DEVELOPMENT AND VALIDATION OF A FIXED-PRECISION SEQUENTIAL SAMPLING PLAN FOR ESTIMATING BROOD ADULT DENSITY OF *DENDROCTONUS PSEUDOTSUGAE* (COLEOPTERA: SCOLYTIDAE)

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Abstract

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The Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins, attacks Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco (Pinaceae), throughout western North America. Periodic outbreaks cause increased mortality of its host. Land managers and forest health specialists often need to determine population trends of this insect. Bark samples were obtained from 326 trees distributed over 21 stands during a 2-year period in late winter to early spring of 1997 and 1998 in the Colorado Front Range. The variance to mean relationship of brood adults was examined using the Taylor power law, and a fixed-precision sampling plan was developed using Green's method. Stop lines and minimum number of samples required to estimate brood adult density per 0.046 m^2 with precision levels of 0.1, 0.2, and 0.3 were calculated. A resampling simulation conducted with an independent data set indicated that desired precision levels were not met. Theoretical precision levels were adjusted until desired precision levels were achieved. Average number of samples needed to estimate brood adult densities up to 25.1 adults per 0.046 m^2 with precision levels of 0.09, 0.2, and 0.3 were 91, 20, and 8, respectively. For densities greater than 25.1 brood adults per 0.046 m^2, conservative estimates are obtained with 72, 15, and 6 samples for precision levels of 0.09, 0.2, and 0.3, respectively. An emergence ratio can be obtained by dividing the estimated density of brood adults by twice the number of gallery starts. This system provides the user with an immediate assessment of the population trend of Douglas-fir beetle. The data collected compare favorably with data from other Douglas-fir beetle outbreaks reported in the literature. The use of this plan outside the Colorado Front Range, or by sampling at a different height, should be cautioned until additional data from other locations and sampling heights are examined.

Negron JF, Schaupp WC, Johnson E. 2000. Mise au point et validation d'un plan d'échantillonnage séquentiel à précision pré-établie pour l'estimation de la densité des adultes à l'émergence chez le Dendroctone du Douglas, *Dendroconus pseudotsugae* (Coleoptera : Scolytidae). *The Canadian Entomologist* **132** : 119–133.

Résumé

Le Dendroctone du Douglas, *Dendroctonus pseudotsugae* Hopkins, s'attaque aux sapins de Douglas, *Pseudotsuga menziesti* (Mirb.) Franco (Pinaceae), dans tout l'ouest nord-américain. Les épidémies périodiques entraînent une hausse de la mortalité chez les hôtes. Les responsables de l'aménagement des terres et les spécialistes en foresterie ont souvent besoin d'évaluer les tendances démographiques de cet insecte. Des échantillons d'écorce ont été recueillis sur 326 arbres répartis dans 21 boisés au cours d'une période de 2 ans, à la fin de l'hiver et au début du printemps

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en 1997 en 1998 dans la chaîne de montagnes Colorado Front Range. Le rapport entre la variance et la moyenne a été étudié chez la progéniture émergente à l'aide de la loi de puissance de Taylor et un plan d'échantillonnage à précision pré-établie a été conçu selon la méthode de Green. Les lignes d'arrêt et le nombre minimum d'échantillons nécessaires pour estimer la densité des adultes émergés par 0,046 m^2 à des niveaux de précision de 0,1, 0,2 et 0,3 ont été calculés. La simulation d'un nouvel échantillonnage avec une nouvelle matrice indépendante de données a permis de constater que les niveaux de précision n'ont pas été atteints. Les niveaux de précision théoriques ont été ajustés jusqu'à ce que les niveaux de précision désirés soient obtenus. Le nombre d'échantillons requis pour estimer la densité des adultes à l'émergence jusqu'à 25,1 adultes par 0,046 m^2 était de 91 à un niveau de précision de 0,09, de 20 à un niveau de 0,2 et de 8 à un niveau de 0,03. Aux densités supérieures à 25,1 adultes par 0,046 m^2, des estimations conservatrices de 72 (0,09), 15 (0,02) et 6 (0,03) échantillons ont été obtenues. Un rapport à l'émergence peut être calculé en divisant la densité estimée d'adultes par deux fois le nombre de galeries commencées. Ce système fournit à l'utilisateur une estimation immédiate de la tendance démographique du dendroctone. Ces données se comparent favorablement à celles obtenues au cours d'épidémies de dendroctones mentionnées dans la littérature. L'utilisation de ce plan en dehors de cette chaîne de montagnes, ou l'échantillonnage à d'autres hauteurs est à déconseiller si l'on n'obtient pas d'abord des données additionnelles sur d'autres localités et hauteurs d'échantillonnage.

[Traduit par la Rédaction]

Introduction

The Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae), is an important bark beetle associated with Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco (Pinaceae), throughout much of its range in the western United States (Furniss and Carolin 1977). Although endemic populations are usually restricted to injured or felled trees (McMullen and Atkins 1962; Furniss 1965; Rudinsky 1966; Wright *et al.* 1984), periodic epidemic populations can kill healthy trees in large numbers (Furniss *et al.* 1979; Johnson and Belluschi 1969).

Land managers and forest health specialists often need methods to determine and predict population trends of forest insects. This information is useful to land managers for planning management strategies and informing the public of population status and potential impacts of beetle populations.

In the past, sequential sampling plans have provided an effective strategy for classifying populations into categories such as light, medium, or heavy, or perhaps determining whether control strategies are needed (Waters 1955). Stark (1952) pioneered the use of sequential sampling for forest insects by developing a procedure for the lodgepole needle miner, *Coleotechnites milleri* Busck (= *Recurvaria milleri*) (Lepidoptera: Gelechiidae). Knight (1960) developed a plan for classifying mountain pine beetle, *Dendroctonus ponderosae* Hopkins, populations in the Black Hills of South Dakota as increasing, static, or decreasing. More recently, Lynch *et al.* (1990) developed a sequential sampling plan for egg mass density of eastern spruce budworm, *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae). All three plans mentioned above used Wald's sequential probability ratio tests (Wald 1947).

More recently, studies have been conducted in agricultural systems to develop fixed-precision sequential sampling plans that estimate mean population densities of the target organism at specified precision levels (expressed as the ratio of standard error to mean) (Boeve and Weiss 1998; O'Rourke *et al.* 1998; Burkness and Hutchison 1998; Badenhausser 1996; Heinz and Chaney 1995; Naranjo and Flint 1994; and other references cited in those studies). With fixed-precision plans, sampling is terminated when estimation of the population density is accomplished with a desired precision level.

In this study, we developed a fixed-precision sequential sampling plan that resource managers and forest health specialists could use to sample Douglas-fir beetle brood adults and determine their density per unit area.

Materials and Methods

The study was conducted in the South Platte Ranger District of the Pike – San Isabel National Forest in the Colorado Front Range along the Sugar Creek (39°18′N, 105°09′W, altitude approx. 2277 m) and West Creek (39°11′N, 105°10′W, altitude approx. 2277 m) drainages. Douglas-fir beetle populations increased significantly following the largest known outbreak of the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Lepidoptera: Lymantriidae), in the Colorado Front Range which resulted in the defoliation of 8000 ha between 1992 and 1995. Prior to full collapse of the Douglas-fir tussock moth outbreak, scattered defoliated trees were being attacked by the Douglas-fir beetle. Two years after Douglas-fir tussock moth populations had completely collapsed, Douglas-fir beetle populations were attacking nondefoliated trees in the vicinity of defoliated stands.

An important consideration when sampling for Douglas-fir beetle brood has been where to sample along the bole of the tree. Furniss (1962) studied infestation patterns along the bole of standing Douglas-fir infested with Douglas-fir beetle in Idaho. He concluded that the greatest density of successful infestation and least variation was found between 4.6 and 19.8 m in height and recommended that brood sampling be conducted within this zone. Chansler (1968) sampled Douglas-fir beetle brood in New Mexico and found higher brood populations and less variance at a height of 3 m than at 1.5 m. Furniss also indicated that the lower zone of Douglas-fir beetle attack and length of the infested bole are proportionally reduced in smaller trees and that this relationship needs to be considered when deciding where on the bole to sample. Data from other parts of the Colorado Front Range collected by Negrón (1998) in a study of Douglas-fir beetle infestation probabilities indicated average height of infested trees to be 10.2 m. Average height of trees sampled by Furniss was 32.6 m. Accordingly, the smaller trees in the Colorado Front Range should have a lower zone of attack. Based on this evidence and the need to devise an easy to use system, we collected samples at breast height (1.37 m).

Sampling was conducted in late winter to early spring, 1997 and 1998. A total of 13 and 8 stands were sampled in 1997 and 1998, respectively. Stands ranged in size from 4 ha to greater than 20 ha. Number of trees sampled per stand ranged from 6 to 24 depending on the size of the stand and the frequency of infested trees. Total number of trees sampled was 207 in 1997 and 119 in 1998. Average (± SE) diameter at breast height (DBH) of trees sampled was 41.5 (± 0.6) cm in 1997 and 39.5 (± 0.7) cm in 1998. The difference was not significant ($F_{1,324} = 3.75$, $P > 0.05$) and the average (± SE) DBH across the two years was 40.8 (± 0.5) cm. A 30.5 × 15.25 cm (0.046 m^2) vertically oriented bark sample was collected from trees that had been attacked by the Douglas-fir beetle during the previous year. For consistency, samples were always collected from the south side of the tree. Signs of attack included the presence of boring dust, the beginning of foliage discoloration in the lower branches, and the presence of brood under the bark. Sample trees were selected at random and scattered throughout the study stands to adequately capture the variability in brood populations across stands. After collection, samples were placed in plastic bags and maintained at low temperatures in coolers. Samples were transported to the laboratory and kept in a walk-in cooler at 3°C until they could be processed.

The number of brood adults, number of galleries intercepted by the sample, length of each gallery, number of gallery starts, and number of entire galleries (galleries whose beginning and end could be clearly identified) were recorded for each sample. An emergence ratio was calculated by dividing the number of brood adults by the number of attacking adults (Furniss *et al.* 1979; Lessard and Schmid 1990). The number of attacking adults was determined by multiplying the number of gallery starts in each sample by two beetles per start.

Data Analysis. Sequential sampling plan. A sequential sampling plan was constructed for the total number of brood adults in the samples. Kuno (1969, 1972) proposed a sequential sampling program where sampling is discontinued upon reaching a given level of precision in the estimate. Green (1970) modified the plan by describing the variance to mean relationship using the Taylor power law (Taylor 1961):

$$\delta^2 = am^b \qquad [1]$$

where δ^2 is the variance, m is the mean number of counts per sample unit, b is a measure of aggregation, and a is a sampling factor. When $b > 1$, the population is aggregated; when $b = 0$, the population is randomly distributed; and when $b < 1$, the population is uniformly distributed. Parameter a is related to sampling procedures such as sampling unit, location, or equipment used. Parameters a and b are obtained from the least-squares regression of the empirical variance s and mean $\bar{x}$ (Taylor and Woiwood 1982):

$$\log s^2 = \log a + b \log \bar{x} \qquad [2]$$

and are used to develop fixed-precision level sampling plans (Green 1970). Parameter a is biased as calculated above because of the logarithmic transformation. Therefore, a correction proposed by Goldberger (1968) was used in the estimation of a:

$$10^{\log a - 0.5\,\mathrm{SE}(\log a)} \qquad [3]$$

where SE(log a) is the standard error of log a from the least-squares regression.

Stop lines are then calculated as described by Green (1970):

$$T_n^{b-2} = \frac{D_0^2}{an^{1-b}} \qquad [4]$$

where T_n is the cumulative number of organisms for the nth sample, and D_0 is the precision level (expressed as the ratio of standard error to mean). Stop lines indicate the minimum cumulative number of organisms counted in a given number of samples that meet the specified theoretical precision levels. Stop lines were obtained for precision levels of 0.1, 0.2, and 0.3.

Attack and brood densities and gallery characteristics. Differences in brood and attack densities, the number of galleries intercepted per sample, number of gallery starts, entire galleries, and emergence ratios for trees sampled were evaluated using a t test to compare the means across the 2 years of the study. ANOVA was used to examine differences across 5.1-cm DBH classes.

Sampling plan validation. To determine actual precision levels obtained with the sampling plan and the number of samples needed to surpass the stopping lines, a resampling validation was conducted with an independent data set. The independent data set consisted of 15 stands obtained from USDA Forest Service records (USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, unpublished

TABLE 1. Geographic location, time of sampling, sampling height, and number of trees sampled in stands used as validation data for fixed-precision sampling of density of brood adult *Dendroctonus pseudotsugae*, Colorado and Wyoming, 1960–1994.

Stand	Approximate coordinates	Time of sampling	Sampling height (m)	No. of trees
1	44°51′N, 109°33′W; 44°51′N,109°29′W	Fall 1992	1.37	33
2	44°51′N, 109°33′W; 44°51′N, 109°29′W	Fall 1993	1.37	11
3	44°51′N, 109°33′W; 44°48′N, 109°35′W	Fall 1994	1.37	20
4	na	Spring 1960	1.37	15
5	44°53′N, 109°30′W	Spring 1960	1.37	13
6	44°45′N, 110°30′W	Spring 1960	1.37	23
7	na	Spring 1961	1.37	24
8	44°53′N, 109°30′W	Spring 1961	1.37	22
9	na	Spring 1960	3.1	15
10	44°35′N, 109°15′W	Spring 1960	3.1	7
11	44°45′N, 110°30′W	Spring 1960	3.1	14
12	39°25′N, 105°14′W	Spring 1960	1.37	24
13	39°25′N, 105°14′W	Spring 1961	1.37	10
14	39°25′N, 105°14′W	Spring 1960	3.1	14
15	40°41′N, 105°19′W	Spring 1961	1.37	31

NOTE: Stands 1–11 are located in the Shoshone National Forest, Wyoming; stands 12–14 are located in the Pike – San Isabel National Forest, Colorado; and stand 15 is located in the Roosevelt National Forest, Colorado. na, not available.

data). The stands varied in location, time of sampling, sample height, and number of trees sampled (Table 1). In all stands, however, trees were sampled by taking a 15.2 × 15.2 cm bark sample from the north and south aspects of the tree. For our purposes, we averaged the north and south counts of brood adults for each tree and standardized brood adult density per 0.046 m^2. We used the Resampling for Validation of Sample Plans software developed by Naranjo and Hutchinson (1997) for validation of our plan. The software allows validation of various sequential sampling approaches including the method of Green (1970). The program requires the user to input parameters a and b, the intended precision level, the number of simulations to be conducted, and whether resampling is to be conducted. We conducted 500 simulations with resampling using the parameters obtained in our analysis and precision levels of 0.1, 0.2, and 0.3. A summary of the simulation for each data set is produced which includes the mean density, average precision, maximum and minimum precision obtained, standard deviation, average number of samples required to surpass the stopping line, maximum and minimum number of samples, and standard deviation. After completing the simulations, the overall precision levels obtained were examined to determine if they met the intended precision levels. If not, additional simulations were conducted by adjusting the intended precision level until average actual precision met or approximated the levels of 0.1, 0.2, and 0.3. The associated average number of samples obtained from this simulation was considered the optimum across the densities examined. Hutchison *et al.* (1988) indicated that through simulation runs desired precision levels could be adjusted to obtain actual desired levels of precision.

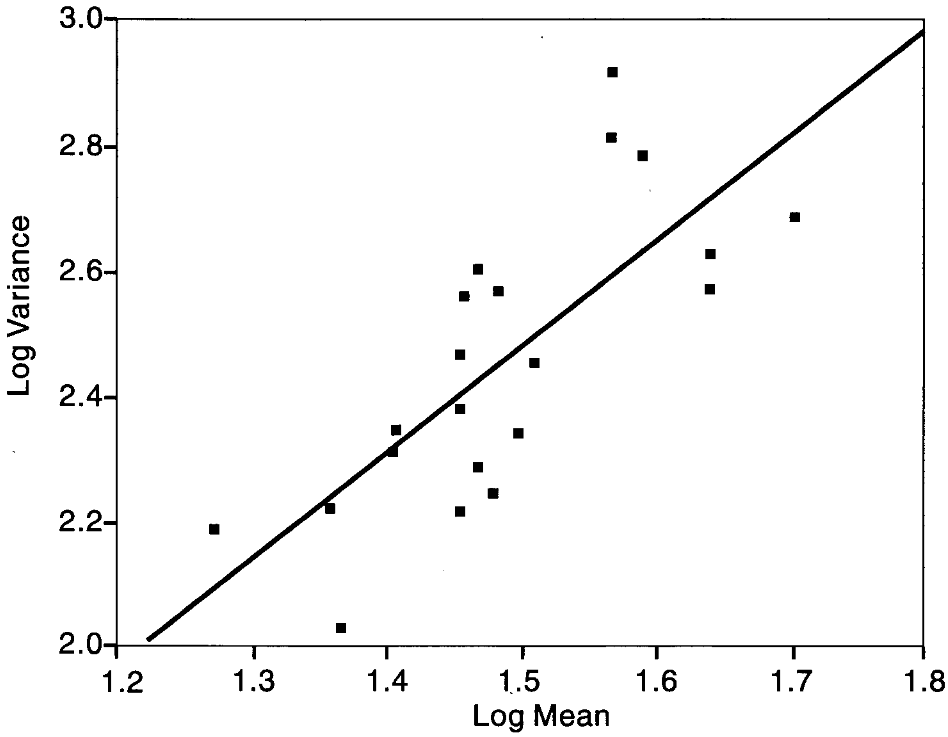

FIGURE 1. **Relationship between empirical log variance and log mean for *Dendroctonus pseudotsugae* brood adults. The scatterplot includes data from 13 stands in 1997 and 8 in 1998 ($F_{1,19}$ = 24.5; P < 0.0001; r^2 = 0.54), Pike – San Isabel National Forest, Colorado, 1997–1998.**

Results

Sequential Sampling Plan. The brood adult variance to mean relationship in the sampled stands was homogeneous across the 2 years of the study ($F_{1,19}$ = 0.5; P > 0.05). Therefore, data for the 2 years were combined when using the Taylor power law (Taylor 1961) to estimate the dispersion parameters. The variance to mean relationship was significant ($F_{1,19}$ = 24.5; P < 0.0001; r^2 = 0.54) (Fig. 1). The value of the aggregation parameter, b (± SE), was 1.687 ± 0.34, which reflects the inherent aggregation of bark beetle brood. The sampling factor, a, was 0.491, after applying the Goldberger (1968) correction.

More samples are needed to obtain estimates with increased precision, particularly at the 0.1 precision level. For a given level of precision, the number of samples must increase as population density decreases. Stopping lines for precision levels of 0.2 and 0.3 converge as population densities become lower and the number of samples needed approaches similar levels (Fig. 2). If the cumulative number of brood adults collected with a given number of samples is below the line for a precision level, that precision has not been reached. When the value obtained is above the line, then the mean number of brood adults per sample can be estimated with the level of precision indicated by the surpassed line.

Attack and Brood Densities and Gallery Characteristics. Significantly more attacking adults, gallery intercepts per sample, gallery starts, entire galleries, and increased total length of galleries were observed in the 1998 samples. A significantly higher

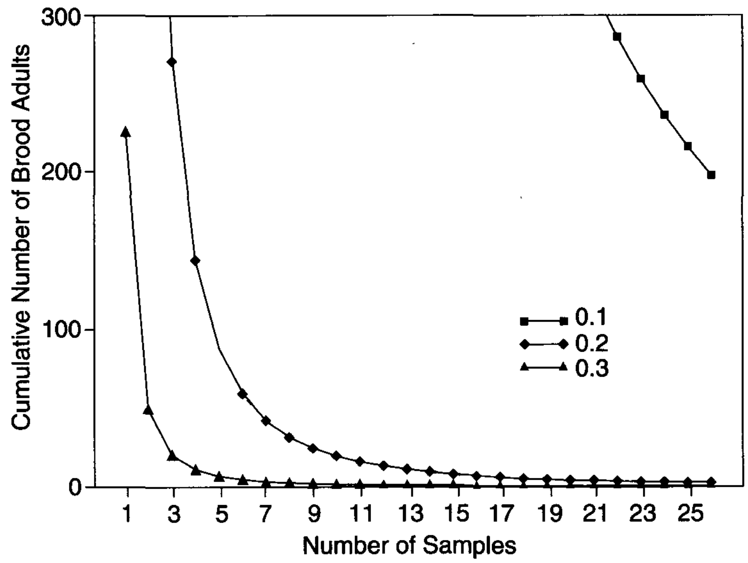

FIGURE 2. **Sequential sampling stop lines for *Dendroctonus pseudotsugae* brood adults in 30.5 cm × 15.2 cm (0.046 m^2) samples with precision levels (*C*) of 0.1, 0.2, and 0.3, Pike – San Isabel National Forest, Colorado, 1997–1998.**

TABLE 2. **Mean (SE) *Dendroctonus pseudotsugae* brood and attack densities and associated gallery characteristics per 0.09 m^2 of bark surface, Pike – San Isabel National Forest, 1997–1998.**

	1997	1998	Both years
n	207	119	326
Brood adults	65.4(2.7)*a*	59.4(3.3)*a*	63.2(2.1)
Attacking beetles	12.8(0.6)*b*	19.9(0.9)*a*	15.4(0.6)
Emergence ratio	6.8(0.4)*a*	4.4(0.4)*b*	5.8(0.3)
Gallery intercepts	13.8(0.5)*b*	19.1(0.6)*a*	15.7(7.3)
Gallery starts	6.4(0.3)*b*	10.0(0.5)*a*	7.7(0.3)
Entire galleries	1.3(0.2)*b*	3.6(0.3)*a*	2.2(0.2)
Length of gallery intercepts (cm)	15.5(0.3)*a*	14.9(0.3)*a*	15.3(0.2)
Total length of galleries (cm)	201.7(6.3)*b*	276.1(8.4)*a*	228.9(5.4)
Length of entire galleries (cm)	14.6(0.6)*a*	15.2(0.5)*a*	14.9(0.4)

NOTE: Means in a row followed by the same letter are not significantly different (*t* test, $P = 0.05$).

emergence ratio was observed in the 1997 samples. These differences, however, did not translate to differences in brood densities between the 2 years (Table 2). Although the total area comprised by our samples is 0.046 m^2, we report these results per 0.09 m^2 to make comparisons with other studies easier.

No differences were detected among diameter classes for emergence ratio, number of gallery intercepts, number of entire galleries, average length of galleries intercepted, total length of intercepted galleries, or average length of entire galleries in the samples (Table 3). Total brood production was significantly lower for the 27.9 cm diameter class than for diameter classes of 38.1 cm and greater. The number of attacking beetles and the number of gallery starts were significantly lower for trees in the 22.9 cm diameter class than for trees in the 43.2 cm diameter class. Average (± SE) emergence

TABLE 3. **Mean (SE) Dendroctonus pseudotsugae brood attack densities and associated gallery characteristics per 0.09 m^2 by 5.1 cm tree diameter classes (DBH shown represents midpoint of diameter class except for the >50.8 cm class), Pike – San Isabel National Forest, 1997–1998.**

	DBH class (cm)						
	22.9	27.9	33	38.1	43.2	>50.8	All
n	35	69	79	66	33	44	326
Total brood	56.8(5.2)*ab*	46.4(3.1)*b*	63.1(3.9)*ab*	70.7(4.9)*a*	73.3(7.5)*a*	75.9(7.4)*a*	63.2(2.1)
Attacking beetles	12.3(1.6)*b*	13.5(1.2)*ab*	16.6(1.2)*ab*	16.7(1.1)*ab*	18.4(2.0)*a*	14.4(13)*ab*	15.4(0.6)
Emergence ratio	7.0(1.0)*a*	5.0(0.6)*a*	5.2(0.6)*a*	5.9(0.7)*a*	5.8(0.9)*a*	7.3(1.0)*a*	5.8(0.3)
Galleries intercepts	14.0(1.3)*a*	14.6(0.9)*a*	17.1(0.9)*a*	16.6(0.8)*a*	16.1(1.3)*a*	14.6(1.0)*a*	15.7(0.4)
Gallery starts	6.2(0.8)*b*	6.8(0.6)*ab*	8.3(0.6)*ab*	8.4(0.5)*ab*	9.2(1.0)*a*	7.2(0.7)*ab*	7.7(0.3)
Entire galleries	2.0(0.5)*a*	2.4(0.4)*a*	2.3(0.3)*a*	2.3(0.4)*a*	2.9(0.8)*a*	1.4(0.4)*a*	2.2(0.2)
Length of gallery intercepts	16.5(0.9)*a*	15.5(0.5)*a*	14.7(0.3)*a*	15.1(0.5)*a*	14.7(0.7)*a*	15.8(0.6)*a*	15.3(0.2)
Total length of galleries	209.0(16.7)*a*	220.1(12.9)*a*	242.3(11.4)*a*	238.3(10.3)*a*	224.1(16.8)*a*	224.3(14.2)*a*	228.9(5.4)
Length of entire galleries	16.7(1.3)*a*	15.4(0.8)*a*	14.6(0.9)*a*	14.8(0.8)*a*	14.3(1.0)*a*	14.1(1.3)*a*	14.9(0.4)

NOTE: Means in a row followed by the same letter are not significantly different (Tukey's HSD test, $P > 0.05$).

ratios in all stands sampled were always >1.0, ranged from 2.2 (± 0.6) to 15.9 (± 3.3), and averaged 5.8 (± 0.3) across the 2 years in all stands sampled.

Sampling Plan Validation. Overall mean precision levels obtained with the independent data set using the resampling validation program were always less precise than the intended precision levels. For intended precision levels of 0.1, 0.2, and 0.3, actual average precision levels were 0.18, 0.32, and 0.38, respectively. Average number of samples across all densities for the intended precision levels of 0.1, 0.2, and 0.3 were 24, 7, and 4, respectively (Table 4). When intended precision levels were adjusted to 0.05, 0.11, and 0.18, overall actual mean precision levels of 0.09, 0.2, and 0.3 were obtained, respectively (Table 5). The adjustment in the desired precision levels resulted in changes in the number of samples required to achieve the different precision levels across all densities. The number of samples required to achieve a precision of 0.09 exhibited the most dramatic change, from an average of 24 to 91. The change was from 7 to 20 for the precision level of 0.2 and from 4 to 8 for the precision level of 0.3. The number of samples required to estimate the density of brood adults always decreased with increasing densities. There was no pattern of increasing or decreasing precision levels with brood density for any of the precision levels examined. Precision was always poor for stand 5.

Discussion

A user of this sampling method can estimate the mean number of brood adults per 0.046 m^2 in a population with a given precision level. Southwood (1978) suggested that a precision level of 0.25 is adequate for management activities; when higher precision is desired, a level of 0.1 may be considered more adequate. In this study we examined precision levels of 0.1, 0.2, and 0.3 to provide potential users with a range of alternatives. Desired precision, available resources such as personnel, and the remoteness of sampling locations may dictate the level of sampling that can be reasonably accomplished.

Waters (1955) indicated that with sequential sampling plans based on the methodology developed by Wald (1947), the least amount of sampling is required when population levels are at high or low densities, with more intense sampling needed at intermediate population levels. This is different from the fixed-precision sequential sampling plan developed in this study and from others in the literature, where the minimum number of samples needed decreases with increasing population densities (Naranjo and Flint 1994; Boeve and Weiss 1998; O'Rourke *et al.* 1998; Burkness and Hutchison 1998). When parameter $b > 2$, populations become highly aggregated and the number of required samples increases with increasing density (Taylor *et al.* 1998).

Average (± SE) brood adult densities per stand observed in our study ranged from 18.8 (± 2.8) to 50.5 (± 6.6) per 0.046 m^2. In general, our observed brood density per stand was higher than the averages (± SE) observed in the validation data sets, which ranged from 4.4 (± 1.4) to 25.1 (± 3.8) per 0.046 m^2 (Table 4). Some of the trees in the validation data set, particularly from the Shoshone National Forest, also contained larvae and pupae. The immature stages were not included in the validation runs, making the results from the validation runs more conservative.

The average number of samples needed to estimate brood density in the validation data set with average precisions of 0.2 and 0.3 was 20 and 8, respectively (Table 5). These sampling levels are quite practical from a management perspective. The average number of samples required to meet a precision level of 0.1 was 91. This level of sampling may be difficult to justify for most purposes, other than for intensive research

TABLE 4. Simulation results from validation analysis for *Dendroctonus pseudotsugae* brood adult density fixed-precision sequential sampling plan with precision levels (*C*) of 0.1, 0.2, and 0.3, Colorado and Wyoming, 1960–1994.

		C = 0.10			*C* = 0.20			*C* = 0.30		
Stand	Observed mean	Mean density	Mean precision	ASN	Mean density	Mean precision	ASN	Mean density	Mean precision	ASN
3	25.1	26.2	0.16(0.08–0.23)	18(16–21)	26.3	0.28(0.05–0.62)	5(4–6)	26	0.33(0.0–0.92)	3(3–4)
7	25.1	25.6	0.17(0.10–0.26)	18(16–23)	25.9	0.33(0.07–0.71)	5(4–7)	25.4	0.42(0.01–0.95)	3(3–4)
4	23.9	25.5	0.21(0.14–0.38)	19(15–23)	26.8	0.38(0.01–0.86)	5(4–8)	25.4	0.46(0.0–0.93)	3(3–4)
12	21.8	21.1	0.13(0.06–0.21)	19(17–22)	21.6	0.23(0.02–0.52)	5(4–7)	21.2	0.29(0.0–0.91)	3(3–4)
9	17.5	18.6	0.16(0.10–0.22)	20(17–24)	19	0.31(0.06–0.58)	5(4–7)	18.4	0.39(0.0–0.88)	3(3–4)
1	15.1	14.8	0.19(0.11–0.28)	22(18–26)	15.2	0.34(0.06–0.75)	6(4–8)	15.5	0.41(0.0–0.85)	3(3–4)
15	14.8	15.1	0.17(0.10–0.25)	22(18–26)	15.5	0.29(0.05–0.60)	6(4–8)	14.8	0.37(0.0–0.82)	3(3–4)
14	14.4	15.1	0.21(0.08–0.29)	22(18–26)	15.5	0.32(0.05–0.66)	6(4–8)	14.2	0.34(0.0–0.89)	3(3–4)
8	12.4	12.8	0.18(0.11–0.26)	23(19–27)	13.3	0.35(0.10–0.75)	6(5–10)	13.2	0.45(0.02–0.93)	3(3–5)
13	9.2	8.8	0.12(0.07–0.15)	25(23–28)	9	0.21(0.03–0.33)	7(6–8)	9	0.26(0.0–0.59)	3(3–4)
6	8.1	6.8	0.16(0.09–0.21)	26(22–30)	8.4	0.29(0.08–0.58)	7(5–10)	8.4	0.39(0.0–0.90)	3(3–5)
10	7.6	6.2	0.20(0.06–0.26)	29(23–33)	6.4	0.30(0.05–0.59)	8(5–9)	6.3	0.31(0.0–0.82)	4(3–5)
5	7.9	8.6	0.33(0.14–0.44)	26(20–35)	9.1	0.51(0.11–0.86)	7(4–11)	9.3	0.55(0.0–0.94)	4(3–6)
2	6.4	6.7	0.15(0.07–0.20)	28(25–32)	6.7	0.26(0.03–0.50)	7(6–9)	7.1	0.34(0.0–0.81)	4(3–5)
11	4.4	4.7	0.19(0.09–0.24)	31(26–37)	4.8	0.34(0.07–0.57)	8(6–11)	5.1	0.40(0.0–0.86)	4(3–6)
Overall mean	14.2	14.5	0.18(0.06–0.44)	24(15–37)	14.9	0.32(0.01–0.86)	7(4–11)	14.6	0.38(0.0–0.95)	4(3–6)

NOTE: Results are based on 500 simulations with resampling. Stand numbers are as given in Table 1 and ordered by decreasing brood adult density. Ranges are given in parentheses. ASN, average sample number.

TABLE 5. Simulation results from validation analysis for *Dendroctonus pseudotsugae* brood adult density fixed-precision sequential sampling plan with desired precision levels (*C*) adjusted to 0.05, 0.11, and 0.18, Colorado and Wyoming, 1960–1994.

		C = 0.05			C = 0.11			C = 0.18		
Stand	Observed mean	Mean density	Mean precision	ASN	Mean density	Mean precision	ASN	Mean density	Mean precision	ASN
3	25.1	25.8	0.08(0.06–0.1)	72(68–76)	25.9	0.17(0.08–0.28)	15(13–18)	26.3	0.26(0.05–0.52)	6(5–8)
7	25.1	25.4	0.09(0.07–0.11)	72(67–78)	25.6	0.19(0.10–0.27)	15(13–19)	25.9	0.29(0.07–0.55)	6(5–8)
4	23.9	25.1	0.11(0.09–0.13)	72(64–82)	25.5	0.23(0.12–0.34)	15(13–20)	26.4	0.35(0.06–0.71)	6(5–9)
12	21.8	21.1	0.07(0.05–0.09)	76(71–81)	20.9	0.15(0.05–0.26)	16(14–19)	21.7	0.22(0.02–0.58)	6(5–8)
9	17.5	18.3	0.08(0.07–0.1)	80(74–87)	18.2	0.18(0.09–0.28)	17(14–20)	18.6	0.28(0.0–0.49)	7(5–9)
1	15.1	14.7	0.10(0.08–0.12)	85(78–85)	14.9	0.21(0.10–0.32)	18(14–22)	15	0.31(0.06–0.59)	7(5–10)
15	14.8	15	0.08(0.07–0.11)	85(79–92)	15.1	0.18(0.10–0.27)	18(15–21)	15.3	0.27(0.11–0.57)	7(5–9)
14	14.4	14.8	0.11(0.08–0.13)	85(78–94)	15	0.22(0.06–0.32)	18(15–22)	15.3	0.31(0.06–0.62)	7(5–9)
8	12.4	12.6	0.09(0.08–0.11)	90(83–98)	12.7	0.20(0.12–0.29)	19(16–23)	13.2	0.32(0.13–0.57)	7(6–10)
13	9.2	8.8	0.06(0.05–0.07)	100(96–107)	8.7	0.13(0.6–0.17)	21(19–24)	8.9	0.20(0.06–0.28)	8(7–10)
6	8.1	8.3	0.08(0.07–0.1)	102(95–110)	8.3	0.17(0.11–0.25)	22(19–25)	8.4	0.27(0.10–0.52)	8(7–11)
10	7.6	6.2	0.11(0.08–0.12)	112(102–124)	6.3	0.22(0.06–0.28)	24(18–28)	6.4	0.30(0.07–0.53)	9(7–11)
5	7.9	8.3	0.17(0.15–0.19)	102(87–120)	8.8	0.36(0.15–0.5)	22(16–29)	9.3	0.51(0.13–0.82)	9(6–13)
2	6.4	6.6	0.08(0.06–0.09)	109(101–117)	6.7	0.17(0.09–0.22)	23(20–27)	6.9	0.25(0.04–0.40)	9(7–11)
11	4.4	4.6	0.10(0.08–0.11)	125(111–134)	4.7	0.21(0.10–0.26)	26(21–32)	4.7	0.31(0.09–0.47)	10(7–13)
Overall mean	14.2	14.4	0.09(0.05–0.19)	91(64–134)	14.5	0.20(0.05–0.50)	20(13–32)	14.8	0.30(0.0–0.82)	8(5–13)

NOTE: Results are based on 500 simulations with resampling. Stand numbers are as given in Table 1 and ordered by decreasing brood adult density. Ranges are given in parentheses. ASN, average sample number.

applications. With brood densities >25.1 per 0.046 m^2, sample sizes of 72, 15, and 6 should also be adequate for actual precision levels of 0.09, 0.2, and 0.3, respectively. As noted earlier, the number of samples required with the plan decreases with increasing brood densities. Because the validation data set did not include average densities of brood adults >25.1 per 0.046 m^2, a conservative approach would be to retain the number of samples obtained with the largest density examined as the smallest number of samples acceptable (Table 5). With brood densities <25.1 per 0.046 m^2, the number of samples indicated in Table 5 for the closest brood density can be used for the actual precision levels of 0.09, 0.2, and 0.3.

In general, the data collected from our study sites used to construct the sequential sampling plan compare favorably with brood and attack density or gallery characteristics data or both presented by McMullen and Atkins (1961), Furniss (1962), and Lessard and Schmid (1990). Attack densities in our data were higher than those reported by Wright *et al.* (1984) and Fredericks and Jenkins (1988). Those studies focused in defoliated trees. The tussock moth outbreak had completely subsided when we conducted our sampling and we intentionally focused on nondefoliated stands in the vicinity of defoliated stands. Nondefoliated trees are likely to require higher attack densities for successful colonization of the tree (Wright *et al.* 1984).

Although our data compare well with those from other studies, it would be desirable to further test the applicability of the sequential plan presented in this study with data from other parts of the Douglas-fir beetle's range, particularly if data can be obtained from different sampling heights. This is particularly important based on the studies by Furniss (1962) and Chansler (1968) which indicated higher brood density and less variability higher in the bole of the tree. Until this is accomplished, application of our results to areas outside the Colorado Front Range, or using a different sampling height, needs to be cautioned or made with discretion.

Previous studies have attempted to set thresholds of beetle attacks which may be indicative of population trend. Lessard and Schmid (1990) suggested that an emergence ratio >1 indicated an increasing population and a ratio <1 indicated a decreasing population. They suggested an increasing population trend ratio when attack density was ≤ 12 beetles per 0.09 m^2 in trees >25 cm in DBH. The population decreased with DBH of <25 cm, and also with attack densities >14 beetles per 0.09 m^2. Mean DBH of <22 cm produced the lowest number of beetles. Larger trees (not defined) were deemed to provide adequate food to produce increasing populations until the attacking population was >12 beetles per 0.09 m^2. Beyond this level, competition and quantity of food could become critical. Fredericks and Jenkins (1988) also used attack densities to define the intensity of a Douglas-fir beetle outbreak: 0–2 attacks per 0.09 m^2 = low populations; 3–5 attacks per 0.09 m^2 = moderate populations (which they considered optimal for brood production); and more than 5 attacks per 0.09 m^2 = high populations. Mean DBH of the trees they sampled was 56.8 cm and bark samples were collected at a height of 3 m.

A variety of factors influence the characteristics of Douglas-fir beetle outbreaks, including geographic location, DBH of host trees, host vigor as influenced by stocking, other stressors such as drought, and the disturbance agents triggering the outbreaks. These may be some of the factors affecting population densities per unit area in terms of attack and brood densities as discussed previously. Calculating an emergence ratio takes into account attacking and potentially emerging populations and could be a more relevant measure of population trend than the number of attacking beetles. Once an estimate of population density is obtained with the sequential sampling plan described, the emergence ratio can be calculated. This approach would allow the user to immediately have an idea of the Douglas-fir beetle population trend. Prudence needs to be practiced when interpreting the emergence ratio. Although the density of brood adults is estimated with a specified precision, the number of attacking adults is not. Therefore, estimation errors of the emergence ratios are unknown.

Fixed-precision sampling plans do not require action thresholds to be effective, as is the case with systems based on the methods of Wald (1947). Thus, fixed-precision plans could have a wider range of applicability with bark beetles because population densities vary with forest or environmental conditions or both. It may also be difficult to set thresholds that denote changes in population trends that could be incorporated in plans using the methodology of Wald.

The land manager or forest health specialist can use the methodology presented to gain knowledge about population trends. This information can be used in conjunction with knowledge about the prevailing forest conditions that influence Douglas-fir beetle populations such as percent host type, diameter classes, and stocking levels to assist in determining the potential behavior of beetle populations. In stands where increasing populations are identified, extent of mortality models can then be used to estimate potential mortality in the stand (Negrón *et al.* 1999).

Using this Sequential Sampling Plan. To execute the sampling plan described in this paper, the user should delineate the stand or area of interest to be sampled. The stand should be scouted so that the user has an idea of the distribution of infested trees in the stand. Sampling would begin by randomly selecting successfully attacked trees at least 25.4 cm DBH. Sample trees should be either randomly or systematically distributed throughout the stand as much as possible. A 30.5 × 15.2 cm vertically oriented sample is extracted at 1.37 m from the south side of the tree. All brood adults and gallery starts are counted, taking care to extract as many beetles as possible with the help of a knife or other suitable instrument. The data are recorded and sampling proceeds using Table 5 as a guide. When the minimum number of samples is obtained for a density of beetles with the desired precision, sampling is complete. The user can choose to estimate an emergence ratio for each tree by dividing the number of brood adults by twice the number of gallery starts. An average emergence ratio for the stand can be calculated by averaging the emergence ratios for every sample tree to determine the population trend.

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