Tools and Technology Article

A Critical Review of Home Range Studies

PETER N. LAVER, *Mogalakwena Research Centre, P.O. Box 60, Alldays, 0909, South Africa*

MARCELLA J. KELLY,[1] *Department of Fisheries and Wildlife, 210B Cheatham Hall, Virginia Polytechnic and State University, Blacksburg, VA 24061-0321, USA*

ABSTRACT No consensus currently exists for the methods of estimation of home range size or for reporting home-range analysis results. Studies currently employ a variety of disparate methods or provide inadequate information for reproducing their analyses. We reviewed 161 home range studies published in 2004, 2005, and 2006 to assess what methods are currently employed and how results are reported. We found that home range reporting was generally inadequate for reproducing studies; that the methods employed varied considerably; that home range estimates were often reported and analyzed using inappropriate methods; and that many comparisons were made between studies that may produce spurious results. We urge for minimum editorial standards for reporting home range studies and we urge researchers to follow a unified methodology for estimating animal home ranges. We supply recommendations for such reporting and methodology. These recommendations will increase the reproducibility of studies and allow for more robust comparisons between studies. (JOURNAL OF WILDLIFE MANAGEMENT 72(1):290–298; 2008)

DOI: 10.2193/2005-589

KEY WORDS asymptote, core, estimators, home range, kernel density, methodology, reporting, software.

While informal home-range estimation has existed for some time, the home range as a formal concept (Seton 1909, Burt 1943) has had a relatively short and tempestuous published lifespan. Several authors have reviewed methods of home range estimation (Hayne 1949, Stickel 1954, van Winkle 1975, Worton 1987, Harris et al. 1990) and home range software (Larkin and Halkin 1994, Lawson and Rodgers 1997, Seaman et al. 1998, Larson 2001, Horne and Garton 2006). Worton (1987) provided a historical review of the development of home range estimators and compared the properties of several estimators. Since Worton (1987) and Harris et al. (1990), many studies have also made descriptive or statistical comparison of home range estimators and their various implementations. Most of these results have been summarized by the reviews of Powell (2000) and Kernohan et al. (2001). Harris et al. (1990) provided the only synthetic review of home range studies published in peer-reviewed journals (over 4 yr from 1984 to 1988) and they found that most studies were on mammals and used minimum convex polygon (MCP) home range estimation. Harris et al. (1990) provided recommendations for improved data collection and analysis but they focused largely on data collection, and they reviewed only studies which employed radiotelemetry. In the interim there have been extensive developments in the field of home range estimation and important issues in performing robust home range estimation have emerged. We reviewed recent home-range studies based on newer criteria such as the analysis of whether data collection has been adequate, the reporting of estimators, and the implementation of advances in estimators. One of the recent advances in estimators, kernel density estimation (KDE), has become prevalent and it requires several choices regarding the parameters used; thus, much of our review was focused on this subject.

Adequate data collection has been a contentious issue with reference to serial autocorrelation (Swihart and Slade 1985*a*, Hansteen et al. 1997, Otis and White 1999, Blundell et al. 2001, Fieberg 2007), site fidelity (Spencer et al. 1990, Swihart and Slade 1997), and number of location estimates per animal (Stickel 1954, Bekoff and Mech 1984, Hansteen et al. 1997, Seaman et al. 1999, Börger et al. 2006). Sensitivity of home range size to the number of location estimates has even led Gautestad and Mysterud (1993) to raise questions about the validity of the asymptotic home-range concept. Another contentious issue has been the delineation of home range boundaries for MCP and associated point-peeling techniques (Robertson et al. 1998). Methods for delineating the core areas of probabilistic home-range models are relatively well-described (Samuel et al. 1985, Samuel and Green 1988, Seaman and Powell 1990).

A great body of literature makes empirical or simulated comparisons of home range estimators and these studies include Boulanger and White (1990), Worton (1995), Robertson et al. (1998), and Kenward et al. (2001). Of these estimators, KDE has been the most influential since its introduction into home range studies by Worton (1989*a*). Kernel density estimation presents a problem for consistency amongst studies because it has a multitude of possible implementations. Many studies from both the statistical and ecological literature have made suggestions for the optimal implementation of KDE. For instance, Bowman (1985) and Silverman (1986) reviewed the type of smoothing (fixed or adaptive) and the method of bandwidth selection, and they reported both issues as highly influential in KDE estimates. Worton (1989*a*, *b*) recommended adaptive over fixed smoothing, but conceded that this choice had far less influence on estimates than the method of bandwidth selection (Worton 1995). Worton (1989*a*) recommended least-squares cross-validation (LSCV) for bandwidth selection (or some multiple thereof; Worton 1995) as did Seaman and Powell (1996) and Börger et al. (2006; but see Hemson et al. 2005, Horne and Garton 2006). Gitzen and Millspaugh (2003) showed that the

[1] *E-mail: makelly2@vt.edu*

LSCV search function employed had little influence on KDE estimates (but see Horne and Garton 2006). Jones et al. (1996) recommended the solve-the-equation and plug-in method for bandwidth selection. Rodgers and Carr (1998) recommended standardizing or scaling the location data before applying KDE, and Gitzen and Millspaugh (2003) showed that the method of standardization had little influence on KDE estimates. Worton (1989*a*) showed that kernel shape or distribution had little influence on KDE estimates, (e.g., bivariate normal kernel, Epanechnikov kernel [Epanechnikov 1969], or bi-weight kernel [Seaman and Powell 1996]). Rodgers and Carr (1998) recommended using volume contouring of the utilization distribution and Worton (1989*a*) and Fieberg (2007) suggested that the 95% contour was commonly used.

The myriad of options available for home range analysis each place certain requirements on data collection and similarly they impose limitations on the analysis and comparison of existing datasets. Our objectives were 1) to present a review of recent published studies that used home range estimation (with the review focused on analysis and reporting rather than on data collection); 2) to ascertain whether recent home-range analysis advances were being implemented in studies; 3) to summarize common pitfalls of home range estimation; and 4) to recommend unified approaches to home range estimation.

STUDY AREA

We reviewed journal articles related to animal home range studies. A multitude of terrestrial and aquatic study sites was used in these 161 articles pertaining to species from the classes Mammalia, Aves, Reptilia, Amphibia, Pisces, or from Phylum Arthropoda. For details on the species and the study sites, please refer to the original literature listed by the authors upon request.

METHODS

We searched for peer-reviewed journal articles containing the phrase 'home range' in the title for the years 2006, 2005, and 2004 using the Institute for Scientific Information (ISI) Web of Science. We used 9 general criteria (Table 1) related to the methods of home range estimation and reporting to meet our objectives. We applied 62 detailed criteria (Appendix) for which we assessed studies with either a binary response (yes, no) or listed a specific method. We report only summary statistics about the number and proportion of studies for which a criterion was met. The list of the literature reviewed is available from the authors upon request.

We assumed that ISI was an unbiased search engine and that the years we reviewed provided an unbiased sample of current home range studies. We assumed that authors would publish the methods and results of home range studies using the word "range" in the title (i.e., our search filter, above). We used the words or phrases "range," "annual range," "seasonal range," "yearly range," "winter range," "summer range," and "home range," and selected the relevant articles from this search. The following caveats apply to our study: we reviewed only articles published in peer-reviewed journals in English and we reviewed only studies yielded by our ISI search (above); hence, we cannot rule out the possibility of unknown bias. Nonetheless, we hope that this review will encourage critical thought and discussion on the subject.

RESULTS

Our searches for other words or phrases in published titles over the same time period revealed 7,840 results for range (with an unknown no. of relevant articles), zero results each for yearly range and yearly ranges, 4 results (1 relevant) for annual range, and zero results for annual ranges. There was 1 result each for seasonal range and seasonal ranges (both articles were relevant). There were 5 results for winter range (2 relevant), 1 result for winter ranges, 4 results for summer range, and 1 result for summer ranges (relevant). Using home range provided 180 hits and from these we collected data from 161 peer-reviewed studies published with home range in the title in 2004, 2005, and 2006. We omitted 20 studies which were not applicable to our review (for lack of reporting or using home range estimates).

Of the remaining 141 studies reviewed from 73 journals, 47, 57, and 37 were published in 2006, 2005, and 2004, respectively. Most journals contained only 1 ($n = 44$) or 2 ($n = 18$) home range studies. The 3 journals with the most studies were *Wildlife Research* ($n = 13$), *Journal of Zoology* ($n = 12$), and *Journal of Mammalogy* ($n = 9$). Most studies ($n = 78$) were on species in Class Mammalia, followed by Aves ($n = 35$), Reptilia ($n = 13$), Pisces ($n = 12$), Phylum Arthropoda ($n = 2$), and Class Amphibia ($n = 1$). Half the studies ($n = 67$) compared their home range estimates to those of other studies in their discussion sections.

Most studies used radiotelemetry to collect location estimates ($n = 105$; Table 2). Few studies addressed serial autocorrelation in location data ($n = 7$), or site fidelity of animals ($n = 11$; Table 2). Few studies addressed home range sensitivity to number of location estimates ($n = 57$) and the methods of assessment were varied, infrequently reported, and often subjective (Table 3). Most studies either used very few location estimates per animal for home-range estimation ($n = 80$), or failed to report sample sizes ($n = 43$; Table 4). Though most studies reported home range estimate results using a mean ($n = 106$) and standard deviation or standard error ($n = 91$), most studies that assessed distribution reported deviations from the assumptions of normality ($n = 21$; Table 4). More than half the studies, either through transforming home range estimates ($n = 26$), or through using nonparametric statistics ($n = 31$), implicitly reported nonnormal distribution of home range estimates (Table 4). Most studies employed MCP ($n = 96$), KDE ($n = 84$), or both ($n = 51$) for estimating home range size (Table 5). Several studies employing MCP cited comparison with other studies as a reason for its use ($n = 38$), and the implementation of this estimator was varied (Table 5). There were 9 criteria required to faithfully

Table 1. General criteria used in the review of home range studies published 2004–2006.

Criterion
1. Did the study report or use the results of home range estimation?
2. Yr of publication, journal, taxonomic group of the study animals.
3. Method of collection of location data.
4. How was serial autocorrelation of location data addressed?
5. How was site fidelity of animals addressed?
6. How did the study address home range sensitivity to no. of location estimates?
7. How did the study report home range estimates: no. of animals, no. of location estimates, central tendency, dispersion, distribution of data, methods of analysis?
8. What estimators were used and how were the estimators implemented?
9. What software packages were used for home range estimation?

reproduce KDE studies, for which the reporting of methods was infrequent (Tables 6 and 7). The methods employed were varied, but the most common implementation of KDE was fixed smoothing using least-squares cross-validation, and with home range and core range areas delineated at user-defined 95% and 50% contours, respectively (Tables 6 and 7). Authors used 19 software packages, but only 3 packages were used frequently (Table 8).

DISCUSSION

Our results showed that despite several recent advances in home range estimation and admonitions for improved reporting thereof, these standards were not reflected in current studies. Although some of the advances and admonitions were published during or after the period under review (and the lack of adoption thereof is understandable), most were published before the start of the review period. Studies currently exhibit a wide variety of home range implementations which render most inter-study comparisons tenuous. In addition, many of these implementations were inadequate or inappropriate. Fortunately, the shortfalls might often be remedied with the correct application of basic statistics and consideration of representative sampling.

Table 2. Criteria for collecting and assessing animal location estimates for home range estimation reported in 141 studies published 2004–2006.

Criterion	Studies[a]	%
Data-collection methods		
Radiotelemetry	105	74
Visual mapping	19	13
Acoustic or ultrasonic telemetry	7	5
Trapping grids	6	4
Global Positioning System collars	3	2
Trailing devices	1	1
Not reported	4	3
Serial autocorrelation		
Tested	7	5
Reduced with sampling strategy	48	34
Not reported	90	64
Site fidelity		
Tested	11	8
Not reported	130	92

[a] Values will not always sum to the total of 141 because some studies employed a combination of methods and criteria.

Table 3. Criteria for assessing the sensitivity of home range estimates to the number of location estimates reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
Assessed sensitivity	57	141	40
Not reported	84	141	60
Methods for assessing sensitivity			
Area-observation plots	40	57	70
Correlation or regression	15	57	26
Not reported	5	57	9
Area-observation plots—implementation			
Tested each animal	25	40	63
Tested subset, applied cut-off	8	40	20
Not reported	8	40	20
Min. convex polygon	31	40	78
Kernel density estimation	9	40	23
Delineated an asymptote	37	40	93
Reported % area reached at *n* fixes	3	40	8
Reported min. fixes required	23	40	58
Asymptote delineation			
Visual inspection	11	37	30
At % total home range area			
95%	1	37	3
90%	2	37	5
80%	1	37	3
Area increment <5% of total area	3	37	8
Not reported	18	37	49

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.

In terms of the latter, we considered our review to be representative of current studies using home range analysis. Using 'home range' in our search excluded only 6 relevant studies for which a subset of home range (i.e., a seasonal home range) was analyzed. We did not use a key word search but rather a title search and, therefore, concede that we may have missed an unknown number of articles for which home range (or a subset thereof) was not explicitly mentioned in the article title. In addition, some journals encouraged authors to use terms other than 'home range' for studies in which the sampling period for each individual was shorter than the individual's lifetime. This suggests that our review may have missed some relevant studies. Nonetheless, our review was a representative sample in terms of both number of studies and breadth of journals.

The high number of journals publishing home range studies introduced the potential for inconsistency in methods and in reporting—as borne out in our results. We recommend that journals establish basic guidelines for reporting home range studies and home range estimates in much the same way as guidelines are provided for reporting statistical analyses and results (i.e., Messmer and Morrison 2006).

The prevalence of mammalian and ornithological home-range studies was probably an artifact of issues such as the popularity of these taxa for ecological study, the long tradition of these studies in the literature, the relative ease of

Table 4. Criteria for reporting and analyzing the results of home range estimation reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
No. of animals			
Reported	122	141	87
Not reported	19	141	13
Mean or min. no. of location estimates			
0–49	80	141	57
50–99	11	141	8
100–149	6	141	4
150–199	0	141	0
>200	4	141	3
Not reported	43	141	30
Central tendency of home range estimates			
$\bar{x}$	106	141	75
Median	14	141	10
Not reported	25	141	18
Dispersion of home range estimates			
SD or SE	91	141	65
Range	82	141	58
Box plots or interquartile range	3	141	2
Not reported	19	141	13
Distribution of home range estimates			
Normal	3	141	2
Nonnormal	21	141	15
Not reported explicitly	117	141	83
Analysis of home range estimates			
Parametric statistics	78	100	78
Nonparametric statistics	31	100	31
Transformed home-range estimates for analysis			
Logarithm	23	100	23
Other	3	100	3

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.

Table 5. Criteria for estimating home range size reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
Home range estimators			
No. of estimators employed			
1	74	141	52
2	58	141	41
3 or 4	9	141	6
MCP[b]	96	141	68
MCP[b] only	34	141	24
KDE[c]	84	141	60
KDE[c] only	29	141	21
MCP[b] and KDE[c]	51	141	36
Harmonic mean	10	141	7
Linear home range	7	141	5
Grid cell count	6	141	4
Bivariate normal ellipse	2	141	1
Other	12	141	9
MCP[b] criteria			
Reason for use: comparison	38	96	40
% location estimates included			
100%	57	96	59
95%	28	96	29
Other	10	96	10
Not reported	17	96	18
Linear home range			
Total distance	4	7	57
Univariate kernel	1	7	14
% location estimates included	2	7	29

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.
[b] Min. convex polygon.
[c] Kernel density estimation.

detection of the species, and because of available technology (techniques and equipment; e.g., radiotelemetry). Future studies could focus on the other taxa for which there is great scope for innovation. Given the economic importance of Class Insecta (as pests, pollinators, disease vectors, etc.), this group may yield future funding opportunities. We also found much potential for an improvement upon volumetric considerations of home range, or 'home-volume' theory, as well as further development of home range theory to incorporate the dimension of time, and eventually, time–volume considerations (but see Garshelis [2000] for commentary on time and habitat-use). Only 2 studies we reviewed assessed home range and height (Rader and Krockenberger 2006) or home range and time (Katajisto and Moilanen 2006).

Serial autocorrelation and asymptote analyses should be linked in home range studies, yet less than half of the studies that addressed serial autocorrelation also addressed home range asymptotes. The key consideration was whether an animal's behavior had been adequately represented over a specific temporal scale (Swihart and Slade 1985*b*, Swihart and Slade 1997, Fieberg 2007). For a given sampling period, serial autocorrelation results in a trade-off between the quantity of unique (independent) information per location estimate and the number of location estimates (Swihart and Slade 1985*a*). Using sampling intervals that satisfy Time to Statistical Independence (TTSI; Swihart et al. 1988) or Time to Biological Independence (TTBI; Lair 1987), without addressing asymptotic requirements, or alternatively, satisfying asymptotic requirements without addressing adequate representation over the temporal scale, could both lead to biased home-range estimates. Tests for site fidelity have value in understanding the spatial ecology and sociality of a population, and are also important for delineating appropriate temporal scales for analysis and for their influence on TTSI (Spencer et al. 1990, Swihart and Slade 1997). We encourage authors to report estimates of TTSI and TTBI to guide the design of future sampling strategies and to perform analyses of site fidelity using mean squared distance from the center of activity (Calhoun and Casby 1958) and linearity index (Bell and Kramer 1979) following Spencer et al. (1990).

We also encourage a shift in the manner home range asymptotes are currently utilized. Many studies used the minimum number of location estimates reported in the literature (for a species or a home range estimator) as the cut-off value for their analyses. The existence of home range asymptotes has been questioned (Gautestad and Mysterud 1993, 1995), though this may be an artifact of using MCP

Table 6. Criteria for estimating home range size using kernel density estimation (KDE) reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
Smoothing			
Fixed	53	84	63
Adaptive	18	84	21
Not reported	14	84	17
Bandwidth selection			
User-defined	9	84	11
Automated selection	38	84	45
Not reported	40	84	48
Automated bandwidth selection			
Least-squares cross-validation	33	37	89
Reference	2	37	5
Ad hoc	2	37	5
Plug-in	1	37	3
Biased cross-validation	1	37	3
Not reported	1	37	3
Kernel			
Bivariate normal	5	84	6
Core weighting	1	84	1
Not reported	78	84	93
Grid resolution			
User-defined	2	84	2
Software default or automated	4	84	5
Not reported	78	84	93
Standardization or scaling			
Separate X Y bandwidths	1	84	1
Not reported	83	84	99

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.

Table 7. Criteria for delineating home ranges using kernel density estimation (KDE) reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
Utilization distribution contours			
Vol	3	84	4
Density	3	84	4
% location estimates included	12	84	14
CI	2	84	2
% time spent in area	1	84	1
Probability contours	2	84	2
Not reported	61	84	73
Contour value			
95%	69	84	82
Other	19	84	23
Not reported	10	84	12
Core areas			
User-defined	37	84	44
50%	33	37	89
Other	4	37	11
Objective methods	9	84	11
P of use vs. area	3	9	33
% area vs. scaled *P* of use	3	9	33
Fixes vs. area	1	9	11
P of use vs. no. of cores	1	9	11
Utilization plots	1	9	11
Objective methods			
Calculated for each animal	2	9	22
Mean contour from subset	5	9	56
Not reported	3	9	33

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.

asymptote analyses (Laver 2005); thus, we recommend using KDE for asymptote analyses. Only 9 of 141 studies reported results from KDE asymptote analyses. Kernel density estimation sensitivity to number of location estimates has been shown through a range of values (Seaman et al. 1999, Hemson et al. 2005, Börger et al. 2006). Recommended minimum sample sizes should, therefore, be used to guide sampling strategy and not as an egalitarian cut-off. Individual behavioral differences also result in great intra-population variability in asymptote analyses, and these analyses should, therefore, be applied on an individual basis and not at the level of the study population. Only 25 studies we reviewed used area-observation plots (MCP or KDE) for each animal. An additional point of contention was the method for assessing where an asymptote is approached. Most studies either used visual inspection (eyeball technique) or did not report their methods. There is currently no consensus on an objective method for this. We suggest using the number of location estimates at which the 95% confidence interval of the bootstrapped home-range estimate is within a specified percentage (i.e., 5–10%) of the total home-range size (using all location estimates) for at least *n* (i.e., 5) consecutive location estimates or for a specified percentage of the total number of location estimates (Laver 2005). We recommend that future studies do not use correlation or regression to assess home range sensitivity to number of location estimates, but do use (KDE) area-observation plots applied to each animal with the appropriate bootstrapping (Harris et al. 1990), and with results reported as the range of values at which an asymptote was approached. Researchers should report home range estimates only for animals for which the home range approached an asymptote. Reporting estimates for home ranges that do not approach an asymptote may encourage dubious comparisons.

The problems associated with comparing home range estimates from different studies were compounded by the descriptive statistics used in reporting results. The population mean was the most commonly used descriptor and the value most commonly compared across studies. Only 24 studies assessed distribution of home range estimates and even though 21 of these 24 studies found departures from the assumptions of normality, 75% of all studies still reported the mean. Some studies did not explicitly report on this criterion. Between the 31 studies that used nonparametric statistics and the 26 studies that used transformed home-range estimates in analyses, more than half of them implicitly reported a departure from the normal distribution. We recommend that authors report the distribution of home range estimates, that they report home range results using the appropriate measure of central tendency, and that they subsequently use the appropriate statistical tests or data transformations.

Minimum convex polygon continues to be a popular

Table 8. Software packages used for home range estimation reported in studies published 2004–2006.

Criterion	Studies[a]	Total	%
Software package			
Reported	114	141	81
Not reported	27	141	19
Package used			
Animal movement extension to ArcView[b]	55	114	48
Ranges, versions IV[c], V[d], VI[e]	29	114	25
Calhome[f]	16	114	14
Other	23	114	20
Software version			
Reported	27	114	24
Not reported	87	114	76
Software reference			
Reported	100	114	88
Not reported	14	114	12

[a] Values will not always sum to the correct total because some studies employed a combination of methods and criteria.
[b] Hooge and Eichenlaub (2000).
[c] R. Kenward, Institute of Terrestrial Ecology, unpublished data.
[d] Kenward and Hodder (1996).
[e] Kenward et al. (2002).
[f] Kie et al. (1996).

estimator in spite of criticism (van Winkle 1975, Worton 1987, Powell 2000). We challenge the view that this estimator is the only one "strictly comparable between studies" (Harris et al. 1990:108). For MCP, sensitivity to the number of location estimates (Bekoff and Mech 1984, Harris et al. 1990, Gautestad and Mysterud 1993, Seaman et al. 1999, Börger et al. 2006), sensitivity to sampling duration (Swihart and Slade 1985*a*, Powell 2000), sensitivity to sampling strategy (Börger et al. 2006), sensitivity to serial autocorrelation (Swihart and Slade 1997), the infrequent use of robust asymptote analyses (this review), and the varied treatment of outliers (Seaman et al. 1999, this review) all preclude its use in comparison across studies. Its continued use, even when in conjunction with more robust techniques, will encourage if not proliferate spurious comparisons and we agree with Börger et al. (2006) that MCP should not be used at all as a home range estimator. The utility of the MCP may be relegated to identifying forays out of the home range (Burt 1943) or for identifying areas visited.

Similarly, comparisons across studies using KDE will only be robust if similar methods are employed. Seaman and Powell (1996) recommended fixed smoothing which many studies used. It was not clear if the adaptive smoothing chosen in some studies was because of biologically or statistically significant reasons, or was rather an artifact of the limitations imposed by the choice of software package. Silverman (1986) concluded that bandwidth selection had the greatest influence on KDE results, yet this was infrequently reported. Of the studies that reported their bandwidth selection methods, most used LSCV as suggested by Seaman and Powell (1996), though criticized by Hemson et al. (2005; but see Börger et al. 2006 for contradictory findings). Though Rodgers and Carr (1998) recommended volume contouring of the utilization distribution, few studies reported using this method, and half of the studies that reported their methods for contouring claimed to use a percentage of the number of location estimates. It is unlikely that any software package offered this as a contouring method, because it contradicts KDE methodology and belies the benefit of KDE as a probabilistic and objective estimator. The terminology may have been borrowed from MCP methods using point-peeling and this may reflect a general misunderstanding of KDE. The contour level used to delineate a home range will probably have a significant influence on the validity of comparisons across studies and the 95% contour was the most common of several contours used. The delineation of the KDE home-range boundary is a field that requires much development as only considerations of bias of KDE have been used in making the recommendations of using <80% (Seaman et al. 1999) or 90% contours (Börger et al. 2006). Considerations of bias may, however, confound the very appeal of using smoothing techniques (Fieberg 2007). Until a biologically relevant method can be found or a consensus can be reached regarding the probabilistic considerations, we recommend using the 95% contour for consistency. Contrarily, the delineation of home range cores is a relatively well-developed field (Samuel et al. 1985, Samuel and Green 1988, Harris et al. 1990, Seaman and Powell 1990, Powell 2000), though largely ignored. Most studies applied an egalitarian 50% contour for core ranges. We recommend implementing core analysis for each animal following Seaman and Powell (1990) and Powell (2000), and we recommend reporting the range of contour values at which cores were delineated. The core-range contour values can be useful in interpreting the shape of utilization distributions. Beyond these methodological criteria, software discrepancies also hamper congruency amongst home range studies (Lawson and Rodgers 1997). We recommend that authors of home range studies and of home range software report how the estimators and their algorithms were implemented.

We concede that the multitude of methods and implementations reported in home range studies reflects that no single technique will suffice in every situation and that a suite of potential tools is needed, but we urge for a more unified approach in methods and to reporting. We provide suggestions for methods and reporting (Table 9). This will facilitate reproducing studies, a basic tenet of the scientific process, and will allow for more plausible post hoc comparisons.

MANAGEMENT IMPLICATIONS

Recent home-range studies have often failed to report methods adequately or have used methods which are now considered dubious in light of recent theoretical advances. Managers using home range estimates in their decision-making should closely review the estimation methods without carte blanche acceptance thereof. Managers also should be aware of the potential biases of different home

Table 9. Recommendations for implementing and reporting animal home-range analyses based on current literature and based on a review of 161 home range studies published in journals between 2004 and 2006.

Recommendation
1. Report which software package and version was used, with its reference.
2. Assess site fidelity for each animal.
3. Assess serial autocorrelation and report time to statistical independence and time to biological independence.
4. Check for home range asymptotes for each animal and for each temporal scale using bootstrapped area-observation plots with kernel density estimation.
5. Use and report objective methods for assessing where the asymptote is approached.
6. Use and report results for those animals for which an asymptote is reached.
7. Report the range of values for the no. of location estimates at which asymptotes were approached.
8. Assess and report the distribution of the home range estimates and report the appropriate measures of central tendency and dispersion.
9. In subsequent analyses, use tests or data transformations appropriate to the distribution of the home range estimates.
10. Use appropriate measures of dispersion and central tendency to report the no. of location estimates used in home range estimates.
11. If kernel density estimation is employed, report the smoothing method (i.e., fixed or adaptive), the bandwidth selection method (i.e., user-defined, reference, least-squares cross-validation), the failure rate for automated bandwidth selection, the treatment of failures of automated bandwidth selection, the kernel function (i.e., biweight, normal), the grid resolution, the contouring method (i.e., vol or density), the contour level, and the standardization or scaling method.
12. If least-squares cross-validation is employed, report the search function (i.e., largest local min., global min.).
13. If core areas are estimated using probabilistic home-range estimators, use an objective and area-independent method for determining the appropriate contour level and use the method for each animal independently, reporting the range of contour values at which the cores were delineated.

range methods and estimators and the implications in subsequent analyses.

ACKNOWLEDGMENTS

Mogalakwena Research Centre and Virginia Tech supported P. N. Laver. We thank the many authors who assisted by sending us reprints not readily available through library loan. We thank 2 anonymous reviewers whose comments greatly improved the manuscript.

LITERATURE CITED

Bekoff, M., and L. D. Mech. 1984. Simulation analyses of space use: home range estimates, variability and sample size. Behavior Research Methods, Instruments and Computers 16:32–37.

Bell, W. J., and E. Kramer. 1979. Search for anemotactic orientation of cockroaches. Journal of Insect Physiology 25:631–640.

Blundell, G. M., J. A. K. Majer, and E. M. Debevec. 2001. Linear home ranges: effects of smoothing, sample size, and autocorrelation on kernel estimates. Ecological monographs 71:469–489.

Börger, L., N. Franconi, G. de Michele, A. Gantz, F. Meschi, A. Manica, S. Lovari, and T. Coulson. 2006. Effects of sampling regime on the mean and variance of home range size estimates. Journal of Animal Ecology 75: 1493–1405.

Boulanger, J. G., and G. C. White. 1990. A comparison of home-range estimators using Monte Carlo simulation. Journal of Wildlife Management 54:310–315.

Bowman, A. W. 1985. A comparative study of some kernel-based nonparametric estimators. Journal of Statistical Computation and Simulation 21:313–327.

Burt, W. H. 1943. Territoriality and home range concepts as applied to mammals. Journal of Mammalogy 24:346–352.

Calhoun, J. B., and J. U. Casby. 1958. Calculation of home range and a density of small mammals. United States Public Health Monograph 55: 1–24.

Epanechnikov, V. A. 1969. Nonparametric estimation of a multidimensional probability density. Theory of Probability and its Applications 14: 152–158.

Fieberg, J. 2007. Kernel density estimators of home range: smoothing and the autocorrelation red herring. Ecology 88:1059–1066.

Garshelis, D. L. 2000. Delusions in habitat evaluation: measuring use, selection, and importance. Pages 111–164 *in* L. Boitani and T. K. Fuller, editors. Research techniques in animal ecology. Columbia University Press, New York, New York, USA.

Gautestad, A. O., and I. Mysterud. 1993. Physical and biological mechanisms in animal movement processes. Journal of Applied Ecology 30:523–535.

Gautestad, A. O., and I. Mysterud. 1995. The home range ghost. Oikos 74: 195–204.

Gitzen, R. A., and J. J. Millspaugh. 2003. Comparison of least-squares cross-validation bandwidth options for kernel home-range estimation. Wildlife Society Bulletin 31:814–822.

Hansteen, T. L., H. P. Andreassen, and R. A. Ims. 1997. Effects of spatiotemporal scale on autocorrelation and home range estimators. Journal of Wildlife Management 61:280–290.

Harris, S., W. J. Cresswell, P. G. Forde, W. J. Trewhella, T. Woollard, and S. Wray. 1990. Home-range analysis using radiotracking data—a review of problems and techniques particularly as applied to the study of mammals. Mammal Review 20:97–123.

Hayne, D. W. 1949. Calculation of size of home range. Journal of Mammalogy 30:1–18.

Hemson, G., P. Johnson, A. South, R. Kenward, R. Ripley, and D. Macdonald. 2005. Are kernels the mustard? Data from global positioning system (GPS) collars suggests problems for kernel home-range analyses with least-squares cross-validation. Journal of Animal Ecology 74:455–463.

Hooge, P. N., and B. Eichenlaub. 2000. Animal movement extension to ArcView version 2.0. U.S. Geological Survey, Alaska Science Center—Biological Science Office, Anchorage, USA.

Horne, J. S., and E. O. Garton. 2006. Likelihood cross-validation versus least-squares cross-validation for choosing the smoothing parameter in kernel home-range analysis. Journal of Wildlife Management 70:641–648.

Jones, M. C., J. S. Marron, and S. J. Sheather. 1996. A brief survey of bandwidth selection for density estimation. Journal of the American Statistical Association 91:401–407.

Katajisto, J., and A. Moilanen. 2006. Kernel-based home range method for data with irregular sampling intervals. Ecological Modelling 194:405–413.

Kenward, R. E., R. T. Clarke, K. T. Hodder, and S. S. Walls. 2001. Density and linkage estimators of home range: nearest-neighbor clustering defines multinuclear cores. Ecology 82:1905–1920.

Kenward, R. E., and K. H. Hodder. 1996. Ranges V. An analysis system for biological location data. Institute of Terrestrial Ecology, Dorset, United Kingdom.

Kenward, R. E., A. South, and S. Walls. 2002. RANGES VI. AnaTrack, Wareham, Dorset, United Kingdom.

Kernohan, B. J., R. A. Gitzen, and J. J. Millspaugh. 2001. Analysis of animal space use and movements. Pages 126–166 *in* J. J. Millspaugh and J. M. Marzluff, editors. Radiotracking and animal populations. Academic Press, San Diego, California, USA.

Kie, J. G., J. A. Baldwin, and C. J. Evans. 1996. CALHOME: a program for estimating animal home ranges. Wildlife Society Bulletin 24:342–344.

Lair, H. 1987. Estimating the location of the focal center in red squirrel home ranges. Ecology 68:1092–1101.

Larkin, R. P., and D. Halkin. 1994. A review of software packages for estimating animal home ranges. Wildlife Society Bulletin 22:274–287.

Larson, M. A. 2001. A catalog of software to analyze radiotelemetry data. Pages 397–406 *in* J. J. Millspaugh and J. M. Marzluff, editors. Radiotracking and animal populations. Academic Press, San Diego, California, USA.

Laver, P. N. 2005. Cheetah of the Serengeti Plains: a home range analysis. Thesis, Virginia Tech, Blacksburg, USA.

Lawson, E. J. G., and A. R. Rodgers. 1997. Differences in home-range size computed in commonly used software programs. Wildlife Society Bulletin 25:721–729.

Messmer, T. A., and M. L. Morrison. 2006. Unified manuscript guidelines for The Wildlife Society peer-reviewed publications. Journal of Wildlife Management 70:304–320.

Otis, D. L., and G. C. White. 1999. Autocorrelation of location estimates and the analysis of radiotracking data. Journal of Wildlife Management 63:1039–1044.

Powell, R. A. 2000. Animal home ranges and territories and home range estimators. Pages 65–110 *in* L. Boitani and T. Fuller, editors. Research techniques in animal ecology: controversies and consequences. Columbia University Press, New York, New York, USA.

Rader, R., and A. Krockenberger. 2006. Three-dimensional use of space by a tropical rainforest rodent, *Melomys cervinipes*, and its implications for foraging and home-range size. Wildlife Research 33:577–582.

Robertson, P. A., N. J. Aebischer, R. E. Kenward, I. K. Hanski, and N. P. Williams. 1998. Simulation and jack-knifing assessment of home-range indices based on underlying trajectories. Journal of Applied Ecology 35: 928–940.

Rodgers, A. R., and A. P. Carr. 1998. HRE: the Home Range Extension for ArcView™: user's manual. Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research, Thunder Bay, Canada.

Samuel, M. D., and R. E. Green. 1988. A revised test procedure for identifying core areas within the home range. Journal of Animal Ecology 54:1067–1068.

Samuel, M. D., D. J. Pierce, and E. O. Garton. 1985. Identifying areas of concentrated use within the home range. Journal of Animal Ecology 54: 711–719.

Seaman, D. E., B. Griffith, and R. A. Powell. 1998. KERNELHR: a program for estimating animal home ranges. Wildlife Society Bulletin 26: 95–100.

Seaman, D. E., J. J. Millspaugh, B. J. Kernohan, G. C. Brundige, K. J. Raedeke, and R. A. Gitzen. 1999. Effects of sample size on kernel home range estimates. Journal of Wildlife Management 63:739–747.

Seaman, D. E., and R. A. Powell. 1990. Identifying patterns and intensity of home range use. International Conference on Bear Research and Management 8:243–249.

Seaman, D. E., and R. A. Powell. 1996. An evaluation of the accuracy of kernel density estimators for home range analysis. Ecology 77:2075–2085.

Seton, E. T. 1909. Life-histories of northern animals. An account of the mammals of Manitoba. Charles Schribner's Sons, New York, New York, USA.

Silverman, B. W. 1986. Density estimation for statistics and data analysis. Chapman and Hall, London, United Kingdom.

Spencer, A. R., G. N. Cameron, and R. K. Swihart. 1990. Operationally defining home range: temporal independence exhibited by hispid cotton rats. Ecology 71:1817–1822.

Stickel, L. F. 1954. A comparison of certain methods of measuring ranges of small mammals. Journal of Mammalogy 35:1–15.

Swihart, R. K., and N. A. Slade. 1985*a*. Testing for independence of observations in animal movements. Ecology 66:1176–1184.

Swihart, R. K., and N. A. Slade. 1985*b*. Influence of sampling interval on estimates of home-range size. Journal of Wildlife Management 49:1019–1025.

Swihart, R. K., and N. A. Slade. 1997. On testing for independence of animal movements. Journal of Agricultural, Biological, and Environmental Statistics 2:1–16.

Swihart, R. K., N. A. Slade, and B. J. Bergstrom. 1988. Relating body size to the rate of home range use in mammals. Ecology 69:393–399.

van Winkle, W. 1975. Comparison of several probabilistic home-range models. Journal of Wildlife Management 39:118–123.

Worton, B. J. 1987. A review of models of home range for animal movement. Ecological Modelling 38:277–298.

Worton, B. J. 1989*a*. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70:164–168.

Worton, B. J. 1989*b*. Optimal smoothing parameters for multivariate fixed and adaptive kernel methods. Journal of Statistical Computation and Simulation 32:45–57.

Worton, B. J. 1995. Using Monte Carlo simulation to evaluate kernel-based home range estimates. Journal of Wildlife Management 59:794–800.

Associate Editor: Lopez.

Appendix. Criteria used to assess home range studies published 2004–2006.

1. Did the study report or use home range estimates?
2. What yr was the study published?
3. In what journal was the study published?
4. In what taxonomic group was the study population?
5. What method was used to collect location data?
6. Did the study test for serial autocorrelation?
7. Did the study take measures to reduce serial autocorrelation?
8. Did the study test for site fidelity?
9. Was the software package reported?
10. What software was used for home range estimation?
11. Did the study report the version of the software used?
12. Did the study give a reference for the software?
13. Did the study test for the sensitivity of home range size to no. of observations?
14. What was the method used for testing sensitivity of home range size to no. of observations?
15. If area-observation plots were used, did the study test this for each animal?
16. If area-observation plots were used, did the study apply a cut-off or lower lim for the no. of location estimates?
17. If area-observation plots were used, what home range estimator was used in the analysis?
18. If area-observation plots were used, did the researcher delineate an asymptote?
19. If area-observation plots were used, and an asymptote was delineated, what method was used for delineation?
20. If area-observation plots were used, did the study report the % area reached for a given no. of locations or the no. of locations for a given % of area instead of delineating an asymptote?
21. Did the study report the no. of animals used in estimating home range size?
22. Did the study report the no. of location estimates for home range estimation?
23. If so, was it the min. or mean no. of location estimates?
24. Did the study report the central tendency of the home range estimates?
25. Did the study use the mean value for central tendency of the home range estimates?
26. Did the study use the median value for central tendency of the home range estimates?
27. Did the study use another value for central tendency of the home range estimates?
28. Did the study report the dispersion of home range estimates?
29. If so, what method was used for reporting the dispersion?
30. Did the study assess and report the distribution of the home range estimates?
31. Were the home range estimates normally or nonnormally distributed?
32. Did the study use the home range estimates in subsequent analyses?
33. In subsequent analyses, did the study use parametric or nonparametric statistics?
34. Did the study transform the home range estimates for analyses?
35. If the home range estimates were transformed, what method was employed?
36. How many home range estimators were used?
37. Which home range estimators were used?
38. If min. convex polygons were employed, what reason did the study cite for their choice?
39. Did the study report how min. convex polygons were employed?
40. What method was used for min. convex polygons?
41. If linear home ranges were used, what method of delineation was employed?
42. If kernel density estimation was used, did the study report what smoothing was employed?
43. Was the smoothing adaptive or fixed?
44. Did the study report the method for selecting the bandwidth?
45. Was the bandwidth selection user-defined or an automated selection?
46. If the bandwidth selection was automated, what method was employed?
47. Did the study report which kernel was employed?
48. What was the kernel employed?
49. Did the study report the grid resolution?
50. Was the grid resolution user-defined or the proprietary default?
51. Did the study use standardization of the data or scaling of the bandwidth?
52. What method of standardization or scaling was employed?
53. Did the study report the method of contouring the utilization distribution?
54. What method of contouring was used?
55. Did the study report the contour level or value?
56. What was the contour level used?
57. Did the study perform a core area analysis?
58. If the study performed a core area analysis, did they choose a user-defined contour or did they use an objective method?
59. If the method employed was user-defined, what contour level was chosen for the cores?
60. If the method employed was objective, which method was used?
61. Did the study calculate the core contour level for each animal or apply the mean level as estimated from a subset or preliminary study?
62. Did the study estimate and report the mean core contour level for the study population?