Identifying habitat cores and corridors for the Iranian black bear in Iran

Kamran Almasieh[1], Mohammad Kaboli[1,3], and Paul Beier[2]

[1]*Department of Environmental Sciences, Faculty of Natural Resources, University of Tehran, Karaj, Iran*
[2]*School of Forestry, Northern Arizona University, Flagstaff, AZ 86011-5018, USA*

Abstract: The Iranian black bear (*Ursus thibetanus gedrosianus;* IBB) is a critically endangered subspecies. The IBB needs connectivity to access seasonally available foods and to provide gene flow among populations in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran. We identified IBB cores to be used as termini for modelled corridors. We mapped 31 habitat cores based on 200 IBB presence points from studies during 2008–2013, and 70 presence points from our own observations of IBB footprints and scats in 2014. We used MaxEnt on 101 spatially independent presence points to map areas of high-quality habitat. The largest population patch (approx. 8,700 km^2) covered 4 protected areas. We used least-cost modelling to model habitat corridors among 31 habitat cores. We considered a corridor locally important if it helped join nearby cores into a cluster that would support a large demographically and genetically vigorous population. We considered a corridor regionally important if it could connect the clusters united by local corridors. The most important local corridors were the corridors creating 4 clusters in the southeast of Iran. Also, we identified the 2 important regional corridors that could connect the 3 most important clusters. Although the density of roads in all habitat corridors was low (18.51 m/km^2), roads crossed many important corridors. Conservation of main habitat cores and corridors for the IBB in southeastern Iran should be considered by the Department of Environment in Iran.

Key words: habitat corridors, Iranian black bear, least-cost models, MaxEnt, population patches, *Ursus thibetanus gedrosianus*

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Natural habitats, including protected areas, are increasingly becoming isolated from each other by human land uses (Wikramanayake et al. 2004). Protected areas are often too small to support all the needs of viable populations of vertebrates over the long term, exposing many of these small and isolated populations to local extinction (Noss et al. 1996, Hilty et al. 2006). Connections between habitat cores—areas large enough to support a population—can mitigate many of the negative effects of habitat fragmentation by facilitating movement of individuals and genes (Beier and Noss 1998, Beier et al. 2008). A variety of approaches grounded in graph theory, including least-cost modelling (Adriaensen et al. 2003), circuit theory (McRae et al. 2008), and centrality analyses (Estrada and Bodin 2008), can be used to identify and describe important connectivity areas. Least-cost modelling in a Geographic Information System (GIS) is the procedure most widely used to design habitat corridors (Beier et al. 2008).

Conservation of large carnivores is a major concern for agencies and the public (Ripple et al. 2014). Because many large carnivores have low population densities, they are strongly affected by loss of connectivity (Beier 1993) and are therefore appropriate focal species for designing habitat corridors (Beier et al. 2008, Romportl et al. 2013). The Asiatic black bear (*Ursus thibetanus*) is a medium-sized bear that is distributed from Far East Russia and Japan to Iran. It is also known as the moon bear because of the white V-shaped mark on its chest (Fujiwara et al. 2013). The Iranian black bear (*Ursus thibetanus gedrosianus;* hereafter, referred to as the IBB) has the most western distribution of the 7 subspecies of the Asiatic black bear (Hwang et al. 2008) and is genetically distinct from other subspecies (Yusefi et al. 2014). In Iran, the IBB occurs only in the mountains of Kerman Province, Hormozgan Province, and Sistan and Baluchistan Province in the southeast of Iran (Fahimi et al. 2011; Fig. 1); the subspecies also occurs in western Pakistan.

[3]email: mkaboli@ut.ac.ir

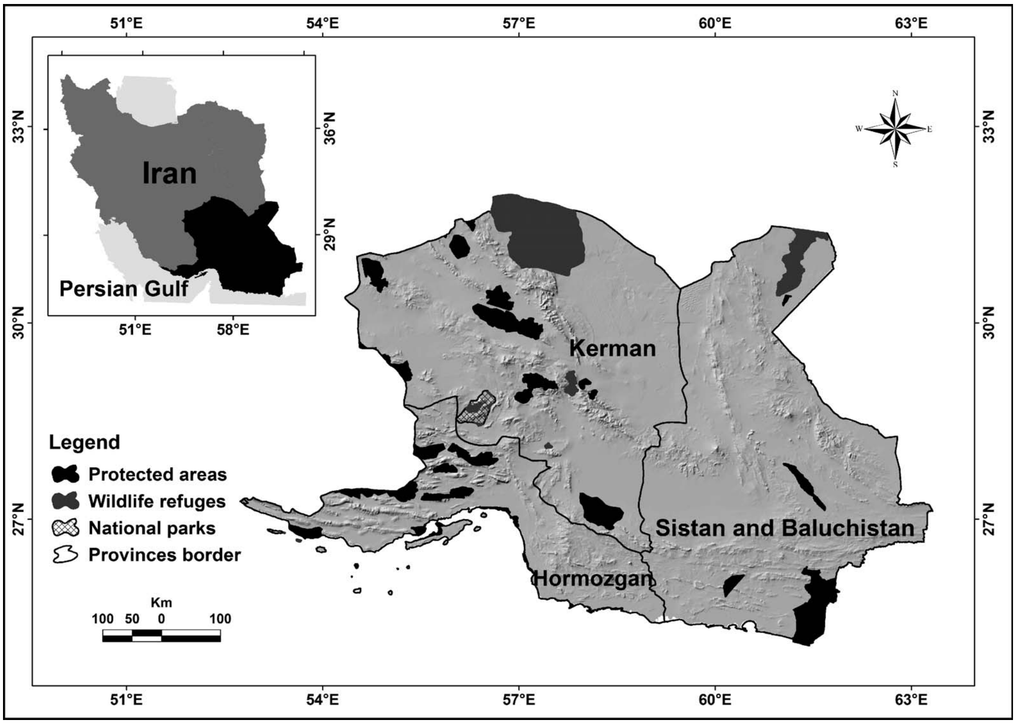

Fig. 1. Study area of the Iranian black bear in Iran (2008–2014).

The International Union for the Conservation of Nature Red List (Garshelis and Steinmetz 2008) lists the Asiatic black bear as vulnerable, while the IBB subspecies is listed as critically endangered as a consequence of its small and isolated populations (Garshelis and Steinmetz 2008). Conservation of habitat patches and corridors for the IBB may also benefit other species that share the same woodland and montane habitats, such as gray wolf (*Canis lupus*) and wild sheep (*Ovis vignei*).

Conservation of the IBB requires identification of habitat cores and corridors. Accordingly, our objective was to identify cores and corridors with the highest priority for IBB conservation in Iran. Therefore, we first mapped plausible IBB cores in Iran, using 270 presence points to model habitat and define likely patches of good habitat for the IBB in Iran. Then, we used least-cost corridor modelling to identify habitat corridors between 31 IBB cores in Kerman, Hormozgan, and Sistan and Baluchistan provinces in Iran (Fig. 1). Finally, we determined the important cores and corridors for IBB conservation. The Department of Environment (DOE) of Iran can prioritize the important cores and corridors into its programs to increase the amount of protected areas in the conservation network up to 15% of Iran's total area.

Study area

The study area covers the distributional range of the IBB in Iran (Fig. 1), a vast arid-plain area with scattered woodlands, primarily in mountainous regions. In Kerman Province, bears occur mainly in montane woodlands that support tree species such as *Pistacia atlantica, P. khinjuk,* and *Amygdalus lycioides,* the fruits of which are eaten by the IBB (Fahimi et al. 2011). The annual precipitation in mountainous areas of Kerman averages 350 mm, with cold winters (average 10°C; IRIMO 2010).

Hormozgan, Sistan and Baluchistan, and southern Kerman provinces are drier (annual precipitation is approx. 100–150 mm) and hotter, averaging 35°C in summer, with short, mild winters (average 20°C; IRIMO 2010). The scattered woodlands are dominated by plants such as *Prosopis cineraria, Nannorrhops ritchiana,* and *Tamarix* spp. In late summer, IBBs seek out date palms (*Phoenix dactylifera*), which are the most common fruit tree in these woodlands (Ghadirian and Pishvaei 2014).

In our study area, there are 31 protected areas, including 1 national park and 7 wildlife refuges (Figs. 1, 2). Many protected areas in the study area coincide with the natural habitat of the IBB.

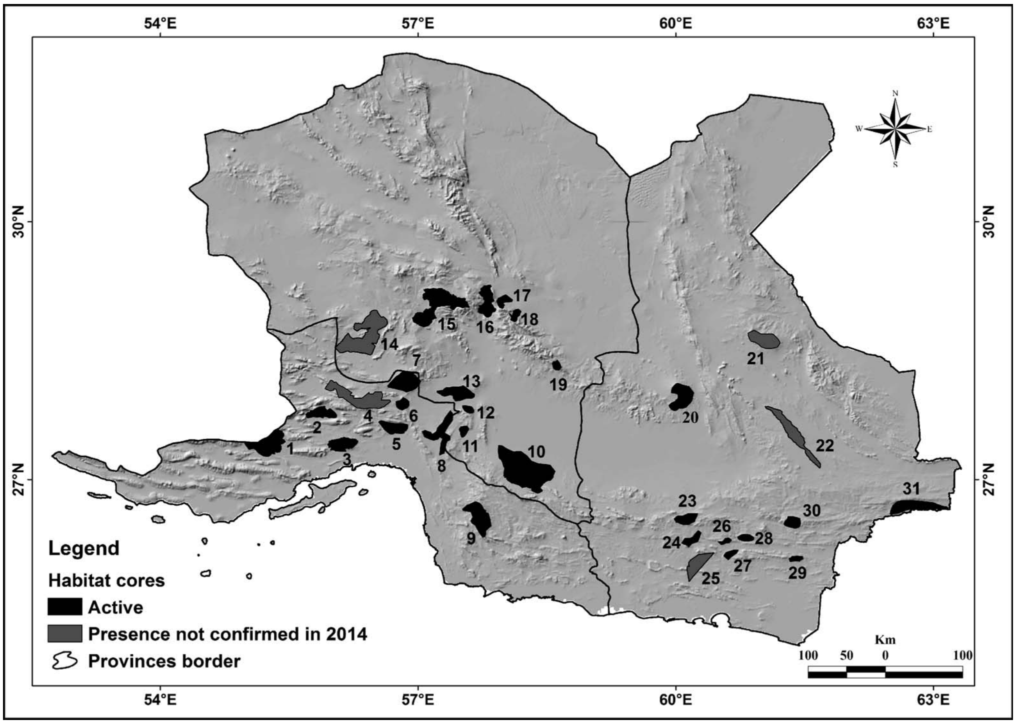

Fig. 2. Habitat cores of the Iranian black bear in Iran. (1) Hormod Protected Area, (2) Baz Mountain Protected Area, (3) Geno Protected Area, (4) Homag Mountain Protected Area, (5) Nian Mountain Area, (6) Shagharud Area, (7) Kusha–Ahmadi Area, (8) Rudan Area, (9) Bashagard Area, (10) Marz Protected Area, (11) Maadan Mountain Area, (12) Sorkh Mountain Area, (13) Kalmorz Mountain Area, (14) Khabr National Park, (15) Bahr–Aseman Protected Area, (16) Zaryab Wildlife Refuge, (17) Shir Mountain Protected Area, (18) Sang -e- Mes Protected Area, (19) Kuhshah Mountain Area, (20) Bazman Area, (21) Taftan Mountain Area, (22) Birk Mountain Protected Area, (23) NikShahr Area 1, (24) NikShahr Area 2, (25) Puzak Protected Area, (26) Nikshahr Area 3, (27) Nikshahr Area 4, (28) Nikshahr Area 5, (29) Begaband Mountain Area, (30) Moshkadem Area, and (31) Nahang River Area.

The 2 largest natural areas in Kerman Province are protected within Zaryab Wildlife Refuge and Bahr–Aseman Protected Area, but most natural areas in Hormozgan, and Sistan and Baluchistan provinces are not protected.

Methods

Presence points and identifying habitat cores

The DOE of Iran provided 24 presence points in Sistan and Baluchistan, Mohitban Society provided 166 presence points in Kerman, and Plan for the Land Society provided 10 presence points in Hormozgan Province. These points were collected from 2008 to early 2014 based on credible reports of direct observations, camera-trap photos, footprints, and scats occurring both inside and outside the protected areas. We conducted additional surveys during September–November 2014. To select survey sites, we built a habitat model (a version of the model described in the next section) from these 200 presence points, and identified the 150 10 × 10-km cells with highest expected mean habitat quality. In each of the high-quality cells, we interviewed local informants for credible reports of sightings, footprints, or scats, and followed up with field surveys, which yielded 70 new presence points based on direct observations of footprints, scats, or other signs. We mapped the 270 presence points to the precision of the Global Positioning System device (<10 m error).

We identified IBB cores so that we could use the cores as termini for modelled corridors. Thus, designating an area as a core does not indicate anything about its demographic status or its long-term viability as an independent population. We used 3 rules to identify IBB habitat cores from our 270 presence points. (1) If IBB presence was confirmed in a protected area, we considered the entire protected area a habitat core. (2) Similarly, if IBB presence was confirmed in a mountain range surrounded by plains, we considered the whole mountain range a core. And (3), in other areas, we drew polygons to include presence points that were close to each other, along with intervening natural woodlands, and considered each such polygon a core.

Habitat suitability modelling

We wished to model habitat suitability so that we could (1) map large areas of potential habitat that could be priorities for future surveys, (2) estimate resistance as a function of habitat suitability, (3) characterize habitat suitability in modelled corridors, and (4) map patches that might support an IBB population (population patches) or might facilitate long-distance movement (stopover patch). We modelled habitat suitability with MaxEnt version 3.3.3k. (Phillips et al. 2006), which compares values of environmental variables in presence cells with values of the same variables at a sample of background cells (pseudo-absence cells) to create a model of predicted suitability. MaxEnt is suitable for models using a small number of presence-only records, and predicts species distributions better than alternative procedures (Phillips and Dudik 2008). MaxEnt includes interactions between different predictors, both continuous and categorical. The algorithm provides a continuous habitat-suitability map (Phillips et al. 2006).

To minimize lack of independence among bear presences, we used the "Spatially Rarify Occurrence Data" in SDMtoolbox (Brown 2014) to exclude any bear presence <1 km from another bear presence. We considered a 1 × 1-km cell a presence cell if it contained ≥1 presence points. These procedures left 101 relatively independent presence cells.

To restrict pseudo-absences to an informative set of available background points (Anderson and Raza 2010, Barbet-Massin et al. 2012), we considered all areas within 120 km of presence points as available (polygon in Fig. 3, top), and excluded islands of southern Iran. This distance is approximately twice the maximum dispersal distance documented for the American black bear (*U. americanus;* Costello 2010). We selected 10,000 pseudo-absence points (Phillips and Dudik 2008), and we randomly selected 75% of the presence points as the training data set and used the other 25% as test data (Pearson et al. 2007).

Environmental covariates included elevation, topographic position, 3 climate variables, land cover, distance from road, and distance from river, all at 1 × 1-km resolution. We calculated topographic position from elevation within a 3-cell neighborhood radius (Majka et al. 2007); we classified a 1 × 1-km cell as canyon bottom if cell elevation was ≥100 m lower than the neighborhood average, ridge-top if the cell elevation was ≥100 m higher than the neighborhood average, flat–gentle slope if the cell was neither a canyon bottom nor a ridge-top and slope was <3°, and steep slope if the cell was neither a canyon bottom nor a ridge-top and slope was >3°. Following the advice of Jenness et al. (2013), we selected elevation and slope thresholds by generating maps using alternative thresholds and selecting the map that produced slopes, valleys, and ridges that best matched topography evident in aerial photographs and hillshade maps. Out of 19 available climate variables (WORLDCLIM- Global climatic data; Hijmans et al. 2005), we initially chose BIO1 (Annual mean temp), BIO4 (Temperature seasonality [SD × 100]), BIO12 (Annual precipitation), and BIO15 (Precipitation seasonality [CV]), because they were uncorrelated with each other (all pairwise correlation coeff. values <70%). We removed BIO1 because it was highly correlated with elevation. We combined 49 land-cover classes (FRWMO 2010) into 9 broad classes: montane woodlands (7.3% of the study area), montane woodlands with low density of trees (1.3%), arid semi-forest mountains (9%), agricultural lands (3.9%), salt lands and sand dunes (6.6%), rangelands (59.6%), bare lands (11%), water resources (1.2%), and human uses (0.1%), and assigned each 1-km cell to the class with the highest proportion of the cell. The first 8 classes are relevant to food, hiding, and thermal cover; and the urban-developed class represented human disturbance. We also calculated distance from road (NCC 2012) because bears likely avoid roads (Brody and Pelton 1989), and distance from water (NCC 2012) because the IBB depends on water in arid areas of southeastern Iran. We converted feature maps of road and water to raster maps and calculated the distance from the center of the cell to the nearest road or water source. Thus, we used 8 predictors to develop the habitat model.

We used area under the receiver operating characteristic curve (AUC) to evaluate model performance. We used a jackknife test within MaxEnt to evaluate the relative contribution of each variable, including categorical predictors (land cover and topographic

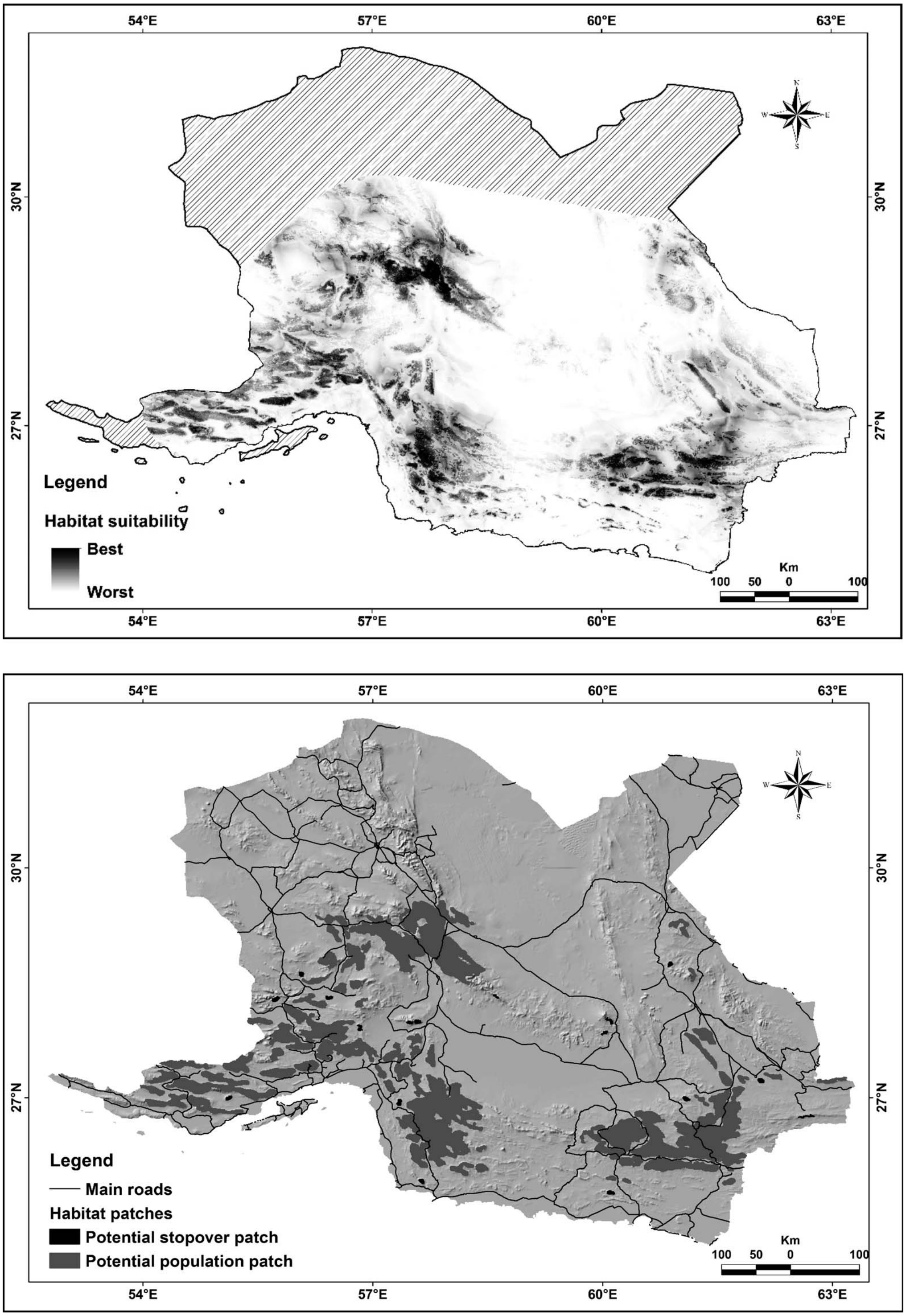

Fig. 3. (top) Relative habitat suitability for the Iranian black bear estimated by MaxEnt. (bottom) 45 modelled potential population patches and 17 modelled potential stopover patches. Data were derived from 200 presence points identified during 2008–2013 and 70 presence points identified during 2014 in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran.

position). MaxEnt assigns a score to each cell that reflects the probability of a cell being used. We rescaled these scores to a 0–100 scale.

We used the habitat suitability map to identify potential stopover patches and potential population patches for the IBB. Following Majka et al. (2007), we first calculated a neighborhood suitability score as the mean score in a 3-cell-radius neighborhood. We identified blocks of ≥10 contiguous cells with neighborhood suitability scores >26 as potential "stopover patches" for the IBB. We chose a threshold of 26 based on the equal training sensitivity and specificity logistic threshold in MaxEnt result (Liu et al. 2005), and a threshold of 10 cells because female Asiatic black bears have a home range size of 10 km^2 (Yamamoto et al. 2012). Although such patches might not be large enough to support long-term occupancy by IBBs, they could provide an opportunity for a bear to eat and rest during movement between widely separated IBB cores. We considered blocks of ≥50 contiguous cells with neighborhood suitability scores >26 as potential "population patches" for the IBB (i.e., large enough to contain approx. 5 females and thus support a population for at least several years).

Habitat corridor modelling

We used CorridorDesigner software in ArcGIS 10.2 to model habitat corridors (Majka et al. 2007). CorridorDesigner identifies least-cost corridors between termini (start–end locations). We identified a terminus in each core area as the set of all potential population patches within the core area. We did not model corridors between each of the 465 pairs of cores. Instead, we modelled corridors for 55 selected core pairs based on reports of local informants about potentially dispersing or wandering IBBs (direct observations, footprints, or scats); presence of some high-quality habitat or mountainous areas between potential pairs; or to ensure ≥2 modelled corridors from each core (1 modelled corridor to each of its nearest 2 neighboring cores).

We used the complement of suitability (i.e., 100 minus suitability) as an estimate of resistance of each cell. CorridorDesigner outputs corridors in nested swaths representing the lowest-cost 0.1–10% of the landscape between habitat cores. The least-cost algorithm causes the width of each swath to increase in areas of high-quality habitat and decrease in low-quality habitats. We selected the swath with an average width of ≥3 km, corresponding to the approximate hypothetical width of a square home range of a female Asiatic black bear (10 km^2; Yamamoto et al. 2012). That swath was used as the modelled corridor.

Within each corridor, we used CorridorDesigner Evaluation Tools to calculate the density of roads and rivers and the proportion of each land-cover type (Jenness et al. 2014). We identified important corridors at 2 scales—local and regional. We considered a corridor to be an important local corridor when all or most of the following criteria were present: (1) the corridor connected cores known to support the IBB, (2) both cores and their modelled corridor existed within the same area of relatively high habitat suitability (e.g., within a potential population patch), (3) a river flowed through the corridor, and (4) dispersers had recently been reported in the corridor. On the other hand, we considered those corridors that potentially connect the clusters united by local corridors to be regional corridors.

Results

IBB habitat cores

We identified 31 IBB cores (Fig. 2), which collectively covered an area approximately 15,282 km^2 and included 12 protected areas (Fig. 1). The smallest core (Core 26) was approximately 65 km^2. Our 2014 field surveys identified several cores that had not been previously mapped, or in which bears had been presumed extinct (e.g., Cores 17 and 18 [identification numbers in Fig. 2]). Our 2014 surveys were the first to document presence of the IBB in Cores 6, 19, and 30. In 2014, we found no signs of bears in some areas where bears previously had been detected (e.g., Cores 4, 5, 22, and 25). Four of the areas lacking bear sign in 2014 were protected areas, including the one national park (Core 14) in the study area. We retained these cores in our map of cores because it is possible that bears still persist there or (provided that connectivity is maintained) the recolonization of these cores may be expected. Also, some of these cores were protected areas (including one national park) that are vital to the network of protected areas of Iran.

Habitat suitability model

Our MaxEnt model had an AUC of 0.91 (on a scale of 0–1, where 1 indicates perfect discrimination of presence points from pseudo-absence points), and thus the model had high accuracy. Topographic position was the most important predictor variable;

Table 1. Relative importance of predictors of the probability of occurrence of the Iranian black bear in a MaxEnt model, derived from 200 presence points identified during 2008–2013 and 70 presence points identified during 2014, in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran.

Environmental predictors	Importance (jackknife test)	Subclasses	Importance (response curves of MaxEnt)
Topographic position	1	Canyon bottom	1
		Steep slope	2
		Ridge-top	3
		Flat–gentle slope	4
Annual precipitation (BIO12)	2		
Distance from river	3		
Temperature seasonality (BIO4)	4		
Land cover	5	Montane woodlands	1
		Montane woodlands with low density of trees	2
		Arid semi-forest mountains	3
		Rangelands	4
		Agricultural lands	5
		Water resources	6
		Salt lands and sand dunes	7
		Bare lands	8
		Human uses	9
Distance from road	6		
Elevation	7		
Precipitation seasonality (BIO15)	8		

canyon bottoms and steep slopes had the highest probability of presence, whereas flat–gentle slopes had the lowest. Among land-cover types, montane woodlands, montane woodlands with low density of trees, and arid semi-forest mountains had the highest probability of presence of the IBB (Table 1).

The IBB cores (Fig. 2) tended to coincide with areas of high-quality habitat (Fig. 3, top), and every IBB core overlapped a modelled potential population patch (Fig. 3, bottom). The 45 potential population patches covered approximately 40,000 km^2 and the 17 stopover patches covered approximately 580 km^2. Approximately 10% of the study area is in potential population patches or stopover patches, of which only approximately 13% is protected by the DOE of Iran (Figs. 1 and 3, bottom).

The largest population patch (approx. 8,700 km^2) covered Cores 15–18; it is probably the most important complex in all of Iran. The second largest population patch (approx. 8.500 km^2) covered all of Core 9 and large areas of Cores 8 and 10; it is the best population patch in Hormozgan Province. The third largest population patch was approximately 8,400 km^2 and covered Cores 23–30, which are the best habitat cores for the IBB in Sistan and Baluchistan Province.

Potential habitat corridors

We identified approximately 55 modelled habitat corridors for the IBB in Iran; some corridors had >1 strand (Fig. 4). Habitat corridors encompassed an area of 17,101 km^2. The mean density of roads and rivers in all habitat corridors was 18.5 m/km^2 and 33 m/km^2, respectively. Rangeland was the dominant land cover across all corridors (55%), followed by arid semi-forest mountains (19.4%) and montane woodlands (14.7%).

The most important local corridors included (A) corridors among the cluster of Cores 15–19 in Jebal -e-Barez Mountains, (B) corridors among the cluster of Cores 6–13 in Great Bashagard, (C) corridors among the cluster of Cores 23–28 in Nikshahr area, and (D) the triangle of corridors between Cores 28 and 30, 27 and 29, and 29 and 30 in Sarbaz area (Fig. 4).

The most important regional corridors were (E) the corridor between Core 15 and Core 7, which would connect the 15–19 cluster to the 6–13 cluster, and (F) the 4 long (173–259-km), parallel, and partially overlapping corridors between Cores 9 and 25, Cores 9 and 24, Cores 9 and 23, and Cores 10 and 23 (Fig. 4). Table 2 shows the mean corridor length and width and mean densities of roads and rivers for corridors in the 4 main clusters and the 2 most

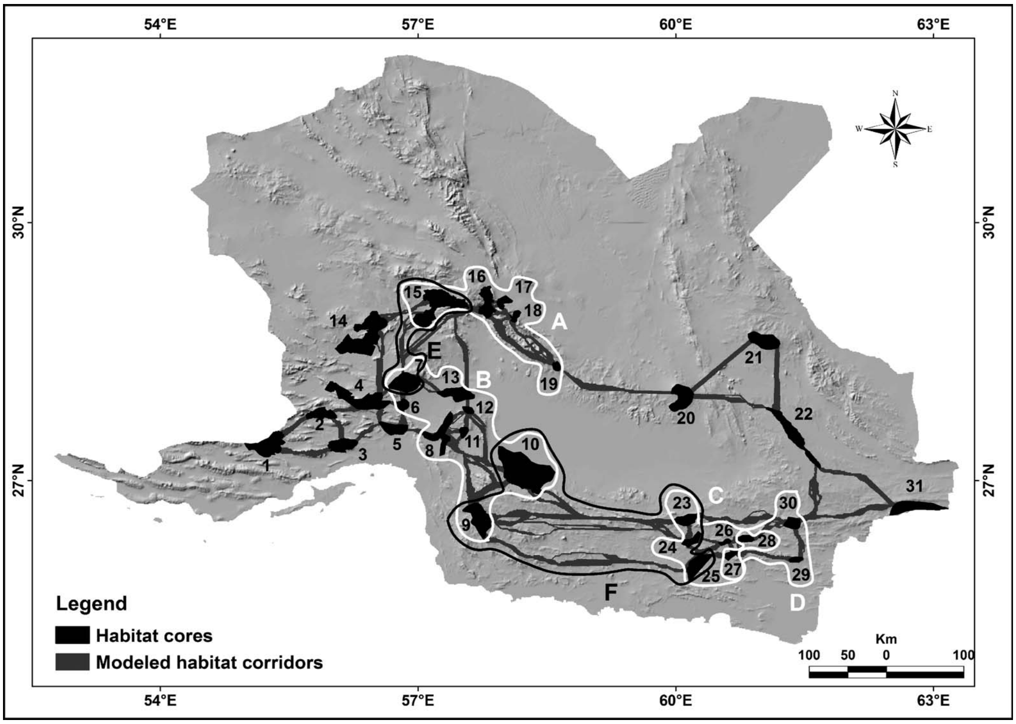

Fig. 4. Modelled habitat corridors of the Iranian black bear. Data were derived from 200 presence points identified during 2008–2013 and 70 presence points identified during 2014 in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran. White lines represent clusters of cores (A: Jebal -e-Barez Mountains, B: Great Bashagard, C: Nikshahr area, and D: Sarbaz area) united by important local corridors. Black lines represent regional corridors (E and F) connecting the 3 clusters.

important regional corridors. Detailed information on individual corridors is provided in Supplemental Material (Table S1).

Discussion

Habitat cores

Our study identified 31 habitat cores, 45 potential population patches, 17 potential stopover patches, and 55 potential habitat corridors between cores for the IBB in Iran. We provide the first documented presence of the IBB in Core 30, which may provide a crucial stepping stone from the cluster of Cores 23–28 to Cores 22 and 31 in Sistan and Baluchistan Province. We also provide the first documented presence of the IBB in Cores 19 and 6. Core 19 is located approximately halfway between Cores 16 and 20 and thus may be a crucial link between Kerman Province and Sistan and Baluchistan Province. Core 6 may provide a link to core areas in

Table 2. Properties of clusters and important regional corridors of the Iranian black bear in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran, derived from 200 presence points identified during 2008–2013 and 70 presence points identified during 2014.

	Corridor properties				
Clusters and important regional corridors	Mean length (km)	Mean width (km)	No. of corridors (strands)	Mean road density (m/km^2)	Mean river density (m/km^2)
Cluster A	39.1	4.6	6 (9)	53.0	30.6
Cluster B	48.5	4.6	11 (15)	17.7	21.4
Cluster C	19.4	4.2	8 (9)	50.7	113.6
Cluster D	51.2	3.9	3 (4)	41.7	28.6
Regional corridor (E)	72.8	3.3	1 (2)	0.0	46.0
Regional corridor (F)	225.7	4.5	4 (8)	7.4	25.8

western Hormozgan Province from the larger cores to the north and east.

Although we did not confirm the presence of IBBs in some areas (e.g., Cores 14 and 22), these areas can be targeted for the recolonization and reintroduction of the IBB. The confirmed presence of the IBB in a large cluster of Cores (6–13, and 15–19) suggests there may be a large source area that could export dispersing bears to the large Core 14 or other suitable habitats without confirmed IBB presence. After 4 decades with no confirmed records of presence (based on local informants and observation of IBB signs), IBB existence in Core 18 during the past 3 years is a promising example of likely recent recolonization. We may have failed to find evidence of the IBB in some occupied cores; therefore, we strongly recommend against inferring absence of the IBB in any of the mapped potential core areas. Although Core 31 is mapped as a relatively unsuitable habitat, we included it as a potential stepping stone to IBB populations in nearby Pakistan.

Many cores are arrayed along continuous chains of mountains (e.g., Cores 15–19), and the modelled corridors identify these mountainous areas as potential corridors. Although some cores are relatively isolated by surrounding plains (e.g., Core 13), IBBs can cross plains. For example an IBB killed by poachers in 2001 in the Abkhan Plain in Khash County between Cores 21 and 22 and 40 km from Core 22 (the nearer of the 2 cores) was likely a dispersing animal.

Habitat modelling and patches

Our model identified topographic position as a strong predictor of IBB presence, probably because IBBs depend on valley bottoms for providing food in riparian areas and because steep slopes provide security against humans. The montane woodlands of Kerman Province and the arid semi-forest mountains in the other 2 provinces had the highest probability of bear existence in our habitat suitability model.

There were 3 large patches of highly suitable modelled habitat, 1 in each of the 3 provinces (Fig. 3, bottom). The largest population patch covered a large area of Cores 15–19 in Kerman Province. We believe this population patch is the most important habitat for the IBB in Iran because these cores are protected, the montane woodlands provide diverse food sources in all seasons, the area has the highest modelled habitat suitability, and because these cores have the highest known density of the IBB in Iran (Fahimi et al. 2011). We consider Cores 8–10 in Hormozgan Province as the second most important habitat patch in Iran because it also lies in a large patch of highly suitable habitat and has the largest known density of the IBB in this province (Ghadirian et al. 2012). Therefore, we recommend that Cores 8 and 9 be protected by the DOE of Iran. Cores 23–30 contain the best habitats for the IBB in Sistan and Baluchistan Province. However, this potential population patch is fragmented by roads, which may reduce habitat quality. Cores 23–30 support the largest number of IBBs in Sistan and Baluchistan Province (Fahimi et al. 2013). Unfortunately, only one of these cores is protected. As a result, we recommend that the DOE of Iran protect some of the remaining cores as well.

IBB corridors

The IBB needs connectivity across the landscape to access seasonally available foods, to provide gene flow and demographic connectivity among populations, and to allow for new populations to be established by dispersal into appropriate but unoccupied habitat patches. Corridors among Cores 15–19 were the most important local corridors, potentially creating a cluster of cores (Fig. 4: Polygon A) with the highest density of the IBB in Iran (Fahimi et al. 2011). A large potential population patch covered these cores, which indicates high connectivity among cores. Conservation of these important corridors should be relatively easy, and conserving these corridors would produce a cluster of cores supporting a large demographically and genetically vigorous population. Corridors that formed 2 other important clusters (Fig. 4: Cluster B consisting of Cores 6–13, and Cluster C consisting of Cores 23–28) are in relatively arid areas with lower bear densities. However the corridors were for the most part short and low-resistance. These corridors may function best when palm dates are ripe. The corridors connecting Cluster C to Cores 29 and 30 are somewhat longer, but could create a "supercluster" (Fig. 4: C plus D).

The most important regional corridor (Fig. 4: Polygon E) runs between Core 7 (in Cluster B) and Core 15 (in Cluster A). This corridor is approximately 73 km long, without any major roads, with relatively high river density (46 m/km^2), and with more mountainous terrain than other potential corridors between Clusters A and B. Another set of important regional corridors (Fig. 4: Polygon F) also consists of the longest modelled IBB habitat corridors (173–259 km). These 4 parallel and partially overlapping corridors run from Cores 9 and 10 (in Cluster B) to Cores 23, 24, and 25 (in Cluster C). We suggest that the IBB may be able to cross this distance because an American black bear moved a straight-line distance of 282 km (Liley and Walker 2015) and the ecology and behavior of the Asiatic black bear is similar to that of the American black bear (Fujiwara et al. 2013). Investigation of these corridors was ruled out because of security reasons and scarcity of roads. Although it may not be possible to conserve all of the corridors in regional corridor F, we encourage retaining >1 corridor through this area to provide redundancy in case one corridor fails. Based on local informants in Polygon F, dispersing IBBs may use the corridors between Cores 9 and 23 and between Cores 10 and 23; therefore, these may be priority areas for conservation.

Cores 20, 21, and 22 in eastern Iran are widely separated by large areas with habitat suitability modelled as low. Density of IBBs is low in Core 20 (Fahimi et al. 2013), and we did not confirm presence of IBBs in Cores 21 and 22. Conservation of these long corridors might be relatively expensive and provide relatively few conservation benefits. Of this group of corridors, the corridor between Cores 20 and 22 offers the largest amount of suitable mountainous habitat.

The local corridors between Cores 15 and 16, and between Cores 8 and 9, are high priority for conservation because of high densities of IBBs and the probability of dispersal between the cores. All local corridors in Cluster C (Fig. 4) are approximately equally important for conservation as a result of short length of corridors and occurrence in a large potential population patch.

Roads fragment IBB populations and vehicle collisions can kill bears moving through habitat corridors (Boulanger and Stenhouse 2014). Although the overall density of roads within IBB corridors was low (18.51 m/km^2), 35 modelled corridors were crossed by roads. Important corridors between Cores 15 and 16, Cores 16 and 17, and Cores 16 and 18 in Kerman Province were crossed by 2 major highways. Also, the most important corridors between Cores 8 and 9 and between Cores 23 and 28 in 2 other provinces were crossed by roads. Two IBBs were killed in road accidents near Core 8 in 2011 and 2014. Road mortalities can be decreased by provision of safe-crossing structures and by fencing the roads to force animals toward the crossing structures (Clevenger and Waltho 2005, Mata et al. 2005). As economic development leads to new highways in currently roadless corridors, it will be much less expensive to incorporate crossing structures into the new highways rather than trying to retrofit these structures into the highways in the future.

The density of the rivers in modelled corridors was low (33 m/km^2) because most of the study area is arid. However, rivers occurred in 39 modelled corridors and probably facilitate movement of IBBs in those corridors. Approximately 60% of the study area is covered by rangelands, so rangeland was also dominant in corridors. However, semi-forest mountains and montane woodlands were disproportionately represented in corridors, reflecting the fact that IBB movement is facilitated by mountains covered by trees.

Our model of IBB habitat quality was based on only 101 independent presence points. Although these presence points are reliable (we believe they include no false presences), the survey efforts were not standardized and did not systematically cover all areas where IBBs might occur. For example, there were no surveys in the large roadless area between Cores 9–10 and Cores 23–24–25. In the future, systematic surveys with standardized effort per unit area could yield data for better models of habitat suitability.

We believe our approach may be useful for other area-sensitive species for which few data exist. Conservation of such species will require identification of habitat cores and potential linkages between cores. As in our example, we recommend modelling connections from each core to ≥2 of its nearest neighbors, and modelling corridors to connect each resulting cluster of cores to the nearest cluster, even if the nearest cluster is quite far away.

Recent work suggests that highly mobile animals readily disperse through areas that are avoided by animals within their home range (Trainor et al. 2013, Mateo-Sánchez et al. 2015, Keeley et al. 2016). This means that managers have considerable flexibility in deciding which lands to conserve as a corridor. In particular, the mapped locations of least-cost corridors (Fig. 4) should not be interpreted as the only places suitable for conservation as a corridor. This is especially true for shorter corridors such as those that an animal could pass through in 1–2 days. In such cases, only the lowest quality habitat, such as mines, cities, or barren areas, might be unable to support a dispersal movement. In such cases, we recommend that the corridor location should be established to accommodate the needs of the least-mobile species with the narrowest habitat niche. If a corridor can support movement of these less behaviorally flexible species, its location will almost certainly support dispersal movements by highly mobile species such as the IBB.

Conclusion

Our maps of cores, habitat quality, potential habitat patches, and potential corridors are the first attempt to comprehensively describe the potential spatial distribution of the IBB, given its status as a critically endangered subspecies through its range. These maps identify 4 priority conservation areas (Clusters A, B, C, D in Fig. 4) for the IBB in Iran, potential corridors within each cluster, and potential regional corridors between clusters. We urge establishment of protected areas in the 2 priority areas where no protected areas currently exist, and steps to conserve and enhance the best potential corridors among these areas. We recommend systematic surveys and studies of genetic patterns and satellite tracking of the IBB in Iran to provide better information on bear movement in the area. This study introduced a method of identifying habitat cores and corridors of bears that should be prioritized for conservation, especially in areas for which there is little information about the species.

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Supplemental material

Table S1. Properties of corridors between habitat cores of Iranian black bears in the mountains of Kerman, Hormozgan, and Sistan and Baluchistan provinces of Iran (no. of cores are available in Fig. 2), derived from 200 presence points identified during 2008–2013 and 70 presence points identified during 2014. The most important local[a] and regional[b] corridors are designated with superscript letters.