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Original Research Article

Risky business: Modeling mortality risk near the urban-wildland interface for a large carnivore

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ABSTRACT

We examined the spatial distribution of 382 black bear (*Ursus americanus*) mortalities in the Lake Tahoe Basin and Western Great Basin Desert (WGB) in Nevada, USA from 1997 to 2013. Of the 364 mortalities for which we could determine cause of death, vehicle collisions ($n = 160$) and direct removal of bears by management personnel ($n = 132$) were the two largest sources of mortality for bears in our study area at the confluence of the Sierra-Nevada Mountains and the Great Basin Desert. Here we use logistic regression and resource selection probability functions (RSPF) to model probability of mortality in the WGB based on anthropogenic and landscape variables. Further, we assessed the impact of spatial resolution on our analyses and resulting probability of mortality models. Human-induced mortalities of black bears were overwhelmingly concentrated near major roads (defined in our analyses as paved roads with two lanes or more), in the town of Incline Village, Nevada, and along the foothills of the Carson Range east of Lake Tahoe. Our results suggest mortality risk is associated with density of and distance to multiple forest types, human population density, landcover, recreation site density and distance, road density and distance, stream distance, hiking trail density, and waterbody distance. Our model results found environmental variables measured at coarse spatial resolutions such as distance to and density of forest best predicted black bear mortality risk, while anthropogenic variables measured at fine spatial resolutions like distance to and density of recreation site best predicted black bear mortality risk in our study area. Our results demonstrate that carnivore mortality as a phenomenon likely operates at multiple spatial resolutions and thus considering scale is important for modeling mortality risk on the landscape.

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1. Introduction

Habitat fragmentation, driven by development and land-use change, has increasingly led to humans and carnivores sharing landscapes in many parts of the world. The wide-ranging nature of large carnivores, and their ability to adapt to human-dominated landscapes, often brings carnivores to areas of increasing human activity, with expansion of human influence into wildlife habitat amplifying these effects (Crooks, 2002; Hanski et al., 2013). In general, these interactions are driven by the availability of resources attractive to both people and carnivores, such as proximity to shelter, water, and food (Knight, 2000; Conover, 2001). Dangerous or destructive human-carnivore interactions, real or perceived, may be the outcome of increased overlap in human-carnivore spatial use (Graham et al., 2005; de Azevedo and Murray, 2007; Basille et al., 2009; Silva-Rodriguez et al., 2009). This may lead to human-induced mortality to carnivores (Bradley et al., 2003; Woodroffe and Frank, 2005; Roger et al., 2011).

In ecosystems with increasing human influence, carnivore mortality rates can threaten population persistence (Baseille et al., 2013; Ordenana et al., 2010). In light of this, conservation scientists and managers seek to understand which landscape and anthropogenic factors best predict the nuanced drivers of carnivore mortality. Risk models accomplish this by analyzing and mapping the magnitude and spatial configuration of probability of mortality across a landscape (Burton et al., 2011). It is particularly important for mortality risk analyses to include anthropogenic variables that specifically reflect the diversity of human influence, and magnitude of human-induced mortality, across a landscape, particularly in areas with a high human footprint (e.g. along the wildland-urban interface; Nielsen et al., 2010).

Scale is an important variable in ecology, and the impacts of scale on patterns and dynamics of carnivore movement, behavior, survival, and mortality are often not well understood, nor do many studies identify how patterns at one scale relate to processes operating at other scales (Bowyer and Kie, 2006; Beever et al., 2006). Several studies demonstrate that landscape heterogeneity can be observed at multiple scales, and identifying the response of wildlife to such heterogeneity is therefore best studied at multiple scales (Beever et al., 2006; Boyce, 2006). Mortality risk analyses are commonly constructed at a single, and often coarse spatial resolution, justified by either the availability of spatial predictor variables at these larger scales and/or the assumption that this reflects the resolution at which large carnivores use a landscape (i.e. home range, territory, etc.). Recent improvements in the resolution at which habitat and movement data are collected have allowed conservation scientists and wildlife managers to test this assumption, finding evidence that finer-resolution variables, especially variables representing anthropogenic land use, may influence human-induced mortality risk (Mayor et al., 2009; Basille et al., 2013; Waller et al., 2013). This finer-scale approach may provide a better understanding of how carnivores use landscapes, and the effects of anthropogenic influence within carnivore habitat (Beckmann et al., 2015).

To understand the impact of spatial scale on predicting black bear (*Ursus americanus*) mortality, we modeled human-induced mortality risk using landscape characteristics at 382 locations of black bear mortality. Aside from information regarding hotspots of black bear-human conflict (Beckmann and Lackey, 2008b), little is known about how the spatial arrangement and magnitude of anthropogenic landscape variables influence black bear mortality risk in the Lake Tahoe Basin and western Great Basin and more broadly the western USA.

2. Study area

The current distribution of black bears in the western Great Basin (WGB), USA is restricted to the Carson Range of the Sierra Nevada, Pine Nut Mountains, Pine Grove Hills, Sweetwater Range, Virginia Range, and the Wassuk Range in western Nevada (Beckmann and Berger, 2003; Lackey, 2004, Fig. 1). These six mountain ranges and associated basins cover an area of approximately 12,065 km^2 and are characterized by steep topography with high granite peaks and deep canyons. Sixty percent of the study area is characterized as mixed sagebrush (*Artemisia* spp), 17% Juniper Woodland, and 10% classified as areas of human development. Mountain ranges are separated by desert basins that range from 16 to 64 km across (Grayson, 1993). These basins are often large expanses of unsuitable habitat (e.g., sagebrush) that bears do not use as primary habitat (Goodrich, 1990; Beckmann and Berger, 2003). The study area also encompasses part of the Humboldt-Toiyabe National Forest in western Nevada. Although most forest areas are under federal protection from resource extraction and development, the region has undergone rapid residential and commercial development in the last half century, driven by demand for recreational areas, resort hotels, and private vacation residences (Raumann and Cablk, 2008). This development has caused a decline in forest and native vegetation (Fig. 2; Beckmann and Lackey, 2008a, Raumann and Cablk, 2008). Areas with intact forest are popular for outdoor recreation, with numerous ski resorts and campsites found throughout the landscape (Goodrich and Berger, 1994). Bears in this region are at the eastern edge of their known range in the Great Basin with the closest viable population about 750 km away in western Utah, although recent evidence suggests black bear populations are expanding into historic habitat in the Great Basin where they have been absent for 80 + years (Lackey et al., 2013).

Historical records from newspapers and pioneer journals dating to 1849 indicate presence of both black bears and grizzly bears (*U. arctos*) in the interior mountain ranges of the Great Basin until their extirpation by the 1930s due in part to predator removal and landscape scale habitat changes (see Beckmann and Lackey, 2008a; Lackey et al., 2013). Habitat regeneration occurring over the past 80 + years due to changes in forestry practices and a post-1920s decline in the reliance on wood as a source of fuel, combined with management and conservation efforts over the past 30 years by the Nevada Department of Wildlife (NDOW) and the Wildlife Conservation Society (WCS), has allowed the black bear population to increase in western Nevada (Beckmann and Lackey, 2008a; b; Lackey et al., 2013).

Fig. 1. Study area in the Western Great Basin (WGB).

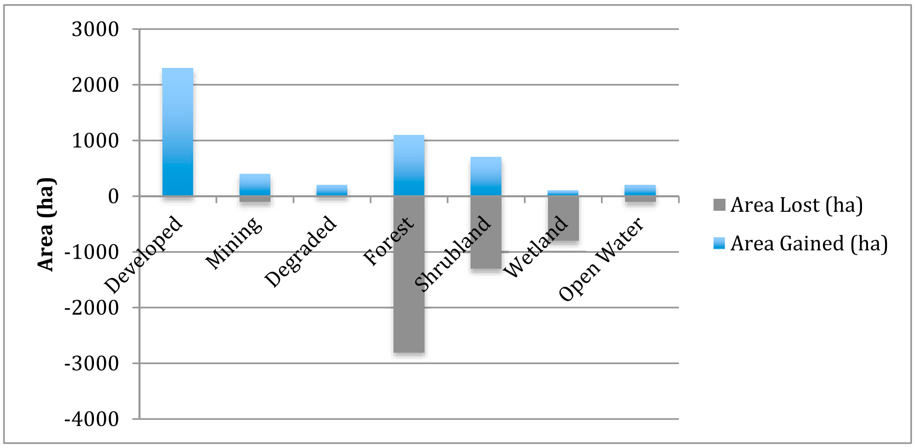

Fig. 2. Landcover type and area lost/gained in the western Great Basin (WGB) Desert, Nevada, USA since 1950 (adapted from Raumann and Cablk, 2008).

Successful recolonization of black bears into historical habitat depends on the availability of sufficient high-quality habitat. Predicting rates and patterns of recolonization requires that we understand the causes, rates and spatial distribution of mortality in order to manage potential “sink” areas on the landscape (Beckmann et al., 2010). An understanding of the characteristics influencing habitat quality, including risk of human-induced mortality, will allow for careful planning across the landscape that protects both human and bear populations. We took a modeling approach that allows us to extrapolate the probability of mortality to regions of the Great Basin that contain suitable and historical habitat that is not yet occupied by this relatively small (500–600 individuals) but recovering population. This is advantageous to managers trying to regulate mortality of an expanding carnivore population along a re-colonizing front.

3. Methods

3.1. Black bear mortality data collection

From 1997 to 2013, NDOW recorded black bear mortalities as personnel responded to incidents of vehicle collisions with bears along local roadways as well as to calls from residents about human-bear conflicts. Further, per NDOWs *Black Bear Conflict Management* policy (2007), managers removed (euthanized) bears if they were considered a public safety threat or a cause of chronic conflict. Mortality data in this study also includes locations of hunting mortalities which began in 2011 when Nevada implemented the state's first ever managed black bear hunting season.

3.2. Geographic information systems and development of landscape parameters

To model mortality risk across the landscape, we used a variety of spatial data layers in a Geographic Information System, representing the environmental and anthropogenic variables in the WGB that have been found to be biologically relevant to black bears and other large carnivores based on published literature (Table 1; Van Why and Chamberlain, 2003, Whittington et al., 2005, Nellemann et al., 2007, Goldstein et al., 2010, Obbard et al., 2010, Morzillo et al., 2011, Beckmann et al., 2015). It

Table 1
Variables used to select candidate models for black bear mortality risk in the Western Great Basin (WGB) Desert in Nevada, USA. Several (e.g. forest, road density, trail density) of the variables were examined at varying spatial scales (500 m, 1 km).

Variable	Type	Description	Units	Source	References
Aspect (w/DEM)	Continuous	Compass direction that a slope faces	–	USGS Digital Elevation Model	Beckmann et al., 2015
Deciduous forest sum 500 m; 1 km	Continuous	Density of deciduous forest in 500 m and 1 km scale	m	USFS LANDFIRE	Nielsen et al., 2010
Distance to forest	Continuous	Straight line distance to nearest forest	km	USFS LANDFIRE	Waller et al., 2013
Elevation	Continuous	Elevation above sea level	m	USGS Digital Elevation Model	Waller et al., 2013
Evergreen forest sum 500 m; 1 km	Continuous	Density of evergreen forest in 500 m and 1 km scale	m	USFS LANDFIRE	Beckmann et al., 2015
Forest sum 500 m; 1 km	Continuous	Density of forested landcover in 500 m and 1 km scale	m	USFS LANDFIRE	Beckmann et al., 2015
Human population density	Categorical	2010 census-defined human population density by zip code	-	US Census	Merkle et al., 2011
Land cover	Categorical	29 vegetative and anthropogenic landcover categories	–	USFS LANDFIRE	Beckmann et al., 2015
Mixed forest distance	Continuous	Straight line distance to mixed forest	km	USFS LANDFIRE	Nielsen et al., 2010
Mixed forest sum 500 m; 1 km	Continuous	Density of mixed forest in 500 m and 1 km scale	m	USFS LANDFIRE	Nielsen et al., 2010
Recreation site sum 500 m; 1 km	Continuous	Density of recreation sites in 500 m and 1 km scale	m	NDOW	Goodrich and Berger 1994
Recreation site distance	Continuous	Straight-line distance to nearest recreation site, trail head, camp site, or ski lodge	km	NDOW	Goodrich and Berger 1994
Road density 500 m; 1 km	Continuous	Density of roads in 500 m and 1 km scale	m	NDOW	Schwartz et al., 2010
Road distance	Continuous	Straight-line distance to nearest road	km	NDOW	Waller et al., 2013
Stream density 500 m; 1 km	Continuous	Density of streams in 500 m and 1 km scale	m	US BLM	Waller et al., 2013
Stream distance	Continuous	Straight-line distance to nearest permanent or seasonal stream	km	US BLM	Waller et al., 2013
Terrain roughness index	Categorical		–		Beckmann et al., 2015
Trail density 500 m; 1 km	Continuous	Density of trails at 500 m and 1 km scale	m	US BLM	Nielsen et al., 2010
Trail distance	Continuous	Straight-line distance to nearest hiking trail	km	US BLM	Nielsen et al., 2010
Urban polygon	Categorical	Census-defined urban areas	–	US BLM	Moyer et al., 2008
Water body distance	Continuous	Straight-line distance to nearest water body	km	NDOW	Moyer et al., 2008
Year	Categorical	Year of mortality incident	–	NDOW	

may be argued that some of our variables, including human population density (reflected in the 2010 census report), represent the landscape as a snapshot in time that may not be consistent across the 17-year period of black bear mortality data collection. However, we posit that these landscape variables did not change dramatically in the area over the period of the study (e.g. human population density increased by five percent over the entire 17-year period of the study). We used the Euclidean distance tool in QGIS to create layers representing the straight-line distance from any map cell to the nearest feature. To test the impact of spatial scale on black bear mortality risk, we constructed certain variables (e.g. forest) by distance to the variable, and the contextual metrics of the amount of the attribute within 500 m and 1 km (Beckmann et al., 2015). We also included fixed effects of year and age of bear by development stage (i.e. cub, sub-adult, adult).

We took the location points of mortality incidents and categorized them by sex (male $n = 240$ and female $n = 142$), and created circular buffers around each location point (Treves et al., 2011). Our circular buffers for male bears had a 6.3-km diameter, representing an average home range size of approximately 31 km^2. We chose a 5-km circular buffer diameter for female bears, representing an average home range size of approximately 20 km^2. Five random locations were generated for each "used" mortality location ($n = 1200$ male, $n = 710$ female) using QGIS to represent "available" resource points. We used Extraction Tools in QGIS to calculate values or characteristics (e.g. land cover type) for the variables measured on the "used" and "available" resource points (Ciarniello et al., 2005, 2007).

3.3. Model construction and data analysis

We developed resource selection probability function (RSPF) models using the statistical software program JMP (SAS Program, 2016) with landscape parameters and black bear mortality points collected over the duration of the study period. RSPF model development and attribute selection followed that proposed in Anderson and Burnham (2002) and Lele (2009). The RSPF model resulted in expected frequencies that are 'accurate' to the landscape from which they are derived (Lele, 2009). Mortality locations ($n = 382$) were identified as 'used' locations in model development. Our RSPF employed a logistic regression approach; using the logit command to compare characteristics of black bear mortality "used" sites with "available" sites in the study region (Manly et al., 2002; Sawyer and Brashares, 2013). For our logistic regression-based RSPF model, a "used" GPS location was considered a "success" and given a value of 1, where an "available" resource unit was given a value of 0. The RSPF is assumed to take the form:

$$w^*(x) = \exp(\beta o + \beta_1 x_1 + ... \_ \beta_p x_p)/1 + \exp(\beta_0 + \beta_1 x_1 + ... + \beta_p x_p)$$

where $x = (x_1, x_2, ..., x_p)$ holds the values for the X variables that are measured on a unit. Maximum likelihood estimates of the β parameters in the equation were calculated. We used chi-squared tests on deviances to assess whether there was any evidence that the probability of use of a location was related to a combination of the variables being considered. Attributes identified *a priori* as factors potentially impacting black bear mortality locations were elevation, forest sum within 500 m and 1 km, distance to forest, human population density, distance to road, road density at 500 m and 1 km, terrain roughness index, aspect, distance to recreation site, recreation site density at 500 m and 1 km, distance to water, urban polygon, distance to trail, trail density at 500 m and 1 km, distance to stream, and stream density at 500 m and 1 km (Beckmann et al., 2015). Our models included year and bear age (by month) as fixed effects. We tested for collinearity of candidate variables using Pearson correlation coefficients, and variables with a correlation coefficient $(r) > 0.7$ were not included together in the models (Ciarniello et al., 2007; Sawyer and Brashares, 2013). We evaluated AICc values for each model iteration (Anderson et al., 1998; Boyce et al., 2002), and we considered models comparable if the delta AIC was <2.0 (Ciarniello et al., 2007). The model with the best balance of model uncertainty and model bias was considered most parsimonious and best fit for the data. For models with similar AICc values, we chose the model with fewer terms (Quinn and Keough, 2002). We assessed the predictive capability of each model based on k-fold cross validation (Boyce et al., 2002). For our study, a model that had strong predictive capabilities would have a higher number of locations in bins with the highest RSPF scores. Once we derived the model that explained the most variance in the data, we used QGIS to display the probability of habitat selection over the entire study area.

4. Results

4.1. Human-induced mortality trends

A total of 364 black bear mortalities were reported during the period of 1997–2013 (vehicle collisions $n = 160$; public safety $n = 132$; and all others $n = 72$ Fig. 3). The majority of mortality reports were for male bears ($n = 214$), with the remaining being females ($n = 150$). Cubs and yearlings represented 46% ($n = 168$) of all mortality reports, 32% were adult bears ($n = 118$), 15% were juveniles ($n = 53$) and the remaining mortalities were of bears of unknown age (Table 2). Our analysis suggests the majority of the WGB landscape has low mortality risk for both male and female bears, with 68% of the study area presenting the lowest mortality risk scores (<25% probability of mortality; Fig. 4). However, patches of high-risk areas occur: in urban centers; along stretches of highways south of the greater Reno, Nevada area; in livestock-rich lands along the foothills of mountain ranges in our study area; and in residential neighborhoods directly north and east of Lake Tahoe, particularly in the town of Incline Village, Nevada (Fig. 4).

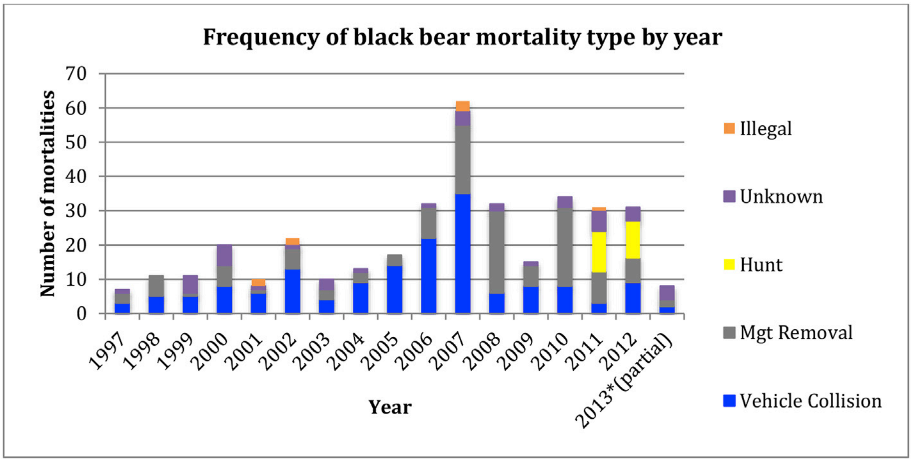

Fig. 3. Incidents of human-induced mortality of black bears in the Western Great Basin (WGB) Desert, Nevada, USA study system 1997–2013.

Table 2
Ages of black bears reported as human-induced mortalities in the western Great Basin of Nevada, USA.

Life stage at death	Number of mortalities
Cub (<16 months old)	110
Yearling (17 months −3 years old)	58
Juvenile (>3 years old)	53
Adult (>5 years old)	118
Unknown	25
Total	**364**

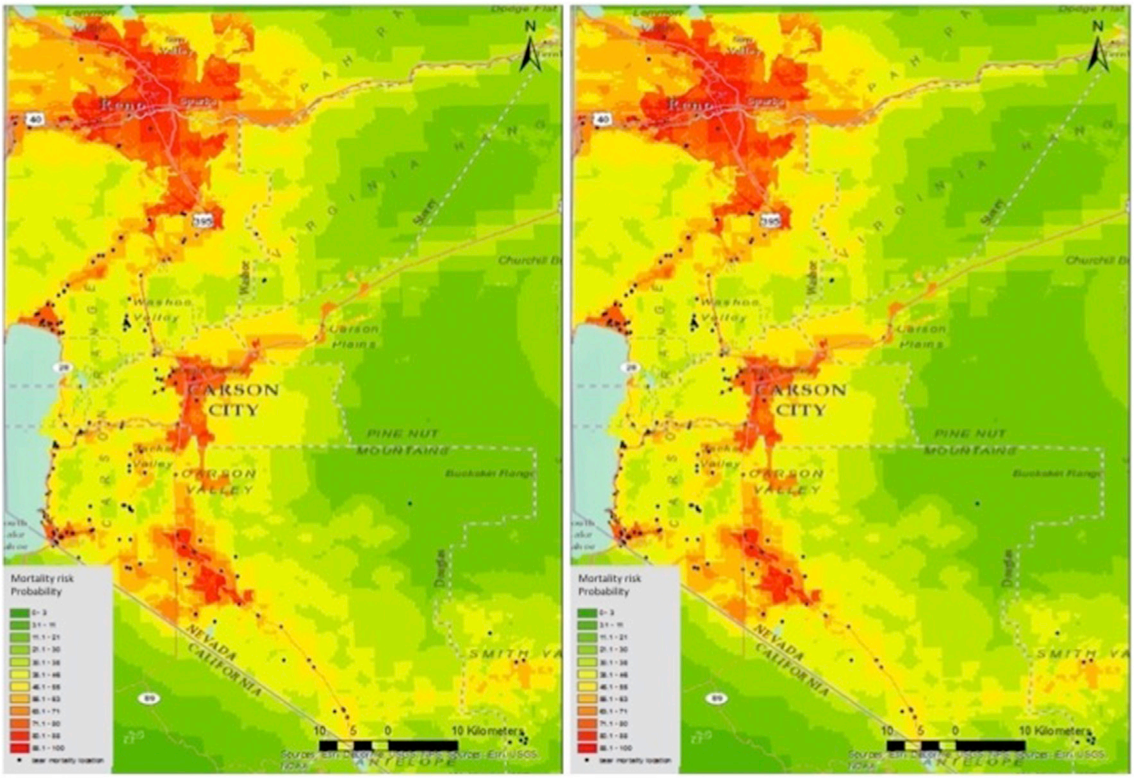

Fig. 4. A & B: Maps displaying fine resolution male (a) and female (b) black bear mortality risk in the WGB. Darker colors represent areas of higher probability of mortality.

Vehicle collisions made up 44% ($n = 160$) of total mortalities reported, and accounted for the majority of mortalities for most years up to 2008 (Fig. 3). In contrast, management removal mortalities accounted for 29% ($n = 106$) of total mortalities reported and were the leading source of black bear mortality in the years 2008 and 2010. For the years 2011 and 2012, when the bear hunt first began in Nevada, hunting mortalities account for 39% ($n = 12$) and 35% ($n = 11$) respectively. Mortalities stemming from known illegal activity were extremely rare ($n = 6$). Black bear mortality reports from unknown causes were also infrequent (12%; $n = 43$) (Fig. 3). The year 2007 had a particularly high number of mortality reports (n = 62), likely due to the severe drought and mast crop failure that year, which drove bears toward wildland-urban interface areas in search of food (Fig. 3).

Vehicle collision and management removal are the two most common types of human-induced mortality to black bears in the WGB, with rates that display significantly different temporal trends (2 sample t-test, $p = 0.009$). Mortality data on a monthly basis reveal management removals peak in the summer between June and August, with 57% ($n = 75$) of all management removals occurring during these three months over the course of the study period. Contrastingly, incidents of vehicle collisions peak in the fall between September and November, with 61% ($n = 98$) of all vehicle collision mortalities occurring during these three months over the course of the study period. Unsurprisingly, all mortality types become infrequent between January–March ($n = 9$) when black bears in the WGB are typically in dens.

4.2. Mortality risk model results

Our mortality risk models for male and female black bears were built with selected variables at two different scales (1 km and 500 m). The most parsimonious model (based on AICc value) for male and female bears were identical in terms of parameters, but different with respect to effect size of each parameter, and identified deciduous forest sum within 1 km, distance to forest, evergreen forest sum within 1 km, forest sum within 1 km, human population density, landcover, recreation site sum within 500 m, recreation site distance, road density within 500 m, road distance, stream distance, trail density within 500 m, and waterbody distance as significant predictors of mortality risk for black bears in the WGB (Table 3a,b). Probability of mortality risk was positively associated with distance to forest, human population density, recreation site sum 500 m, road density within 500 m, and trail density within 500 m (Table 3a,b). Probability of mortality risk was negatively associated with

Table 3A
Candidate models of mortality risk for male black bears in the Western Great Basin (WGB) Desert, Nevada, USA. Covariates selected in final model are in grey shading.

Covariate	p-stat	AICc	AUC
Deciduous forest sum 500m	2.58 x 10^-11	1.5823	0.50221
Deciduous forest sum 1km	4.28 x 10^-11	4.1421	0.51334
Distance to forest	4.47 x 10^-12	-391.7542	0.6192
Elevation	2.67 x 10^-3	-24.1662	0.52116
Evergreen forest sum 500m	3.3 x 10^-10	-73.7455	0.63498
Evergreen forest sum 1km	4.72 x 10^-10	-95.7324	0.72422
Forest sum 500m	1.03 x 10^-12	-482.9742	0.50451
Forest sum 1km	4.99 x 10^-10	-275.6121	0.58256
Human population density	8.69 x 10^-3	3.15764	0.51578
Landcover	3.1 x 10^-2	-97.9225	0.61321
Mixed forest distance	7.21 x 10^-15	-102.6121	0.67303
Mixed forest sum 500m	2.93 x 10^-14	-73.28771	0.59646
Mixed forest sum 1km	6.873 x 10^-15	-100.5386	0.59525
Recreation site sum 500m	5.89 x 10^-4	-14.62548	0.51182
Recreation site sum 1km	1.44 x 10^-3	-7.35283	0.51183
Recreation site distance	4.74 x 10^-4	-31.7934	0.57812
Road density 500m	1.36 x 10^-12	-14.9274	0.65211
Road density 1km	5.23 x 10^-11	-9.2651	0.65134
Road distance	3.14 x 10^-12	-103.9562	0.5921
Stream distance	3.3 x 10^-2	-48.6253	0.58256
Terrain roughness index	2.13 x 10^-7	-91.7263	0.56216
Trail density 500m	6.9 x 10^-5	-100.5211	0.51134
Trail density 1km	3.19 x 10^-3	-86.6273	0.51312
Trail distance	4.3 x 10^-3	-131.7534	0.50031
Urban polygon	1.00	-12.8123	0.71165
Water body distance	3.1 x 10^-1	-47.2912	0.51657
Year	1.00	-88.5102	0.50241

Table 3B
Candidate models of mortality risk for female black bears in the Western Great Basin (WGB) Desert, Nevada, USA. Covariates selected in final model are in grey shading.

Covariate	p-stat	AICc	AUC
Deciduous forest sum 500m	1.51 x 10^-11	16.7539	0.50221
Deciduous forest sum 1km	7.88 x 10^-11	7.326	0.51334
Distance to forest	3.90 x 10^-7	-100.9116	0.6192
Elevation	1.11 x 10^-3	-16.6109	0.52116
Evergreen forest sum 500m	3.42 x 10^-5	-59.4754	0.63498
Evergreen forest sum 1km	3.22 x 10^-4	-33.7784	0.72422
Forest sum 500m	3.91 x 10^-6	-261.3543	0.50451
Forest sum 1km	1.89 x 10^-12	-475.8823	0.58256
Human population density	6.57 x 10^-3	11.3190	0.51578
Landcover	3.21 x 10^-3	-125.2471	0.61321
Mixed forest distance	2.111 x 10^-10	-88.7764	0.67303
Mixed forest sum 500m	1.041 x 10^-11	-104.3765	0.59646
Mixed forest sum 1km	1.133 x 10^-9	-99.7365	0.59525
Recreation site sum 500m	3.87 x 10^-6	-8.5232	0.51182
Recreation site sum 1km	4.29 x 10^-3	-3.119	0.51183
Recreation site distance	2.74 x 10^-5	-51.0078	0.57812
Road density 500m	1.05 x 10^-9	-29.1322	0.65211
Road density 1km	3.71 x 10^-11	-4.1647	0.65134
Road distance	1.74 x 10^-8	-144.2319	0.5921
Stream distance	3.2 x 10^-4	-80.7486	0.58256
Terrain roughness index	2.13 x 10^-7	-91.9443	0.56216
Trail density 500m	8.8 x 10^-5	-93.2647	0.51134
Trail density 1km	1.17 x 10^-4	-64.30078	0.51312
Trail distance	4.5 x 10^-4	-213.5464	0.50031
Urban polygon	1.00	-14.9432	0.71165
Water body distance	2.1 x 10^-2	-67.4324	0.51657
Year	1.00	-100.3657	0.50241

deciduous forest sum 1 km, evergreen forest sum 1 km, forest sum 1 km, road distance, stream distance, and water body distance.(see Table 4a,b)

4.3. Model validity tests

We employed a k-fold cross-validation with the most parsimonious model for male and female bears, which for male bears suggested 79% of all mortality locations fell within the upper 2 bins, which were significantly different than rank ($t = 9.21$, $df = 7$, $P = 0.000032$), and for females 83% of all mortality locations fell within the upper 2 bins, which were significantly different than rank ($t = 8.87$, $df = 6$). These tests suggest our most parsimonious RSPF models are better predictors of black bear mortality locations than we can expect by random sample.

Table 4A
Parameter estimates and standard error of variables for the top RSPF model of male black bear mortality risk in the WGB.

Covariate	Estimate	SE	t	p
Deciduous forest sum 1 km	−0.029	0.52	−0.0557	3.92×10^{-8}
Distance to forest	1.5535	0.2891	5.3735	<0.001
Evergreen forest sum 1 km	−0.039	0.271	−0.143	8.86×10^{-3}
Forest sum 1 km	−0.093	0.319	−0.291	0.023
Human population density	1.559	0.1173	13.291	<0.001
Landcover				
Recreation site sum 500 m	0.338	0.776	0.4356	0.043
Road density 500 m	0.495	0.056	8.8392	<0.001
Road distance	−1.5325	0.3881	−3.9487	<0.001
Stream distance	−2.186	8.614	−0.25377	8.00×10^{-4}
Trail density 500 m	0.558	0.874	0.6384	0.079
Water body distance	−1.347	1.952	−0.69006	7.75×10^{-5}

Table 4B
Parameter estimates and standard error of variables for the top RSPF model of female black bear mortality risk in the WGB.

Covariate	Estimate	SE	t	p
Deciduous forest sum 1 km	−0.012	0.41	−0.0358	1.81×10^{-6}
Distance to forest	1.0043	0.2284	5.4866	<0.001
Evergreen forest sum 1 km	−0.051	0.178	−0.214	7.42×10^{-8}
Forest sum 1 km	−0.003	0.481	−0.337	0.011
Human population density	1.004	0.1101	11.262	<0.001
Landcover				
Recreation site sum 500 m	0.028	0.656	0.5355	0.009
Road density 500 m	0.726	0.004	7.9341	<0.001
Road distance	−1.860	0.3112	−2.1485	<0.001
Stream distance	−3.004	5.527	−0.16379	0.002
Trail density 500 m	0.443	0.980	0.7382	5.2×10^{-7}
Water body distance	−1.002	0.995	−0.62017	8.4×10^{-4}

5. Discussion

5.1. Scale impacts of modeling mortality risk

We found spatial scale of analysis to affect prediction of mortality risk for black bears in the WGB. In particular, variables representing the anthropogenic landscape at finer spatial resolutions (500 m vs 1 km) influenced probability of black bear mortality. There have been numerous studies of black bear ecology and space use, and almost all of these studies have been at relatively coarse resolutions of analysis of 1 km^2 or greater (Carter et al., 2010; Obbard et al., 2010; Merkle et al., 2011). This is because, until recently, few studies have had the capacity to collect finer-grained data (Brody and Pelton, 1989; Clark et al., 1993; Van Why and Chamberlain, 2003; Merkle et al., 2011), and the assumption that since black bears are relatively wide ranging, and omnivorous in their diet, their behavior would not reflect finer resolution variation in landscape structure (Mitchell and Powell, 2007; Moyer et al., 2007). Our results stand in contrast to this assumption. Our RSPF models using a suite of parameters measured at differing spatial scales identified key anthropogenic variables that are significant predictors of mortality risk measured at a finer scale (500 m density) – density of recreation site, density of road, and density of trail - yet did not identify these as significant at a coarser (1 km density) resolution. Similarly, Beckmann et al. (2015) found that incorporating a spatial hierarchical structure in RSPF models identified the importance of spatial scale for black bear resource use across the landscape in the Greater Yellowstone Ecosystem. Clearly, while black bears may select habitat at coarse spatial resolutions (Clark et al., 1998; Hersey et al., 2005; Garneau et al., 2008; Moyer et al., 2008; Obbard et al., 2010; Wynn-Grant, 2015), the human activities that drive the majority of mortalities in this system likely operate at finer resolutions and may not be detected in analyses with only coarse-resolution (i.e. 1 km-scale) variables.

The importance of several landscape features were significant predictors of mortality risk across spatial and temporal scale (e.g. amounts of deciduous forest, evergreen forest, and other forest cover). However, our models demonstrate that finer-resolution (i.e 500 m resolution) variables such as density of recreation site, road density, and trail density were factors that increase risk of mortality for black bears in the WGB Desert. These additional variables suggest management of certain human activities may be critical to bear population persistence. As conflict, particularly around the availability of anthropogenic food resources at the wildland-urban interface, appears to be the root of black bear mortality in many areas (Bunnell and Tait, 1985; Elowe et al., 1991; Pace et al., 2000; Hebblewhite et al., 2003; Koehler and Pierce, 2005; Howe et al., 2007; Beckmann and Lackey, 2008b; Beston, 2011), and urban areas are densely populated, these patterns are hardly surprising. Recreation sites in the WGB are typically located in heavily forested regions and near water sources, two characteristics of prime black bear habitat in the Great Basin Desert (one of the driest systems in North America in which black bears occur). Consequently, it was not surprising that density of recreation sites was an important predictor of black bear mortality on the landscape. It was surprising that scale influenced the importance of this factor, as density of recreation sites at the 500 m scale was important in predicting bear mortality, but not at the 1-km scale. The elevated mortality risk also associated with these sites serve as an example of how the pervasiveness of human activity in the WGB, even outside of regions with urban development, can fragment the landscape for wide-ranging animals like bears and generate habitat heterogeneity that can lead to negative interactions between humans and wildlife. Black bears are already present in many areas near recreation sites, and may become attracted to these sites due to the anthropogenic foods available in these areas.

5.2. Black bear mortality trends

In the last several decades, both the black bear population and human population in the study area have increased, while incidents of human-induced mortality to black bears have also increased (Beckmann and Berger, 2003; Lackey, 2004; Lackey et al., 2013).

Trends and variability in the causes of human-induced mortality to black bears are of interest to wildlife managers in the region. Wildlife-vehicle collisions were the leading source of human-induced mortality to black bears in the study system, a pattern in line with many areas where human activity fragments critical carnivore habitat (Beckmann et al., 2010). Incidents of vehicle collisions spiked in 2006 and 2007 likely due to the severity of drought in the region potentially causing black bears to range more widely, and thus more often in wildland-urban interface areas in order to find adequate food and water resources (Baruch-Mordo et al., 2014). These habitat use changes would bring them into closer and more frequent contact with roadways. These two years, along with 2010, also included a spike in management-related mortalities, where certain black bears were deemed a public safety threat by NDOW.

The majority of vehicle collision mortalities were black bears aged two years or younger, and many ($n = 89$) were cubs likely following their mother across the roadway. This trend suggests vehicle collision mortalities may be a limiting factor to the growth rate of the black bear population in the WGB, and we suggest the state continue examining options of road crossing structures (e.g. overpasses and/or underpasses) for bears and other wildlife in key linkage areas in western Nevada, particularly as bears move or disperse within and between various mountain ranges in the western Great Basin Desert. Clearly, vehicle collisions pose a significant mortality risk for bears, but human property and lives are also threatened by these accidents, making collision reduction a priority for wildlife managers and other policy makers. Even in areas of low human influence, crossing roads is often fatal and can have consequences for black bear population growth, especially when paired with other population pressures (Grilo et al., 2009; Roger et al., 2011).

5.3. *Management implications*

Our mortality risk models and resulting maps identify areas of heightened risk from vehicle collision and public safety mortality and are useful for wildlife management in the WGB (Fig. 4A and B). Patches of high-risk areas occur along stretches of highways south of the greater Reno, Nevada area, in livestock-rich lands along the foothills of mountain ranges in our study area, and in residential neighborhoods directly north and east of Lake Tahoe, particularly in the town of Incline Village, Nevada (Fig. 4). These areas require special management attention to reduce human interactions with bears that may lead to their mortality.

Increased prevalence of human-bear conflict, often leading to black bear mortality, may be a limiting factor in the local persistence of black bear populations, particularly in areas where they are just beginning to recolonize and expand their range (Beckmann and Lackey, 2008a; Schwartz et al., 2010; Rich et al., 2012). This trend is of elevated concern in the WGB, as human populations in many regions are expected to rapidly increase over the next few decades, thus potentially influencing frequency of black bear mortality incidents and possibly enhancing the magnitude of mortality risk in high conflict areas. Globally, human-induced mortality to carnivores may impact carnivore population persistence in systems with a considerable human footprint and activity (Nielsen et al., 2010; Bateman and Fleming, 2012). While highly variable in its form and level, human influence is pervasive, and the response of carnivores to heterogeneous landscapes can also vary spatially and temporally. Finer-scale patterns of human influence as seen in the form of roads, recreation sites, hiking trails, and coarse-scale patterns of forested vegetation that bears prefer characterize the landscape features that can attract, and increase mortality risk, for black bears. In light of these patterns, research at multiple spatial resolutions yields comprehensive ecological understanding of a system and will inform wildlife management decisions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2018.e00443.

Appendix A. 29 landcover classes included in USFS LANDFIRE landcover variable (Table 1):

Mediterranean California Alpine Bedrock and Scree
Sierra Nevada Cliff and Canyon
Inter-Mountain Basins Cliff and Canyon
Inter-Mountain Basins Active and Stabilized Dune
Inter-Mountain Basins Playa
Rocky Mountain Aspen Forest and Woodland
Inter-Mountain Basins Subalpine Limber-Bristlecone Pine Woodland
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland
Northern Pacific Mesic Subalpine Woodland
Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland
Rocky Mountain Montane Dry-Mesic Mixed Conifer Forest and Woodland
Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland
Rocky Mountain Montane Mesic Mixed Conifer Forest and Woodland
Great Basin Pinyon-Juniper Woodland
Inter-Mountain Basins Mountain Mahogany Woodland and Shrubland
Great Basin Semi-Desert Chaparral
Inter-Mountain Basins Big Sagebrush Shrubland
Great Basin Xeric Mixed Sagebrush Shrubland
Mojave Mid-Elevation Mixed Desert Scrub
Inter-Mountain Basins Mixed Salt Desert Scrub

Inter-Mountain Basins Montane Sagebrush Steppe
Inter-Mountain Basins Big Sagebrush Steppe
Inter-Mountain Basins Semi-Desert Shrub Steppe
Inter-Mountain Basins Semi-Desert Grassland
Rocky Mountain Subalpine-Montane Riparian Shrubland
Rocky Mountain Subalpine-Montane Riparian Woodland
Inter-Mountain Basins Greasewood Flat
North American Arid West Emergent Marsh
Temperate Pacific Montane Wet Meadow
Mediterranean California Subalpine-Montane Fen
Great Basin Foothill and Lower Montane Riparian Woodland and Shrubland
Mediterranean California Red Fir Forest and Woodland
Sierra Nevada Subalpine Lodgepole Pine Forest and Woodland
Mediterranean California Ponderosa-Jeffrey Pine Forest and Woodland
North Pacific Montane Grassland
Open Water
Developed, Open Space - Low Intensity
Developed, Medium - High Intensity
Barren Lands, Non-specific
Agriculture
Recently Burned
Recently Mined or Quarried
Invasive Southwest Riparian Woodland and Shrubland
Invasive Perennial Grassland
Invasive Annual Grassland
Invasive Annual and Biennial Forbland

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