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A Method for Determining Asymptotes of Home-Range Area Curves

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Home-range area curves are used to estimate the number of locations needed to accurately estimate home range size based on the asymptote of the curve. However, the current methodology used to identify asymptotes for home-range area curves is largely subjective and varies between studies. Our objective was to evaluate the use of exponential, Gompertz, logistic, and reciprocal function models as a means for identifying asymptotes of home-range area curves. We radio monitored northern bobwhite (*Colinus virginianus*) coveys during mid-September through November 2001-2002 in Jim Hogg County, Texas. We calculated home-range size of radiomarked coveys using the 95% fixed kernel with least squares cross validation and minimum convex polygon estimators. We fitted area observations and coefficient of variation to the number of locations using exponential, Gompertz, logistic, and reciprocal function models to estimate the minimum number of locations necessary to obtain a representative home range size for each home range estimator. The various function models consistently provided a relatively good fit for home range area curves and coefficient of variation curves ($0.58 \leq R^2 \leq 0.99$; $P < 0.05$) for both home range estimators. We used an information-theoretic framework (AICC) to select the best model to estimate area-curve asymptotes. The use of function models appears to provide a structured and useful approach for calculating area-curve asymptotes. We propose that researchers consider the use of such models when determining asymptotes for home-range area curves and that more research be conducted to validate the strength of this method.

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Key words: area curves, home range, kernel estimator, minimum convex polygon, northern bobwhite

Introduction

Home-range size, hereafter home-range, is a parameter commonly reported in many radiotelemetry studies (Garton et al. 2001). Home-range is affected by factors such as time elapsed between consecutive locations (Swihart and Slade 1985*a*,*b*), techniques used to collect location data (Adams and Davis 1967), and the number of observations used to obtain the estimate (Stickel 1954, Jennrich and Turner 1969, Bekoff and Mech 1984, Seaman et al. 1999). Several studies have attempted to provide guidelines for calculating home-range by comparing the performance of home range estimators under varying sample sizes (Boulanger and White 1990, Worton 1995, Seaman and Powell 1996, Seaman et al. 1999). However, results have been disparate (Kernohan et al. 2001).

Home-range area curves have been used to estimate the number of locations necessary for estimating home range (Odum and Kuenzler 1955, Bond et al. 2001, Gosselink et al. 2003). A home-range area curve for a species plots the number of independent locations on the x-axis against the estimated home-range size on the y-axis for that particular sample size. From the resulting graph, the number of required locations is denoted when increasing the number of locations does not result in an increasing home range size (i.e., the asymptotes of the graph; Odum and Kuenzler 1955). However, the methodology used to identify asymptotes for home-range area curves is largely subjective and varies between studies. For example, Odum and Kuenzler (1955) defined an asymptote as being the point when additional locations produced <1% change in mean

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home range size, whereas Bond et al. (2001) identified asymptotes through visual inspection. Given this subjective and discordant approach, a more structured methodology is needed to determine the optimum number of locations necessary to produce a representative home range.

The objective of our study was to evaluate the use of exponential, Gompertz, logistic, and reciprocal function models as a means for identifying asymptotes of home-range area curves (i.e., area-curve asymptotes). We used radio locations obtained from radio marked northern bobwhites (*Colinus virginianus*; hereafter bobwhites) to develop home-range area curves and evaluate our proposed methodology.

Study Area

We conducted our radiotelemetry study on a private ranch located 8 km east of Hebbronville, Texas in Jim Hogg County. The study area is contained within the Rio Grande Plains ecoregion (Gould 1975). Topography within the Rio Grande Plains is level to rolling, and the elevation ranges from sea level to 330 m. The Rio Grande Plains is characterized by rangeland, open prairies with a growth of mesquite (*Prosopis glandulosa*), huisache (*Acacia smallii*), granjeno (*Acacia berlandieri*), and Texas pricklypear cactus (*Optuntia lindheimeri*). Annual rainfall ranges from 35 to 66 cm and soils range from clays to sandy loams (Correll and Johnston 1979). Although large acreages of cultivated land exist within the Rio Grande Plains, the predominant land use is livestock production (i.e., rangeland) (Correll and Johnston 1979).

Methods

We trapped bobwhites from mid-August through September 2001 and 2002 using funnel traps baited with milo (Stoddard 1931) and by night netting roosting coveys (Labisky 1968) on 3 pastures (601 ha, 1031 ha, and 1563 ha), each separated by $>$3 km. We banded all captured bobwhites and radiocollared any bobwhite weighing $\geq$150 g. We fitted bobwhites with 6-7 g neck-loop radiotransmitters (American Wildlife Enterprises®, Tallahassee, Florida).

We monitored coveys via radiotelemetry 5 times per week from mid-September through November 2001-2002. We defined this 10-week period as the fall season. We located coveys by homing (White and Garrott 1990) and obtained a global positioning system (GPS) coordinate using a hand-held unit with an accuracy of $\pm$5 m (Garmin 90 GPS). We monitored coveys once or twice a day during 1 of 3 time periods: morning (0700-1000 hrs.), afternoon (1200-1500 hrs.), or evening (1600-1900 hrs.). These time periods corresponded to periods of biological activity for bobwhites in southern Texas (i.e., morning feeding, afternoon loafing, and evening feeding, respectively). If 2 locations were taken during the same day for 1 covey, then one location was taken during a loafing period and the other during a feeding period to obtain independent locations. However, if 2 locations were taken during the same day for a specific covey the next location taken for that covey was not taken until 2 days later. For example, if locations were taken on the loafing and evening-feeding period for 1 covey on Monday, then the next location was not taken for the same covey until Wednesday. We followed this procedure in order that covey location is not recorded on the same feeding or loafing site due to temporal autocorrelation of location data.

We calculated home range size of radiomarked coveys using the 95% fixed kernel (Worton 1989) with the least squares cross validation (LSCV) smoothing parameter, and minimum convex polygon (Mohr 1947) home range estimators within the animal movement extension (Hooge and Eichenlaub 1997) of the program ArcView 3.2 (Environmental Systems Research Institute, Inc., Redlands, CA.). We chose to use the kernel home range estimator recommended by Kernohan et al. (2001) because it has the ability to compute home range boundaries that included multiple centers of activity, lacks sensitivity to outliers, is based on complete utilization distribution, and is a nonparametric methodology. We selected the fixed kernel with LSCV because it has lower bias and better surface fit than adaptive kernel

Table 1: Mean home range size (ha), standard error, and coefficient of variation of northern bobwhite coveys over 7 location intervals using the 95% fixed kernel estimator with least squares cross validation (LSCV) smoothing parameter, and minimum convex polygon home range estimator, Jim Hogg County, Texas, USA, Sep-Nov, 2001-2003.

				95% Fixed Kernel (LSCV)			Minimum Convex Polygon		
Year	Location Interval	n[a]	N[b]	Mean	S.E.	CV[c]	Mean	S.E.	CV
2001	Monthly	3	14	20.69	4.55	1.22	1.05	1.02	0.94
	Biweekly	6	14	16.08	4.01	1.01	4.51	2.12	1.17
	Weekly	11	14	17.23	4.15	0.54	8.73	2.95	0.64
	2× Week	20	14	15.32	3.91	0.43	11.06	3.33	0.67
	3× Week	30	14	15.96	3.99	0.36	14.04	3.75	0.5
	4× Week	40	14	15.1	3.89	0.34	14.6	3.82	0.49
	5× Week	50	14	15.02	3.88	0.36	15.6	3.95	0.46
2002	Monthly	3	20	22.84	4.78	0.76	1.42	1.19	1.03
	Biweekly	6	20	11.18	3.34	0.74	2.74	1.66	0.53
	Weekly	11	20	11.34	3.37	0.52	4.69	2.17	0.4
	2× Week	20	20	10.27	3.20	0.42	6.04	2.46	0.29
	3× Week	30	20	11.06	3.33	0.41	8.23	2.87	0.34
	4× Week	40	20	11.34	3.37	0.39	9.45	3.07	0.31
	5× Week	50	20	12.06	3.47	0.41	10.93	3.31	0.3

[a]Number of locations

[b]Number of bobwhite coveys observed

[c]Coefficient of variation

with LSCV for a selected bandwidth (Seaman and Powell 1996, Seaman et al. 1999). We also chose minimum convex polygon because we wanted to assess this commonly used estimator (Seaman et al. 1999).

We developed home-range area curves following a protocol similar to Odum and Kuenzler (1955). We consistently obtained 5 covey locations a week. Based on this schedule we developed separate location intervals to find the minimal number of locations needed to estimate bobwhite home-range size during the fall season. Intervals consisted of 1 location/month, 1 location every other week, 1 location/week, 2 locations/week, 3 locations/week, 4 locations/week, and 5 locations/week, respectively. We calculated mean, standard error, and coefficient of variation (CV) for all covey home range estimates for each location interval. From this data, we then developed home-range area curves (i.e., hereafter area curves) and CV curves for each estimator by year.

Odum and Kuenzler (1955) defined the asymptote as the first location interval at which any additional locations produced <1% change in mean home range size indicating a point of diminishing return. In an attempt to provide a more objective identification of the asymptote, we fitted mean home range size and CV to the number of locations using a exponential, Gompertz, logistic, and reciprocal function models and used an information-theoretic framework (AICC) score to select the best model (lowest AICC; Burnham and Anderson 1998). We used the SAS procedure NLMIXED to run all mod-

Table 2: Model parameters resulting from fitting means of home range size (ha) of northern bobwhite coveys to the number of locations using 4 separate function models. Home ranges were calculated using the 95% fixed kernel least squares cross validation (LSCV) smoothing parameter and minimum convex polygon home range estimators, Jim Hogg County, Texas, USA, Sep-Nov, 2001-2003.

Year *Estimator* Model	Function	Model parameters a	b	C	Asymptote Estimate (ha)	SE	-1SE	$+1$SE	AIC_C	ΔAIC_C	R^2
2001											
Fixed-Kernel											
Reciprocal	$f(x) = a + \frac{b}{x}$	14.8	15.90	NA	14.8	0.38	14.5	15.2	29.1	0.0	0.85
Exponential	$f(x) = C + a * e^{(-b*x)}$	-53.0	0.80	15.7	15.7	0.32	15.4	16.0	42.7	13.6	0.86
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	7.7	0.95	15.7	15.7	0.32	15.4	16.0	42.7	13.6	0.86
Gompertz	$f(x) = 2C - C * e^{(-e^{(a-b*x)})}$	109.3	36.76	15.7	15.7	0.29	15.4	16.0	43.0	13.9	0.85
MCP											
Exponential	$f(x) = C + a * e^{(-b*x)}$	18.1	0.08	15.6	15.6	0.46	15.1	16.1	37.0	0.0	0.99
Reciprocal	$f(x) = a + \frac{b}{x}$	14.6	-45.67	NA	14.6	1.04	13.6	15.6	41.0	4.0	0.89
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	7.6	0.18	14.8	14.8	0.77	14.0	15.6	48.3	11.3	0.96
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	8.3	0.82	13.8	13.8	1.08	12.7	14.9	58.7	21.7	0.82
2002											
Fixed-Kernel											
Exponential	$f(x) = C + a * e^{(-b*x)}$	7.9	2.94	11.2	11.2	0.12	11.1	11.3	37.8	0.0	0.99
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	4.6	7.49	11.3	11.3	0.16	11.1	11.4	38.2	0.4	0.99
Gompertz	$f(x) = 2C - C * e^{(-e^{(a-b*x)})}$	27.0	6.51	11.3	11.3	0.16	11.1	11.5	38.2	0.4	0.99
Reciprocal	$f(x) = a + \frac{b}{x}$	9.4	34.12	NA	9.4	1.04	8.3	10.4	43.3	5.5	0.77
MCP											
Exponential	$f(x) = C + a * e^{(-b*x)}$	13.5	0.03	14.0	14.0	1.46	12.6	15.5	30.0	0.0	0.99
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	0.8	0.06	11.8	11.8	0.89	10.9	12.7	35.0	5.0	0.99
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	5.3	0.09	11.1	11.1	0.74	10.3	11.8	37.8	7.8	0.98
Reciprocal	$f(x) = a + \frac{b}{x}$	9.0	-26.81	NA	9.0	0.86	8.1	9.8	40.7	10.7	0.75

Table 3: Model parameters resulting from fitting coefficients of variation (CV) of home range size of northern bobwhite coveys to the number of locations using 4 separate function models. Home ranges were calculated using the 95% fixed kernel least squares cross validation (LSCV) smoothing parameter and minimum convex polygon home range estimators, Jim Hogg County, Texas, USA, Sep-Nov, 2001-2003.

Year *Estimator*		Model parameters			Asymptote						
Model	Function	a	b	C	Estimate (ha)	SE	-1SE	$+1$SE	AIC_C	ΔAIC_C	R-square
2001 *Fixed-Kernel*											
Reciprocal	$f(x) = a + \frac{b}{x}$	0.3	3.05	NA	0.3	0.05	0.25	0.34	-0.1	0	0.93
Exponential	$f(x) = C + a * e^{(-b*x)}$	1.43	0.15	0.34	0.34	0.03	0.32	0.37	4.8	4.9	0.98
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	-0.88	-0.04	0.28	0.28	0.06	0.22	0.34	8.8	8.9	0.97
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	17.67	1.82	0.5	0.5	0.04	0.46	0.53	19.4	19.5	0.84
MCP											
Reciprocal	$f(x) = a + \frac{b}{x}$	0.52	0.71	NA	0.52	0.08	0.43	0.6	8.1	0	0.58
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	6.57	0.72	0.53	0.53	0.02	0.5	0.55	13.4	5.3	0.88
Exponential	$f(x) = C + a * e^{(-b*x)}$	0.76	0.07	0.43	0.43	0.13	0.3	0.56	17.3	9.2	0.79
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	-0.79	-0.01	0.24	0.24	0.4	-0.16	0.64	17.6	9.5	0.78
2002 *Fixed-Kernel*											
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	2.52	0.31	0.39	0.39	0.01	0.39	0.4	-11.6	0	0.99
Reciprocal	$f(x) = a + \frac{b}{x}$	0.39	1.31	NA	0.39	0.03	0.36	0.42	-5.7	5.9	0.85
Exponential	$f(x) = C + a * e^{(-b*x)}$	0.58	0.12	0.39	0.39	0.02	0.37	0.41	-0.3	11.3	0.96
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	-0.64	-0.06	0.37	0.37	0.03	0.34	0.41	1.8	13.4	0.94
MCP											
Reciprocal	$f(x) = a + \frac{b}{x}$	0.22	2.29	NA	0.22	0.02	0.2	0.25	-10.0	0	0.97
Logistic	$f(x) = C/(1 + a * e^{(b*x)})$	-1.15	-0.17	0.31	0.31	0.01	0.3	0.32	-9.0	1	0.99
Exponential	$f(x) = C + a * e^{(-b*x)}$	2.16	0.37	0.32	0.32	0.01	0.31	0.33	-4.2	5.8	0.99
Gompertz	$f(x) = C * e^{(-e^{(a-b*x)})}$	17.02	3.02	0.41	0.41	0.04	0.37	0.45	16.9	26.9	0.80

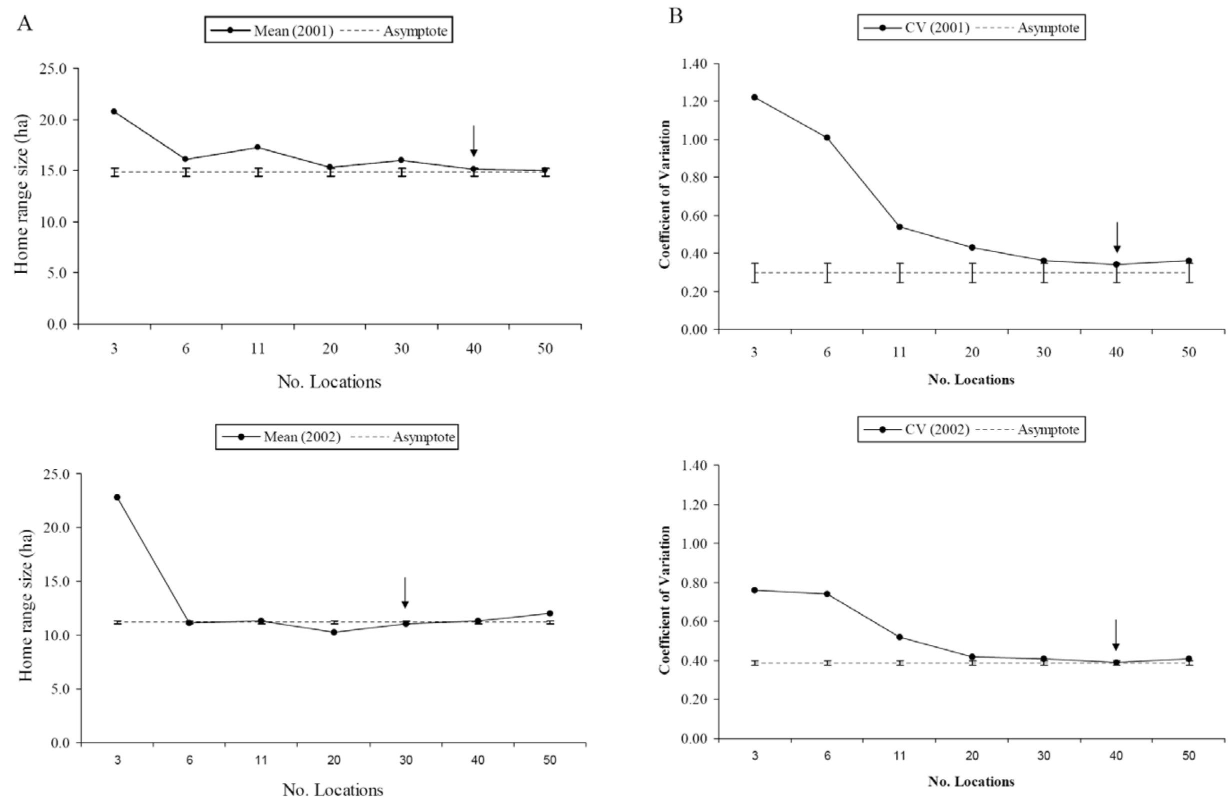

Figure 1: Asymptotes for A) mean home range size of northern bobwhite coveys calculated using 95% fixed kernel (n = 14 coveys in 2001 and n = 20 coveys in 2002) and B) coefficients of variation (CV). Asymptotes were determined by modeling mean home range size or CV as exponential, Gompertz, logistic, and reciprocal functions of the number of locations (no. locations) and then identifying the best model based on an information-theoretic framework (AIC_C). Arrows denote first observed value to fall within 1 standard error of the estimated asymptote.

els (SAS Institute, Inc. 2002-2004).

We used the asymptote obtained for the best model to estimate the minimum number of locations necessary to obtain a representative home range size for each home range estimator by year. We defined this to be the minimum number of locations when an observed point first fell within ± 1 standard error of the estimated asymptote.

Results

We monitored 14 coveys in 2001 and 20 coveys in 2002 (Table 1) with an average of 2 to 3 birds in a covey. All function models provided a relatively good fit ($0.58 \leq R^2 \leq 0.99$; $P < 0.05$) for area curves and CV curves for both home range estimators (Table 2, 3).

Using the 95% fixed kernel estimator, AICC scores were the lowest for the reciprocal model in 2001 with an asymptote estimate of 14.8 $\pm$ 0.38 (ha) and scores were lowest for the exponential model in 2002 with an asymptote estimate of 11.2 $\pm$ 0.12 (ha) for mean home range size (Table 2). Based on these estimates we determined that $\geq$40 locations were required to estimate home range size in 2001, whereas $\geq$30 locations were sufficient in 2002 (Figure 1). For the CV, AICC scores were lowest for the reciprocal model in 2001 with an asymptote estimate of 0.30 $\pm$ 0.05 and scores were lowest for the Gompertz model in 2002 with an asymptote 0.39 $\pm$ 0.01 (Table 3). Based on these estimates we determined

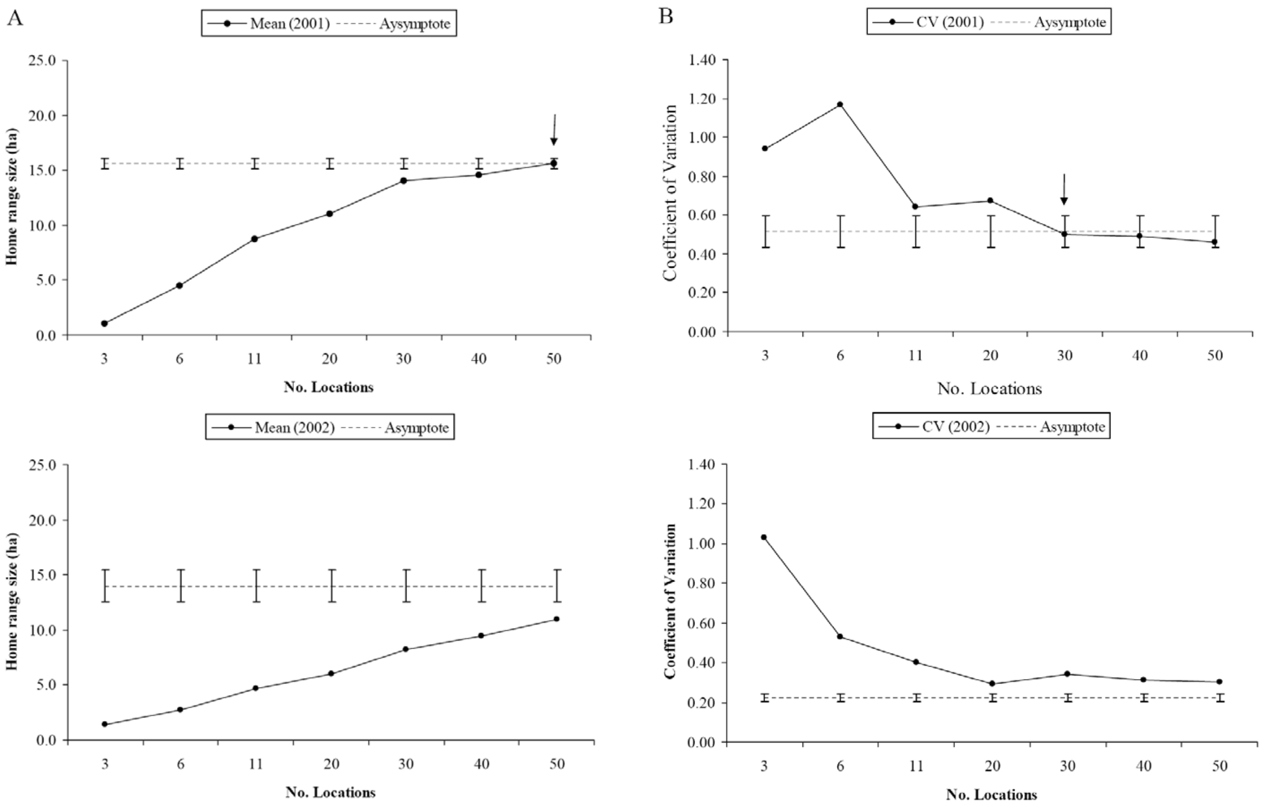

Figure 2: Asymptotes for A) mean home range size of northern bobwhite coveys calculated using minimum convex polygon (n = 14 coveys in 2001 and n = 20 coveys in 2002) and B) coefficients of variation (CV). Asymptotes were determined by modeling mean home range size or CV as exponential, Gompertz, logistic, and reciprocal functions of the number of locations (no. locations) and then identifying the best model based on an information-theoretic framework (AIC_C). Arrows denote first observed value to fall within 1 standard error of the estimated asymptote.

that ≥40 locations were required to minimize variation in home range estimation in both 2001 and 2002 (Figure 1).

Using minimum convex polygon, AICC scores in 2001 were lowest for the exponential model with an asymptote estimate of 15.6 ± 0.46 (ha) for mean home range size and AICC scores were lowest for the reciprocal model with an asymptote estimate of 0.52 ± 0.08 for the CV in 2001 (Table 2, 3). Based on these estimates we determined that ≥50 locations were required to estimate mean home range size while ≥30 locations were required to minimize variation in home range estimation (Figure 2). The AICC scores in 2002 were lowest for the exponential model with an asymptote estimate of 14.0 ± 1.46 (ha) for mean home range size and scores were lowest for the reciprocal model with an asymptote estimate of 0.22 ± 0.02 for the CV (Table 2, 3). Based on these estimates we determined that an asymptote could not be reached because actual home range size and the CV did not come within ±1 SE of the estimated asymptote calculated by the models selected by the AICC (Figure 2). Thus, there were not enough locations to estimate home range size using minimum convex polygon in 2002.

Discussion

Based on our modeling simulations we found that ≥40 locations were adequate to reach an asymptote for home range area estimation using the 95%

fixed kernel estimator for our sample of bobwhite coveys during the fall season. Our estimate using field data is similar to Seaman et al. (1999) who reported that bias and variance for the kernel estimator approached an asymptote at 50 locations using computer simulation points. They recommended using a minimum $\geq$30 locations to obtain home range estimates when using kernel estimators with LSCV, but preferably $\geq$50.

Regarding the minimum convex polygon, we documented that in 2001 $\geq$50 locations were necessary to obtain a representative home range estimate for our sample of bobwhite coveys. However, in 2002 an area-curve asymptote was not reached to obtain a representative home range. Home range estimates from the minimum convex polygon estimators continued to increase with increasing locations (a property of this estimator), though this increase was minimal in 2001. However, CV's remained relatively constant. This observation can occur because CV's are a ratio of mean:standard deviation. Therefore, similar CV's can result in spite of increasing means if their corresponding standard deviations also increase in similar proportion. Previous research has suggested a much larger number of locations (100-200) to estimate home range size using the minimum convex polygon (Bekoff and Mech 1984, Laundre and Keller 1981, Harris et al. 1990). Gautestad and Mysterud (1995) believed that asymptotes using the minimal convex polygon method would only occur when using more than several thousand locations.

Kernohan et al. (2001) evaluated 12 home range estimators, including the estimators used in this study. Overall, Kernohan et al. (2001) favored the kernel home range estimator because it required a reasonable sample size ($\geq$50 location points), had the ability to compute home range boundaries that included multiple centers of activity, was based on complete utilization distribution, was a nonparametric methodology, and lacked sensitivity to outliers. However, kernel estimators have no real comparability to other home range estimators due to its estimate being greatly affected by bandwidth choice. Minimum convex polygon also is a nonparametric home range estimator, but unlike the kernel estimator it is not impacted by bandwidth choice and can be compared to other estimators. However, the minimum convex polygon estimator requires a large sample size (i.e., $>$100 locations total), does not use utilization distribution, does not account for outliers, and does not calculate multiple centers of activity (Kernohan et al. 2001, p. 140).

Regardless of the estimator used, we recommend that verification is needed showing that an area-curve asymptote had been reached prior to home range estimation. However, identifying the asymptotes for home-range area curves has been difficult because it generally has involved much subjectivity. Previous studies identified asymptotes through visual inspection (e.g., Bond et al. 2001) or when additional locations produced $<$1% change in mean home range size (Odum and Kuenzler 1955). We estimated asymptotes by modeling mean home range or CV as a model function of number of locations. We identified the minimum number of locations when the first point fell within $\pm$1 SE of the estimated asymptote. We found that function models provided a relatively good fit for our data ($0.58 \leq R^2 \leq 0.99$) and provided a structured and useful approach for calculating area-curve asymptotes. Therefore, we recommend fitting mean home range size and CV to the number of locations using function models and an AICC score to select the best model in identifying area-curve asymptotes.

This manuscript presents a robust quantitative approach to calculating area-curve asymptotes. However, we recommend that this method be used to validate estimates of area-curve asymptotes that are based on visual inspection or the point at which there is a $<$1% change in mean home range size (Odum and Kuenzler 1955). In addition, we recommend more research be conducted to validate the strength of this method.

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