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TESTING A MAHALANOBIS DISTANCE MODEL OF BLACK BEAR HABITAT USE IN THE OUACHITA MOUNTAINS OF OKLAHOMA

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Abstract: Regional wildlife-habitat models are commonly developed, but rarely tested with truly independent data. We tested a published habitat model for black bears (*Ursus americanus*) with new data collected in a different site in the same ecological region (i.e., Ouachita Mountains of

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Arkansas and Oklahoma). We used a Mahalanobis distance model developed from relocations of black bears in Arkansas to produce a map layer of Mahalanobis distances on a study area in neighboring Oklahoma. We tested this modeled map layer with relocations of black bears on the Oklahoma area. The distribution of relocations of female black bears was consistent with model predictions. We conclude that this modeling approach can be used to predict regional suitability for a species of interest.

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Key words: black bear, habitat modeling, Mahalanobis distance, Oklahoma, *Ursus americanus*, validation.

Successful wildlife management depends partly on our ability to assess and understand wildlife-habitat relationships. Models are useful tools to assist in that understanding, especially if used to evaluate potential effects of land management and habitat changes on species or communities of interest. Unfortunately, models created for a species or group of species in 1 geographic area rarely have been tested to predict habitat selection in other, independent areas.

Because bears have large home ranges, omnivorous feeding habits, and seasonal use patterns (Clark et al. 1993*a*), modeling bear-habitat relationships has been effective at the landscape scale. For example, Gaines et al. (1994) used LANDSAT multispectral scanner imagery and a Geographic Information System (GIS) to evaluate the suitability of the North Cascades Grizzly Bear Ecosystem to support grizzly bears (*Ursus arctos*). Kobler and Adamic (2000) developed a habitat suitability model for brown bears using a raster (grid-based) system. Spatial representation of this model identified habitat fragmentation that would have otherwise gone unnoticed. Predictive models of habitat use by black bears (*Ursus americanus*) were developed by Clark et al. (1993*a*) and van Manen and Pelton (1997). Recently, researchers tested a habitat suitability index model for black bears (Mitchell et al. 2002) and used it to evaluate responses of the species to forest management in the southern Appalachians (Mitchell et al. 2003).

There are 5 basic steps of GIS habitat modeling: 1) extraction of descriptive habitat data with GIS; 2) statistical analysis outside GIS environment; 3) spatial modeling in GIS based on statistical analysis; 4) mapping and simulations; 5) model testing (van Manen and Pelton 1997). Hellgren et al. (1998) performed steps 1-4 to develop a multivariate model of habitat suitability for black bears for the Ouachita National Forest using the original model of Clark et al. (1993*a*). Although the final step, model testing or validation, is often conducted with the same data sets through techniques such as jackknifing and splitting of data sets (Cressie 1993), testing with independent data is rare.

The availability of the model developed by Clark et al. (1993*a*), developed in the Ouachita Mountains of Arkansas, provided a unique opportunity to test a habitat use model for black bears. The Clark et al. (1993*a*) model was based on the Mahalanobis distance statistic, which is a multivariate measure of dissimilarity between points. The Mahalanobis statistic has been applied to a wide array of species, including black-tailed jackrabbit (*Lepus californicus*; Knick and Dyer 1997), gray wolves (*Canis lupus*; Corsi et al. 1999), and timber rattlesnakes (*Crotalus horridus*; Browning et al. 2005). A related metric, the Penrose distance statistic, was used to assist in modeling relative abundance of bobcats (*Lynx rufus*) in southern Illinois (Nielsen and Woolf 2002).

A modeling approach using the Mahalanobis distance can be used to assess management alternatives or scenarios by predicting animal responses to a particular management activity (Knick and Dyer 1997). For example, the effects of forest management activities, road-building, or recreation development on landscape use by black bears can be predicted *a priori* with this type of model, as illustrated with a habitat suitability index model by Mitchell and Powell (2003). In turn, these predictions could be tested by monitoring animal responses during and after implementation of management. Impacts of these activities on animal demographics would require additional data on population vital rates linked to individual habitat patches and landscape configurations (i.e., spatially explicit population models; Beissinger and Westphal 1998).

Our objective was to test a multivariate, GIS model of black bear habitat use at the landscape scale with independent data from a separate site in the same region. Our study area was the Ouachita Mountains in southeastern Oklahoma, 80 km west of where the model was originally developed. Black bears in the study area have recolonized and expanded in numbers in the past 20 years (Bales et al. 2005). We used relocations of bears in Oklahoma to test a model based on relocations of bears in Arkansas. We predicted that habitat characteristics associated with bear radiolocations would correspond with a higher proportion of smaller Mahalanobis distance values than expected if habitat use was random (smaller Mahalanobis values represent more favorable habitat; Clark et al. 1993*a)*.

Study Area

We conducted this study in the Kiamichi and Choctaw Ranger Districts of the Ouachita National Forest, LeFlore County, southeastern Oklahoma (Fig. 1). The Ouachita Mountains are characterized by east-west ridges with elevations ranging from 400 m to 813 m. The southeastern Oklahoma climate consisted of mild winters (average January temperature 3.9°C) and hot, humid summers (average July temperature 27.7°C; National Weather Service Oklahoma 2006); however, temperatures were lower in higher elevations. LeFlore County received an average of 122 cm of annual precipitation (Oklahoma Climatological Survey, Norman, Oklahoma).

Rolley and Warde (1985) described three main cover types for the area: pine (*Pinus* spp.) forests (primarily on south-facing slopes), deciduous forests (primarily on north-facing slopes and creek bottoms), and mixed pine-deciduous forests. Pine forests were characterized by an overstory dominated by shortleaf pine (*P. echinata*), a midstory including winged elm (*Ulmus alata*), sparkleberry (*Vaccinium arboreum*), and low blueberry (*V. vacillans*), and an understory including greenbriar (*Smilax* spp.), poison ivy (*Toxicodendron radicans*), and little bluestem (*Schizaparium scoparius*). Deciduous forests included an overstory dominated by oaks (*Quercus* spp.) and hickories (*Carya* spp.), a midstory including flowering dogwood (*Cornus florida*), eastern redbud (*Cercis canadensis*), red maple (*Acer rubrum*), and St. Johnswort (*Hypericum* spp.), and an understory consisting of sparglegrass (*Chasmanthium* spp.), panicum (*Panicum* spp.), and wildrye (*Elymus* spp.). Mixed pine-deciduous forests primarily occurred at lower elevations in transition zones between pine forests and deciduous forests (Rolley and Warde 1985).

Methods

We captured 51 black bears 73 times during 1,495 trapnights with barrel traps and Aldrich spring-activated snares modified for bear safety (Johnson and Pelton 1980) during May to August and October to November, 2001and 2002. We anesthetized most bears (n = 66) with Telazol (A.H. Robins Company, Richmond, Virginia), a combination of tiletamine hydrochloride and zolazepam hydrochloride, at a dosage rate of 4.8 mg/kg (Doan-Crider and Hellgren 1996). Alternatively, we tranquilized 7 bears with a 2:1 mixture of ketamine-xylazine (Clark and Smith 1994) at a rate of 6.6 mg/kg. We administered drugs with a pole syringe. We fitted 28 adult females (≥36 kg) with radiocollars equipped with mortality sensors (Telonics, Mesa, Arizona). All collars included a cotton spacer (Hellgren et al. 1988).

We relocated radio-collared bears 5 to 10 times monthly from July 2001 to January 2003 using triangulation (3 azimuths obtained in <50 minutes and collected primarily during daylight hours) by ground telemetry with receivers and hand-held H-type antennas. We collected data for the original model under a similar scheme (Clark et al. 1993*a*; same time limits for azimuths and 56% of locations between 0800 and 1700). We recorded Universal Transverse Mercator (UTM) coordinates of telemetry stations, azimuth, and time of reading. We assigned UTM coordinates to location estimates of radiocollared bears with LOCATE software (Pacer Computer Software, Truro, Nova Scotia, Canada; Nams 1990). To determine triangulation error, assistants placed test collars in topographic positions and distances from the observer consistent with typical bear radiolocations (Clark 1991). We located test collars using the same methods as for bear locations. Telemetry error was determined by calculating the average distance from true locations to test locations (Clark 1991) using SAS (SAS Institute Inc., 1999-2001, Cary, North Carolina). Four personnel conducted radio telemetry; however, only 2 (author Bales and 1 technician) tracked enough test collars ($n > 10$) to calculate reliable error estimates. Observations of telemetry conducted with other technicians led us to believe that error estimates calculated were representative of the telemetry error of all observers.

We based the habitat model (Fig. 1) based on the Mahalanobis distance statistic, which is approximately distributed as Chi-square with n-1 degrees of freedom (n being the number of map layers; Clark et al. 1993*a*). Mahalanobis distance is a measurement of dissimilarity and represents the standard squared distance between a set of sample variates and an ideal habitat as estimated from a set of animal relocations (Clark et al. 1993*a*). An inverse relationship exists between Mahalanobis distance value and similarity of a site to the ideal habitat (Hellgren et al.

1998). Thus, smaller Mahanolobis distance values represent more favorable habitat (i.e., closer to the ideal) as represented by the multivariate mean vector of habitat characteristics associated with bear relocations.

Hellgren et al. (1998) used the mean vector of habitat characteristics from Arkansas bear relocations and the estimated covariance matrix from Clark (1991) to produce a map layer containing a Mahalanobis distance value within each 30 x 30-m pixel on the Kiamichi and Choctaw Districts in Oklahoma (Fig. 1). In other words, habitat use by black bears on the Arkansas study area was used to model the Mahalanobis distance values on the Oklahoma study area. Map layers used in the habitat model were forest cover type (combination of stand type and stand condition from the Continuous Inventory of Stand Condition (CISC) management system [U.S. Forest Service 1981]), elevation, aspect, slope, distance to roads and streams, and cover type diversity. Overall, the model contained maps for 5 continuous variables (slope, elevation, distance to roads, distance to streams, diversity) and 2 discrete variables, which consisted of 17 categorical maps for each of the forest cover types and 7 maps for the aspect categories, for a total of 29 data layers.

We intersected coordinates of bear radiolocations collected on the Oklahoma study area with the 30- x 30-m pixel model of Hellgren et al. (1998) using ArcInfo (ESRI, Redlands, California). To incorporate telemetry error, we created buffers with radii equal to mean error distance (300 m) around each bear relocation in ArcView (ESRI, Redlands, California). We used the Random Point Generator v. 1.1 extension (Jenness Enterprises, Flagstaff, Arizona) for ArcView (ESRI, Redlands, California) to generate a set of random points within each buffered zone (hereafter random-buffered points) based on a uniform distribution. Note that these random-buffered points represent possible relocations of bears within the mean error distance from the triangulated point. We then randomly selected sets of random-buffered points such that each set included 1 random location per bear relocation. We developed 350 sets of points to ensure that each pixel in the buffered area had a reasonable probability of being included in the random set (note: the area of a circle (πr^2) with a 300-m radius contains 314 30- x 30-m pixels). We also intersected those locations with the Hellgren et al. (1998) model in ArcInfo (ESRI, Redlands, California).

Finally, we created 4 cumulative frequency distributions of Mahalanobis distance values: the model for the Ouachita National Forest (ONF) in Oklahoma, the study area, Oklahoma bear relocations, and sets of random-buffered points. We defined the study area as the 95% minimum convex polygon for all radiolocations of adult females used in home-range analyses (Bales et al. 2005). We compared the distribution of Mahalanobis distance values associated with Oklahoma bear radiolocations with the distribution of Mahalanobis distance values from a stratified random sample of study area pixels with a Kolmogorov-Smirnov (K-S) test. We also compared the ONF model and study area distribution to the distributions of sets of random-buffered points. We concluded that distributions differed if the cumulative frequency distribution of distance values for ONF model or study area fell outside the range of the distribution of the sets of random-buffered points. The distribution tests allowed us to test our prediction that habitat characteristics associated with bear relocations would correspond with a higher proportion of smaller Mahalanobis distance values than the model (e. g., study area) distribution. They also served as tests of the model's validity; similar distributions of Mahalanobis distances between the study area and bear relocations would indicate that the model was not informative of bear habitat selection.

Results

A total of 824 radiolocations was collected from 28 female black bears during daylight hours (0700-1900) in Oklahoma, and 655 of these locations had an associated Mahalanobis distance value. Locations collected on private land did not have Mahalanobis distance values. Observer error averaged 311.2 m (*SE* = 81.9) and 278.1 m (*SE* = 104.9) for the 2 main observers. The distribution of Mahalanobis distance values for bear relocations was within the range of distributions of distance values for sets of random points in the buffered zone surrounding bear locations, indicating correspondence between modeled values for points representing telemetry relocations and points within areas defined by error surrounding telemetry locations. The distributions of Mahalanobis distance values for bear radiolocations and study area pixels differed (K-S statistic = 0.096, $P < 0.001$). The distribution of modeled Mahalanobis distance values for the ONF and study area were to the right of the distribution of distance values for sets of buffered bear relocations (Fig. 2). These results supported our prediction that habitat characteristics associated with bear relocations would correspond with a higher proportion of smaller Mahalanobis distance values than the model (e. g., study area) distribution, thus validating the model. In addition, the distribution of Mahalanobis distance values for the study area was to the left of the distribution of distance values for the entire National Forest.

Discussion

Our analysis supported the model of Clark et al. (1993*a*). We conclude from the shifts in the cumulative frequency distributions that bears in Oklahoma were selecting points closer to the ideal habitat (e.g., the multivariate mean habitat vector of bear locations) than expected had habitat use been random with respect to the Mahalanobis distance values on our study area or National Forest. In addition, the difference between the distributions for our study area and Ouachita National Forest indicated that our study area was composed of a higher proportion of ideal habitat than the National Forest as a whole.

Sites on the Oklahoma study area with smaller Mahalanobis distance values were primarily on north-facing slopes and ridgetops, where the predominant habitat type was oakhardwood pole timber (Hellgren et al. 1998). As predicted, female black bears utilized areas with these smaller distance values with greater frequency than expected based upon availability within the study area and Ouachita National Forest. The results of model validation indicated multivariate models of habitat suitability developed for one area can sometimes be used to predict habitat use in other, independent areas of similar habitat. However, it is imperative to assess each model independently. Differences in population characteristics, habitat structure and composition, and model variables may influence a model's applicability to other areas (Knick and Rotenberry 1998, Mitchell et al. 2002).

We acknowledge potential biases in our results. For example, the proportion of nocturnal locations was higher in the data set collected by Clark et al. (1993*a*) than in our Oklahoma study. However, this bias would lead to poorer model fit and presumably less power for validation. Second, our definition of the study area (95% convex polygon surrounding female radiolocations) included areas not used by our sample of bears and thus may have inflated our power to detect a difference in the Mahalanobis distance distribution if these unused areas had large distance values (i.e., poorer habitat). We counter that this argument actually validates the habitat model because it suggests that habitat modeled as unsuitable was indeed not used by bears.

The Mahalanobis distance statistic should be used to describe habitat suitability when distribution of the habitat variable does not change, the landscape is thoroughly sampled to determine the mean habitat vector, and animals are distributed optimally (Podruzny et al. 2002). Our finding that the model accurately predicted bear habitat use in Oklahoma is evidence that these assumptions were not seriously violated. There were no large-scale changes in the landscape in our study area between model creation and collection of bear habitat-use data, although limited timber harvesting occurred. The multivariate mean habitat vector was based on a thorough sample (1,395 relocations from radiocollared female bears in a 518-km^2 area of the Ouachita Mountains in Arkansas; Clark et al. 1993*a*, Clark and Smith 1994). We were unable to test the assumption that animals were distributed optimally, but our findings in support of the Clark et al. (1993*a*) model do not indicate a significant bias.

Management Implications

Habitat models are commonly used for making management decisions although predictions have not been tested with independent data. Our results suggest that the Mahalanobis distance model we tested for black bears was robust when applied to an area with similar environmental conditions. If no independent data are available, managers can be more confident in making management decisions based on habitat models if similarly applied. However, if environmental conditions on the application area differ markedly from the area where the model was developed, managers are much more likely to make errors when prescribing actions. Given the feasibility of model validation demonstrated by our results, we recommend that managers incorporate model testing into their habitat management programs.

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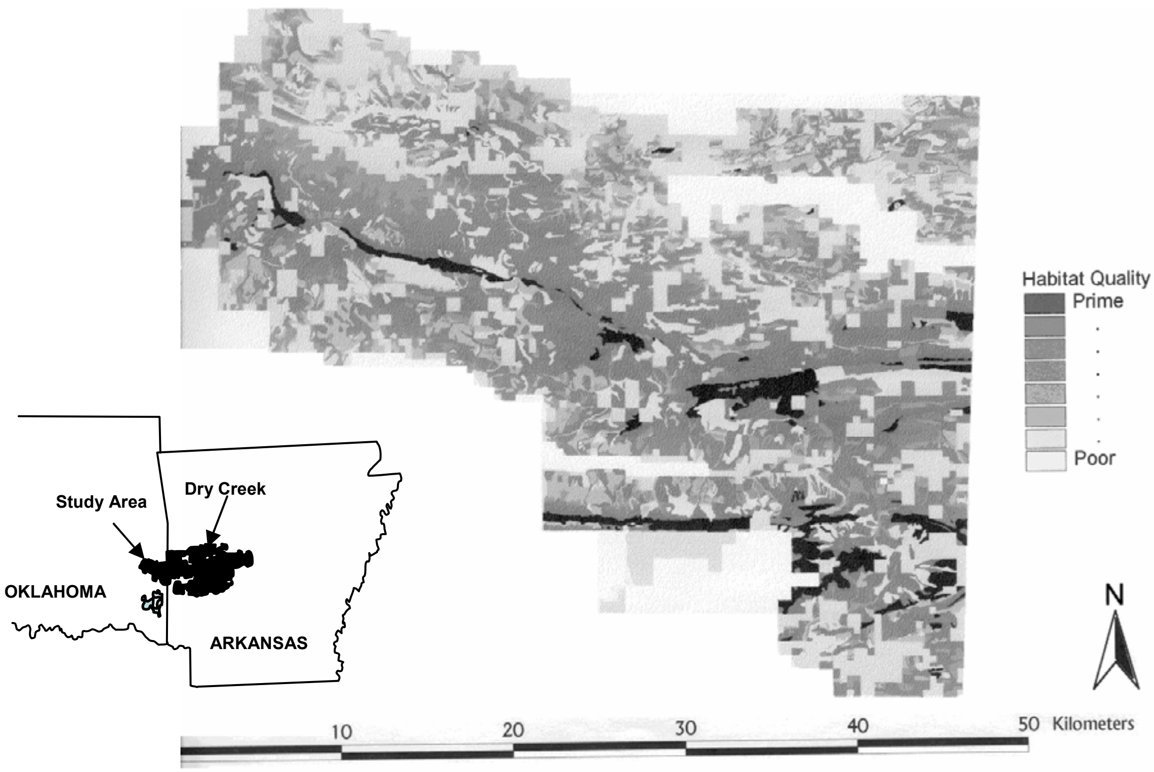
Figure Captions.

Figure 1. Map depicting distribution of modeled black bear habitat quality, based on Mahalanobis distance values in the >800-km^2 Kiamichi and Choctaw Ranger Districts of the Ouachita National Forest in southeastern Oklahoma. The east side of this map is the Oklahoma-Arkansas state border. Darker shades are associated with smaller Mahalanobis distances, which represent sites approaching $\underline{\hat{u}}$, or the mean vector of habitat characteristics calculated from relocations of black bears in the Dry Creek study area of Ouachita National Forest (Clark 1993*a*). Inset shows geographic relationship of the Oklahoma and Arkansas (Dry Creek) study areas.

Figure 2. Cumulative frequency distributions of Mahalanobis distance values for 350 sets of random points within buffered relocations (gray shading), bear relocations (solid line), study area (dashed line), and entire Ouachita National Forest (dotted line) in southeastern Oklahoma, 2001-2003. Random points within buffered relocations represent possible relocations of bears within the average error distance from the triangulated point.


Habitat Quality
Prime
Poor
Study Area
Dry Creek
OKLAHOMA
ARKANSAS
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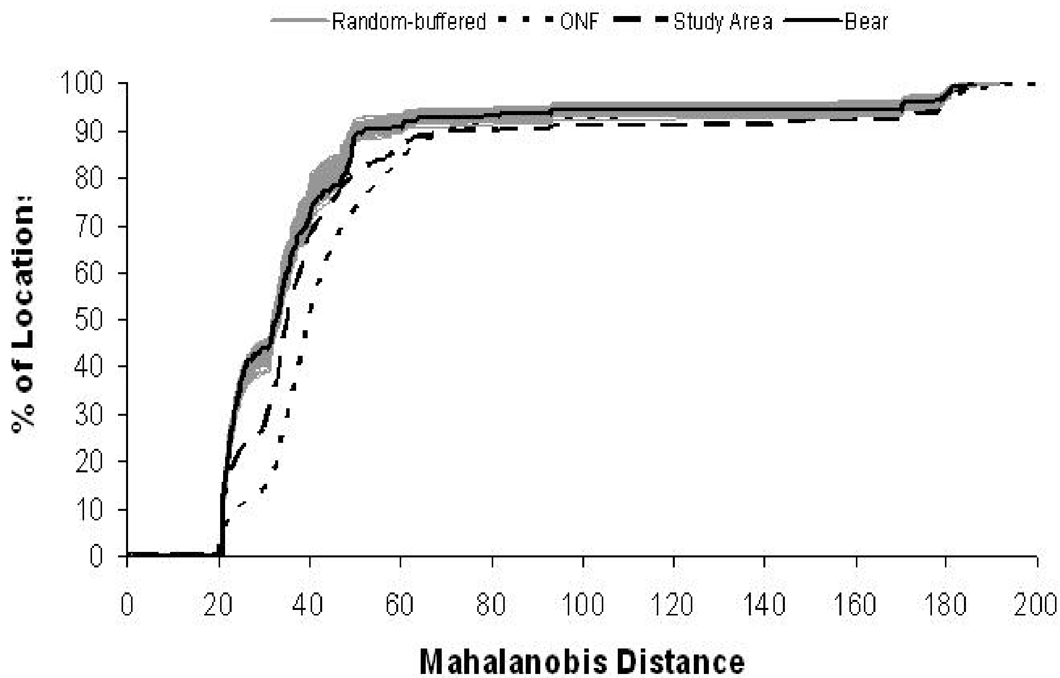
50 Kilometers


Random-buffered
ONF
Study Area
Bear
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Mahalanobis Distance