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FACTORS AFFECTING LINE TRANSECT ESTIMATES OF DOLPHIN SCHOOL DENSITY

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Abstract: An experimental aerial survey of dolphins was conducted to investigate the effects of sea state, sun glare, cloud cover, and observer experience on line transect estimates of school density and detectability. Although estimates during rough seas were lower than estimates during calm seas, and estimates from inexperienced observer teams were lower than estimates from experienced teams, these differences were not significant. School density estimates during poor visibility conditions, due to sun glare or cloud cover, were 39% smaller than during good conditions. Therefore, aerial survey designs should position tracklines to minimize glare under and forward of the plane. If possible, sea-state conditions greater than Beaufort 3 should be avoided, and experienced observers should be utilized.

J. WILDL. MANAGE. 51(4):836–843

Line transect theory has been used to estimate population densities of cetaceans (Leatherwood 1979, Leatherwood and Show 1980, Scott and Winn 1980, Hammond 1981, Smith 1981, Holt and Powers 1982, Hammond and Laake 1983, Hammond 1984, Cooke 1985, Hiby and Thompson 1985, Holt 1985). The valid use of line transect theory is based upon several requirements (Seber 1973, Burnham et al. 1980) that have been assumed to be true or to have minimal effect on the estimates. One requirement, often suspected of not being met for cetaceans, is that all schools are detected on the trackline during all sighting conditions encountered during the surveys (Scott and Winn 1980, Holt and Powers 1982, Leatherwood 1982, Basson and Butterworth 1984). The ability of observers to detect all schools on the trackline may be affected by sea conditions or poor visibility and by the abilities of the observers. These factors are often confounded with each other or with other variables. For example, surveys that traverse nearshore and offshore tracklines may encounter rougher seas offshore, but animal density may decrease offshore. Thus, sea-state effects may be confounded with actual density.

In this paper we present results of an experimental aerial survey for dolphins that investigated the effects of sea state, visibility conditions, and observer performance on detecting dolphins and on density estimates that were determined using line transect methods.

We would like to express our appreciation to W. F. Brinkeroff, L. J. Hanson, M. S. Lowry, F. M. Ralston, and W. A. Walker for unselfishly participating in the survey and collecting the data. Special recognition is given to B. J. Vorndam for providing valuable programing assistance during the analyses, and K. S. Raymond and R. M. Allen for completing the illustrations. J. P. Barlow, J. M. Michalski, W. W. Parks, G. T. Sakagawa, S. N. Sexton, and T. D. Smith provided many constructive review comments. We also benefitted from technical reviews by G. Broadhead, K. P. Burnham, D. G. Chapman, W. B. Clark, and P. S. Hammond.

METHODS

Line Transect Model

Density was estimated by the line transect method. Burnham et al. (1980) provide a thorough review of line transect theory, and, if all requirements are met, then the density of the dolphin schools can be estimated as:

$$\hat{D} = \frac{n\hat{f}(0)}{2L}, \tag{1}$$

where n is the number of sightings, L is the length of trackline searched, and $\hat{f}(0)$ is an estimate of the probability density function (PDF) with a perpendicular distance (distance from sighting to trackline) equal to 0. The sampling variance of $\hat{D}$ was estimated using the Taylor expansion (Seber 1973):

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Table 1. Number of transect segments classified by Beaufort sea-state conditions, in which from 0 to 6 sightings[a] of dolphins were detected/segment, Liberia, Costa Rica, 1981. Percents are of column totals.

No. of sightings/ segment	Beaufort condition[b]											
	1	%	2	%	3	%	4	%	5	%	Total	%
0	8	38	65	51	106	56	45	87	7	100	231	58
1	9	42	43	33	57	29	6	12			115	29
2	2	10	11	9	17	9					30	8
3	2	10	6	5	6	3					14	4
4			3	2	4	2	1	2			8	2
5												
6					1	1					1	0
Total	21		128		191		52		7		399	

[a] Segments with >1 sighting were pooled during analyses because relatively few segments had >1 sighting.
[b] Increasing number indicates increasing sea-surface roughness.

$$\widehat{\mathrm{Var}}(\hat{D}) = \hat{D}^2\left[\frac{\widehat{\mathrm{var}}(n)}{n^2} + \frac{\widehat{\mathrm{var}}\,\hat{f}(0)}{(\hat{f}(0))^2}\right]. \tag{2}$$

The variance of n was determined empirically as:

$$\widehat{\mathrm{Var}}(n) = \frac{R\sum_{i=1}^{R}(n_i - \bar{n})^2}{(R-1)}, \tag{3}$$

where $n = n_i/R$ with n_i denoting the number of schools observed on the ith trackline segment and R = total number of equal trackline segments. We used the average length of all effort legs (28.64 km) as the length of the trackline segments. Equal line segments for data in each stratum were formed by either partitioning effort legs or by summing contiguous parts of legs with identical conditions or whole legs until 28.64 km were searched. Use of Equation 3 is appropriate (Burnham et al. 1980) because the detection rates of trackline dolphin schools among the segments were not serially correlated ($r = 0.085$).

Several models have been used to estimate $f(0)$ (Burnham et al. 1980). The Fourier series (FS) model was used in our study because, theoretically, the model could fit perpendicular sighting distributions of a wide variety of shapes. These included distributions with large numbers of sightings detected on or near the origin (trackline); i.e., "spiked" distributions.

The number of terms selected for the FS model was determined independently for data in each sea state, visibility, or observer-team stratum. Because the experimental objectives were to determine if schools were missed on the trackline during each stratum and to investigate these effects upon the density estimates, the number of terms used in the FS model was selected to provide the best fit of the data near the origin. Therefore, models were selected that had more terms than would have been selected using standard selection techniques (Burnham et al. 1980).

Experimental Design

The experimental survey was done from 7 March through 5 April 1981 near Liberia, Costa Rica, using a Beech AT11 aircraft equipped with a plexiglass nose cone. A study area was selected from the coast westward to approximately 86°40′W and from 11°N southward to about 9°30′N. During each flight, the plane flew at approximately 274 km altitude and 278 km/hour along systematically placed tracklines. Searching effort was recorded in time periods (effort legs) during which sea state, observability conditions, and observer positions were constant. A new effort leg was recorded when either of these conditions changed.

Dolphin species included in the data analyses were spotted (*Stenella attenuata*), spinner (*S. longirostris*), striped (*S. coeruleoalba*), Risso's (*Grampus griseus*), and unidentified dolphins. Data recorded for each school included species identification, estimate of perpendicular distance of the school from the trackline, observer who detected the school, and estimates of the school size. Dolphin schools with <15 animals were omitted because all animals of such schools may have been submerged at the same time, and thus not detectable, and because these species typically do not occur in small schools. Holt and Powers (1982) reported that schools averaged approximately 200 animals. The estimates of school size were not verified because the plane was not diverted to fly over a school that obviously contained >15 dolphins. Schools de-

Table 2. Estimates of parameters used in computing dolphin density ($\hat{D}$) for calm and rough sea conditions, during good and poor visibility conditions, and for experienced and inexperienced observer teams, Liberia, Costa Rica, 1981.

Variable	$\hat{D}$ (schools/ 1,000 km^2)	SE($\hat{D}$)	No. of line segments searched
All data	25.00	3.349	423
Sea state conditions[a]			
Calm	25.72	4.986	161
Rough	24.94	4.279	262
Visibility conditions[b]			
Good sun	34.83	7.112	120
Poor sun	21.15	3.692	303
Sea state–visibility interactions			
Calm sea–good sun	29.18	7.357	52
Calm sea–poor sun	23.78	5.888	109
Rough sea–good sun	39.42	8.193	68
Rough sea–poor sun	20.16	4.513	194
Observer teams			
Experienced	30.15	4.784	218
Inexperienced	20.52	4.177	205
Observer team–sea state interactions			
Experienced–calm sea	30.66	7.853	79
Experienced–rough sea	31.18	4.352	139
Inexperienced–calm sea	23.09	5.178	82
Inexperienced–rough sea	20.10	5.836	123
Observer team–visibility interactions			
Experienced–good sun	43.28	9.410	67
Experienced–poor sun	24.06	3.039	151
Inexperienced–good sun	24.09	9.800	53
Inexperienced–poor sun	20.08	4.773	152

[a] Calm = Beauforts 1–2 and rough = Beauforts 3–5.

[b] Poor = sun glare on trackline or cloudy skies and good = all other conditions.

tected at perpendicular distances >1.94 km (1.05 nm) were not used in the analyses.

Three observers searched for dolphin schools from observation positions aboard the aircraft: a bow station located in the nose cone and left and right stations located at the sides of the plane in the extreme aft of the cabin. The bow observer searched the region directly underneath the plane (the trackline or center area of the transect), while left and right observers searched areas from the edge of the plane outboard to a distance that varied with environmental conditions. A bow monitor, who occupied the bow station which is adjacent to the bow observer, had clear vision of the trackline to check the bow observer's performance in detecting schools. It was not possible to determine if the bow monitor missed schools detected by the bow observer because the bow observer upon detecting a school immediately indicated its location. Schools detected by the bow monitor were not included in the density comparisons because the bow monitor was not a member of the 3-member searching team.

Data were recorded for each Beaufort sea state (Bowditch 1966) and grouped into sea-state conditions without (Beaufort numbers 1–2) or with (Beaufort numbers 3–5) whitecaps. The presence of whitecaps was important because animal splashes were used as sighting cues during calm seas when whitecaps were present but were easily confused with whitecaps during rough seas.

Visibility effects were investigated by recording the horizontal and vertical position of the sun relative to the plane (Holt 1983). The bow observer periodically noted when sun glare was on the trackline during certain positions of the sun (Holt 1983). When sun glare was noted on the trackline at any time during the survey, visibility was classified as poor. During conditions when clouds obscured the sun, diminished light penetration into the water reduced an observer's ability to detect dolphins; therefore, visibility under these conditions was classified as poor. Visibility under all other conditions was classified as good.

Two methods were used to collect data on the observers' abilities to detect schools. First, the bow monitor provided a direct visual check of the bow observer's failure to detect trackline schools. When a school was detected by the bow monitor but was missed by the bow observer, the plane was turned to ensure that a school had been missed. Second, detection rates of an inexperienced team were compared to an experienced team. The 2 teams alternated searching at approximately 40-minute intervals.

Data Analyses

Statistical differences within and among sea state, visibility, and observer teams were investigated using estimates of the density of schools, $\hat{D}$ (schools/1,000 km^2). However, because the number of schools detected was insufficient to calculate density estimates for the interaction effects, the rates of detecting all (combined on and off the trackline) schools (schools/1,000 km searched) and the rates of detecting trackline schools (schools/1,000 km of trackline searched) were tested. Three-way analysis of variance (ANOVA) was used to investigate interaction effects; but, because of small sample sizes, 2-way ANOVA was used to compare density estimates under different sea-state and visibility conditions. Because sea-state effects were not significant, data were pooled over sea states and visibility conditions, and observer team effects on the density estimates were tested. Unless otherwise indicated, statistical significance was tested at the $P = 0.05$ level.

The application of the ANOVA models was modified (Appendix 1) because data were not sufficient to compute independent, replicate detection rates or school densities for each level of interaction of sea state, visibility condition, and observer-team strata. Instead, the mean density and variance (Equations 1 and 2) or mean detection rates were estimated for each level of interaction and used in the ANOVA model.

In addition to investigating sea-state effects using our calm and rough sea classifications, which were derived a priori, we investigated sea-state effects by comparing data among individual sea states (Beaufort states). These comparisons were made using 2 methods. First, ANOVA compared trackline detection rates of individual Beaufort data (Sea-State-5 data were omitted because they represented only 2% of the effort during which there were no sightings). Second, a nonparametric contingency table analysis compared the number of equal-length line segments with dolphin sightings vs. those without sightings (Table 1). This is equivalent to analyzing detection rates.

RESULTS

Sea-State and Visibility Effects

The estimate of school density with calm seas was slightly larger than the estimate with rough seas (Table 2) but the difference between the 2 estimates was not significant ($F = 0.003$, $P > 0.10$). Differences among trackline detection rates during individual Beaufort sea states were not significant ($F = 0.869$, $P > 0.10$). However, little effort during Beaufort 5 conditions existed, and detection rates during Beauforts 4 and 5 were lower than during Beauforts 1 through 3 (Fig. 1). In addition, Beaufort 3 trackline rates were higher than Beaufort 2 rates. The association between Beaufort state and proportion of segments with and without sightings was not significant for trackline sightings ($\chi^2 = 5.15$, $P = 0.161$) but was highly significant for all sightings ($\chi^2 = 26.35$, $P < 0.001$).

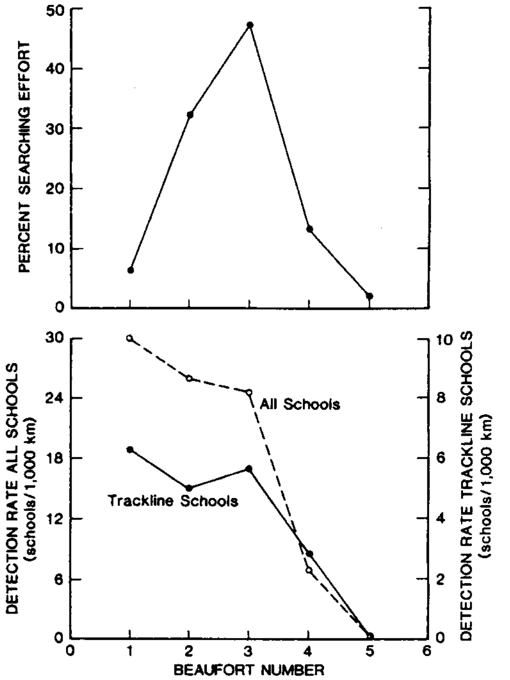

Fig. 1. Percent searching effort and detection rates of all schools and trackline schools of dolphins relative to sea state (Beaufort number), Liberia, Costa Rica, 1981. Increasing numbers indicate increasing sea roughness.

Density estimates of dolphin schools observed during good and poor visibility were 34.83 and 21.15 schools/1,000 km², respectively, and were statistically different ($F = 4.061$, $P < 0.05$). No significant interaction of visibility and weather effects on the density estimates was demonstrated ($F = 1.049$, $P > 0.10$). In general, density estimates during good visibility conditions were larger than during poor visibility conditions at each corresponding sea-state condition. However, the density estimate during good visibility conditions with rough seas was larger than during good visibility conditions with calm seas.

Observer Comparisons

Bow Monitor Comparisons.—During the experiment, bow monitors did not detect any large (>15 animals) dolphin schools on the trackline

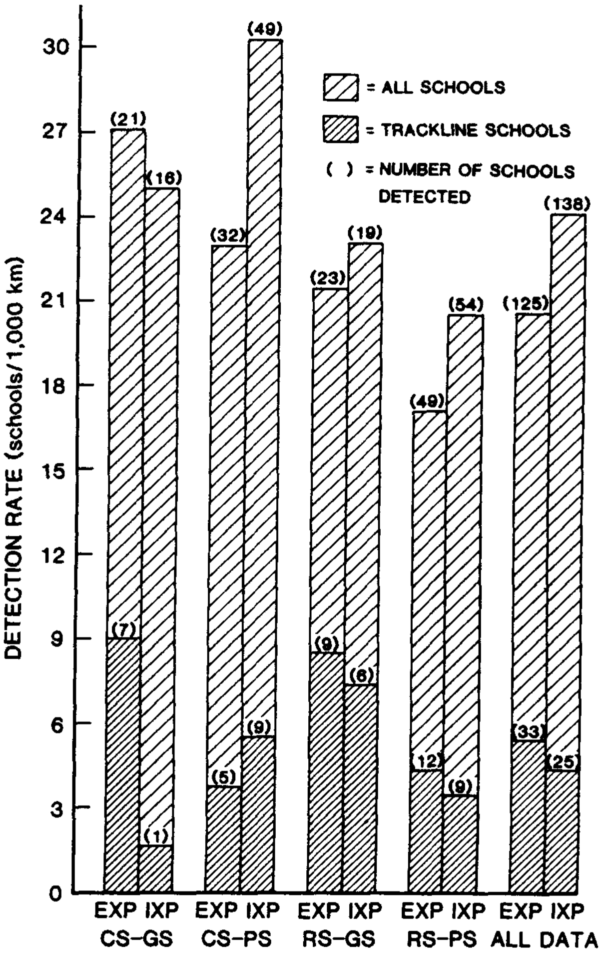

Fig. 2. Rate of detecting dolphin schools for perpendicular distance data for the experienced (EXP) and inexperienced (IXP) teams during calm sea–good visibility (CS-GS), calm sea–poor visibility (CS-PS), rough sea–good visibility (RS-GS), and rough sea–poor visibility (RS-PS) conditions, Liberia, Costa Rica, 1981.

that were missed by the bow observer. The only direct evidence that bow observers missed large dolphin schools on the trackline was the detection of 20 unidentified dolphins by the left observer. This school was sighted on the left boundary of the trackline in an area surveyed by both bow and left observers.

Observer-Team Comparisons.—Estimates of school densities were not statistically different between the inexperienced and experienced observer teams ($F = 2.497$, $P > 0.10$). However, the experienced team's density estimate was larger than that of the inexperienced team (30.50 vs. 20.52 schools/1,000 km^2, Table 2). Density estimates for the experienced team were larger than for the inexperienced team with calm sea conditions and with rough sea conditions (Table 2). Estimates of school densities were not statistically different for the 2 teams for good and poor visibility conditions ($F = 1.505$, $P > 0.10$). Estimates of school density for the experienced team were larger than for the inexperienced team during good visibility conditions and were slightly larger during poor visibility conditions (Table 2). The inexperienced team's estimates were similar with calm and rough seas and with good and poor visibility conditions. The experienced team's estimates were similar with calm and rough seas, but their estimate during good visibility was much larger than their estimate during poor visibility.

Neither consistent nor significant patterns were evident among observer-team detection rates, either trackline or all schools, for the various interaction effects with visibility and sea conditions. However, for either visibility condition, the detection rates of all schools for both teams were lower during rough than during calm seas (Fig. 2). Trackline rates for all categories and teams ranged from 1.56 to 9.04 schools/ 1,000 km. However, some categories had small sample sizes.

DISCUSSION

Observers were required to continue searching for marine mammal cues despite severe glare on the trackline or cloudy conditions that prevented visibility into the water. Bow observers frequently looked under and to the rear of the plane to avoid glare forward of the plane. Because the density estimate was 39% lower during poor visibility than during good visibility conditions, "acceptable" survey conditions must be rigorously defined prior to conducting future surveys.

The left observer's detection of a dolphin school on the trackline illustrated that bow observers missed some trackline schools. However, the detection of this school out of 265 total schools does not explain differences in the density estimates noted among the variables tested. In addition, bow monitors were subject to the same limitations as the bow observers.

The larger density estimate for the experienced team than for the inexperienced team was due predominantly to a relatively large estimate for the experienced team during good visibility conditions (Table 2). Density estimates were very similar for the experienced team under poor visibility conditions and the inexperienced team under good and poor visibility conditions. The relatively large estimate of density for the experienced team's good-visibility-condition data may be caused by: (1) incorrectly recording sightings near the trackline, as on the trackline by the experienced team during good visibility conditions so that estimates of $\hat{f}(0)$ were too large; (2) missing trackline schools by the experienced team during poor visibility conditions and by the inexperienced team during both good and poor visibility conditions; or (3) sampling error because of small sample sizes.

If incorrect data recording occurred for the experienced team during good visibility conditions, the rate at which schools in that stratrum were detected off the trackline should be correspondingly lower. However, the experienced team's good visibility and poor visibility off-track detection rates were approximately equal and were only slightly less than the inexperienced team's off-track detection rates during both visibility conditions (Fig. 3). It is possible, but not likely, that trackline schools were missed by the experienced team only during poor visibility conditions, whereas the inexperienced team missed schools during both visibility conditions. However, the estimate for the experienced team during good visibility conditions was based on a relatively small sample. (Only 16% [1,840 km] of the total searching effort and 17% of the total sightings were completed by the experienced team during good visibility conditions.)

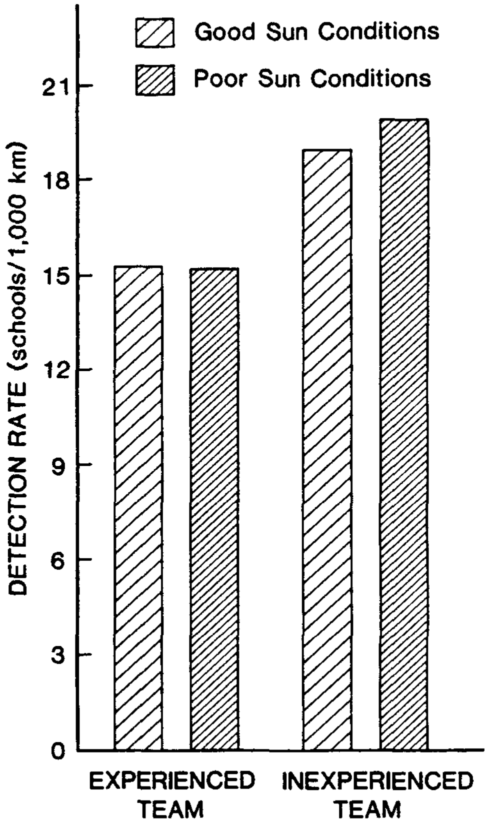

Fig. 3. Detection rate of dolphin schools off the trackline for experienced and inexperienced observer teams, Liberia, Costa Rica, 1981.

Erroneous differences among density estimates for variables being tested may result if the estimation models fit poorly or are applied inconsistently among data strata. We attempted to avoid these problems by ensuring that the models closely fit the sighting distributions near the origin. One indication of a model's performance is how well the pooling robustness criteria were met (see Burnham et al. [1980] for criteria development). Pooling robustness occurs when the sum of the density estimates of data in each stratum (such as calm- and rough-sea strata) equals the estimate of the total data set. The estimate for all data equalled 25.00 schools/1,000 km^2. Differences between this estimate and the sum of calm- and rough-sea-state data, the sum of good and poor visibility data, or the sum of experienced and inexperienced team data were not >0.66 schools/1,000 km^2.

Tracklines should be positioned to minimize glare under and forward of the plane. Sea conditions at ≥Beaufort 4 should be avoided during a survey. In addition, observer experience may not be critical, but the experienced team's estimates were consistently larger than those of the inexperienced team. Because operational and viewing conditions during our survey may not be consistent with conditions of other surveys, we caution against using our survey to correct for differences in other surveys.

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Received 21 November 1985.
Accepted 30 March 1987.

APPENDIX 1

A problem common to many studies of animal abundance is that a large effort must be expended to compute a single estimate of abundance with acceptable precision. Unfortunately, factorial experiments are often limited by resources to 1 estimate of animal abundance/cell in a multifactorial design. If the abundance estimate is approximately normally distributed, then the usual ANOVA method for a factorial design with 1 observation/cell may be applied; however, this is not a powerful procedure because of lack of replication in the individual cells, and testing interactions, except for the special conditions of Tukey's 1-degree-of-freedom test (Scheffe 1959), are not possible. In addition, the 1 observation/cell analysis ignores information about the variability of the abundance estimates. The following describes a method to analyze the factorial design to make use of within-cell variability.

If true replicates exist, the empirical estimate of the variance of an estimated density is (Burnham et al. 1980):

$$\widehat{\mathrm{Var}}(\hat{D}.) = \frac{\sum_{r=1}^{R} l_r(\hat{D}_r - \hat{D}.)^2}{(R - 1)\sum_{r=1}^{R} l_r},$$

where $\hat{D}$ is the average over all replicates ($r = 1, \ldots, R$). If line lengths are equal ($l_1 = l_2 = \ldots = l_r$), then:

$$\widehat{\mathrm{Var}}(\hat{D}.) = \frac{l\sum_{r=1}^{R} (\hat{D}_r - \hat{D}.)^2}{L(R - 1)} = \frac{\sum_{r=1}^{R} (\hat{D}_r - \hat{D}.)^2}{R(R - 1)}, \qquad \text{(A1)}$$

because $R = L/l$, where $L = \sum_{r=1}^{R} l_r$. Equation (A1) is the square of the standard error of $\hat{D}.$. Because the sum of squares within a single cell of an ANOVA table is the sum of squared deviations of the individual replicates about the cell mean, or

$$SS_{error} = \sum_{r=1}^{R} (\hat{D}_r - \hat{D}.)^2,$$

the error sum of squares within a cell may be obtained from the variance of $\hat{D}.$ (Equation A1) as:

$$SS_{error} = R(R - 1)[\mathrm{Var}(\hat{D}.)], \qquad \text{(A2)}$$

where R is the number of replicates in the cell of the ANOVA table and $\hat{D}.$ is the cell mean. Therefore, if there were replicated densities, ANOVA tests could be performed using cell means and variances in lieu of individual density estimates.

When true replicates of density do not exist within each cell of the factorial design, the estimated density and its standard error, if statistically consistent, estimate the same quantities that the mean and standard error of the mean, respectively, would have estimated if true replicates were obtained. In this sense consistency is that the estimates would converge in theory to the correct values if complete enumeration were approached.

In the absence of true replicates, one must determine a value for the number of degrees of freedom (no. of hypothetical replicates minus 1) in each cell. This value cannot be arbitrary because it will affect both the size of the F-statistic and the critical level of the F-test through the number of degrees of freedom for error. We used the number of independent legs of effort searched as the degrees of freedom. Because Equation A2 assumes replicate lines are of equal length, we used a leg length equal to the average length of all legs in the study area.

We wrote routines to compute the ANOVA within- and between-group sums of squares and to compute F statistics for main effects and interactions. Because we had no control over the number of replicate tracklines in each cell in the analysis, we used weighted means formulas for the case of unequal *but proportional* cell sizes (Snedecor and Cochran 1967). If true cell sizes are not proportional, the weighted means analysis is only approximate. How good the approximation is for nonproportional cell sizes is not clear, but we believe the approximation improves with larger individual cell sizes.