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Author(s): Kari Bjørneraas, Bram Van Moorter, Christer Moe Rolandsen, and Ivar Herfindal
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Tools and Technology Article

Screening Global Positioning System Location Data for Errors Using Animal Movement Characteristics

KARI BJØRNERAAS, *Centre for Conservation Biology, Department of Biology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

BRAM VAN MOORTER,[1] *Centre for Conservation Biology, Department of Biology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

CHRISTER MOE ROLANDSEN, *Centre for Conservation Biology, Department of Biology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway; and Norwegian Institute for Nature Research, NO-7485 Trondheim, Norway*

IVAR HERFINDAL, *Centre for Conservation Biology, Department of Biology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway; and Section for Natural History, Museum for Natural History and Archaeology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

ABSTRACT Animal locations estimated by Global Positioning System (GPS) inherently contain errors. Screening procedures used to remove large positional errors often trade data accuracy for data loss. We developed a simple screening method that identifies locations arising from unrealistic movement patterns. When applied to a large data set of moose (*Alces alces*) locations, our method identified virtually all known errors with minimal loss of data. Thus, our method for screening GPS data improves the quality of data sets and increases the value of such data for research and management.

KEY WORDS *Alces alces*, data screening, Global Positioning System, location accuracy, location error, moose, movement behavior, Norway, positional dilution of precision.

Global Positioning System (GPS) technology is widely used for animal tracking because GPS allows for frequent, automatic sampling of animal locations over long periods of time, which generates large amounts of data useful for research and management (Gustine et al. 2006, Wegge et al. 2007, Olsson and Widen 2008). However, locations obtained through GPS collars contain errors (D'eon and Delparte 2005, Cargnelutti et al. 2007, Lewis et al. 2007), which may influence conclusions based on such data (Frair et al. 2004, Visscher 2006, Ganskopp and Johnson 2007, Johnson and Gillingham 2008, Swain et al. 2008). Two types of errors can occur in GPS location data: missing location fixes and location errors of successfully acquired fixes (Graves and Waller 2006, Lewis et al. 2007).

Location error is the difference between the recorded location and the animal's true location. Accuracy of a position estimate often depends on the number of satellites from which the GPS unit on the collar receives signals. Two-dimensional (2-D) fixes are often less accurate than 3-dimensional (3-D) fixes, which are estimated from 3 and $\geq$4 satellites, respectively (Lewis et al. 2007, Jiang et al. 2008). Missing location fixes occur when the GPS unit receives signals from $<$3 satellites. However, performance of GPS collars has improved, and recent studies have reported that overall GPS fix rate successes can be close to 100% (Cargnelutti et al. 2007, Hebblewhite et al. 2007, Lewis et al. 2007). Location error is also influenced by the distribution of satellites in space, and their geometry can be described by a measure called dilution of precision (DOP; Langley 1999, Ministry of Environment, Land and Parks [MELP] 2001). A low DOP value usually represents better GPS location accuracy because of wider angular separation between the satellites (Langley 1999, MELP 2001). Probability of acquiring a fix, as well as fix accuracy, can also be related to environmental conditions and the physical and behavioral characteristics of the animal (Di Orio et al. 2003, Cain et al. 2005, D'eon and Delparte 2005, Graves and Waller 2006, Hansen and Riggs 2008).

The first step when analyzing GPS data should be exclusion or correction of location errors. Acceptable location accuracy must be defined, based on the purpose of the study, with the aim to limit error without hiding the pattern under study. Screening procedures can only identify locations expected to be highly inaccurate, which can lead to removal of locations with accuracy adequate for the purpose of the study, reducing statistical power in analyses of animal space use. On the contrary, inclusion of inaccurate locations can introduce systematic biases and wrong conclusions (Visscher 2006, Hurford 2009).

Recommended criteria for identifying an incorrect GPS fix from wildlife location data are commonly based on the number of satellites used to calculate the GPS position, geometry of those satellites, or a combination of both (Moen et al. 1996, Edenius 1997, D'eon et al. 2002, D'eon and Delparte 2005, Lewis et al. 2007). However, applying the same screening method to data obtained from stationary test collars compared with animal location data results in different amounts of data reduction, where location data sets from animals are more heavily reduced, but large obvious errors remain (D'eon and Delparte 2005, Lewis et al. 2007). One approach to minimize the loss of data while optimizing detection of unacceptably large errors is to account for movement characteristics of tracked animals.

[1] *E-mail: bram.van.moorter@gmail.com*

A method that explicitly uses characteristics of the animal's movement to correct location error is state-space modeling, which estimates the animal's true location based on observed locations together with models for location error and animal movement (Jonsen et al. 2003). Simulations of animal movement based on tracking data started decades ago (e.g., Siniff and Jessen 1969), but realistic models can still be complex and computationally challenging (Morales et al. 2004). Thus, when a movement model is not the aim of the study, it may be advantageous to screen GPS data without assuming an underlying movement model. Fortunately, in many cases, data correction may not be necessary, and removing errors will be sufficient. Identification of highly erroneous positions is possible using a negative movement model, describing how an animal does not move (Villepique et al. 2008).

Our primary objective was to develop a method that effectively identified large location errors with minimal data reduction in large data sets of animal location data collected using GPS collars. By focusing on characteristics of movement behavior of the focal species, we tried to make the screening method simple but more accurate than previous simple screening methods.

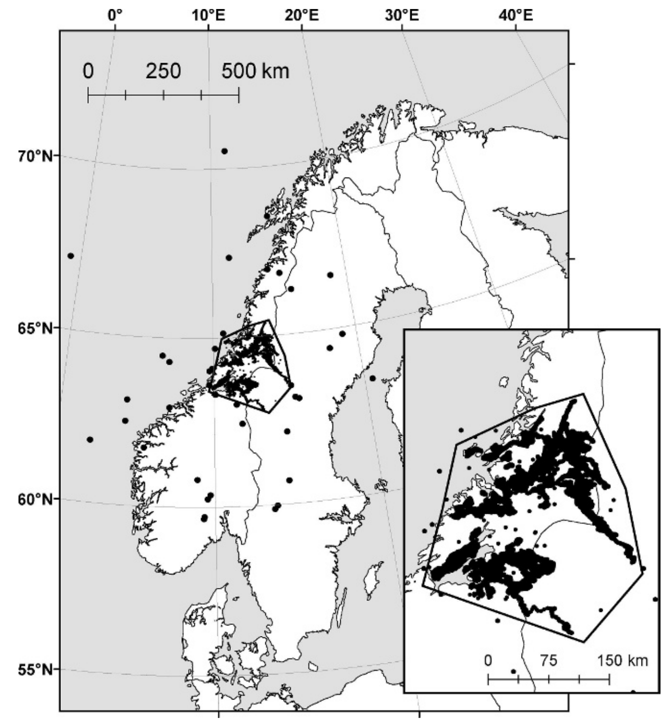

Figure 1. Global Positioning System locations (black dots) of study population of moose in central Norway during 2006–2008. The black border illustrates the extent of the study area.

STUDY AREA

The study area covered large parts of central Norway and extended into Sweden (Fig. 1). The study area ranged from coastal areas with boreonemoral characteristics to alpine zones over continuous elevational gradients. Coniferous forest and, to a lesser extent, deciduous forest dominated the study area, whereas cultivated land comprised an important vegetation type at lower altitudes (Moen 1999).

METHODS

The GPS data screening process consisted of 2 primary steps (*R* script is provided in supplemental material, <http://dx.doi.org/10.2193/2009-405.s1>). First, we removed all fixes located farther from the surrounding points than predefined distances (Δ and μ, see below). Second, we considered all fixes forming a spike in the movement trajectory to be errors (Fig. 2A). We defined a spike as a point in the movement trajectory where the outgoing and incoming speed exceeded a certain limit, α, and where the turning angle was sharper than a predefined threshold, θ. Our method depended on a given number of fixes and estimates of speed and turning angles; thus, missing fixes could be ignored and would not be limiting for data screening.

In the first data-screening step, we determined how far a fix was from surrounding fixes to identify locations farther away than the preset distances. We determined an animal's general position using a moving window ($n = 21$ for the moose example below) to allow for nonstationarity in the animal's general location when the species movement capacity is large. For each fix, we calculated distance to the median of the x and y coordinates of fixes within the moving window (i.e., 10 fixes before and after the focal fix). If the fix was located farther than a preset distance Δ (a large distance that the animal could not travel within the max. sampling interval) from the median location within the moving window, we labeled the fix as erroneous.

The median is less sensitive than the mean to outliers. However, if an animal makes a rapid and long movement with no intermediate fixes sampled along its path, the distance to the median can be as long as the path travelled. A threshold criterion that is too small could remove nonerroneous positions. Therefore, after excluding fixes using the criterion with the median (cutoff distance Δ), we classified fixes as erroneous if they were located farther than distance μ from the mean of remaining positions within a moving window ($n = 21$). Hence, we set μ to a more restrictive distance than Δ.

In the second step, we used the turning angle together with distance and time difference from surrounding points. We considered it unlikely for an individual to travel at high speed and return immediately afterwards at high speed in the direction whence it came, which would result in a spike in the trajectory (Fig. 2A). To determine erroneous spikes, we used 3 consecutive GPS fixes. We identified a fix as a spike if the outgoing and incoming speed exceeded a predefined limit α and if the cosine of the turning angle was sharper than a predefined threshold θ.

Our method for screening GPS data is based on knowledge and assumptions of how species or individuals do not move; thus, we refer to our screening technique as the nonmovement method. We developed our screening method for use in the statistical software R (version 2.10.1, <www.r-project.org>, accessed 20 Dec 2009) and it depends on the package Adehabitat (Calenge 2006). A digital version is available online (<http://ase-research.org/moorter/>, accessed 10 Mar 2010).

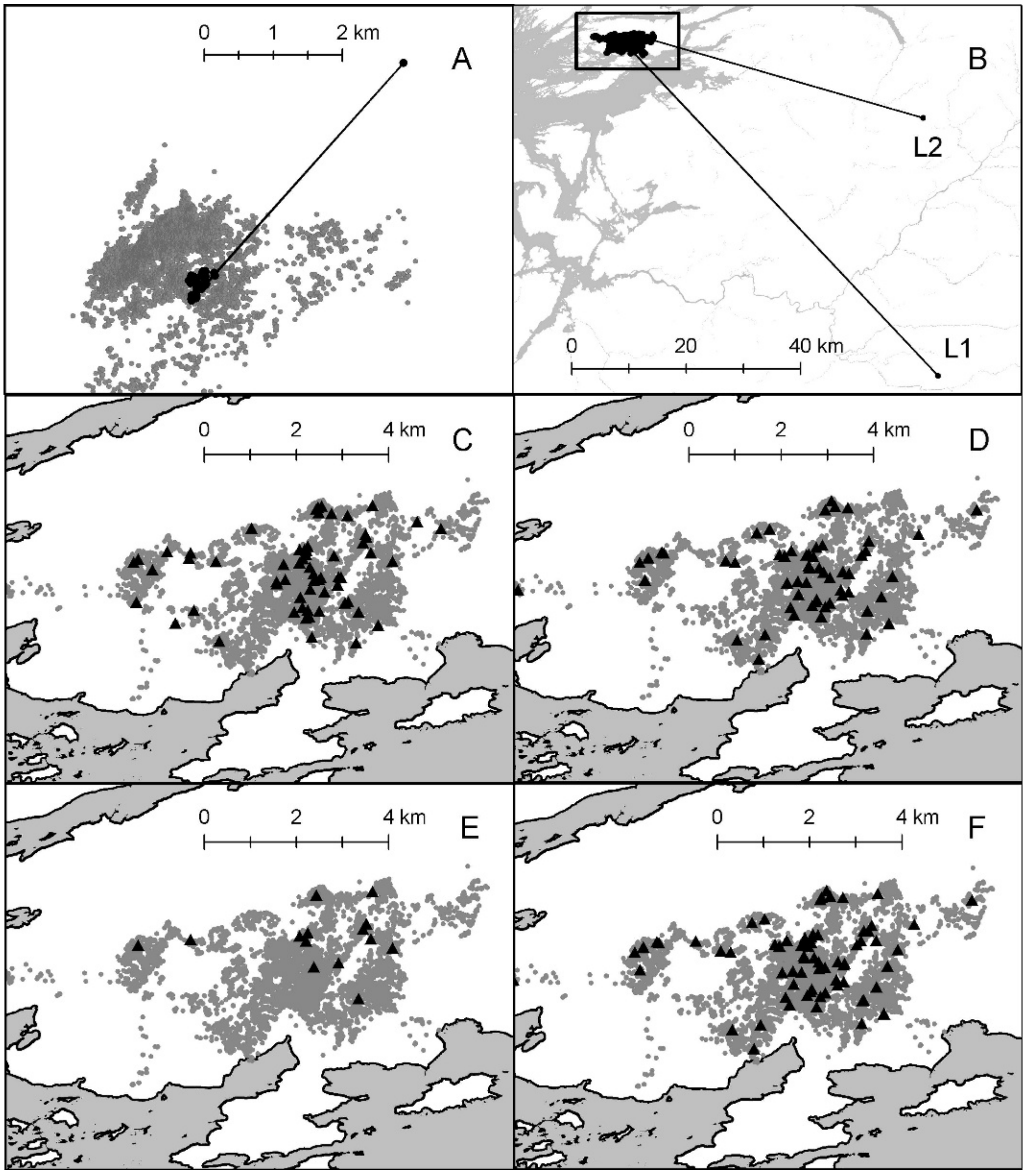

Figure 2. (A) Illustration of a Global Positioning System (GPS) location identified as a spike by our method for excluding large location errors. Gray dots show moose GPS locations over a longer period, whereas black dots combined with the line show the trajectory at the time of the occurrence of the error. (B) There were 12,533 GPS locations acquired for one moose located near the coast of Norway in 2007–2008, with fixes taken every hour; L1 and L2 were the only 2 fixes identified as erroneous by our nonmovement method. (C–F) Locations (gray dots) from the same moose, excluding locations L1 and L2, where black triangles show GPS fixes identified as location errors by 4 alternative screening methods: (C) 2-dimensional (2-D) fixes, (D) dilution of precision (DOP) >10, (E) 2-D fixes with DOP >5, and (F) 3-dimensional (3-D) fixes with DOP >10 and 2-D fixes with DOP >5. Of those 4 methods, the one excluding all 2-D positions was the only other method that identified L1 and L2 as errors.

Moose Data

We collared 171 moose (ad: 38 M, 107 F; calves approx. 8 months old: 14 M, 12 F) from a partially migratory population during 2006–2008. We fitted 7 moose with Tellus GPS collars (Followit AB/Televilt, Lindesberg, Sweden) and 164 moose with GPS PLUS/GPS PRO Light collars (VECTRONIC Aerospace GmbH, Berlin, Germany). All collars were equipped with very high frequency transmitters. Capture, handling, and anesthetizing of moose were approved by the Norwegian Directorate for Nature Management and the Research Animal Committee in Norway (Approvals 2005/44882-3, 07/1059–07/6838-3, and 07/68902). We programmed GPS collars to obtain one fix every hour or every second hour. We programmed a few collars to obtain fixes at more-frequent intervals but for 1–5 days only. We collected approximately 88% of data at 1-hour intervals. Fix-rate success was 98.9% for the total data set. We obtained fixes for 169 collared individuals, giving 1,660,657 locations, of which 97.8% were 3-D. We recorded the positional dilution of precision (PDOP) value for all 3-D fixes and the horizontal dilution of precision for all 2-D fixes.

We opted for conservative cutoff criteria in the first step of the data-screening procedure to remove the largest errors only. Based on knowledge of the behavior of moose, we set Δ to 100 km because an animal could not move that distance

Table 1. Five methods for identifying location errors from Global Positioning System–derived estimates of animal positions.[a]

	Screening method	Criteria
1	2-D	Rejecting all 2-D fixes.
2	DOP >10	Rejecting fixes with DOP >10.
3	2-D DOP >5	Rejecting all 2-D fixes with DOP >5.
4	3-D DOP >10 and 2-D DOP >5	Rejecting all 3-D fixes with DOP >10 and all 2-D fixes with DOP >5.
5	Nonmovement method	Rejecting all fixes exceeding distance Δ from the median, and μ from the mean within a moving window; and rejecting all spikes with outgoing and ingoing speed >α, and cosines of the turning angle >θ.

[a] Abbreviations: 2-D, 2-dimensional; 3-D, 3-dimensional; Δ, a large, predefined distance that the animal could not travel within the max. sampling interval; μ, a large, predefined distance that the animal is not likely to have traveled; α, a predefined threshold for speed; θ, a predefined threshold for turning angle; and DOP, dilution of precision.

in 2 hours (max. sampling interval we configured for our GPS collars). We set μ to 10 km, which is also conservative but is a distance that moose could travel in 2 hours. To determine μ, we examined distribution of distances from the mean and found that only 0.01% of distances exceeded 10 km.

We defined an erroneous spike as a point where step length exceeded $\alpha = 1.5$ km/hour, and the cosine was less than $\theta = -0.97$, which corresponded to turning angles between 166° and 194°. For moose in our study area, movement that formed a spike in the trajectory might be observed for females during the calving season, before calves are capable of moving larger distances, and during the rutting season. We tried to define a speed threshold to avoid eliminating true locations while removing most large erroneous spikes during both calving and rutting seasons. To evaluate whether our speed threshold was successful, we determined whether spikes identified as errors occurred more frequently during calving (May and Jun) or rutting (Sep and Oct).

We compared our method for excluding large location errors with 4 previously suggested methods (Table 1): 1) removal of all 2-D fixes (D'eon et al. 2002); 2) removal of fixes with DOP >10 (D'eon and Delparte 2005); 3) removal of 2-D fixes with DOP >5 (Moen et al. 1996, Edenius 1997); and 4) removal of 2-D fixes with DOP >5 and 3-D fixes with DOP >10 (Lewis et al. 2007). We compared the distribution of step lengths (Euclidian distance between 2 consecutive locations) and turning angles of fixes in the data set and among locations identified as errors by the 5 screening methods. For this last analysis, we only used GPS fixes collected at 1-hour intervals.

RESULTS

Of 1,660,657 GPS locations, we identified 179 (0.011%) as large outliers, distributed on 78 moose (*n*/moose = 0–9). We removed 82 of these locations because of the Δ criterion and 97 as a result of the μ criterion. We identified 40 fixes (0.002%) distributed on 33 moose (*n*/moose = 0–3) as spikes. Of these, we collected 33 at 60-minute intervals, 5 at 20-minute intervals, and 2 at 120-minute intervals, constituting 0.002%, 0.010%, and 0.001%, respectively, of all fixes for those respective sampling intervals. Of the 179 locations identified as errors based on the Δ and μ criteria, 19% were among the 10 first fixes recorded for each moose (fixes/moose $\bar{x} = 9,826$). We observed only 2.5% of the spikes within the first 10 fixes. The proportion of locations identified as errors during calving (0.016%) and rutting (0.009%) did not differ from the rest of the year ($\chi^2 = 1.6$, $P = 0.197$; and $\chi^2 = 3.7$, $P = 0.053$, respectively). Errors occurred at a higher frequency for Televilt (0.09%) than VECTRONIC (0.01%) collars ($\chi^2 = 146.3$, $P \leq 0.001$).

Rejection of all 2-D fixes led to the largest reduction of moose data (2.19%), whereas the other screening methods, based on the number of satellites and on the DOP cutoff values, reduced the data set 0.58%–1.77%, which were large reductions compared with our nonmovement method (0.01%; Table 2). When examining step lengths and turning angles for data collected at 1-hour intervals, we found these parameters to be more extreme for locations identified as errors by the nonmovement method (method 5; Table 1) compared with the 4 alternative screening methods (methods 1–4; Table 1). Of errors identified by the nonmovement method, 97% of step lengths exceeded the 95% quantile of step lengths in the overall data set, in contrast to approximately 7% for the 4 other screening methods (Table 2). Similarly, we found the distribution of turning angles of fixes identified as location errors by the screening methods based on DOP, 2-D, and 3-D to be similar to the distribution of turning angles in the overall data set in contrast to the nonmovement method (Table 2).

The different screening methods showed different abilities to detect large, obvious errors. Of the 4 methods based on number and geometry of satellites, exclusion of all 2-D positions performed best, identifying 77% of 83 GPS fixes located outside a polygon defining the boundary of the study area (see Fig. 1) as erroneous (Table 2). For the 3 other methods (methods 2–4; Table 1), <30% of these locations were identified as errors. The nonmovement method identified all 83 of these locations as errors in the first data-screening phase.

DISCUSSION

Although screening methods have been found to improve location accuracy without substantial data loss for stationary test collars, applying these methods to animal location data has led to large data reductions without eliminating all obvious outliers (D'eon and Delparte 2005, Lewis et al. 2007). Our results also showed that none of the 4 screening methods based on DOP cutoff values, the number of satellites, or a combination (methods 1–4; Table 1) excluded all the evident outliers in the moose data. Although the total data reduction resulting from these 4 screening methods was

Table 2. Data reduction, error detection, and extreme distances and turning angles (%) related to locations identified as errors by 5 screening methods (Table 1) applied to Global Positioning System (GPS) location data from moose in central Norway during 2006–2008. We defined large location errors as 83 GPS fixes outside a defined study area (Fig. 1).[a]

Quality	Screening method[b]				
	1	2	3	4	5
Total data reduction[c]	2.19	1.38	0.58	1.77	0.01
Distances >95% quantile[d,e]	6.8	7.2	7.4	7.1	97.1
Turning angles >97.5% quantile or <2.5% quantile[e,f]	6.9	6.8	10.0	7.0	86.3
Detection of large location errors[c]	77	20	29	28	100

[a] Abbreviations: 2-D, 2-dimensional; 3-D, 3-dimensional; and DOP, dilution of precision.
[b] Screening methods 1–4 (for further explanation, see Table 1): (1) 2-D, (2) DOP >10, (3) 2-D DOP >5, (4) 3-D DOP >10 and 2-D DOP >5, (5) nonmovement method.
[c] Based on the total data set: 1,660,657 fixes.
[d] Based on fixes collected at 1-hr intervals (88% of total data set) with missing coordinates inserted for missing fixes.
[e] Euclidian distance between the fix identified as an error and the successive fix.
[f] Turning angle for the fix identified as a location error.

low, we observed a trade-off with increased data accuracy in exchange for larger loss of data (Table 2). As a consequence, a large proportion of locations identified as errors were most likely fairly precise moose locations (Fig. 2C–F), as supported by the similar distribution of step lengths and turning angles among locations identified as errors and distribution of these parameters in the overall data set (Table 2).

Our method (method 5; Table 1) successfully identified all evident location errors and reduced the data minimally (Table 2). Thus, our method handled well the trade-off between data accuracy and data reduction, in addition to excluding few locations found within the area generally used by the moose (Fig. 2B). Our method did exhibit some limitations because the number of the fixes identified as errors were not evenly distributed in time. The large proportion of errors recorded immediately after a moose had been collared (i.e., within approx. the first 10 fixes) implies that when movement patterns of collared individuals differed from expected or normal behavior, our method may have eliminated fixes that were true locations. However, studies that aim to analyze animal movement and behavior under natural conditions should exclude a certain number of fixes obtained immediately after collaring because these fixes may reflect abnormal behavior. When removing the earliest acquired locations, the low number of locations identified as errors (method 5; Table 2) suggests that erroneous exclusion of positions by the nonmovement method is unlikely to bias results. In the worst case, only a few actual locations have to be removed. On the other hand, due to our conservative choice of parameters we applied to the moose data, it is likely that some errors still remain.

For a correct screening of location data for migratory individuals, we evaluated accuracy of each GPS fix in relation to a limited number of prior and subsequent locations. Alternatively, we could evaluate each fix in relation to all fixes acquired within a given time interval. However, if locations for an individual are collected at different time intervals, accuracy of the method would decrease with increasing sampling intervals. We could solve this problem by considering a fixed number of GPS locations. When determining location accuracy based on turning angles in combination with speed, the proportion of fixes identified as erroneous is likely to decrease with increasing sampling intervals. We caution that if sampling intervals are very short, the speed between 2 consecutive locations will be sensitive to even small positional errors. Fortunately, at very short fix intervals, the proportion of erroneous positions is low (Swain et al. 2008).

We applied our method of screening to a data set consisting of locations from a partial migratory population of moose. Based on knowledge of the behavior and movement pattern of our example species, we chose to identify spikes as errors (Fig. 2A). Besides resulting from erroneous location estimates, a spike could be caused by an animal being startled and leaving an area at high speed and then returning at high speed. It is unlikely that the animal will rush back to the same area it was startled from, but we cannot exclude this possibility a priori. For species with movement characteristics similar to moose, the spike-exclusion criterion should be adjusted to suit behavioral characteristics. Larger modifications of the method may be necessary if study species exhibit markedly different movement patterns, for example for central-place foragers, such as nesting birds.

Our error-screening method identifies locations that seem to have arisen from implausible movements. Villepique et al. (2008) provide a similar approach designed to detect spike movements (i.e., comparable to our second step), but our method also detects other unlikely movements that do not necessarily form an out-and-back geometry. Additionally, we applied a moving window, which allowed different movement behaviors at different times. However, the idea of using angles, time, and distances between successive telemetry fixes to model animal movement and identify errors was already developed and discussed in the 1960s (Heezen and Tester 1967, Siniff and Jessen 1969).

In practice, it is impossible to know the exact location of an animal when using GPS telemetry. The objective of screening procedures is not one of knowing exact locations, but one of achieving satisfactory accuracy. For instance, to relate an animal's position to the environment, positional accuracy that corresponds to the accuracy of the environmental data (e.g., a vegetation map or a temp grid) is required. Failing to account for serious errors may lead to inaccuracies in evaluation of animal space use or even to incorrect conclusions (Visscher 2006, Hurford 2009). However, exclusion of locations with acceptable accuracy may lead to substantial data loss, possibly introducing other forms of bias into analyses. Thus, the choice of screening method for location errors should be adapted to the research question because it will influence what is regarded as a large or a small location error.

MANAGEMENT IMPLICATIONS

Management practices and priorities are often derived from studies of habitat use and spatial ecology of the focal species; therefore, it is important to derive conclusions based on high-quality field data. Using our nonmovement screening method, we believe that, in many cases, errors will be sufficiently reduced without suffering considerable loss of data, improving the quality of GPS location data sets and their value for both research and management.

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