of airphoto plots and ground subplots, Bridge River, 1981.

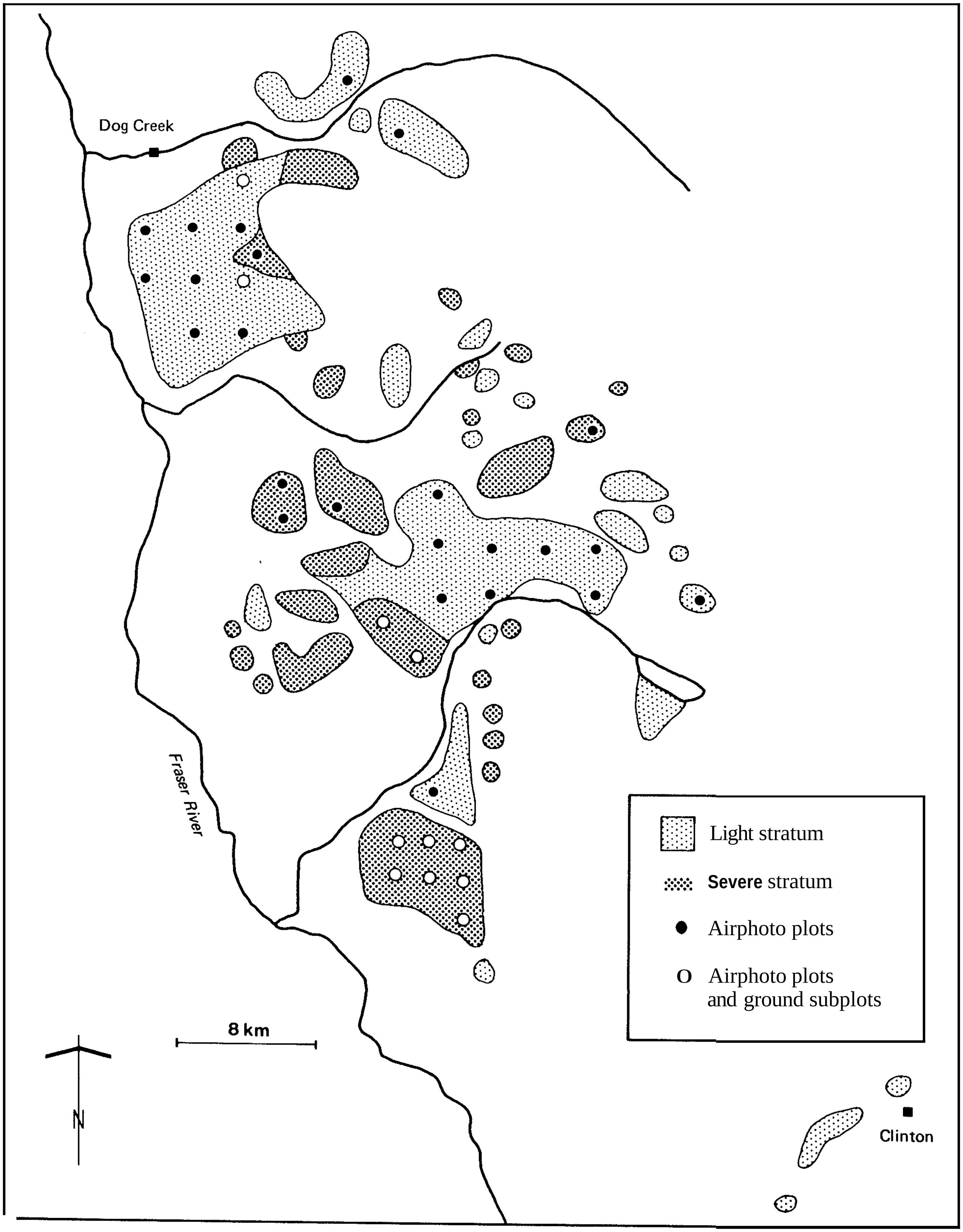

Figure 3. Mountain pine beetle damage sketch-mapped from the air, and location of airphoto plots and ground subplots, Clinton-Dog Creek, 1981.

amounting to nearly 1.6 million m^3, had been killed by mountain pine beetle (Table 4). At Clinton-Dog Creek, nearly 2.1 million trees were estimated to have been killed in the two strata, amounting to over 550 000 m^3. Sampling errors at Bridge River for total killed trees were 12.5% (light) and 17.1% (severe) and 16.5% (light) and 20.2% (severe) for volume of killed trees. At Clinton-Dog Creek the sampling errors were 29.1% (light) and 17.0% (severe) for killed trees and 41.1% (light) and 20.0% (severe) for volume of killed trees.

A comparison of the estimated number of recently-killed (red) lodgepole pine made during aerial sketch-mapping and taken from the photo plot and ground subplot counts is shown in Table 5. Aerial estimates of numbers of red trees were only 15-33% of that estimated using combined photo plot and ground subplot counts.

Costs averaged 41¢/ha (Table 6) for the two study areas (costs were about the same for each area). The approximate number of person-days required for the study was 150; initial planning 40 days, aerial sketch-mapping 12 days, aerial photography 12 days, photo interpretation 10 days, field work 40 days, and data analysis and reporting 36 days.

DISCUSSION AND CONCLUSIONS

The simplified multistage sampling procedure examined in this study could aid in assessing mortality in lodgepole pine stands attacked by the mountain pine beetle. The area of damage obtained from aerial sketch-mapping is applied to factors obtained from limited ground cruises and large-scale color aerial photography to estimate the number of trees killed and the volume loss.

The sampling design uses aerial sketch-mapping to delineate damage, aerial estimates of dead-tree densities to stratify damage, airphoto plot dead-tree counts to estimate the average density of dead-trees in each stratum, ground subplot dead-tree counts to adjust photo plot average dead-tree densities, and tree measurements from ground subplots to determine average dead-tree volume. The total number of trees killed, is estimated as the product of the damaged area and the adjusted density of dead trees. The number of killed trees is multiplied by the average dead-tree volume to give the total volume loss.

Aerial sketch-mapping of forest damage is difficult, observers generally using topographic maps at a scale which hinders accurate mapping of the correct location and size of damaged stands (Harris and Dawson 1979). In this study, mosaics of several medium-scale vertical black-and-white airphotos proved the most useful for sketch-mapping. Individual airphotos covered so little ground area that observers were continually shifting between photos and easily became lost. Estimating the number of killed trees within damage polygons was also difficult; ideally, a damage polygon should have an even dead-tree density throughout, and be bounded by distinguishable changes in topography.

The 4-ha airphoto plot used in this study covered 44% of the 70-mm frame area at the desired scale of 1:6 000. Actual photo scale varied from 1:4 962 to 1:6 875, though most plots were close to 1:6 000. Edge distortion was generally minimal on the outside subplots at these scales. The Vericolor II negative film, when processed to 13-cm x 13-cm print enlargements, proved adequate for field and laboratory use, but some loss of resolution was apparent and for some trees it was difficult to judge tree crown color (i.e., red vs grey, yellow vs green). The number of ground subplots established was fewer than desirable, especially for the light stratum.

Sampling errors were at acceptable levels for total number and volume of dead trees (15% and 17-20%, respectively, versus 18% and 40% in 1980). Sampling errors for estimates of red and grey trees separately were similar or slightly higher (under 35%, versus red under 28%, grey under 60% in 1980), except for the light stratum at Clinton-Dog Creek (over 42%), where only four ground subplots were established.

The cost in 1981 (41 cents/ha) was less than half that in 1980 (85 cents/ha), with over three times the area surveyed (48 382 ha vs 14 750 ha), reflecting the decrease in cost/ha as the size of the area sampled increases (Harris et al. 1982).

ACKNOWLEDGEMENTS

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Table 1. Sketch-mapped areas, sampling statistics, and estimated numbers of lodgepole pine killed by mountain pine beetle, Bridge River and Clinton-Dog Creek, B.C., 1981.

Location	Stratum	Area (ha) sketch-mapped	Damage polygons[1]	Dead trees	Dead trees/ha		Photo plots	Sampling interval (km)
					range	avg		
Bridge River	Light	9 040	37	40 365	1-10	4.5	7	3.6
	Severe	12276	23	350540	10.1-51.2	28.6	26	3.3
	Total	21 316	60	390 905	1-51.2	18.3	33	
Clinton-Dog Creek	Light	20 778	34	40 640	1-10	2.0	21	3.1
	Severe	6 228	49	124070	1.1-80	19.7	14	2.1
	Total	27 066	83	164 710	1-80	6.1	35	

[1] Finite geographic areas of any shape defined by topography, site type, etc., and group of damaged trees.

Table 2. Number and average density of dead lodgepole pine on airphoto plots, and ground-corrected average density **of** dead trees, Bridge River and Clinton-Dog Creek, B.C., 1981.

Location	Stratum	Tree category[1]	Trees counted	Dead trees/ha	Ground-corrected dead trees/ha[2]
Bridge River	Light	Red	754	27	30
		Grey	224	8	31
		Total	978	35	-
	Severe	Red	12 090	116	39
		Grey	5 732	55	66
		Total	17 822	171	
Clinton-Dog Creek	Light	Red	530	6	6
		Grey	883	11	26
		Total	1413	17	-
	Severe	Red	6 582	18	26
		Grey	2 012	36	101
		Total	8 594	154	

[1] Total = all dead trees (red **plus** grey).

[2] The ground-corrected average number of dead trees/ha for red and grey trees is calculated by multiplying the average number of dead trees/ha by $\bar{\bar{R}}$ from Table 3.

Table 3. Dead lodgepole pine counted on ground subplots and corresponding airphoto subplots, and average subplot tree volumes (m^3), Bridge River and Clinton-Dog Creek, B.C., 1981.

Location	Stratum	Subplots	Tree category	Dead trees counted[1] ground	Dead trees counted[1] airphoto	Average ratio ground count/airphoto count[2] ($\overline{R}$)	Average tree volume (m^3)
Bridge River	Light	6	Red	136	123	1.121	0.6653
			Grey	77	28	3.878	0.3543
			Total	213	151		
	Severe	9	Red	473	398	1.195	0.3821
			Grey	538	224	3.015	0.3174
			Total	1011	622		
Clinton-Dog Creek	Light	4	Red	36	36	0.988	0.5001
			Grey	58	32	2.472	0.2728
			Total	94	68		
	Severe	9	Red	309	294	1.069	0.2491
			Grey	213	103	2.807	0.2334
			Total	522	397		

[1] Trees counted on the ground are IO-cm dbh or greater.

[2] $\overline{R}$, the average of the ratios for all subplots in each category, and the average tree volume are calculated separately for red and grey trees.

$\overline{R} = (\Sigma r)/n$ where r = each subplot ratio
n = number of subplots

Table 4. Estimates of number and volume (m^3) of lodgepole pine killed by mountain pine beetle, Bridge River and Clinton-Dog Creek, B.C., 1981

Location	Stratum	Tree category[1]	Trees killed	Standard error	Volume killed (m^3)	Standard error (m^3)
Bridge River	Light	Red	270 296	57 955	179 828	41 001
		Grey	280 240	79 737	99 289	34 155
		Total	550 536	68 704	279 117	46 104
	Severe	Red	1 706 364	285 532	652 002	146 048
		Grey	2 039 044	604 884	647 193	224 576
		Total	3 745 408	640 807	1 299 195	263 186
	Total		4 295 944	644 480	1 578 312	267 194
Clinton-Dog Creek	Light	Red	124 668	64 378	62 347	40 588
		Grey	540 228	228 558	150 075	94 547
		Total	664 896	193 235	212 422	87 268
	Severe	Red	790 402	198 386	196 889	54 172
		Grey	635 717	175 254	148 376	41 100
		Total	1 426 119	242 088	345 265	69 168
	Total		2 091 015	309 846	557 687	111 355
Overall Total			6 386 959	715 094	2 135 999	289 469

[1] Total category is total number and volume of dead trees (red plus grey).

Table 5. Comparison of estimates of recently killed (red) lodgepole pine based on aerial sketch-mapping and airphoto-plot and ground-subplot counts, Bridge River and Clinton-Dog Creek, B.C., 1981.

Location	Stratum	Estimated red trees: From photo plot and ground subplot counts (A)	Estimated red trees: From aerial sketch-mapping (B)	Ratio A:B
Bridge River	Light	270 296	40 365	6.7:1
	Severe	1 706 364	350 540	4.9:1
	Total	1 976 660	390 905	5.1:1
Clinton-Dog Creek	Light	124 668	40 640	3.1:1
	Severe	790 402	124 070	6.4:1
	Total	915 070	164 710	5.6:1

Table 6. Estimated costs for airphoto assessment of mountain pine beetle damage on 48 382 ha in 1981 (Bridge River and Clinton-Dog Creek areas combined).

Item	cost ($)
Aerial sketch-mapping (6 hr)	1500
Film, printing, and processing	1000
Airphotos and maps	200
Aerial photography of photo plots (6 hr)	1500
Salaries - 150 person-days	12 070
Field expenses	2 600
Vehicle fuel	900
Total cost	19 770
Cost/ha	0.41