Studies in Avian Biology No. 6:445–449, 1981.

AVIAN CENSUSING WITH THE STRIP METHOD: A COMPUTER SIMULATION

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ABSTRACT.—Variable-width line transect censuses were simulated by computer to identify variation due to random fluctuation of density estimates inherent in the technique. Effects of transect length (457–1828 m), number of censuses (up to 15), and density value (4/40 ha to 201/40 ha) were tested. For moderately abundant species (35 to 37/40 ha), between six and nine censuses of transects, at least 914 m in length were sufficient to obtain accurate and consistent estimates. At least 15 censuses were needed for shorter transects. Estimates of rare and abundant species were equally close to known densities after 15 censuses, but estimates of rare species were too variable to be statistically reliable. Variation in estimates obtained by simulation are probably greater than those from real censuses.

Since J. T. Emlen (1971) popularized the variable-width line transect method for estimating bird densities in large tracts of habitat, thousands of transects have been walked, and millions of bird detections have been recorded. The reliability of this technique has been continually questioned, although some practical aspects of reliability have been addressed (Anderson and Ohmart 1977). Unfortunately, many questions cannot be answered using real data. In this paper, we attempt to answer some of these questions by simulating a simple habitat within which the number of species, their densities, and their degrees of detectability are known.

Specific questions that we address are: (1) How many censuses are needed to accurately estimate the true density in an area? (2) How long should a transect be? (3) Does the density of a species affect its density estimates?

The purpose of this paper is to explain that portion of the variance inherent in the line transect technique, assuming a random distribution of species in a habitat. Our feeling is that if one could find a uniform habitat with a known density of birds and a known number of species, find a perfect censuser, and keep weather conditions constant, one could calculate the minimum number of censuses of a known transect length needed to obtain a required degree of statistical confidence in the data. We have created such a situation using the computer simulation approach.

METHODS

Habitats of different sizes and different species compositions were generated (Fig. 1) using computer program RANGRID (available from the authors upon request). Each simulated habitat was 251 m wide with the center line as a transect. This gave census areas of 11.4 ha with a 457 m transect, 22.7 ha with a 914 m transect, and 45.4 ha with a 1829 m transect. Fifteen species, each with an equal density and represented by a letter, A to O, were randomly distributed. For this purpose, each habitat was treated as a grid 100 units wide by 300 units long, such that each individual bird occupied a single square equal to 0.33×10^{-5} times the area of each grid. No two birds occupied the same square. For each species, there was an equal probability of any individual occurring in any strip lateral to the transect line.

Each transect was censused fifteen times. For each census individuals were uniquely randomly distributed, and all species were equally detectable. Transects were censused by tallying all individuals of each species occurring within 15.2 m of the transect (A1), one-half of the detections 15.2 to 30.5 m (A2), one-fourth of the detections 30.5 to 61 m (A3), and one-eighth of the detections 61 to 126 m (A4) (Fig. 1). We next calculated the density of detections (birds per m^2) in each of the lateral strips out to 15.2, 30.5, 61, or 126 m. The area containing the highest density (transect length × lateral distance) was then extrapolated to the number per 40 ha.

Since each species had the same known density, we performed one-way analysis of variance on density estimates to find the minimum number of censuses needed to obtain a reliable estimate of that density. A nonsignificant F-statistic would indicate that the censuses were indeed estimating the same density. The only variable causing a difference in estimates was random variation in distributions. Using a χ^2 test, the mean density estimates of the 15 species were compared with their expected (known) densities for each of the three transect lengths and census replicates.

In a second set of simulations, sensitivity of the line transect method to different densities was tested using known densities ranging from 4/40 ha to 201/40 ha. Estimates using transect lengths of 457.2 m, 914.4 m, and 1828 m were also compared. Coefficients of variation were calculated for each estimate based on 15 censuses.

RESULTS

Means of density estimates based on sets of 3, 6, 9, and 15 censuses were calculated for the three transect lengths, as well as ranges of es-

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TABLE 1
DENSITY ESTIMATES (NO. PER 40 HA) FOR SPECIES OF KNOWN DENSITY AFTER 3, 6, 9, AND 15 CENSUSES OF A SIMULATED 457.2-M TRANSECT

Species	Known dens.	3 censuses[a]	6 censuses[a]	9 censuses[a]	15 censuses[a]
A	35	33 (59) 11–58	29 (25) 11–58	32 (12) 11–58	40 (13) 11–87
B	35	18 (25) 9–29	25 (19) 9–58	22 (15) 7–58	35 (21) 7–145
C	35	39 (41) 29–58	40 (29) 7–87	46 (22) 7–87	42 (14) 5–87
D	35	10 (13) 6–16	32 (44) 6–116	34 (31) 5–116	44 (22) 5–116
E	35	39 (41) 29–58	30 (17) 5–58	27 (11) 5–58	29 (10) 5–58
F	35	32 (61) 9–58	29 (25) 9–58	39 (28) 5–116	37 (26) 5–116
G	35	24 (20) 15–29	21 (9) 9–29	28 (14) 9–58	32 (13) 7–87
H	35	48 (42) 29–58	36 (19) 11–58	39 (26) 9–116	34 (16) 7–116
I	35	39 (41) 29–58	27 (19) 7–58	40 (25) 7–116	46 (19) 7–116
J	35	21 (33) 6–29	19 (12) 5–29	32 (20) 5–87	31 (12) 5–87
K	35	24 (38) 7–36	27 (10) 7–36	31 (18) 5–87	33 (13) 5–87
L	35	16 (28) 9–29	11 (9) 6–29	27 (19) 6–58	32 (13) 6–58
M	35	46 (52) 22–58	42 (18) 22–58	50 (20) 18–87	49 (16) 7–87
N	35	29 (0) 29–29	20 (11) 7–29	36 (20) 7–87	38 (13) 7–87
O	35	34 (54) 15–58	56 (41) 15–116	50 (28) 15–116	47 (18) 15–116

[a] For each number of censuses the columns are as follows, left to right: mean estimate, 95% confidence interval in parentheses, and range.

timates from individual censuses (Tables 1, 2, 3). In each case, lengthening the transect and/or increasing the number of censuses reduced the variation among estimates. For example, for a 914.4 m transect (Table 2) the estimate based on sets of three censuses ranged from 18 to 68/40 ha; after six censuses the range was 18 to 56/40 ha; after nine censuses the range was 28 to 50/40 ha; and after 15 censuses it was 33 to 44/40 ha. Transects 457.2 m long were more variable (Table 1) and 1828.8 m transects were less variable (Table 3).

Although mean estimates from multiple censuses came close to the known density (35 or 37/40 ha), estimates from single censuses varied greatly. Even for the 1828.8 m transect, single estimates ranged from 9 to 94/40 ha.

Table 4 lists the results of the χ^2 test and 1-way analysis of variance (ANOVA) for 15 equally abundant species after 3, 6, 9, 12, and 15 censuses. For transects of 914.4 m or longer, between six and nine censuses were sufficient to give estimates of the densities of the species that did not differ significantly from their true

TABLE 2
DENSITY ESTIMATES (NO. PER 40 HA) FOR SPECIES OF KNOWN DENSITY AFTER 3, 6, 9, AND 15 CENSUSES OF A SIMULATED 914.4-M TRANSECT

Species	Known dens.	3 censuses[a]	6 censuses[a]	9 censuses[a]	15 censuses[a]
A	37	21 (18) 15–29	24 (12) 15–44	28 (8) 15–44	38 (11) 15–87
B	37	20 (20) 15–29	34 (27) 15–73	36 (19) 15–73	40 (14) 15–87
C	37	34 (22) 29–44	26 (13) 8–44	32 (14) 8–58	35 (10) 8–73
D	37	53 (20) 44–58	38 (20) 8–58	39 (16) 8–73	36 (10) 8–73
E	37	18 (27) 7–29	18 (10) 7–29	31 (20) 7–87	36 (14) 7–87
F	37	20 (28) 12–33	19 (7) 12–33	30 (14) 12–58	36 (11) 12–73
G	37	42 (41) 25–58	46 (12) 25–58	48 (9) 25–58	43 (9) 22–73
H	37	50 (51) 33–73	42 (17) 29–73	36 (13) 15–73	40 (10) 15–73
I	37	54 (86) 18–87	48 (28) 18–87	46 (19) 18–87	41 (13) 6–87
J	37	68 (75) 44–102	56 (26) 29–102	50 (20) 15–102	42 (13) 15–102
K	37	57 (69) 25–73	53 (20) 25–73	48 (17) 15–73	44 (12) 15–73
L	37	34 (22) 29–44	29 (10) 15–44	39 (14) 15–73	37 (10) 15–73
M	37	20 (20) 15–29	25 (12) 15–44	28 (11) 15–58	33 (13) 15–102
N	37	39 (22) 29–44	41 (12) 25–58	36 (9) 18–58	36 (9) 18–73
O	37	29 (58) 29–58	41 (15) 29–58	39 (12) 15–58	39 (8) 15–58

[a] For each number of censuses, the columns are as follows, left to right: mean estimate, 95% confidence interval in parentheses, and range.

TABLE 3
DENSITY ESTIMATES (NO. PER 40 HA) FOR SPECIES OF KNOWN DENSITY AFTER 3, 6, 9, AND 15 CENSUSES OF A SIMULATED 1828.8-M TRANSECT

Species	Known dens.	3 censuses[a]	6 censuses[a]	9 censuses[a]	15 censuses[a]
A	37	20 (9) 15–22	27 (9) 15–36	30 (8) 15–51	38 (2) 15–73
B	37	44 (18) 36–51	31 (17) 10–51	35 (14) 10–65	35 (8) 10–65
C	37	18 (24) 10–29	17 (8) 9–29	30 (17) 9–73	35 (11) 9–73
D	37	44 (36) 29–58	43 (10) 29–58	41 (8) 29–58	41 (6) 22–65
E	37	61 (25) 15–73	50 (16) 31–73	46 (12) 20–73	40 (8) 20–73
F	37	44 (47) 22–58	40 (14) 22–58	43 (12) 22–73	40 (8) 22–73
G	37	27 (20) 22–36	31 (9) 22–44	30 (6) 22–44	34 (9) 18–87
H	37	35 (25) 24–44	34 (12) 22–51	35 (9) 22–51	33 (7) 13–51
I	37	29 (32) 22–44	26 (13) 11–44	37 (16) 11–73	34 (10) 11–73
J	37	27 (20) 22–36	28 (11) 13–44	31 (8) 13–44	33 (6) 13–58
K	37	27 (10) 22–29	32 (11) 22–51	38 (11) 22–65	37 (9) 18–65
L	37	34 (37) 25–51	34 (14) 22–51	34 (12) 15–58	36 (7) 15–58
M	37	68 (57) 51–94	52 (24) 18–94	50 (17) 18–94	42 (11) 11–94
N	37	29 (17) 22–36	34 (14) 22–58	32 (9) 16–58	35 (8) 16–73
O	37	32 (24) 22–44	36 (11) 22–51	35 (8) 22–51	35 (6) 20–51

[a] For each number of censuses, the columns are as follows, left to right: mean estimate, 95% confidence interval in parentheses, range.

densities ($P \geq .25$). For the 457.2 m transect, 15 censuses were barely sufficient ($P \geq .1$).

Results of the ANOVA were more complex. For transects of 914.4 m or longer, between six and nine censuses were also sufficient to reliably estimate a known density. With six or fewer censuses, a significant difference existed between censuses (F prob. $< .05$). For 457.2 m transects, lack of differences between estimates was a result of large variation within census replicates and not closeness of the estimates. Short transects, therefore, cannot be considered reliable or accurate.

Results of censuses using 14 known densities are shown for the three transect lengths in Table 5. After 15 censuses, mean estimates of both

TABLE 4
ACCURACY AND RELIABILITY OF COMPUTER-SIMULATED LINE TRANSECT ESTIMATES[a]

	Number of censuses	Known density	Mean estimate[b]			Single reading estimate	ANOVA[d]	
			χ^2	P[c]	Min.–max.	Max.–min.	F ratio	P of F
Transect length = 457.2 m;	3	35	60.860	.001	10–48	6–58	1.434	0.197
area sampled per transect = 11.3 ha	6	35	59.772	.001	11–56	5–116	1.499	0.132
	9	35	29.215	.005	22–50	5–116	0.835	0.630
	12	35	28.152	.01	24–50	5–116	1.021	0.435
	15	35	19.992	.1	29–49	5–145	0.765	0.707
Transect length = 914.4 m;	3	37	100.263	.001	18–68	7–102	2.621	0.013
area sampled per transect = 22.7 ha	6	37	56.739	.001	18–56	7–102	3.298	0.000
	9	37	17.879	.25	28–50	7–102	1.326	0.202
	12	37	8.949	.75	31–47	6–102	0.640	0.829
	15	37	5.066	.975	33–44	6–102	0.401	0.973
Transect length = 1828.8 m;	3	37	74.889	.001	18–68	10–94	3.993	0.001
area sampled per transect = 45.5 ha	6	37	34.390	.001	17–52	9–94	2.871	0.002
	9	37	14.781	.25	30–50	9–94	1.553	0.102
	12	37	4.695	.99	33–45	9–94	0.613	0.852
	15	37	3.477	.995	33–42	9–94	0.565	0.891

[a] All density estimates in number per 40 ha.

[b] Means are for the number of censuses listed; the minimum-maximum are from 15 species with equal densities.

[c] Probability of mean estimate; 14 degrees of freedom.

[d] Treatments are the density estimates for each of 15 species.

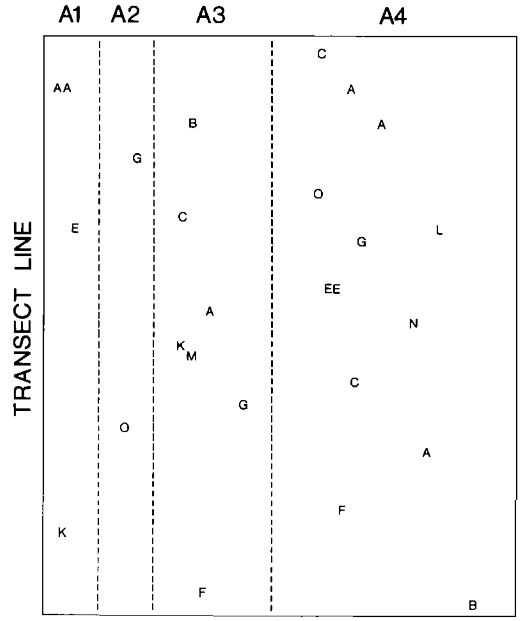

FIGURE 1. Portion of a simulated habitat 251 m wide. Each letter represents an individual bird of species A to O, which occupies an area equal to 0.33 × 10^{-5} of the total habitat. Letters are randomly distributed among the lateral strips, A1 to A4.

common and rare species were reasonably close to the true values. However, as either transect length or known density decreased, the coefficient of variation of mean estimates increased greatly.

DISCUSSION

When outside factors are controlled, the random variation inherent in the variable-width line transect technique ultimately limits the strength of such census data. To compare avian densities in different areas or over distinct time intervals, it is essential that differences due solely to such variation are eliminated. We have shown that line transect censusing can both accurately and consistently estimate a known density given the proper sample design. However, differences between, or changes in, the densities of very rare species become increasingly difficult to detect because of high coefficients of variation associated with those estimates.

We feel that the required sampling effort suggested by this model is conservative for several reasons. First, the computer simulation represented the maximum variation due to redistribution of birds between censuses. It assumed that the distribution of birds in a habitat during one census was independent of their distribution during any other census. In practice, this is probably not often the case. For moderately sedentary or territorial species, and especially during the breeding season, individual birds would not move great distances relative to an established transect line during a short time period. Therefore, consecutive density estimates during that period will often be less variable than those presented here.

A second assumption in our simulation was that all detections were counted within 15.2 m of a transect and only half were counted in the next 15.2 m strip. If, as real census data suggest, birds often are equally detectable in both the first and second 15.2 m strips, then the variability among consecutive estimates will again be reduced.

These hypotheses can be tested with further simulations and by examining large census data

TABLE 5

Known Density and Estimates (15 censuses) and Coefficients of Variation of Means

Known density/40 ha.			Est. density/40 ha.			C. V. of mean		
1828.8 m	914.4 m	457.2 m	1828.8 m (±95 CI)	914.4 m (±95 CI)	457.2 m (±95 CI)	1828.8 m	914.4 m	457.2 m
192	201	201	193 (22)	217 (26)	187 (53)	20.6	21.8	51.3
97	100	99	93 (16)	100 (21)	92 (34)	31.6	39.2	66.2
70	70	70	65 (8)	60 (15)	75 (22)	22.7	46.1	52.8
62	60	60	59 (14)	55 (20)	52 (13)	42.0	65.4	47.7
47	49	49	49 (9)	47 (15)	43 (19)	34.0	58.2	80.3
38	41	39	45 (8)	46 (13)	42 (12)	31.7	53.5	54.0
32	30	28	35 (7)	34 (10)	23 (9)	37.2	54.8	70.6
23	25	25	21 (5)	26 (10)	29 (15)	47.5	68.0	93.2
19	21	21	17 (4)	24 (7)	15 (9)	45.3	50.3	105.0
16	18	18	18 (5)	24 (8)	28 (13)	46.4	61.5	84.4
14	14	14	15 (6)	14 (6)	20 (11)	73.8	69.4	95.6
11	11	11	12 (6)	10 (4)	9 (6)	92.3	78.0	116.0
7	7	7	7 (3)	6 (4)	7 (6)	88.2	101.4	161.0
4	4	4	4 (2)	2 (2)	5 (5)	119.1	152.4	179.7

sets. Both will be the subjects of forthcoming papers, and the results presented here should be regarded as preliminary.

CONCLUSIONS

(1) Transects of 914 m or longer estimated known densities with greater accuracy and consistency than did 457 m transects.

(2) Between six and nine censuses of 914 m transects were sufficient to minimize random fluctuations in density estimates.

(3) Estimates of rare and abundant species were equally close to known values. However, high coefficients of variation for rare species' estimates reduced the statistical confidence in those estimates.