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Original Article

Importance of Evaluating GPS Telemetry Collar Performance in Monitoring Reintroduced Populations

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ABSTRACT Global Positioning System (GPS) tracking collar technology has been widely employed in wildlife research and is valuable for understanding movement patterns of reintroduced populations, yet the associated fix-rate bias and positional errors are a serious concern. During 2013, we deployed GPS collars at fixed sites varying by habitat and terrain conditions in the mountains of southwestern Virginia, USA, where elk (*Cervus elaphus*) were recently reintroduced, to test 2 hypotheses: 1) collar precision would decrease and fix rate bias would increase with increasing terrain and vegetation obstructions; and 2) variability in fixes and associated errors can affect evaluations of habitat use by reintroduced elk populations. Our model predicted a 1.67-m decrease in root mean square error (RMSE) for every 100-m increase in elevation, and a 1.14-m increase in RMSE for every 10° increase in slope. We found that collars under deciduous, mixed, and coniferous cover were predicted to decrease the fix rate by 14.5%, 25.6%, and 47.4%, respectively. We computed an uncertainty index based upon Monte Carlo simulations to show the effects of variability in fixes on habitat assignment of elk locations. Based upon the uncertainty index, we predicted that the relatively small and patchily distributed herbaceous cover type had the most potential for misassignment of use. Failure to account for these sources of error could improperly indicate that elk almost exclusively use open ridge tops and erroneously affect manager's decisions regarding potential human–elk conflict and disease transmission. Our results illustrate a potential danger in interpreting raw point data from a GPS tracking study of reintroduced populations. Errors caused by local habitat conditions in patchy and structurally complex landscapes should be accounted for in future models and management decisions. © 2017 The Wildlife Society.

KEY WORDS *Cervus elaphus*, collar performance, elk, GPS telemetry, habitat use, restoration, Virginia.

Global Positioning System (GPS) technology within telemetry collars has been widely employed in wildlife spatial ecology and resource use studies, yet the habitat-induced fix-rate bias and positional errors are a concern (Cain et al. 2005, DeCesare et al. 2005, Cagnacci et al. 2010, Frair et al. 2010, Montgomery et al. 2010). Performance of GPS collars may depend upon a wide array of conditions including vegetation features, terrain features, weather conditions, and available sky (see Dussault et al. 1999, D'Eon et al. 2002, D'Eon and Delparte 2005, Hebblewhite et al. 2007, Hansen and Riggs 2008). Thus, performance of GPS collars under field conditions should be evaluated before units are used in habitat studies that require precise estimates of an animal's location (White and Garrott 1990, Dussault et al. 1999).

Reliability and precision of GPS tracking data are particularly important for monitoring dispersal and movement of reintroduced populations. Understanding dispersal and movement of reintroduced or translocated populations is critical to ensuring establishment of restored populations and for limiting human–wildlife conflict outside of designated restoration zones (Le Gouar et al. 2012, Jachowski et al. 2014). Accordingly, GPS telemetry is increasingly being used to monitor movement of released individuals (Yott et al. 2011, Reynolds et al. 2012, Armstrong et al. 2013, Berger-tal and Saltz 2014). However, while some reintroduction studies have tested their GPS telemetry technology because of concerns about the assumptions of fix rate bias and lack of precision (Mills et al. 2006, Chadwick et al. 2010,

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Gil-Sánchez et al. 2011), many studies fail to directly evaluate the reliability of GPS tracking hardware in acquiring locations and assessing precision of fixes—both of which are critical to interpreting animal movements postrelease.

Elk (*Cervus elaphus*) have been reintroduced to eastern North America after being extirpated for decades (Popp et al. 2014). However, approximately 40% of documented elk reintroductions in eastern North America have failed (Popp et al. 2014) because of a variety of factors including hunting and poaching, disease and parasites, and lack of available habitat (Witmer 1990, Larkin et al. 2002, O'Gara and Dundas 2002). Further, elk restoration has been controversial, with public concern over crop and property damage, transmission of disease to livestock, and auto collisions (Virginia Department of Game and Inland Fisheries [VDGIF] 2010). For multiple reintroduced elk populations, GPS-collar tracking technology has been used as a tool to promote a better understanding of postrelease movements and population management (Larkin et al. 2001). Specifically, GPS tracking of reintroduced elk has provided critical information for decisions regarding the creation and management of food plots, future conservation planning, prioritization of private landowner outreach, identification of priority areas to restrict public access, and refuting claims of potential disease transmission or crop damage by reintroduced elk. However, use of this technology to address these objectives is only effective if the information gained is reliably accurate and precise.

To evaluate the reliability of collars and precision of locational fixes used in decision-making for reintroduced elk, we performed a GPS telemetry collar evaluation in the mountains of southwestern Virginia, USA, at a current elk restoration site. We hypothesized that collar precision would decrease and fix rate bias would increase in a predictable manner with increasing terrain and vegetation obstructions. To test our hypotheses, we experimentally evaluated and quantified GPS collar performance under varying terrain and habitat conditions. Further, because of the key role GPS collar data play in informing current habitat management and future conservation planning for reintroduced elk, we evaluated potential effects of locational errors on determining elk habitat-selection patterns.

STUDY AREA

Our study occurred around the elk release site in the mountainous terrain of Buchanan County, Virginia. Buchanan County was located in the southwestern corner of the Commonwealth of Virginia and part of the Cumberland Plateau physiographic province, commonly known as the Coalfields. This region was composed of horizontal layers of sedimentary rock that contained coal, natural gas, and petroleum. Extraction of these resources altered the topography and vegetation of the landscape. Surface mining, underground mining, and gas wells have created large patches of relatively open and flat spaces with scattered, small patches of herbaceous cover, surrounded by steep, dense forests. Slope aspects varied from 1° to 360°, with slope gradients >200%.

The climate was generally characterized as humid subtropical with warm, humid summers and generally mild to cool winters. Forests were mostly deciduous, consisting of oaks (*Quercus* spp.) and hickories (*Carya* spp.) on the ridges with greater diversity in the more fertile valleys. Widespread timber harvest has produced forests dominated by yellow-poplar (*Liriodendron tulipifera*) matrixed with white pine (*Pinus strobus*) plantings. The most common evergreen species were *Rhododendron* spp., along with hemlock (*Tsuga canadensis*) and Virginia pine (*Pinus virginiana*).

Historically, eastern elk (*Cervus canadensis canadensis*) were found across the eastern United States, including Virginia (O'Gara and Dundas 2002). Elk numbers declined as a result of overharvest and habitat destruction; the last known native elk of Virginia was killed in 1855. Attempts to reintroduce elk in Virginia in the early 20th Century failed because of a lack of available habitat and knowledge of elk ecology; by 1970, elk were once again extirpated from Virginia (VDGIF 2010).

From spring 2012 to spring 2014, 71 adult elk were relocated from Kentucky, USA, into Virginia as part of the Virginia Department of Game and Inland Fisheries Elk Restoration Project (VDGIF 2010). Prior to release, each adult elk brought into the state was fitted with an Advanced Telemetry Systems G2110E Iridium Global Positioning System (Isanti, MN, USA) satellite collar that was programmed to record a locational fix every 5 hr. Collars were programmed to attempt to collect a locational fix for up to 120 s, and uplink to the satellite to transfer data via e-mail to project personnel once per day.

METHODS

Collar Deployment

To evaluate the performance of the GPS collars experimentally, we deployed collars at 20 fixed locations across a range of habitat and terrain features within 1 km of the release site. Sites were not randomly chosen, instead we selected sites in a stratified fashion to represent the available habitat and terrain conditions with initial selection based upon aspect. Based upon the available geography around the release site, we chose 15% of our sites to have a north aspect, 25% an east aspect, 30% a south aspect, and 30% a west aspect. Based upon the available cover around the release site, we further stratified our selection of sites according to cover type. We located 2, 6, 6, and 3 sites on open areas, brush areas, deciduous forests, coniferous forests, and mixed forests, respectively. Finally, while elk were released at the top of the mountain to distance animals from human habitation in valley bottoms, animals likely ranged widely away from the release site, so we attempted to select sites at a range of available elevations (range = 417–689 m, $\bar{x} = 616$ m).

Collar deployment occurred during a period of peak foliage (30 Jul 2013 to 16 Aug 2013) to best evaluate the potential for canopy cover to interfere with collar performance. During this period, we rotated 5 collars every 4–5 days among the 20 locations. We deployed collars either on fiberglass rods in open areas or on strings suspended between trees in forested areas at heights 85–105 cm ($\bar{x} = 95.4$ cm; SD = 6.5 cm) above ground. Similar to collars deployed on released elk, we programmed collars to take fixes every 5 hr with a 120-s fix duration, and uplinked to the satellites to transfer data once per day.

Evaluation of Precision and Fix Rate

The GPS collars provided the number of satellites, horizontal dilution of precision (HDOP), and dimensionality (2-dimension vs. 3-dimension) along with the coordinates for each GPS locational fix. We removed from the data set fixes with HDOP values >5 ($n = 7$; Moen et al. 1997). To determine the precision of the GPS collars, we computed the average x-coordinate and average y-coordinate for all GPS locational fixes at a collar site. We then computed the Root Mean Squared Error (RMSE) at each site as the square root of the average squared distance between each coordinate location and average coordinate location:

$$\mathrm{RMSE}_j = \sqrt{\frac{\sum_{i=1}^{n_j} \left(d_{ij}\right)^2}{n_j}}$$

where $j = 1, \ldots, 20$ indicates the jth site, n_j is the number of coordinate locations at the jth site, and d_{ij} is the Euclidian distance between the ith coordinate location and the average coordinate location for site j. The RMSE measures collar precision relative to the average coordinate location and can be thought of as the variability in determining a locational fix.

To evaluate which environmental factors best explained observed variation in collar precision and fix rate, we developed and tested *a priori* models using multiple linear regression and Akaike's Information Criteria corrected for small sample size (AIC_c). The *a priori* model set was generated using plausible combinations of variables as subsets of the full model. We considered approximating models as strongly competitive based upon $\Delta\mathrm{AIC}_c < 2.0$, with Akaike weights ($w_i$) used to measure model selection uncertainty. We chose the best representative model for making inferences based upon the smallest AIC_c value (Burnham et al. 2011). To verify model assumptions, we computed variance inflation factors (VIFs), and correlation coefficients. For our analyses, the response variable was either the RMSE (meters) or the fix rate for each of the 20 sites. The regressors in the full model included elevation (meters), aspect (degrees), slope (degrees), percent canopy cover (percent), height from ground to top of collar (cm), and 4 indicator variables ($\times 1$, $\times 2$, $\times 3$, $\times 4$) corresponding to habitat cover types open, deciduous, mixed, and coniferous, respectively. We used open cover as the control variable corresponding to no cover type. To account for the periodic nature of the aspect variable, where an aspect value of 359° is very similar to an aspect value of 1° with both indicating true north, we transformed the aspect regressor by defining $\upsilon = \sin\left(\frac{\pi \times \mathrm{aspect}}{360}\right)$. This transformation allowed for the conversion of the aspect from degrees to radians with the transformed regressor values ranging from 0 to 1. We performed all statistical analyses in Program R Version 3.1.3 (www.r-project.org, accessed 5 Jun 2015). We considered sites ($n = 20$) as the experimental units.

Habitat-Based Simulation

We conducted a Monte Carlo simulation to evaluate the effect of locational errors on determining elk habitat-selection patterns per habitat type (Hammersley and Handscomb 1964). In the first 9 months after the 2012 Virginia elk release, we recorded 9,683 GPS fixes from the collars placed on the 16 released adult elk. In a Monte Carlo simulation, the locational fix is recognized as only one possible realization of the true collar position. We computed random errors to represent the possible error in locational fixes and added these random errors to the locational fixes to generate a new realization of the fix.

We computed 30 realizations in the RiskAMP (Structured Data, LLC, New York, NY, USA) Monte Carlo Add-in for Excel by adding random errors in the x- and y-coordinates to each of the 9,683 GPS fixes. We generated random errors by drawing from normal distributions with mean zero and our estimates of standard deviation derived from the field study ($\mathrm{SD_x} = 7.04$ m, $\mathrm{SD_y} = 7.69$ m). For the x-coordinates, we found the average simulated error was 1.27 m with a minimum of −20.20 m, maximum of 16.53 m, and standard deviation of 7.39 m. For the y-coordinates, we found the average simulated error was −0.87 m with a minimum of −15.48 m, maximum of 17.98 m, and standard deviation of 8.12 m. To keep track of the realizations, we assigned each locational fix an index number based upon the realization resulting in 290,490 simulated locational fixes or points.

We computed the proportion of points in each land-cover type per realization and the percent change from the original proportion. Land-cover types were categorized into 7 categories as water, barren–mine, mature forest, mature forest–shadow, scrub–shrub, herbaceous, and clouds–developed based on a VDGIF raster compiled from Landsat Thematic Mapper imagery (lta.cr.usgs.gov/TM, accessed 10 May 2009). We assigned a value of zero in ArcGIS (Environmental Systems Research Institute, Redlands, CA, USA) to grid cells without an assigned land-cover category. To evaluate the uncertainty in presence of elk per habitat type, we created an uncertainty index by multiplying the mean of the distribution of percent changes per habitat type by the corresponding mean number of fixes.

RESULTS

Collar Precision

Mean RMSE over the 20 sites ranged from 2.4 m to 19.8 m ($\bar{x} = 10.3$, SD = 5.8). One of the 331 coordinate locations was removed from the data set because it was considered an anomaly. This point was located 151 m from the mean location for the 16 other data points at the site with standard deviation for the x-coordinates of 5 m and standard deviation for the y-coordinates of 8.6 m. Removing the point reduced the RMSE for that site from 36.80 m to 9.58 m. For the remaining 330 fixes, the average HDOP was 2.1 (SD = 0.80) and average number of seconds to acquire the fix was 74 s

(SD = 31.61 s). Additionally, a mode of 5 satellites (min. = 3 and max. = 9) was used to calculate the locations, with 78.2% being 3-dimensional fixes.

The full multiple linear regression model was significant ($R^2 = 73.1$, $F_{9,10} = 3.03$, $P = 0.05$) indicating a linear relationship between the RMSE and some of the regressors. The normal probability plot indicated that errors were normally distributed. To achieve constant variance of the residuals, we used a natural logarithmic transformation of the response variable RMSE. The log-transformed regression was significant ($R^2 = 78.7$, $F_{9,10} = 4.11$, $P = 0.02$), with elevation as the only significant regressor ($P < 0.01$). Although the log-transformed model was incomparable to the full model without a transformation, the increase in R^2 and decrease in *P*-value indicated improvement in model fit under the log transformed RMSE.

Predictor variables of the most strongly competitive models were related to elevation, slope, percent canopy cover, and type of canopy cover (Table 1). The model with the most explanatory power ($R^2 = 74.9$, $F_{4,15} = 11.16$, $P \leq 0.001$) was ln(RMSE) = 4.38 − 0.00511 Elevation + 0.0127 Slope + 0.702 ×2 + 0.673 ×4 with the lowest AIC_c value of −31.41. With *P*-values for individual *t*-tests on coefficients <0.03, elevation, slope, deciduous cover type, and coniferous cover type were significant predictors of collar precision as measured by the RMSE. Also, the VIFs were small (all <1.2) and did not artificially inflate the *t*-values. Along with correlation values between −0.48 and 0.36, these low VIFs did not indicate a problem with multicollinearity in the model.

For this model, a 100-m increase in elevation was predicted to decrease the log transformation of RMSE by 0.511 m, which corresponded to a 1.67 m (95% CI = 1.33–2.09 m) decrease in RMSE. A 10° increase in slope was predicted to increase RMSE by 1.14 m (95% CI = 1.01–1.26 m). Collars under deciduous cover were predicted to increase RMSE by 2.02 m (95% CI = 1.33–3.06 m) and collars under coniferous cover were predicted to increase RMSE by 1.96 m (95% CI = 1.17–3.27 m).

Collar Fix Rate

Of the 401 possible fixes (every 5 hr) for the 5 collars over the 17 day study period, 331 fixes were successful, resulting in a 82.5% overall fix rate with a range from 29.2% to 100% (SD = 19.2%). The full multiple linear regression model of collar fix rate against all terrain and habitat attributes was significant ($R^2 = 79.3$, $F_{9,10} = 4.25$, $P = 0.02$), with coniferous cover type as the only significant individual predictor ($P < 0.05$). A natural logarithmic transformation of the response variable was not needed. The most strongly competitive models contained predictor variables related to slope, percent canopy cover, and type of canopy cover (Table 2). The significant regression ($R^2 = 75.3$, $F_{3,16} = 16.23$, $P < 0.01$) leading to Fix Rate = 0.984 − 0.145 ×2 − 0.256 ×3 − 0.474 ×4 where ×2, ×3, and ×4 correspond to deciduous, mixed, and coniferous cover types, respectively, was the model with the most explanatory power. This model had the lowest AIC_c value of −84.25. Because the *P*-values for individual *t*-tests on coefficients were <0.021 with VIFs <1.3, the model showed that deciduous, mixed, and coniferous cover types were significant predictors of the collar fix rate.

The coefficients were more negative and had lower *P*-values with increasing coniferous cover. Collars under deciduous cover were predicted to decrease the fix rate by 14.5% (95% CI = 2.5%–26.4%), collars under mixed forest cover were predicted to decrease the fix rate by 25.6% (95% CI = 10.6%–40.5%), and collars under coniferous cover were predicted to decrease the fix rate by 47.4% (95% CI = 32.5%–62.4%) compared with an open habitat.

Effects of Errors on Habitat Selection per Habitat Type

Of the original 9,683 GPS fixes, 8 were determined to be in water, 2,389 in barren–mine, 2,767 in mature forest, 45 in mature forest–shadow, 1,984 in scrub–shrub, 2,146 in herbaceous, 1 in clouds–developed, and 343 in grid cells without an assigned land-cover type. For the 30 realizations, we calculated the mean number of fixes along with the corresponding standard deviations in each category and average number of points that switched into another habitat type from the original location because of the simulated errors in fix location (Table 3). For example, over the 30 realizations, on average 14 locations in the barren–mine habitat type switched to a different habitat type. The overall average percent change in the number of fixes in each category was 8.96%. Moreover, 26.67% of the simulated

Table 1. Competing models and selection statistics for Global Positioning System collar precision from data collected near the elk release site in Buchanan County, Virginia, USA, 2013. Only strongly competitive models are listed.

Model description	R^2	AIC_c[a]	ΔAIC_c[b]	w_i[c]
Elevation + slope + ×2[d] + ×4[e]	74.9	−31.41	0.00	0.316
Elevation + slope + cover[f] + ×2	72.5	−29.59	1.82	0.128
Elevation + slope + cover + ×2 + ×4	78.1	−29.96	1.45	0.154

[a] Akaike's Information Criteria corrected for small sample size.

[b] AIC_c differences, relative to the smallest AIC_c value.

[c] Akaike weights.

[d] ×2 corresponds to deciduous cover type.

[e] ×4 corresponds to coniferous cover type.

[f] Cover corresponds to the percent of canopy cover.

Table 2. Competing models and selection statistics for Global Positioning System collar fix rate from data collected near the elk release site in Buchanan County, Virginia, USA, 2013. Only strongly competitive models are listed.

Model description	R^2	AIC_c[a]	ΔAIC_c[b]	w_i[c]
×2[d] + ×3[e] + ×4[f]	75.3	−84.25	0.00	0.348
Cover[g] + ×3 + ×4	72.8	−82.34	1.90	0.134
Slope + ×2 + ×3 + ×4	78.3	−83.22	1.02	0.209

[a] Akaike's Information Criteria corrected for small sample size.

[b] AIC_c differences, relative to the smallest AIC_c value.

[c] Akaike weights.

[d] ×2 corresponds to deciduous cover type.

[e] ×3 corresponds to mixed cover type.

[f] ×4 corresponds to coniferous cover type.

[g] Cover corresponds to the percent of canopy cover.

Table 3. Locational fixes in each land-cover type for 30 simulated realizations of elk translocated to Buchanan County, Virginia, USA, based on Global Positioning System collar data, 2012–2013.

Cover type	$\bar{x}$ no. of fixes	SD of fixes	% of total	$\bar{x}$ no. that switched
Water	7.4	2.06	0.08%	1
Barren–mine	2,402.5	26.32	24.81%	14
Mature forest	2,760.6	28.05	28.51%	6
Mature forest–shadow	46.6	5.22	0.48%	2
Scrub–shrub	1,989.0	23.61	20.54%	5
Herbaceous	2,152.3	52.41	22.23%	6
Clouds–developed	0.7	0.52	0.01%	0
Blank[a]	323.8	19.58	3.34%	19

[a] Blank corresponds to grid cells without an assigned land-cover type.

points were within 5 m of the original point, 46.67% within 5–10 m of the original point, 16.67% within 10–15 m of the original point, and 10% further than 15 m from the original point.

Based upon our uncertainty index, the herbaceous cover type had the most potential to affect GPS location classification and thus a habitat selection study (Fig. 1). The configuration of herbaceous cover across our study site (i.e., in relatively small patches) and uncertainty in the fix locations led to an incorrect classification of elk presence in herbaceous cover. Barren–mine, mature forest, scrub–shrub, and unassigned had medium uncertainty index values with water, mature forest–shadow, and clouds–developed at low uncertainty index values. The chance that a locational fix will switch into a different habitat type as a result of an imprecise fix was lower in the larger more contiguous cover types of mature forest and barren–mine. The unassigned category had a relatively high index compared with the number of simulated points located in that category because it consisted of small patches of raster cells.

DISCUSSION

Reintroduction of fish and wildlife populations often is costly and controversial, making the tracking of released animals a critical component of many management plans (Le Gouar et al. 2012). This is particularly true for reintroduced elk and other large herbivores that often are tracked because of potential, real, or perceived detrimental foraging impacts and disease risks (Larkin et al. 2001, 2004). Our study illustrates the need to carefully consider error associated with topographic and habitat attributes when interpreting movement data; failure to do so can result in potentially biased estimates or erroneous expectations of reintroduced animal behavior. Even though our locational error appeared to be relatively small, it still can affect habitat use analyses, especially in areas that have small patches of herbaceous cover as in our study site.

Similar to previous studies (e.g., D'Eon and Delparte 2005, Hansen and Riggs 2008), we found a strong influence of topography and habitat type on collar precision and fix rate. The positive influence of elevation and negative influence of slope on collar precision was likely primarily due to the physical structure of this human-modified landscape. The restoration site occurred within a mountain-top removal, coal mining site that was comprised of high elevation, flat plateaus that drop off precipitously leading to steep slopes along valley sides, and narrow stream bottoms. Thus, locations at high elevations were typically on areas with low

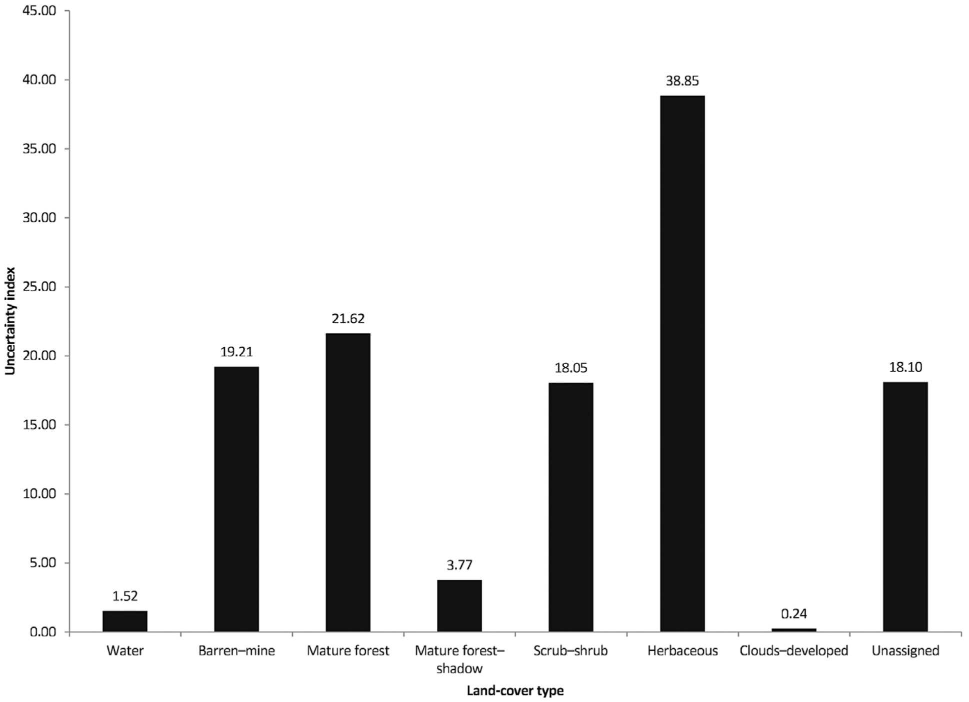

Figure 1. Uncertainty index per land-cover type computed as the product of the mean of the distribution of percent changes per cover type with the corresponding mean number of fixes (i.e., percent change per cover type × mean number of fixes) derived from 30 simulated Global Positioning System collar realizations of elk translocated to Buchanan County, Virginia, USA, during 2012–2013.

slope values and high exposure to satellites, while lower elevation sites had high slope values and were less exposed to clear views of the sky for exposure to satellites and thus decreased the precision of fixes.

The influence of habitat conditions on collar fix rate and precision was likely due to the amount of cover associated with each habitat type (Hebblewhite et al. 2007, Hansen and Riggs 2008). We generally observed a gradient of this influence, where habitat types with the largest amount of cover had the greatest potential for error. For example, collars under coniferous cover had an almost 50% decrease in fix rate, and almost 9% of all simulated fixes were assigned to a different habitat type. Collar performance was generally better in deciduous and mixed forests, but declines of 14.5% and 25.6% in each of these habitat types, respectively, should still be of concern when assessing habitat use patterns. Our study was conducted in the summer when the effect of foliage was likely greatest. However, while loss of foliage cover during winter should intuitively improve collar performance, defoliation alone has not been found to explain observed declines in collar precision and fix rates in deciduous forests (Dussault et al. 1999, Hebblewhite et al. 2007), and thus deserves further investigation.

Our findings were not unexpected given the rugged topography and habitat complexity inherent to the region, but have important implications for the interpretation of tracking data for 2 key factors in enhancing reintroduction success: refugia and dispersal–travel corridors. First, refugia are critical to reintroduced animals as they physiologically and behaviorally acclimatize to their surroundings post-release (Jachowski et al. 2012). Our study suggests that interpretation of refugia based on GPS tracking data for elk in Virginia could be biased to higher elevation, open habitats, which contradicts other studies that suggest reintroduced elk select for areas with extensive edge habitat near or within forest cover postrelease (Larkin et al. 2004). Second, it is critical for conservation planning of reintroduced populations to identify corridors early on for both repeated movements and dispersal (Yott et al. 2011, Le Gouar et al. 2012, Jachowski et al. 2013). These areas, which often are only used for short periods of time (thus there are inherently fewer data points), are difficult to identify as crucial pathways, and instead we are likely to overemphasize the use of open, high-elevation habitats. Overall, open areas and roads were extensively used by elk as foraging areas and travel corridors respectively, but our results illustrate how errors in fix rates could overemphasize their importance if such bias is not accounted for.

Interpretation of habitat use patterns often is a goal in GPS tracking studies of reintroduced populations. Understanding these patterns not only aids in understanding species ecology, which can be site-specific (Jachowski et al. 2012), but is critical to designing appropriate postrelease monitoring and management strategies (Armstrong and Seddon 2008). Our results illustrate that canopy cover and topography-induced variability in the precision of GPS tracking collars can potentially influence evaluations of habitat use in complex environments with high habitat diversity and small patch size. In contrast, collar precision is potentially a lesser issue for species that are being restored into landscapes with low amounts of fragmentation or habitat diversity. Further, any evaluation of collar precision should be paired with careful evaluation of accuracy of the underlying habitat classifications or maps (Thompson et al. 2007, Gallant 2009). Therefore, we encourage managers considering reintroduction programs occurring in structurally complex landscapes to be particularly concerned with both accuracy of habitat maps, and precision of tracking collars during design and subsequent analysis of movement data from reintroduced wildlife populations.

MANAGEMENT IMPLICATIONS

The issues we identified with GPS tracking collars highlight important concerns for current and future elk management following reintroduction. First, in our study area, households typically occur in valley river bottoms, thus the loss of precision at low elevations with steep slopes is concerning because managers may not be attaining a full picture of potential human–elk conflict and potential for disease transmission. Second, while preliminary data from collared elk suggest that they likely did use open areas with food plots near the release site extensively postrelease, our study indicates that it is also likely that use of other habitat types could be falsely underrepresented. If so, this could lead to a poorly formed understanding of elk movement and resource selection patterns that are often used to guide future habitat management and conservation planning. Our findings provide another cautionary tale for managers in interpreting GPS data points unless there has been careful validation of performance of the tracking device. This is particularly important for reintroduction programs, where resulting data often are used to guide current and future management of imperiled and controversial restored populations.

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