Containment and Concentration of Mountain Pine Beetle (Coleoptera: Scolytidae) Infestations with Semiochemicals: Validation by Sampling of Baited and Surrounding Zones

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ABSTRACT Attack intensification within mountain pine beetle, *Dendroctonus ponderosae* Hopkins, infestations in five stands of lodgepole pine, *Pinus contorta* var. *latifolia* Englemann, was compared within a central zone (A) and two concentric, surrounding zones (B and C) that were 50 and 100 m wide, respectively. When trees in Zone A were baited at 50-m centers with semiochemicals (*trans*-verbenol, *exo*-brevicomin, and myrcene), ratios of newly attacked (green) trees to previously attacked (red) trees were greater in Zone A than the outer zones in two of three stands, indicating successful containment and concentration of these infestations. In two control stands in which Zone A was unbaited, the green/red ratios were higher in Zone B than in the other two zones, indicating an outward spread of the infestation. Baiting of trees caused an increase in attack density in Zone A. Attack density and diameter were positively correlated for all sites. Incorporating attack density and tree diameter into a weighted green/red ratio or an attack intensification ratio amplified the results obtained by calculating unweighted green/red ratios, and indicated containment and concentration in the third experimental stand. These results confirm that tree baiting is an effective method of containing and concentrating mountain pine beetle infestations.

KEY WORDS Insecta, *Dendroctonus ponderosae,* pheromones, forestry

MOUNTAIN PINE BEETLE, *Dendroctonus ponderosae* Hopkins, is the most damaging insect pest of lodgepole pine, *Pinus contorta* var. *latifolia* Engelmann, in western North America (Furniss & Carolin 1977). In British Columbia, annual volumes of mountain pine beetle-killed timber averaged 10.5 million m^3 on 304,000 ha from 1981 to 1986 (Fiddick & Van Sickle 1982; Wood & Van Sickle 1983, 1986, 1987; Wood et al. 1984, 1985).

Mountain pine beetle management and the minimization of timber losses have relied primarily on the harvesting of infested stands (Amman et al. 1977, McMullen et al. 1986). The effectiveness of this tactic can be seriously reduced if delays allow beetle broods to emerge before harvesting is completed and beetles leave the proposed clearcutting to attack new trees. Such delays are common and are caused by many factors including the requirements for obtaining a cutting permit, operators' commitments in other areas, poor timber markets, labor unrest, and poor or inadequate access.

The use of semiochemicals has been proposed as a means by which an infestation can be contained and concentrated within its current borders during the beetle flight and attack period. Semiochemicals have received relatively widespread acceptance and use for this purpose in British Columbia (Borden & Lacey 1985, British Columbia Ministry of Forests and Lands 1985, Borden in press) despite the limitations of studies done to assess the containment and concentration objectives.

The ratio of newly attacked trees (green-attacked or green trees) to trees attacked the previous year (red-attacked or red trees) has been used to assess the success of containment and concentration programs. Borden et al. (1983b) and Heath (1986) reported higher green/red ratios in baited than in unbaited infestations on the basis of a grid baiting pattern (50 by 50 m). However, the assumption that containment and concentration within baited blocks would result in a higher green/red ratio than in unbaited blocks is valid only if baiting does not cause a proportionately lighter attack on more trees. In addition, the green/red ratios were significantly different in only two of five paired baited and unbaited blocks (Borden et al. 1983b) and in two of four paired blocks (Heath 1986).

Assessments that examine the quantity of beetle attacks and the probable location of the source of attacking beetles rather than the number of attacked trees would better measure the success of the containment and concentration objectives. In addition, assessments of operational sites should be designed so that comparisons with untreated sites are not necessary. Here we assess the effectiveness of semiochemical baiting to contain and concentrate attacking mountain pine beetle populations within the borders of a baited area. We also introduce an assessment method that does not require untreated control sites for evaluation.

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Table 1. Stand characteristics and mountain pine beetle attack incidence for all trees with dbh ≥12.5 cm

Site	Treatment	Size of Zone A, ha	Stems per ha, all spp.	Lodgepole pine		No. trees attacked per zone					
				Stems per ha	$\bar{x}$ dbh, cm	Red			Green		
						A	B	C	A	B	C
Lussier River	Control	4.0	505	353	20.9	396	71	132	618	632	340
Linklater Creek	Control	2.5	520	340	28.6	57	68	26	19	141	15
Mitchell River	Zone A baited	5.0	626	595	21.5	9	1	23	132	8	47
Caven Creek	Zone A baited	9.0	470	335	18.8	35	63	72	251	111	104
Sam's Folly	Zone A baited	6.5	406	392	20.4	177	58	51	633	249	129

Materials and Methods

Field Treatments. Five mountain pine beetle infestations ranging from 2.5 to 9.0 ha were selected from 1984 to 1986 in lodgepole pine stands in the Nelson Forest Region, B.C. (Table 1). The stands were relatively pure, mature lodgepole pine in composition and averaged 505 stems per ha, 80% of which were lodgepole pine. The mean diameter at breast height (dbh, 1.3 m) for lodgepole pine ranged from 18.8 to 28.6 cm.

Infestation boundaries were determined by field examination, and a grid (50 by 50 m) that encompassed the main infestation was superimposed on each site. In three experimental sites, Mitchell River, Caven Creek, and Sam's Folly, semiochemical baits (Phero Tech, Vancouver, B.C.) were affixed on the north side of large-diameter trees at grid points in May or June preceding the first mountain pine beetle emergence. The baits contained *trans*-verbenol (70% [−] and 30% [+]), (±)-*exo*-brevicomin and myrcene, released at rates (determined at 20°C in the laboratory) of 1.0, 0.2, and 18 mg per 24 h, respectively. Two sites, Lussier River and Linklater Creek, served as untreated controls.

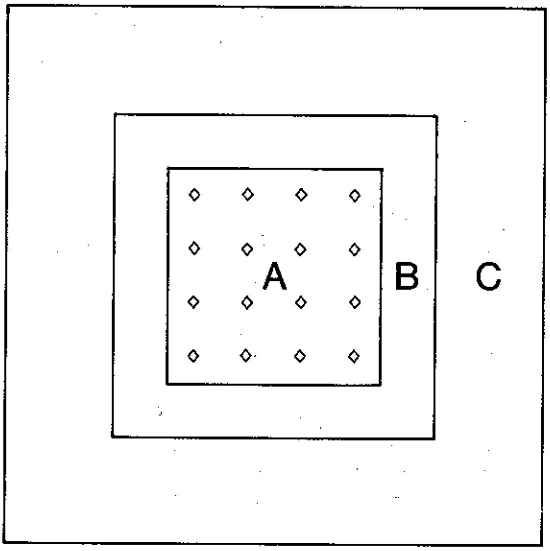

Fig. 1. Experimental design of containment and concentration experiment depicting three zones: a central zone (A) that in experimental treatments was baited with mountain pine beetle tree baits at 50-m centers (diamonds), and two concentric surrounding zones, one (B) 50 m wide and the other (C) 100 m wide.

Assessment at each infestation site was done in three zones (Fig. 1): the gridded infestation (baited in the experimental sites) plus a 25-m border as the total central area (Zone A), a 50-m-wide strip around the central area (Zone B), and a 100-m-wide strip around Zone B (Zone C). After completion of the flight period, a 100% survey was done in which every lodgepole pine ≥12.5 cm dbh in all three zones was examined. The diameter at breast height (dbh) of every green tree was recorded, and attack density as determined by two (20 by 40 cm samples; long axis oriented vertically; total area, 0.16 m^2) was taken at eye level from opposite sides of the tree. The dbh of every red tree also was recorded. In the Lussier River site, the attack density was not recorded for 20–30% of the trees, from which woodpeckers had removed large amounts of bark. These trees were assigned the mean attack density for the zone in which they occurred.

Assessment of Containment and Concentration. For each zone in each site, the attack intensification was calculated in three ways: the standard green/red ratio calculated from the raw data in Table 1, a weighted green/red ratio, and an attack intensification ratio (AIR).

The weighted green/red ratio used the attack density per 0.16 m^2 and dbh of green trees, and an assumed attack density and dbh of an average red tree (red-tree-equivalent or RTE), to compute the number of green tree equivalents (GTE) for each zone. Presuming that trees in unbaited stands would be attacked at the same densities in successive years, the mean attack density on all green trees in the two control sites (6.72 attacks per 0.16 m^2) was used as the assumed attack density on red trees. We assumed that, on average, trees of equal diameter will be attacked to the same height, making it unnecessary to weight attack intensification by tree height in calculating either the weighted green/red ratio or the AIR.

For each zone, the weighted green/red ratio was calculated by the following formulae:

$$\text{RTE} = 6.72(\bar{x}\ \text{dbh of red trees})$$

$$\text{No. GTE} = \frac{\Sigma(\text{dbh} \times \text{attack density per } 0.16\ \text{m}^2 \text{ on green attacked trees})}{\text{RTE}}$$

$$\text{Weighted green/red ratio} = \frac{\text{No. GTE}}{\text{No. red trees}}$$

The AIR for each zone was calculated as:

$$\text{AIR} = \frac{\Sigma(\text{dbh} \times \text{attack density per } 0.16\ \text{m}^2 \text{ on green attacked trees})}{\Sigma\ \text{dbh of red attacked trees}}$$

If there is no net movement of attacking beetles among Zones A, B, and C, and assuming no difference among zones in the mean emergence of brood per square meter of bark surface from red trees, $\text{AIR}_A = \text{AIR}_B = \text{AIR}_C$. If, however, beetles were to emerge from trees in Zone A and attack trees in Zone B, AIR_B would be greater than AIR_A, because there would be attacks in Zone B without the accompanying red trees. Thus, containment and concentration can be judged by the ranking of the three AIRs.

In an attempt to design a sampling system that would reliably assess containment and concentration through use of the AIR, the position of each tree in the Sam's Folly infestation was mapped at 1:315 (¼ in. = 2 m) scale. This stem map was used to pass a simulated sample strip (5 or 10 m wide) through the center of the infestation and then to repeat the sample five times by reorienting the survey strips by 72° increments.

Statistical Analysis. The overall green/red ratios for the baited and control Zones A were compared by χ^2 tests (Zar 1984). Green/red ratios (weighted and unweighted) among zones for each site were compared by a Kruskal–Wallace test (Zar 1984) followed by Zar's (1984) procedure for multiple comparisons between proportions. Because the AIR is an abstract proportion that does not compare two populations of individuals, as do green/red ratios, no statistical analysis could be done.

Attack densities were compared by t tests or analysis of variance followed by the Newman–Keul's test (Zar 1984) on the raw data. The relationships between mean attack densities and tree diameters were analyzed by linear regression. If the slopes and intercepts of the regressions for two or more zones within a site were not different ($P > 0.05$) (Zar 1984), data were pooled. Zones with less than five trees represented in four or fewer diameter classes were eliminated from regression analysis. In all cases, α was set at 0.05.

Results and Discussion

Using the past methodology of Borden et al. (1983a) and Heath (1986) to assess containment and concentration by comparing the green/red ratios between baited and control stands (Zone A only), a significant containment and concentration effect was observed. The overall green/red ratio for the three baited Zones A (4.6) was significantly higher (χ^2 test, $P < 0.001$) than that for the two unbaited Zones A (1.4).

Comparison of the green/red ratios between Zones A–C within each site (Fig. 2) showed that, for each control (unbaited) stand, the ratio was significantly higher in Zone B than in A or C. Thus, in the absence of baits in the heavily infested Zone A, the infestations in both stands expanded outward approximately 50 m to trees in Zone B. Within the baited Zone A of two of the experimental stands, green/red ratios were significantly higher than in the outermost Zone C (Mitchell River) or both Zones B and C (Caven Creek), indicating that these infestations had been fairly well contained and concentrated. For the third experimental stand (Sam's Folly), green/red ratios suggested incomplete containment and concentration. The ratio was numerically highest in Zone B, but the ranking differed from the two control stands in that the ratios in Zones A and B were significantly higher than in Zone C.

Within Zone A in the experimental stands, attack density on baited trees was significantly higher than on unbaited trees ($80.6 \pm 4.8/\text{m}^2$, $n = 77$, versus 53.3 ± 1.4, $n = 939$). This result confirms the findings of Borden et al. (1983a,c) and demonstrates the power of the baits to concentrate the attacking beetles.

When the attack densities were compared between sites for each zone (Table 2), densities in the three semiochemical-baited Zones A were significantly higher than in their unbaited counterpart in the Lussier River site, again indicating a concentration effect of baiting. Although numerically the lowest, density in the Linklater Creek site was statistically intermediate between the Lussier River and the three experimental sites. Attack densities in all Zones B were equal, suggesting that the attraction because of the naturally high attack frequency in this zone in the control stands resulted in densities that matched the uniformly high attack densities in the experimental stands. In Zone C, a higher attack density in the baited stands than in control stands was once again evident, possibly indicating that the drawing power of the semiochemical baits extended into this zone. However, a conflicting effect occurred. As indicated by the low numbers of attacked trees (Table 1) as well as low green/red ratios (Fig. 2), few trees in Zone C in the experimental stands were attacked, but the attack density was high on those that were infested (Table 2). In Zone C for both control sites, and in Zone A in the Linklater Creek site, the mean attack densities were lower than the threshold of 40 attacks per m^2 necessary to kill a tree (Raffa & Berryman 1983), once again showing the dispersive nature of the beetles in the absence of semiochemical baits to induce attack.

When attack densities for baited or unbaited zones within each stand were regressed against diameters of the attacked trees, positive linear correlations occurred in each case (Fig. 3). The lowest r^2 value for any regression was 37% for Sam's Folly (Zone C) and the next lowest was 70.7% (Fig. 3).

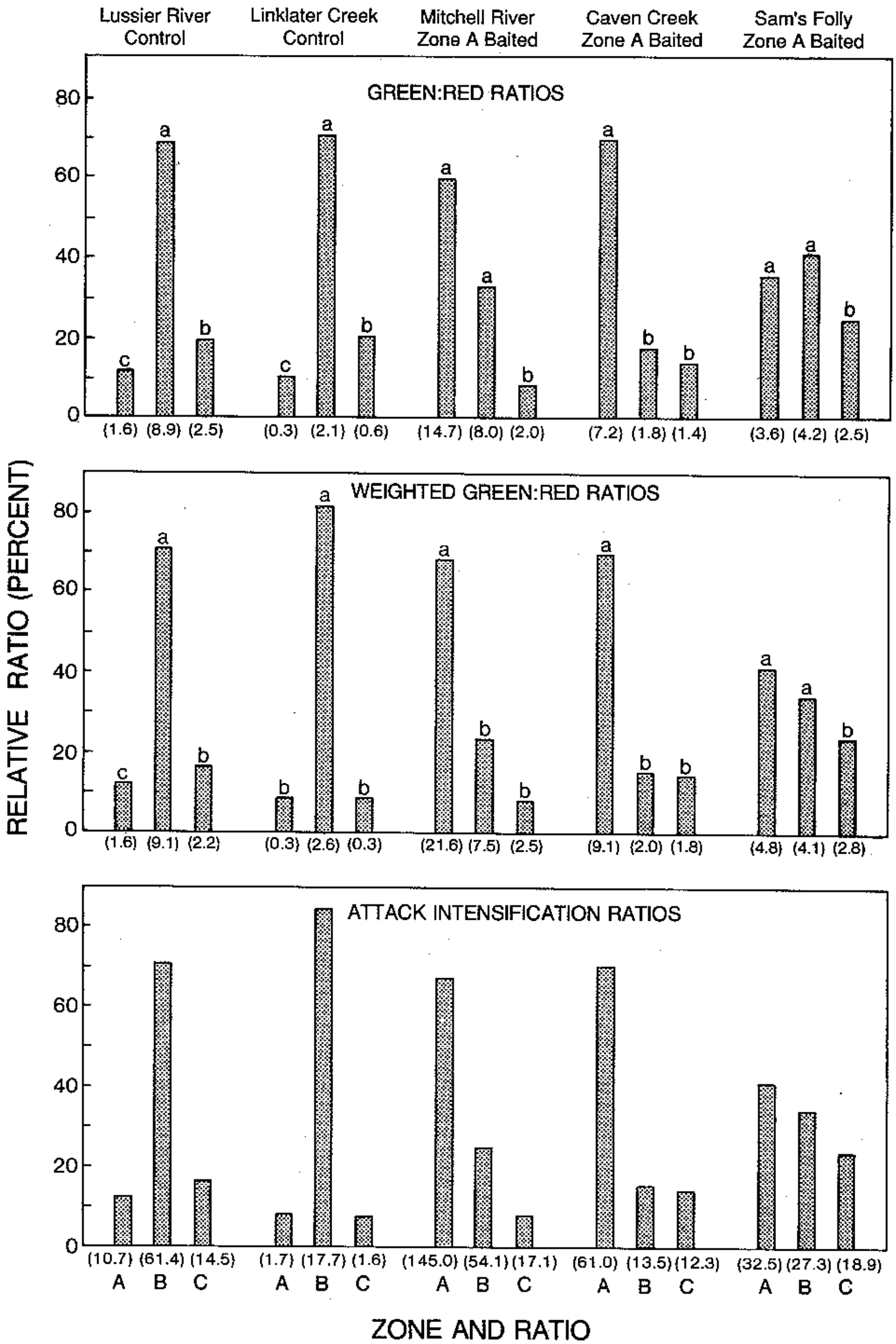

Fig. 2. Relative ratios used to assess attack intensification in five mountain pine beetle infestations, each divided into three zones (Fig. 1). Trees in central zone (A) baited with semiochemical baits on a 50-m grid in the Mitchell River, Caven Creek, and Sam's Folly infestations. Within each site, all bars identified by the same letter are not significantly different from each other ($P < 0.05$; Zar's [1984] test for comparisons between proportions). Actual ratios are given in parentheses below each bar.

These results confirm those of Borden et al. (1983c) for two infestations in widely separated geographical zones.

The increased attack densities in baited stands (Table 2) and the positive correlations between attack density and tree diameter (Fig. 3) justify use of attack density and tree diameter to weight any method of determining attack intensification. In-

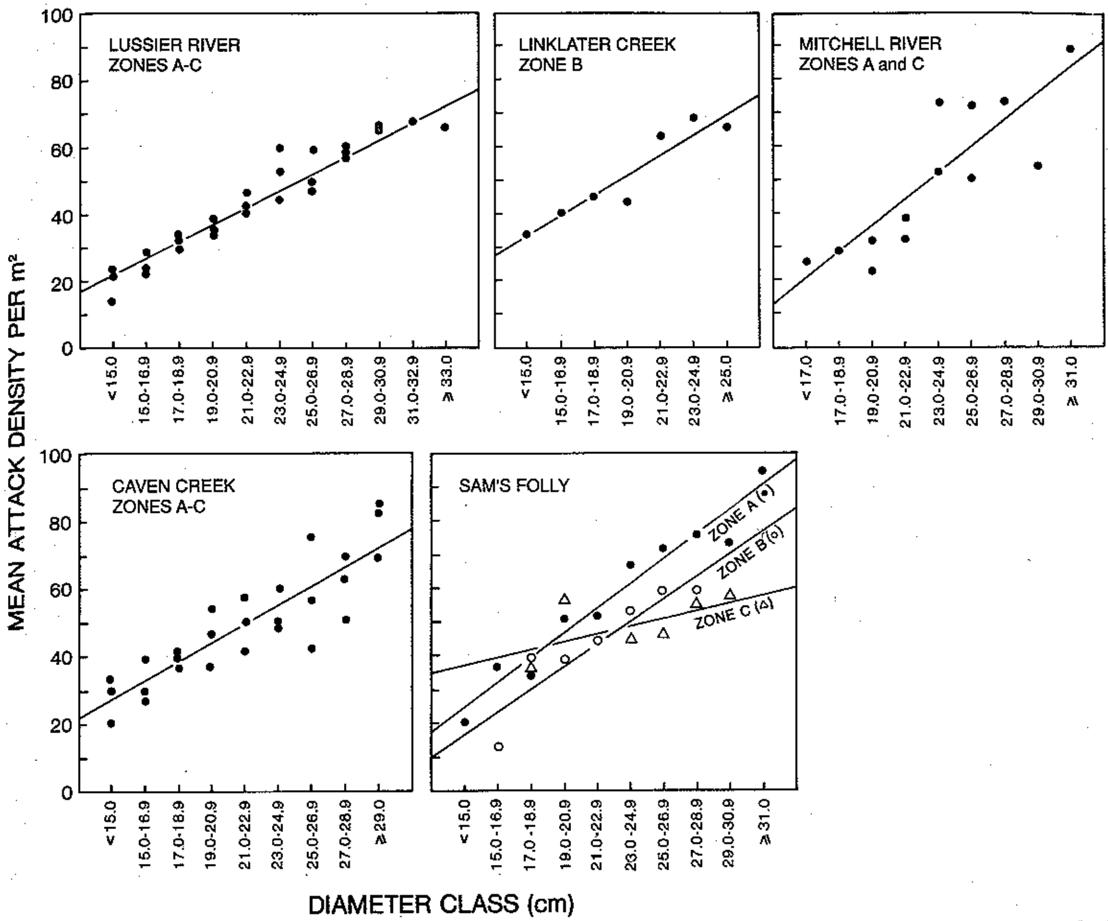

Fig. 3. Relationships between attack densities and diameter at breast height for mountain pine beetle-attacked trees. Regression equations and coefficient of determination (r^2) values as follows: Lussier River, Zones A–C, y = −12.8 + 2.50x, r^2 = 89.6%; Linklater Creek, Zone B, y = −7.64 + 2.97x, r^2 = 89.7%; Mitchell River, Zones A and C, y = −40.6 + 3.84x, r^2 = 70.7%; Caven Creek, Zones A–C, y = −12.0 + 2.81x, r^2 = 76.8%; Sam's Folly, Zone A, y = −26.4 + 3.66x, r^2 = 95.2%, Zone B, y = −31.5 + 3.43x, r^2 = 85.9%, Zone C, y = 21.5 + 1.14 x, r^2 = 37.0%. The test for differences in slopes of the three regressions for the Sam's Folly site indicate that A ≥ B ≥ C.

corporating attack density and tree diameter into the weighted green/red ratio and AIR formulae should then provide a much better method of determining attack intensification than the simple green/red ratios.

Our results (Fig. 2) support this hypothesis. When weighted green/red ratios were used, the shifting of attack to Zone B in control stands was even more clear or significant, as was the containment and concentration within Zone A in two of the experimental stands (Mitchell River and Caven Creek). Moreover, in the Sam's Folly stand, the apparent movement of beetles into Zone B as measured by green/red ratios was reversed, although the significant containment effect still extended into Zone B (Fig. 2). Even though no statistical analysis is

Table 2. Comparison of attack densities by the mountain pine beetle on green trees within Zones A, B, or C (Fig. 1)

Treatment	Site	Attack density per m³, $\bar{x}$ ± SEM		
		Zone A	Zone B	Zone C
Control	Lussier River	42.7 ± 1.2b	43.1 ± 1.1a	36.9 ± 1.3b
(Zone A not baited)	Linklater Creek	38.3 ± 10.3ab	49.8 ± 3.4a	17.5 ± 4.9c
Experimental	Mitchell River	53.7 ± 4.5a	48.4 ± 18.5a	52.3 ± 7.0a
(Zone A baited)	Caven Creek	53.1 ± 2.6a	44.1 ± 3.6a	47.1 ± 3.4a
	Sam's Folly	56.7 ± 1.7a	44.1 ± 2.0a	47.6 ± 3.3a

Means within a column followed by the same letter are not significantly different ($P < 0.05$; Newman–Keul's test [Zar 1984]).

Table 3. Comparison of three ratios used to measure containment and concentration after 100% survey of trees on the Sam's Folly site or after simulated strip surveys on stem-mapped trees

Type of survey[a]	Zone	Green/red ratio	Weighted green/red ratio	AIR
100% Trees surveyed	A	3.6a	4.8a	32.5
	B	4.2a	4.1a	27.3
	C	2.5b	2.8b	18.9
Five strips, each 5 m wide	A	1.7b	2.7a	23.8
	B	3.0a	2.8a	18.9
	C	0.5c	0.5b	3.7
Five strips, each 10 m wide	A	2.8a	3.9a	26.6
	B	1.7b	1.5b	10.0
	C	1.2c	1.6b	10.5

Ratios within a survey method and column followed by the same letter are not significantly different ($P < 0.05$; Zar's [1984] test for comparisons between proportions).

[a] Each of five strip surveys, 5 or 10 m wide, passed through the plot center, with each successive strip offset 72° from the preceding one.

possible on the AIRs, the almost identical relative ratios obtained for the weighted green/red ratios and the AIRs (Fig. 2) suggest that both are valid measures of attack intensification. Standard green/red ratios may fail to indicate containment and concentration or its true effect accurately because they do not encompass the higher attack densities induced by baiting (Table 2) or the positive relationship between attack density and dbh (Fig. 3). Because calculation of weighted green/red ratios requires assessment of mean attack density in the absence of baiting, we recommend use of AIRs for qualitative assessment of an operational project.

In the experimental stands, the most probable causes of the weighted green/red ratio and AIR ranking are inhibition of emigration of beetles from Zone A and an overall inward movement of beetles toward Zone A from Zones B and C. The higher values of all three ratios in Zones B than in Zone C in the Mitchell River and Sam's Folly sites (Fig. 2) could be because a lesser proportion of beetles leave from Zone B than from Zone C, or to some portion of beetles from Zone C being arrested in Zone B. We have often found characteristic elliptical infestations extending 25–50 m downwind of baited trees. Such an event would be consistent with the arrestment of incoming beetles in Zone B. Whatever the reason, containment and concentration were shown in all three experimental stands as indicated by the ranking of weighted green/red ratios and AIRs and the differences in ratio distributions between baited and control stands. Furthermore, the semiochemical lures apparently attracted beetles from at least 75 m. These results suggest that the boundaries of clearcuttings designed to remove beetles after baiting should be set 75 m beyond the outermost baited trees.

Individually, the 5- or 10-m-wide simulated survey strips on the stem-mapped layout of the Sam's Folly site did not indicate containment and concentration reliably. However, when all five strips were combined, containment was indicated in both, although only the 5-m-wide strips assessed by a weighted green/red ratio or by an AIR faithfully reproduced the trend obtained with 100% survey (Table 3). Thus, for ease of application and likelihood of correctly assessing the general trend of containment and concentration, use of AIRs and a sampling method of five 5-m-wide strips appears to be sufficient for application in the field. We conclude that semiochemical baiting of mountain pine beetle infestations as proposed and conducted by Borden et al. (1983b), Borden & Lacey (1985), and Heath (1986) is a valid method of containing and concentrating infestations.

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