Sampling plan for *Adelges cooleyi* (Hemiptera: Adelgidae) in spruce seed orchards

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Abstract—Within-plant and between-plants distributions of Cooley spruce gall adelgid, *Adelges cooleyi* (Gillette), fundatrices were measured in ''interior spruce'', *Picea glauca* × *P. engelmannii* (Moench) Voss. & Parry (Pinaceae), seed orchards in central British Columbia to develop a quantitative sampling plan. Adelgids (number of fundatrices per shoot) were abundant at the lower and middle crown heights of the tree crowns but scarce at the upper crown height, and more abundant on the ends and central one-third of branches than on the inner portions. The northern and eastern aspects of trees had slightly but significantly more adelgids than did the southern and western aspects, and terminal shoots had more adelgids than did distolateral shoots. Variance was much greater between than within trees. These data were used to create a sampling plan with a sample unit consisting of a single 1-year-old shoot selected from the ends or central area of main branches in the lower or middle portion of each sample tree. Collecting 104 samples required 69 min, and yielded an estimate of the mean number of fundatrices per shoot with a standard error of 10% of the mean.

Résumé—Nous avons mesuré la répartition sur les plantes et entre les plantes des fondatrices du puceron de l'épinette de Sitka, *Adelges cooleyi* (Gillette), dans des pépinières à graines de l'« épinette de l'intérieur », *Picea glauca* × *P. engelmannii* (Moench) Voss. et Parry (Pinaceae), dans le centre de la Colombie-Britannique, afin de mettre au point un plan quantitatif d'échantillonnage. Les adelgidés (nombre de fondatrices par tige) sont abondants aux niveaux inférieurs et moyens de la cime des arbres, mais rares dans les niveaux supérieurs; ils sont plus abondants à l'extrémité et sur le tiers central des branches que sur les sections internes. Les expositions nord et est des arbres portent une densité un peu plus élevée, mais significative, d'adelgidés que les expositions sud et ouest et les pousses terminales portent plus d'adelgidés que les pousses distolatérales. La variance entre les arbres est beaucoup plus importante que la variance sur un même arbre. Ces données ont servi à bâtir un plan d'échantillonnage qui comprend comme unité d'échantillonnage une seule pousse âgée d'une année sélectionnée sur les bouts ou le centre de branches principales dans la région inférieure ou médiane de chaque arbre échantillonné. La récolte de 104 échantillons requiert 69 min et permet de faire une estimation du nombre moyen de fondatrices par tige avec une erreur type de 10 % de la moyenne.

[Traduit par la Rédaction]

Introduction

The Cooley spruce gall adelgid, *Adelges cooleyi* (Gillette) (Hemiptera: Adelgidae), develops on many species of spruce (*Picea* A. Dietr., Pinaceae) in North America, causing galling of vegetative and reproductive shoots (Johnson and Lyon 1991). In ''interior spruce'', *P. glauca* × *P. engelmannii* (Moench) Voss & Parry (Pinaceae)), seed orchards in British Columbia, damage caused by *A. cooleyi* (primarily) and other adelgid species is

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responsible for up to 50% and 100% seed loss in orchards and individual cones, respectively (W.B.S., unpublished data). Preventing such loss in British Columbia seed orchards is necessary to realize full seed-yield potential.

Adelges cooleyi alternates hosts between interior spruce and Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco (Pinaceae) (Cumming 1959), and goes through several generations annually on each host. On spruce in interior British Columbia, sessile first-instar female nymphs (fundatrices) overwinter on the bark of 1-year-old shoots and resume development in March (Wood 1977). In April, fundatrices mature into sessile apterous adults covered with waxy wool-like secretions. They lay eggs that hatch into mobile nymphs (gallicolae) synchronously with bud burst. Gallicolae invade opening buds (Furniss and Carolin 1977), which subsequently turn into distinctive galls. Gallicolae live and develop inside the galls until late July, when the galls dehisce. Mature, alate gallicolae emerge from the galls and fly to Douglas-fir. Over the next 12 months, two more generations occur on Douglas-fir before alate sexuparae return to spruce the following July. Sexuparae give rise to male and female sexuales (the only sexual generation in Adelgidae), which mature and mate on needles of spruce in late summer. Sexuales oviposit in September and mobile fundatrix nymphs hatch by October. Fundatrices insert their stylet mouthparts into new bark and become sessile prior to overwintering. For details of the life cycle and biology of *A. cooleyi* and other adelgids see Cumming (1959), Furniss and Carolin (1977), and Foottit and Richards (1993).

Effective management of any pest depends upon accurate estimation of population densities. Estimates of *A. cooleyi* populations can be based upon the number of galls resulting from the current year's attack. Fidgen *et al.* (1994) found that galls of the eastern spruce gall adelgid, *Adelges abietis* (L.), were distributed on lateral shoots of midcrown branches of open-grown white spruce, *Picea glauca* (Moench) Voss, and were not influenced by cardinal direction. They proposed a stratified random sampling plan based on these distributions. On blue spruce, *Picea pungens* Engelm., in landscape and nursery plantings, galls were most abundant on the northern and eastern aspects (Cranshaw 1989), and variation in the extent of galling between trees was significant.

To improve seed yields from spruce seed orchards it is necessary to predict densities of galls and prevent their formation. Thus, an effective adelgid management program must include an estimate of populations prior to gall initiation. Therefore, it would be advantageous to monitor overwintered fundatrices, the life stage that stimulates gall formation either directly or through production of the bud-invading gallicolae generation (Shorthouse and Rohfritsch 1992). To our knowledge, no system for estimating adelgid densities based on sampling of fundatrices exists. A study of within-plant distributions of *A. cooleyi* on *Picea engelmannii* Parry *ex* Engelm. (Fay and Whitham 1990) indicated that fundatrices were nearly absent from shoots in upper branch whorls and most abundant in lower and mid whorls, but these data were not suitable for the development of a sampling system.

A single 1-year-old spruce shoot is a natural sample unit to use in a scheme for sampling *A. cooleyi* fundatrices. This unit is easily delineated in the field, it is of a manageable size, and all units are equally accessible. These are desirable features of sample units (Southwood 1978). Moreover, fundatrix and sample-unit densities remain constant through the early-spring sampling period. The offspring of fundatrices are gallicolae (not more fundatrices), and bursting buds will either be galled and colonized by the current season's gallicolae or will become next season's sample units (but are not available for fundatrix colonization in the current year). The objectives of this study, therefore, were to examine the spatial distributions of *A. cooleyi* fundatrices within and between trees in spruce seed orchards in central British Columbia, and to develop a quantitative monitoring plan for fundatrices using 1-year-old shoots as the sample units. Such a plan would allow the development of a density/damage relationship and action or economic thresholds, without the need to

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estimate the population in an entire tree or orchard (Southwood 1978).

Materials and methods

Selection of sample strata

To determine the within-tree location from which sample units should be collected, trees were stratified and sample units from each stratum assessed. Nineteen trees from four seed orchards near Vernon, British Columbia (50.3°N, 119.3°W), were randomly selected. Trees were 10–14 years old and 4–5 m high. In March 1996 and 1997, all overwintered fundatrices on the bark of a single 1-year-old shoot in each of 72 different strata of the tree were counted. The strata were classified as follows:

Crown height: lower (<1.5 m), middle (1.5–2.5 m), or upper (>2.5 m)

Aspect: north, south, east, or west

Branch position (only main branches (with terminal shoots reaching the outer portion of the crown) were used): end (distal 0.5 m of branch), central (middle 1/3 of branch), or inner (proximal 1/3 of branch)

Shoot type: terminal (1 shoot collected) or distolateral (4 shoots collected, treated as subsamples in the analysis).

In total, 180 shoots from each of the 19 trees (3 heights × 4 aspects × 3 branch positions × 5 shoots) were assessed. Analysis of variance (ANOVA) of $\log(x + 1)$-transformed data was used (Steel and Torrie 1960). We modelled the experiment as a randomized block split-split-split plot design, with trees acting as blocks, and shoot type, branch position, aspect, and crown height acting as factors. Main-effect means were separated by the Ryan–Einot–Gabriel–Welsch multiple range test using the REGWQ option (SAS Institute Inc. 1996) in the SAS GLM procedure ($\alpha = 0.05$).

If an adequate proportion of the population is represented in a certain stratum, this stratum alone can be used in the sampling program (Southwood 1978). The proportions of the total number of fundatrices found in various strata were therefore computed. Ideally, the proportion of fundatrices found within the selected stratum should remain relatively constant from tree to tree. This was determined by calculating, for each of the 19 trees, the proportion of the total number of fundatrices found in various strata, then examining the mean, range, and variation of the 19 resulting proportions.

Quantitative aspects

When the sample stratum or strata has (have) been selected (see above), it is necessary to determine how many sample units per tree and how many trees per orchard to assess. Thirty-one trees were surveyed in March of 1996 and 1997 in several spruce seed orchards in the north Okanagan Valley, British Columbia (50.3°–50.5°N, 119.2°–119.3°W), by counting all fundatrices on each of 20 first-year shoots per tree (620 sampling units in total). Sample units were selected from the lower or middle crown heights and from the ends and centers of branches, as determined by the results of sample-stratum selection (see Results and discussion). Fundatrices were counted in the field with a 2.75× headband magnifier (Donegon Optical Company, Kansas City, Missouri). Surveys were timed with a stopwatch to determine the cost (in seconds) of sampling within trees *versus* moving between trees. Variances within and between trees were determined by ANOVA of untransformed data. Also, a single shoot on each of 2329 trees from 28 seed orchards was randomly selected and fundatrices counted in March 1997 and 1998. Variances were calculated for each seed orchard and pooled to arrive at an overall variance term from which the standard deviation was calculated.

Number of sample units per tree

This was calculated following Southwood (1978):

$$[1] \quad n_s = \sqrt{\frac{s_w^2}{s_b^2} \times \frac{C_b}{C_w}}$$

where s_w^2 and s_b^2 are the variances in the number of fundatrices per shoot within and between trees, respectively (calculated from

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the above 31 trees); C_w is the cost of selecting and assessing a sample unit within one tree (in seconds) and C_b is the cost of moving to another tree and selecting and assessing a sample unit within it (in seconds). This equation assumes that the ratio of s_w^2 to s_b^2 remains constant regardless of the mean.

Number of trees per orchard

This was computed following Southwood (1978):

$$[2] \quad n_t = \left(\frac{s}{E\cdot\bar{x}}\right)^2$$

where s is the overall standard deviation of fundatrix numbers between sample units (calculated from the above 2329 single sample units), E is the predetermined standard error of the sampling scheme as a percentage of the mean, and $\bar{x}$ is the grand mean for the 2329 sample units. Sampling schemes for standard errors of 0.02, 0.05, 0.10, and 0.20 were calculated. The half-width of the 95% confidence interval (CI) for the mean (expressed as a percentage of the mean) was also estimated for each level of standard error, using $CI_{0.95}$ (half-width) $= Et_{n-1,0.025}$, where $t_{n-1,0.025}$ is Student's t statistic at the 0.025 level of significance, and $n-1$ degrees of freedom.

Sampling-plan testing

The sampling plan created using data from 1996–1998 was verified by testing on an independently collected data set. In 2000, four spruce seed orchards were intensively sampled to estimate densities of adelgid fundatrices to a high degree of precision. Only trees >3.0 m in height were sampled. Sample units determined by means of the sample-stratum-selection methods were used: a 1-year-old terminal or distolateral shoot (sampled in a ratio of 1 terminal to 4 distolaterals) from below 2.5 m height, on the ends or central portions of main branches on random cardinal quadrants of the tree (see Results and discussion). Sample densities were as follows: orchards 1 (SAL) and 2 (MEK), one sample unit per tree, total sample units (n) = 960 and 1020, respectively; orchard 3 (ERA), two sample units per tree, n = 960; orchard 4 (ERB), three sample units per tree, n = 1080. Each orchard was also sampled independently of the intensive sampling, following the proposed sampling plan (see Results and discussion), as though the orchards were being sampled for routine decision-making. Sample densities were as follows: SAL, 112 sample units; MEK, 100 sample units; ERA, 66 sample units; ERB, 50 sample units. ERA and ERB were sampled at approximately half the recommended densities. Means and CI values for the two samples from each orchard were calculated and compared.

Results and discussion

Sample-stratum selection

The whole-model ANOVA was significant ($F_{1214,1816} = 3.94$, $P < 0.0001$), and adelgid densities varied among all factors (Table 1). A small proportion of adelgids was found at the upper crown height of the trees (12%). Because of the difficulty of sampling at the upper crown height (>2.5 m above ground), the low proportion of adelgids found there, and the low densities of fundatrices and galls found in treetops in other studies (Fay and Whitham 1990; Fidgen *et al.* 1994), we excluded the upper crown height from the sampling scheme and reanalyzed the data. Hereinafter, only data from the lower and middle crown heights will be considered. The whole-model ANOVA without data from the upper crown height was also highly significant ($F_{910,1360} = 3.97$, $P < 0.0001$), and differences in densities among all factors were again found (Table 1). Four of the 11 interactions were also significant ($P < 0.05$): height × position, shoot × position, aspect × position, and height × shoot × position (Table 2).

Adelgids were most abundant at the lower crown height of the tree, on the northern and eastern aspects, on the ends of branches, and on terminal shoots (Table 1). Though significant, differences among aspects were not large, with mean adelgid densities varying between 0.959 and 1.397/shoot. Similarly, differences between terminal and distolateral shoots were highly significant, but mean densities were 1.484 adelgids/shoot for terminals *versus* 1.126 for distolaterals. The differences were

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Table 1. Mean numbers of *Adelges cooleyi* fundatrices per shoot and percentages of the total *A. cooleyi* fundatrix population found at different heights, aspects, branch positions, and shoot types of *Picea glauca* × *P. engelmannii* seed orchard trees in central British Columbia.

Factor	Stratum	Mean	Percentage of total	df	*F*	*P*
All data						
Height	Upper	0.342	12.5	2,36	35.56	<0.0001
	Middle	0.941	34.4			
	Lower	1.454	53.1			
Aspect	West	0.802	20.4	3,54	3.60	0.0191
	South	0.898	22.8			
	East	1.106	28.1			
	North	1.125	28.6			
Branch	Inner	0.364	12.5	2,36	4.49	0.0182
Position	Central	0.894	30.7			
	End	1.657	56.8			
Shoot	Distolateral	0.925	43.3	1,18	17.32	0.0006
	Terminal	1.213	56.7			
Without upper crown height						
Height	Middle	0.941	39.2	1,18	18.70	0.0004
	Lower	1.454	60.7			
Aspect	West	0.959	19.9	3,54	3.25	0.0288
	South	1.123	23.4			
	East	1.311	27.4			
	North	1.397	29.1			
Branch	Inner	0.458	12.6	2,36	5.02	0.0120
Position	Central	0.894	24.9			
	End	2.234	62.4			
Shoot	Distolateral	1.126	43.2	1,18	19.98	0.0003
	Terminal	1.484	56.8			

Note: Analysis of variance (ANOVA) was performed on numbers per shoot transformed by $\log(x + 1)$.

significant, but we felt that they were too small to be biologically relevant, therefore all aspects and both shoot types should be included in the sampling plan. However, differences in density between tree heights and between branch positions were large, so we explored the possibility of restricting sampling to certain strata within each tree.

On average over 19 trees, 52% of all adelgids found were located on the ends and centers of lower branches; 82% were located on the ends and centers of lower and middle branches (Table 3). Overall (not averaged by individual trees), 87.3% of all adelgids were located on the ends and centers of lower and middle branches. The strata selected for sampling should have the lowest possible variation. Assuming that the underlying distribution is random (Poisson), the nominal variation, v_r, is described by

$$v_r = \frac{p(1-p)}{n}$$

where n is the sample size and p is the mean incidence ($0 < p < 1$) (Hughes and Madden 1992). Variations between stratum combinations were compared by computing the ratio of observed variance to nominal variance for each stratum combination. The ratio was lowest for adelgids sampled from the ends and centers of lower and middle branches (Table 3). Sampling should therefore be conducted by collecting 1-year-old shoots from within these strata.

The significant interactions, all of which involve branch position, do not affect the previous conclusions. In all cases, the highest adelgid densities were found on the ends of branches, intermediate densities in the middle,

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Table 2. Means (adelgids/shoot) and standard errors of interaction terms in the stratum-selection analysis of variance (ANOVA) (see Table 1) that were significant ($\alpha = 0.05$).

A. Height × position (df = 2,36, $P = 0.0343$).

	Lower	Middle
End	2.73 ± 0.316	1.74 ± 0.214
Central	1.06 ± 0.091	0.73 ± 0.094
Inner	0.57 ± 0.064	0.35 ± 0.041

B. Shoot × position (df = 2,36, $P = 0.0064$).

	Distolateral	Terminal
End	2.25 ± 0.200	2.18 ± 0.528
Central	0.74 ± 0.060	1.50 ± 0.215
Inner	0.38 ± 0.041	0.78 ± 0.094

C. Aspect × position (df = 6,108, $P = 0.0004$).

	Eastern	Northern	Southern	Western
End	2.42 ± 0.459	2.92 ± 0.389	1.75 ± 0.320	1.85 ± 0.352
Central	1.15 ± 0.131	0.80 ± 0.115	1.11 ± 0.181	0.52 ± 0.066
Inner	0.36 ± 0.062	0.47 ± 0.071	0.51 ± 0.099	0.49 ± 0.069

D. Height × shoot × position (df = 2,36, $P = 0.0193$).

	Lower		Middle	
	Distolateral	Terminal	Distolateral	Terminal
End	2.67 ± 0.311	2.99 ± 0.977	1.83 ± 0.250	1.37 ± 0.389
Central	0.87 ± 0.089	1.79 ± 0.268	0.61 ± 0.082	1.21 ± 0.335
Inner	0.51 ± 0.071	0.79 ± 0.145	0.24 ± 0.039	0.76 ± 0.121

Table 3. Percentages of all *Adelges cooleyi* fundatrices counted in nine sample strata composed of various combinations of lower (L) or middle (M) crown height and the end (E) or center (C) of the branch, on 19 *Picea glauca* × *P. engelmannii* trees in central British Columbia.

		Variance		
Stratum	Mean percentage	Observed	Nominal	Observed:nominal ratio
M/C	14	0.009	0.006	1.42
M/E	16	0.016	0.007	2.26
L/C	20	0.012	0.008	1.43
M/E + C	30	0.018	0.011	1.63
L/E	31	0.037	0.011	3.29
L + M/C	34	0.026	0.012	2.20
L + M/E	47	0.059	0.013	4.50
L/E + C	52	0.021	0.013	1.60
L + M/E + C	82	0.01	0.008	1.29

Note: For example, L/E is the percentage of the total number of adelgids found at the lower crown height on branch ends and L + M/E + C is the percentage found at the lower and middle crown heights on branch ends and centers. The observed variance was computed from the data for that stratum; the nominal variance was computed from the mean and *n*, assuming a random population distribution.

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and the lowest in the inner position. The position effect changed in magnitude but not direction for the lower crown height compared with the middle crown height (height × position interaction; Table 2A), for terminal shoots compared with distolateral shoots (shoot × position interaction; Table 2B), and also for aspect (shoot × aspect interaction; Table 2C). In all cases, the magnitude of the interaction was small. The shoot × position interaction also changed in magnitude but not direction, depending on crown height (height × shoot × position interaction; Table 2D); there was almost no interaction at the lower crown height but a noticeable interaction in the middle of the trees. Again, the magnitude of this 3rd-order interaction is considered small.

Quantitative aspects

Number of samples per tree

Within-tree variance for the 31 trees with 20 samples each was 25.36 adelgids/shoot squared; between-trees variance was 356.8 adelgids/shoot squared (n = 620). Mean time to select and examine a sample unit within a tree was 22.8 s, whereas mean time to move between trees and select and examine a sample unit was 38.6 s. Using equation 1, the appropriate number of samples to examine per tree was calculated to be 0.35, or 1 in a practical sampling program.

Number of trees per orchard

The standard deviation, s, pooled by orchard, for fundatrix numbers on all sample units (n = 2329) was 4.180; the grand mean, $\bar{x}$, was 2.245. Using equation 2, the number of trees to sample per orchard was calculated for different standard errors and CI values (Table 4). For example, a sample of one 1-year-old shoot from each of 86 trees would yield an estimated mean number of fundatrices per shoot with a standard error of about 20% of the mean, and would take about 58 min. Changes in population density by at least a factor of 2 would be detected using a sample with a precision level this low, which would thus be minimally suitable for routine field monitoring purposes (Southwood 1978).

As adelgid population densities increase, fewer samples are required for estimating a population with the same precision (Fig. 1; calculated from equation 2). At the mean population of 2.25 adelgids/shoot observed in this study, estimating density with a standard error of 20% about the mean is impractical (*e.g.*, it would take 349 samples and 231 min per orchard for a standard error of 10% about the mean). When population densities are near an action threshold, it is desirable to obtain more precise population estimates. Without knowledge of economic injury levels or economic action thresholds, it is difficult to determine when low-precision sampling is acceptable. However, the 2.25 adelgids/shoot in this study resulted in a vegetative shoot gall rate of 2.43% (W.B.S., unpublished data), which was not economically important. Currently, an ad-hoc action threshold of 5 adelgids/shoot is used; at a sample mean of 5 per shoot, only 70 sample units would be required (Fig. 1), taking 47 min, to estimate the population with a standard error of 10% about the mean; this is adequate for making decisions concerning adelgid management.

Table 4. Number of *Picea glauca* × *P. engelmannii* to sample per orchard, at one sample per tree, to obtain desired levels of sample standard error (SE, expressed as a proportion of the sample mean) or 95% confidence interval (CI).

		No. of samples	Time (min)
SE			
	0.02	8666	5777
	0.05	1387	924
	0.10	347	231
	0.20	87	58
95% CI			
	0.05	7095	4730
	0.10	1774	1182
	0.20	443	296
	0.40	111	74

Note: To sample an orchard with a standard error of 20% about the mean, for example, 87 samples, taking approximately 58 min, should be collected; to sample with a 95% CI, 443 samples, taking about 296 min, should be examined.

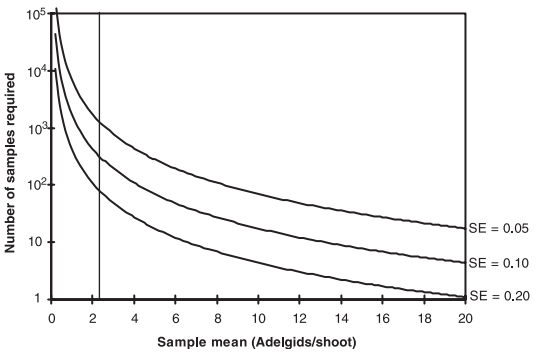
Proposed sampling plan

A single 1-year-old terminal or distolateral shoot should be selected , from below 2.5 m height, on each tree, from the ends or central

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Fig. 1. Numbers of samples required to estimate the density of *Adelges cooleyi* populations with standard errors (SE, expressed as a proportion of the mean) of 0.01, 0.05, and 0.10 in spruce seed orchards in central British Columbia. The vertical dotted line represents the sample mean found in this study, 2.25. Note that the ordinate is presented on the logarithmic scale.



portions of main branches on any side of the tree. The differences in adelgid densities between strata can be addressed by collecting each shoot from a random location within the appropriate strata. Shoots should be collected in the proportions in which they are found on trees: approximately 1 terminal to 4 distolaterals. The entire shoot should be examined for overwintered fundatrices. In 1996 we found that 58% of fundatrices were concentrated on the underside of the distal 3 cm of shoots (shoots are usually 10–25 cm long), but we feel that the benefits of reducing sampling time by examining only a portion of the shoot would be offset by the added trouble and error of delineating the distal 3 cm portion of a shoot in the field.

A random sampling pattern is required for statistical validity (Steel and Torrie 1960), but this is often not practical for routine monitoring. Walking a zigzag or "W" pattern through an orchard can approximate a random pattern and avoids systematic sampling errors due, for example, to drawing many samples from a single row (Pedigo 1996). Similarly, truly random selection of shoots from within a tree is not practical in the field; however, an unbiased sample can be approximated by collecting approximate proportions from among terminal or distolateral shoots, from different strata, and from different aspects.

A sample density of 100−150 shoots per orchard should be used. If the orchard mean is around 2 adelgids/shoot (well below the ad-hoc action threshold currently in use), 150 shoots will give an estimated standard error of about 12% about the mean; this is sufficient to determine that the true orchard mean is likely below 5 adelgids/shoot. If the orchard mean is around 8 adelgids/shoot, 100 shoots will give an estimated standard error of about 9% about the mean; this is sufficient to indicate that the true orchard mean is likely above 5 adelgids/shoot. If the orchard mean is near 5 adelgids/shoot, a sample of 150 will yield an estimate of the mean with a standard error of approximately 5% around the mean. This degree of precision alerts the manager that the true orchard mean is near the ad-hoc threshold, and other factors must be used to make a decision.

Sampling should be conducted in early to mid-March, before fundatrices have started to grow and produce woolly secretions. These secretions can render counting of fundatrices located close together difficult and can protect the adelgids from pesticide applications. Monitoring could be conducted the previous November, but variable winter mortality of up to about 80% (Baurant 1975; W.B.S., unpublished data) and other factors make reliable interpretation of November counts difficult.

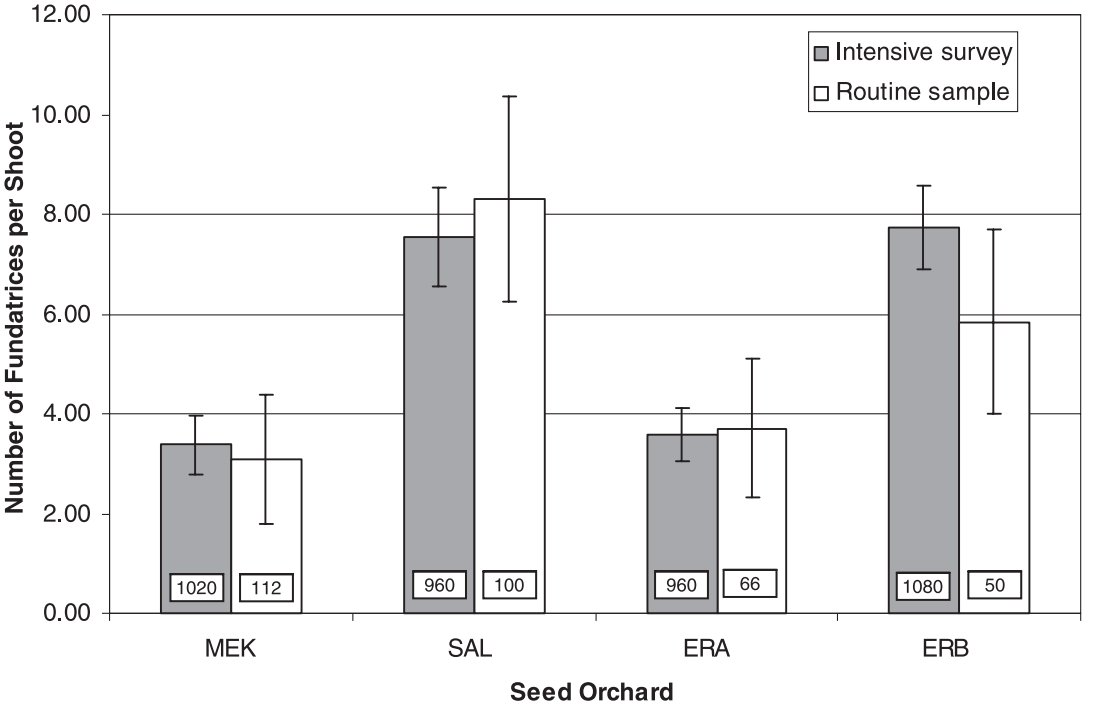
Sampling-plan testing

Intensive sampling of the four test orchards yielded orchard means between 3.39 and 7.73 fundatrices/shoot (Fig. 2), with standard errors (measured as a proportion of the mean) between 0.03 and 0.05. When the proposed sampling plan was followed, orchard means were between 3.09 and 8.30 fundatrices/shoot (Fig. 2), with standard errors between 0.13 and 0.21. The 99.9% CI values for the intensive sample (shown in Fig. 2) are very likely to contain the true orchard mean. These were entirely contained within the 95% CI values for the proposed sampling plan for orchards SAL, MEK, and ERA. Therefore, for these three orchards the proposed sampling plan allowed the true orchard mean

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Fig. 2. Numbers of mean adelgids per shoot estimated for four spruce seed orchards in central British Columbia, using intensive sampling (shaded columns) or the proposed sampling plan (open columns). Error bars for the shaded and open columns represent the estimated 99.9% and 95% confidence intervals, respectively. The numbers in boxes show the number of sample units taken in each sample.



to be estimated with adequate precision for routine monitoring for management decision-making.

In orchard ERB, the 95% CI for the proposed sampling plan did not contain the 99.9% CI for the intensive sampling plan. Therefore, the mean for this orchard was not estimated with adequate precision for routine monitoring. The number of sample units taken was only 50, about half of the recommended number. This corroborates our recommendation that 100−150 shoots should be the sample size for routine monitoring leading to decisions concerning adelgid management. Only 66 sample units were collected from orchard ERA; that sample size did allow the true orchard mean to be adequately estimated, therefore the recommendation of 100−150 shoots was conservative for this orchard. We feel that time spent taking the recommended number of shoots provides reassurance that the mean has been adequately estimated.

Mean adelgid densities in the test orchards were near the ad-hoc action threshold of 5 adelgids/shoot at which sampling-plan precision is most important. Our sampling plan performed well in this density range, allowing for accurate decision-making. At much lower or much higher densities, the likelihood of making a judgement error is greatly reduced. Therefore, we feel that this plan will be adequate for all adelgid densities encountered in central British Columbia.

Conclusions

Our sampling plan will provide an estimate of the number of *A. cooleyi* fundatrices per shoot in British Columbia spruce seed orchards with a known level of precision. For routine field-monitoring purposes this plan

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will allow adequate population estimation in 1.5 h. Testing with an independent data set confirmed that the sampling plan functions as designed and is expected to perform adequately at all adelgid densities.

For use in an operational pest-management program, however, several other components are required. First, a damage/density relationship must be determined, so that adelgid densities estimated using the proposed sampling plan can be related to subsequent galling densities and seed loss. Second, economic or action thresholds must be developed, so that control actions can be initiated before unacceptable seed loss occurs. The current ad-hoc action threshold of 5 adelgids/shoot has been set largely by trial and error; actual seed loss at this density remains unquantified. Finally, control tactics must be tested. Currently, broadcast sprays of insecticidal soap against fundatrices give up to 95% kill (W.B.S., unpublished data). Other control tactics, applied in either in spring or in the previous fall, may prove useful; percent kill must be incorporated into any action threshold. When these three areas have been addressed, an integrated pest management program will be available for use in interior spruce seed orchards in British Columbia.

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References

Baurant, R. 1975. Les *Chermesidae* sur epicea : la mortalite des fondatrices hivernantes. Bulletin des Recherches Agronomique Gembloux, **10**: 399–418.

Cranshaw, W.S. 1989. Patterns of gall formation by the cooley spruce gall adelgid on Colorado blue spruce. Journal of Arboriculture, **15**: 277–280.

Cumming, M.E.P. 1959. The biology of *Adelges cooleyi* (Gill.) (Homoptera: Phylloxeridae). The Canadian Entomologist, **91**: 601–617.

Fay, P.A., and Whitham, T.G. 1990. Within-plant distribution of a galling adelgid (Homoptera: Adelgidae): the consequences of conflicting survivorship, growth, and reproduction. Ecological Entomology, **15**: 245–254.

Fidgen, J.G., Teerling, C.R., and McKinnon, M.L. 1994. Intra- and inter-crown distribution of the eastern spruce gall adelgid, *Adelges abietis* (L.), on young white spruce. The Canadian Entomologist. **126**: 1105–1110.

Foottit, R.G., and Richards, W.R. 1993. The insects and arachnids of Canada. Part 22. The genera of the aphids of Canada — Homoptera: Aphidoidea and Phylloxeroidea. Publication No. 1885, Research Branch, Agriculture Canada, Ottawa, Ontario.

Furniss, R.L., and Carolin, V.M. 1977. Western forest insects. Miscellaneous Publication No. 1339, United States Department of Agriculture, Forest Service, Washington, District of Columbia.

Johnson, W.T., and Lyon, H.H. 1991. Insects that feed on trees and shrubs. Cornell University Press, Ithaca, New York.

Pedigo, L.P. 1996. Entomology and pest management. Prentice−Hall, Saddle River, New Jersey.

SAS Institute Inc. 1996. SAS/STAT guide for personal computers. Version 6.12. SAS Institute Inc., Cary, North Carolina.

Shorthouse, J.D., and Rohfritsch, O. 1992. Biology of insect-induced galls. Oxford University Press, New York.

Southwood, T.R.E. 1978. Ecological methods. Chapman and Hall, New York.

Steel, G.D., and Torrie, J.H. 1960. Principles and procedures of statistics. McGraw-Hill Book Company, New York.

Wood, C. 1977. Cooley spruce gall aphid. Pacific Forestry Center Pest Leaflet No. 6, Canadian Forestry Service, Environment Canada, Victoria, British Columbia.

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