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Altitudinal heterogeneity and vulnerability assessment of protected area network for climate change adaptation planning in central Iran

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ABSTRACT

One of the most serious challenges facing biodiversity conservation is associated with the efficiency of protected areas for conserving biodiversity under future climate change. To address it, conservationists recommend shifting conservation planning from just focusing on protecting animal populations and their present habitat to including areas of high habitat heterogeneity. It is now well documented that range shifts of many species are occurring along altitudinal gradients. Thus, species in reserves extending over larger altitudinal gradients would have more opportunities for shifting their range toward higher altitudes. In this study, we evaluated the network of protected areas (PAs) in central Iran for their altitudinal heterogeneity. We then used a comparison index to quantify representativeness level of each altitudinal zone within the PAs. To detect if altitudinal heterogeneity may contribute in vulnerability of PAs to climate change, a climate change vulnerability assessment was performed using climate change velocity index. Our results demonstrated that the overall altitudinal heterogeneity within the PAs in central Iran is low. This was mainly attributed to the disproportionate size of the sites regarding topographic position. Among the altitudinal zones, only those at higher altitudes were well represented by the network suggesting a bias in the selection of protected sites toward higher altitudes. Altitudinal heterogeneity was found as a significant factor influencing vulnerability of the Iranian PAs to future climate change. In this regard, the sites most at risk were those distributed in east and across more topographically homogeneous landscapes. Thus, they are more urgently in need of taking actions for ameliorating the negative impacts of climate change. We suggest applying these assessments to other PAs to more completely plan for the efficiency of the Iranian PAs to future climate change.

1. Introduction

Protected areas (PAs) are considered as one of the most important and effective tools for conservation of biodiversity (Bruner, Gullison, Rice, & Da Fonseca, 2001), as they buffer ecosystems and species against the pressures from human activities (Campbell et al., 2009) such as land use changes (Verburg, Overmars, Huigen, de Groot, & Veldkamp, 2006). For this reason, they are key components of conservation strategies planned to minimize biodiversity loss globally (Walden-Schreiner, Leung, & Tateosian, 2018). However, they may play a limited role in facilitating biodiversity adaptation to climate change (Campbell et al., 2009) which is known as a threat to biodiversity globally (Trisurat, Shrestha, & Kjelgren, 2011). PAs are established to conserve species and ecosystems under stable climatic conditions (Huntley, 2007; Lemieux & Scott, 2005). At best, they were selected based on current distribution of biodiversity features estimated when performing initial assessment and planning (Huntley, 2007; Lemieux & Scott, 2005), and at worst they were established in inaccessible areas with no other interests in order to reduce the conflicts between human land use and biodiversity conservation (Mackey, Watson, Hope, & Gilmore, 2008; Pressey, 1994). However, as the main driver of species distribution (Heller et al., 2015), climate is changing. These changes will have significant implications for the relevant characteristics of protected habitats and currently available approaches for selecting conservation sites (Halpin, 1997). For example, there is now ample evidence indicating that species are responding to climate changes with significant shifts in their distribution ranges (Hannah, Midgley, Hughes, & Bomhard, 2005; Parmesan, 2006). With respect to the inadequate size

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of many PAs, these shifts may contribute to reduce the functionality of these areas in protecting species under future climate change.

Owning to the advances in conservation planning, a variety of methods have been developed to evaluate (Southworth, Nagendra, & Munroe, 2006) and select protected areas. However, they may not be efficient in evaluating the potential of current protected areas and candidate areas for conserving biodiversity under future climate change. Several approaches have been suggested for conserving biodiversity in a changing climate including reserves designing based on projections of species distribution models (SDMs) (Hannah et al., 2007). Through relating species occurrence data to a group of environmental variables, SDMs provide predictions of the geographic distribution of species (Priego-Santander et al., 2013), which could be implemented in reserve design algorithms. However, the uncertainty embedded in forecasting of SDMs and unpredicted response of species question the effectiveness of reserves selected based on future projections of SDMs (Carvalho, Brito, Crespo, Watts, & Possingham, 2011). To deal with this challenge, a recommended adaptive approach is to conserve large areas including highly heterogeneous habitats (Krobsy, Tewksbury, Haddad, & Hoekstra, 2010). Conserving habitat heterogeneity would benefit species in two different ways during climate change. First, habitat heterogeneity is considered as a surrogate for diversity of various plants and animal groups in a region (Bonn & Gaston, 2005). The positive relationship of habitat heterogeneity with species diversity has already been verified by several studies (Jiménez, Distler, & Jørgensen, 2009; Paudel & Heinen, 2015; Priego-Santander et al., 2013; Rahbek & Graves, 2001; Stein, Gerstner, & Kreft, 2014). Thus, selection of large heterogeneous reserves may result in conservation of unprotected species that are sensitive to climate change (Paudel & Heinen, 2015). Second, according to the theory of altitudinal-response (Peters & Darling, 1985), one impact of climate change on PAs is species' range shifts along altitudinal gradients within the sites. Large PAs often extend over diverse altitudinal zones (Cantú-Salazar & Gaston, 2010). Such reserves provide a wide range of climatically suitable habitats, and therefore assist species in responding to climate change within their present borders (Halpin, 1997). In contrast, reserves containing limited altitudinal range may fail in capturing the magnitude of climate change and thus force species to migrate outside the protected area (Halpin, 1997). As a result, topographically rich reserves may provide more opportunities for persistence of the species in the face of climate change (Cantú-Salazar & Gaston, 2010). In addition, in heterogeneous habitats, temperatures may change significantly over very short distances (Ackerly et al., 2010; Sears, Raskin, & Angilletta, 2011). Thus, the speed at which species are required to move in order to maintain suitable climatic conditions over time (or velocity of climate change) (Hamann, Roberts, Barber, Carroll, & Nielsen, 2015; Loarie et al., 2009), is lower in PAs having high topographic and altitudinal diversity.

Iran is known as an important biodiversity area in western Asia (Kolahi, Sakai, Moriya, & Makhdoum, 2012). However, selection of protected areas in Iran has traditionally been based on a high density of large mammals or rare birds. As a result, the effectiveness of PAs in protecting broader biodiversity has largely been ignored (Kolahi et al., 2012). Such practices have resulted in selection of PAs that may not have performed well in conserving species under current and future conditions. For example, nearly 12% of the Iranian PAs are estimated to be already too small to support habitats for large mammal species (Kolahi et al., 2012). This means that they probably may not support much of the range shifts by these species in future. Several studies have also reported the potential failure of the Iranian PAs in protecting species under future climate change scenarios (Kafash, Kaboli, Koehler, Yousefi, & Asadi, 2016; Yousefi et al., 2015). The climate of Iran is warming; according to future climate scenarios, the average temperature of the country is predicted to undergo a 0.4–5.3C increase by the 2100 (Abbasi, Babaeian, Habibi-Nokhandan, Golimokhtari, & Malbousi, 2011). Threats from climate change and the ineffectiveness of the existing Iranian PAs raise concerns upon the future of species they harbor. As a result, there is an urgent need for revising the existing reserve selection methods and incorporating climate adaptive approaches for ensuring successful management of species under expected future climate change in Iran. So far, evaluating the effectiveness of the Iranian PAs has been concentrated on the distribution of biotic features such as plant (Jafari, Yavari, Yarali, & Valipour, 2011) and mammal species (Momeni Dehaghi, Mahiny, Shabani, & Karami, 2013). The main goal of these assessments was to investigate the potential of these areas for representing these biodiversity features and selection of new candidate sites under current climate conditions. However, studies on the potential of the current network of Iranian PAs in reducing the impacts of future climate change based on abiotic features have not been performed yet.

In this study, we provided the first assessment of habitat heterogeneity in Iran and applied it to the network of PAs within the country. Here, we based our assessment on the topographic variable of altitude to estimate habitat heterogeneity represented by the protected areas in Iran. For this reason, we extracted altitudinal zones within each protected area and used the Shannon index to calculate the altitudinal diversity. We then determined how much altitudinal diversity (or habitat diversity) of the PAs would contribute to buffer them against effects of future climate change. For this reason, we performed a vulnerability assessment to climate change impacts using a climate change velocity index (Loarie et al., 2009). Calculated values of climate change velocity were considered as a measure for the vulnerability of each protected area in terms of the migration requirements of major species within it. Contribution of altitudinal diversity of a given protected area for reducing its vulnerability to climate change was then determined using the Spearman correlation index.

2. Materials and methods

2.1. Study area

Our assessments were applied to the PAs and the entire landscape of Isfahan province with an approximate area of 107,000 km^2 situated in central Iran. Topographic diversity favors a variety of climatic conditions within the province. As a result, extensive variation in temperature and precipitation variables across different regions is expected. Table 1 shows measured mean annual values for four temperature and precipitation related variables based on data from synoptic stations within different climate zones in Isfahan. The east and north of the province range within the hyper arid climate zone where deserts and plains are the dominant landscape features. Western and southern parts in contrast include the most heterogeneous landscapes and are categorized into humid and semi-humid climate zones. Comparing long-term mean values in Table 1 shows the gradients in precipitation and temperature respectively, from east to west of the province as climate conditions change. A Network of PAs in the region includes 24 sites falling into four categories of National Parks (IUCN Category II), Wildlife Refuges (IUCN Category IV), Protected Area (IUCN Category V), and No Hunting Areas. All four categories (hereafter PAs) account for nearly 20% of the province's total area (Fig. 1). Altitude in the

Table 1
Long term average of four precipitation and temperature variables obtained from 22 synoptic stations in the Isfahan province during a period of 22 years from 1992-2014.

Synoptic station	Bio1 (°C)	Bio10 (°C)	Bio (11)°C	Bio12[a](mm)
East and north (hyper arid and arid zones)	26.0	41.1	10.2	5.52
Center and north (semi-arid zone)	15.6	27	4.2	9.31
West and south (humid and semi humid zones)	14.5	25.6	3.2	26.38

[a] Mean Annual Precipitation.

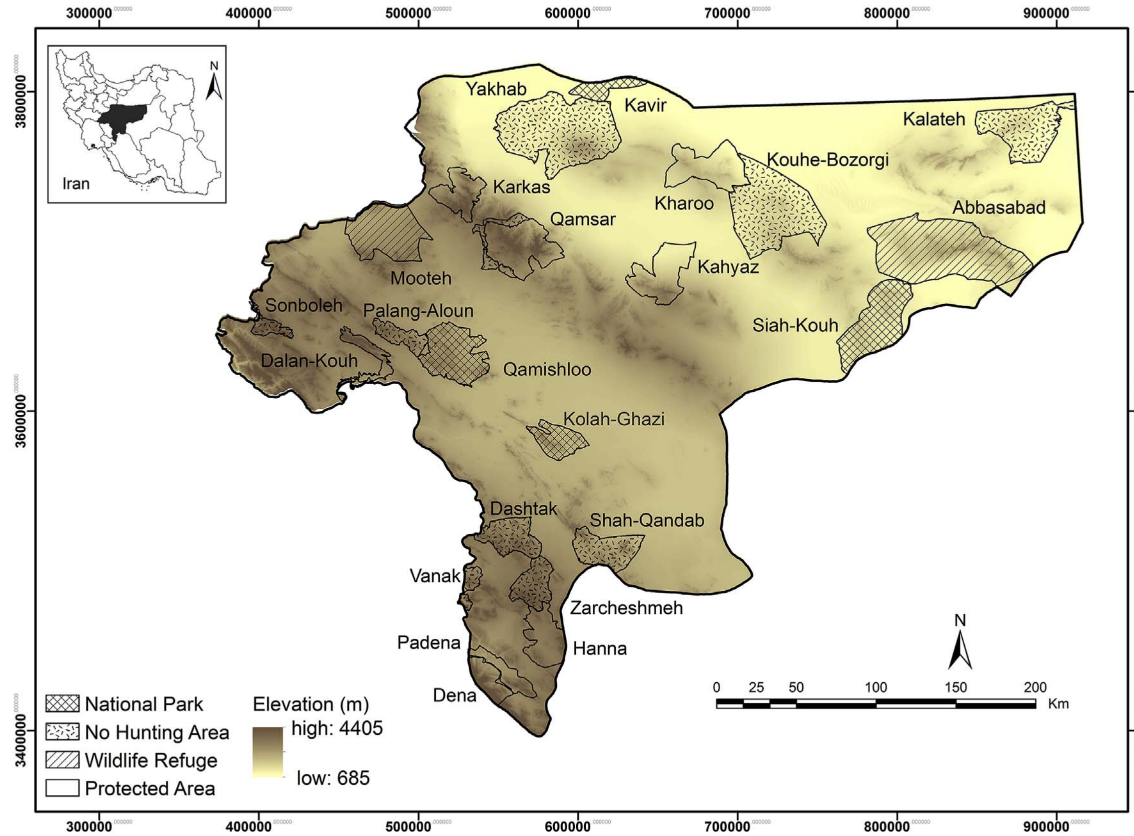

Fig. 1. Distribution of the four categories of protected areas in the study region and across altitudinal ranges in Isfahan province-central Iran.

region ranges from 685-4405 m incorporating a range of topographic attributes. Plains make up the dominant topographic terrain in east, north-east, south-east and central parts of the province. High altitudes, including isolated mountains in desert areas and mountain ranges in the south-west and the north-west of the province.

Regarding the distribution of protected lands across the climate zones, the majority of the sites (41.6%) are within a single climate zone (e.g., arid or semi-arid climate) and others include a mixture of several climate types within their boundaries. This high variability in topographic and climatic conditions is responsible for providing a diverse range of habitats and thus high species diversity in the region. For example, Isfahan's PAs harbor the largest remaining populations of three Iranian vulnerable ungulates including goitered gazelle *(Gazella subgutturosa*), wild sheep *(Ovis orientalis*) and wild goat (*Capra aegagrus*) (Hemami & Groves, 2001).

2.2. Quantifying habitat heterogeneity of PAs

Habitat heterogeneity assessments in this study were based on quantifying local topographic heterogeneity and altitude. Altitudinal heterogeneity for each PA was calculated as a measure of habitat heterogeneity using the Shannon index of diversity (Magurran, 2004; Paudel & Heinen, 2015). The Shannon index is one of the most widely used indices of species diversity (Janssen, Birnie, & Bonsel, 2007). This index accounts for both components of species diversity, richness and evenness, and ranges from 1.5-3.5 (Magurran, 2004). The index is high when both richness and evenness are high. If an area contains a high number of species, but only one or two species are abundant, the index will be low. Incorporating the component of evenness, as a measure of abundance equality in a community (Alatalo, 1981), the Shannon index quantifies the ecological heterogeneity as an important measure of biodiversity (Duelli & Obrist, 2003). When applied to a conservation site in order to measure its altitudinal heterogeneity, the index is calculated as follows (Paudel & Heinen, 2015):

$$H = \sum_{i=1}^{s} - (Pi \times lnPi)$$

where Pi is the proportion of a PA occupied by altitudinal zone *i*, *s* the number of zones inside the PA and H is the Shannon index of the PA altitudinal diversity. As an index of altitudinal heterogeneity, Shannon values are strongly influenced by the number and proportion of each altitudinal zone protected within a given PA. When a PA contains only one altitudinal zone, the value of the Shannon index is zero. With increasing number of altitudinal zones each occupying the same proportion of a PA total area, the value of the index increases. Altitudinal zones were defined using a 30 m digital elevation model (DEM) of the study area (www.USGS.org), which was re-sampled to 1 km spatial resolution. The DEM was then classified study based on 100 m intervals that resulted in 36 altitudinal zones. We selected this interval because vegetation community in steppe areas in the vicinity of Zagros mountain chain and also other similar areas in the country usually change within every 100 m interval (e.g., Heshmati, 2012; Tamartash, Yousefian, Tatian, & Ehsani, 2010). To ensure, we tested this interval with respect to the change in vegetation communities across the province, and the same result was obtained for most classes of vegetation as well. Finally, for each of the 36-altitudinal zone, the proportion of a given PA and the study landscape occupied by that zone was calculated and used for measuring the altitudinal heterogeneity.

2.3. Representativeness of altitudinal zones within the PAs

To quantify the representative level of altitudinal zones within the current network of PAs, we used the comparison index (CI) introduced by Hazen and Anthamatten (2004) and Trisurat (2007). CI is calculated by dividing the proportion of PAs in an altitudinal zone by the proportion of the study area (here Isfahan province) occupied by that altitudinal zone. The threshold value of CI for determining a representative level is 1 where a heterogeneity class is protected proportional to its coverage in the landscape. Therefore, values lower and higher than 1 indicate under and over-representation of a given class respectively (Trisurat, 2007).

2.4. Landscape based analysis of climate change velocity

Climate change velocity index (Hamann et al., 2015; Loarie et al., 2009) was calculated using algorithms developed by Hamann et al. (2015). This index is calculated as the ratio of projected climate change (°C/yr) to the rate of spatial climate variability (°C/km) (Hamann et al., 2015). The resulting value represents an initial rate required by a species to migrate in order to find similar climatic conditions in future (Hamann et al., 2015; Loarie et al., 2009). Velocity algorithms apply the nearest neighbor search to find all the pixel across the landscape representing analogue climatic conditions corresponding to that of a source pixel in current time (Hamann et al., 2015). The Euclidean distance between each pairs of matching pixels is then measured and the shortest distance is assigned to the source pixel as the velocity value (Hamann et al., 2015).

In this study, present and future climatic conditions were set as the source and target data set respectively, to find the closest pairs of pixels across the Isfahan province. For current (1961–1990) and future climate change projections (2041–2070), we used three temperature-related variables of Minimum Annual Temperature (bio1), Mean Temperature of Warmest Quarter (bio10), and Mean Temperature of Coldest Quarter (bio11) all at the spatial resolution of 1 km (www.worldclim.org). In Isfahan province, climatic conditions vary greatly across different regions (especially west and south). As a result, at the same time of the year, different regions may experience completely different temperatures. Since bio1 is a mean proxy of temperature over a year, we tested how well it would perform for representing patterns of velocity across the province. For this reason, we also calculated the climate change velocity under two extremes of seasonal changes in temperature (i.e. warmest and coldest months of the year) using bio10 and bio11 climatic variables. Future temperature projections were taken from two global circulation models (GCM) of CCSM4 and MIROC-5 (Kafash et al., 2016; Yousefi et al., 2015) from the World Climate Research Program Coupled Model Intercomparison Project Phase5 (CMIP5). These temperature projections were based on RCP 8.5 greenhouse-emission scenario simulations averaged over a 30-year period from 2041-2070. The RCP8.5 is based on the A2r scenario (Riahi, Grübler, & Nakicenovic, 2007), which provides an updated and revised quantification of the original IPCC A2 SRES scenario storyline (Nakicenovic et al., 2000). Here, measures of climate velocity were used to 1) evaluate the vulnerability of PAs to climate change, and 2) investigate the relationship between this metric and the altitudinal heterogeneity. Climate change velocities can be calculated in two ways which include forward (the shortest geographic distance from current climate cells to those projected to have similar climate in future) and backward (the shortest geographic distance from future projected cells back to cells with similar climate under current conditions) (Carroll, Lawler, Roberts, & Hamann, 2015). We selected to use forward velocity because it reflects species exposure to climate change (Carroll et al., 2015; Hamann et al., 2015) and as a measure for assessing the vulnerability of a site to climate change (Carroll et al., 2015). Forward velocity was calculated for the whole landscape of the Isfahan province including the network of the PAs. For each 1 km pixel within the Isfahan PAs, the forward algorithms searched for the nearest target pixel with climate analogue across the province. Using velocity metric, we then ranked the Isfahan PAs based on their vulnerability to climate change. This was achieved by classifying the forward velocity values into three classes (low, moderate, and high) using quantiles reclassification method. We then assigned each PA to a vulnerability class based on the mostly represented velocity class within the PA (i.e. based on majority value) (Batllori, Parisien, Parks, Moritz, & Miller, 2017). In the next step, we investigated how well altitudinal heterogeneity of PAs may mitigate the impact of future climate change. This was achieved by examining the strength of association between altitudinal heterogeneity and climate change velocity values using a Spearman correlation.

Since velocity algorithms estimate species migration requirements between a present source and a future target time, there is no value in present time to be considered as reference. Thus, to reveal the changes among the three climate change velocity indices, we considered the values of velocity index derived from the bio1 as a reference and estimated the changes with respect to this variable. We separately subtracted values of the two other indices from the velocity index based on bio1 and summed up the calculated changes for each pixel in the study landscape. This resulted in a single raster map of change in the velocity index for the Isfahan province.

3. Results

3.1. Assessment of altitudinal heterogeneity and representation

Values of the Shannon index obtained for the PAs network of Isfahan ranged from 0.99-3.66 with an average of 2.17 (Table 2). Distribution of PAs over this range suggested that the majority of the protected sites (nearly 71%) had altitudinal heterogeneity within the range of 2–3 of the Shannon Index. Minimum level of altitudinal heterogeneity was measured for the Kavir National Park in the furthest north of the province. Kavir is an inter-provincial national park and this value represents altitudinal heterogeneity for the part within Isfahan province. However, the Shannon value for the whole site was also low ($H = 1.65$). Among 24 PAs, the most heterogeneous site was Dena NP in south of the study area following by Karkas and Qamsar PAs both located in north-west of the Isfahan province.

CI values for the altitudinal zones within the Isfahan PAs ranged from 0.00-5.34 (Fig. 2). The minimum CI was obtained for the zone of 600–700 m as the smallest altitudinal zone across the province (only 0.006%) with no proportion of its area occupied by the PAs. Among the 37 altitudinal zones, the poorly represented ones by the PAs network were five altitudinal zones between 700-1000 m and 1400–1900m with CI values lower than one. All other zones were well represented ($CI > 1$) among which altitudinal zones higher than 3900 m had the highest CI value ($CI > 3$).

3.2. Altitudinal diversity and climate change velocity

Similar patterns of vulnerability to climate change were observed based on velocity calculations under the three climate variables (Fig. 3). Values of climate velocity index did not vary significantly among the three climate variables with only maximum of 0.34 difference in the estimated rate. The index reached its highest value for the mean temperature of the coldest quarter at 4.08 km/yr, while, the lowest velocity value was associated with the mean temperature of the warmest quarter estimated at about 3.7 km/yr. Comparing classes of vulnerability showed that regions highly exposed to climate change occupy almost the same proportion of the province under all three temperature variables but, with very small differences compared to other classes (Table .3). The geographic distribution of climate change velocities revealed remarkable differences among regions within the province. The regions highly exposed to climate change were primarily found across the flat areas in the east, north and east of the province. Whereas, western and central mountain chain and isolated mountains in east were predicted to experience lowest rates of climate velocities in the province. Highest rates of velocities were observed in isolated zones displaying significantly contrasting velocities compare to their surrounding landscape. These zones were actually mountain tops as the most exposed regions to future climate changes in the province.

The maximum calculated change in values of velocity index for a

Table 2
Altitudinal heterogeneity, altitudinal range and assigned vulnerability class for individual PAs to future climate changes based on three temperature-related variables.

Conservation site	Shannon index	Altitudinal range (m)	Vulnerability class Bio1	Vulnerability class Bio10	Vulnerability class Bio11
Kolah-Ghazi	1.92	1500–2300	low	low	low
Hanna	2.04	2300–3000	low	low	low
Zarcheshmeh	2.43	2300–3300	low	low	low
Shah-Qandab	2.46	1500–2700	low	low	low
Dshtak	2.62	1900–3000	low	low	low
Sonboleh	2.77	2500–3500	low	low	low
Palang-Aloun	2.68	1900–2900	low	low	low
Padena	2.74	1800–3000	low	low	low
Vanak	2.80	1900–3000	low	low	low
Abbasabad	2.76	700–2200	low	low	low
Dalankouh	3.22	2000–3400	low	low	low
Kahyaz	3.44	900–2700	low	low	low
Qamsar	3.51	1500–3200	low	low	low
Karkas	3.44	1400–3600	low	low	low
Dena	3.66	1700–4200	low	low	low
Sheyda	1.39	2000–2600	moderate	moderate	moderate
Yakhab	2.41	700–2200	moderate	moderate	high
Ghamishloo	2.38	1600–2500	moderate	moderate	moderate
Mooteh	2.34	1500–2800	moderate	moderate	moderate
Kalate	1.91	700–1600	high	high	moderate
Kavir	0.92	700–1800	high	high	high
Siah-Kouh	2.04	800–1800	high	high	high
Kouhe-Bozorgi	2.28	700–1600	high	high	moderate
Karoo	2.72	700–1700	high	high	high

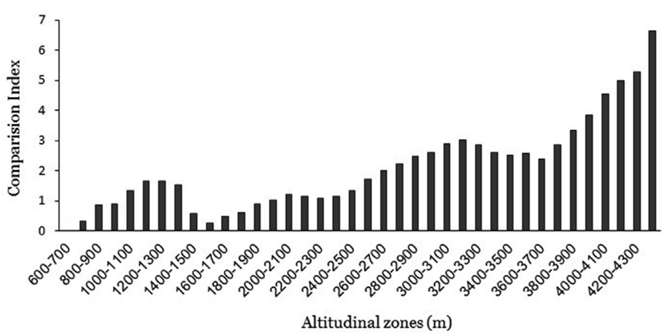

Fig. 2. Representativeness level of altitudinal zones by the Isfahan PAs network.

given pixel in the Isfahan province was around 7 km/yr (Fig. 4). As it is shown, for the majority of the province there is no significant difference among the velocity values with respect to the three temperature variables (Fig. 4). High variations were observed across high elevation areas where high exposure to climate change was predicted under all three temperature variables. This result was expected because the highest difference in present and future values of the three temperature variables is observed across high elevation areas within the province. Such areas however, occupy a very small proportion of the province and mostly fall within the PAs (including Abbasabad, Qamsar, Karkas, Dalan-Kouh and Sonboleh) as demonstrated in Fig. 4.

Result of the vulnerability assessment showed that 62.5% of the Isfahan PAs have majority of their area occupied by the low velocity class (Table 3). 37.5% of the sites were predicted to become exposed to moderate to high climate velocities within the Isfahan protected network. We found a significant correlation between the altitudinal heterogeneity and vulnerability of the PAs under all three bioclimatic variables ($r_{bio1} = -0.65$, $p = 0.001$; $r_{bio10} = -0.65$, $p = 0.002$; $r_{bio11} = -0.61$, $p = 0.0001$). This implies that PAs with higher level of altitudinal heterogeneity are less susceptible to future climate change.

4. Discussion

4.1. Heterogeneity of PAs

Most of the PAs within the Isfahan province include some mountains even those located in more homogeneous parts of the landscape. However, the results of quantifying the zone-based altitudinal diversity of the Isfahan PAs showed that the overall heterogeneity of the current network is low. This result could be attributed to the size and distribution of PAs regarding topographic positions across the province. For example, the largest PAs in Isfahan are situated in the east of the province (including Abbasabad, Yakhab, Kahyaz, Kalate, Kavir, Siah-Kouh, Kouhe-Bozorgi and Kharoo; average size = 1478 km^2) with more than half of their areas at altitudes lower than 1500 m (low altitudes PAs). Except for some isolated mountains, low topographic reliefs are the dominant landscape feature found in these regions. As a result, despite being large enough, eastern PAs mostly protect homogenous parts of the Isfahan landscape. On the other hand, when moving further west and south toward higher altitudes, heterogeneous habitats become more common. Although the majority of Isfahan PAs are distributed across these regions, due to small size (average size of 677 and 376 km^2 for intermediate and high altitudes sites respectively), they cover a limited range of altitudinal gradients. However, this did not hold true for all of these sites. For example, Dena NP which was identified as the most heterogeneous sites, has an area of only 93 km^2 and thus is among the smallest sites within the network. This national park includes remarkably the highest number of altitudinal zones proportional to its size. Dena is located on the Zagros mountain chain where the altitudinal gradient in the Isfahan province reaches its highest point (up to 4200 m). In such a place of extensive altitudinal gradients, even a relatively small area is expected to include a variety of altitudinal zones. As with increasing altitude, the area of the altitudinal zones decreases (Paudel & Šipoš, 2014). Thus, an equal surface on a mountain is supposed to include a higher number of altitudinal zones compared to a flat region. This also hold true for the two other heterogeneous sites Karkas and Qamsar, which both included high mountains of the Karkas range.

Among altitudinal zones, we found two major zones, 700–1000 m and 1400–1900m, that were under-represented in the PAs network. This could be explained by the distribution of agricultural lands and urban areas which were mainly distributed in these altitudinal zones in Isfahan province. In the last decades, urbanization and agricultural development significantly impeded further expansion of PAs across these altitudinal zones, which justify their inadequate representation by the PAs network. Poor representation of low altitudes and over-representation of higher altitudes in this study imply the bias in selection

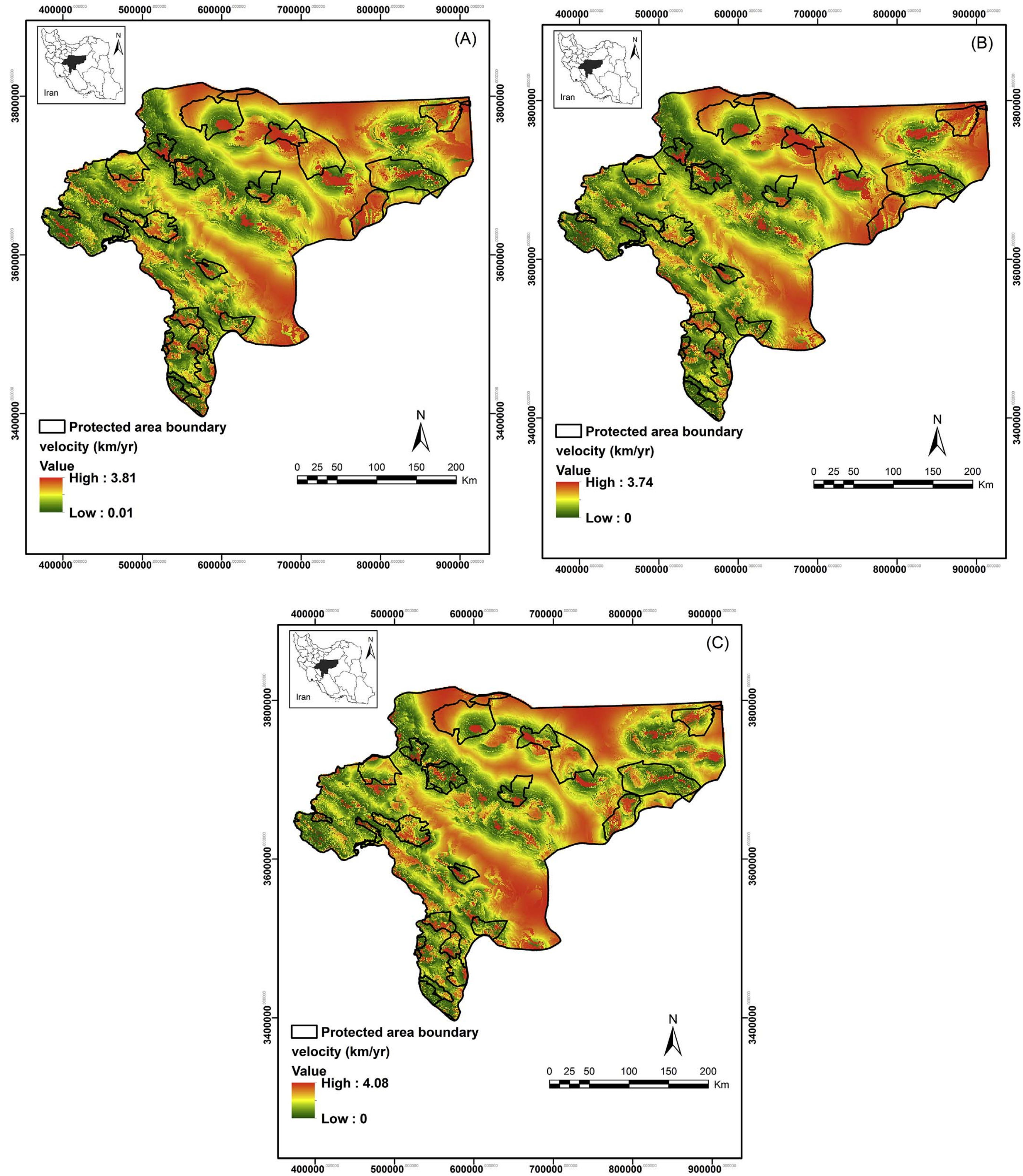

Fig. 3. Distribution of velocity values (km/yr) across the landscape of Isfahan province and the PAs using variables of a) Mean Annual Temperature b) Mean Temperature of Warmest Quarter and c) Mean Temperature of Coldest Quarter. The values indicate the speed required to be traversed in order to catch up with the pace of climate changes in 2050.

of PAs toward higher altitudes, an outcome that has been observed in systems of PAs in other countries too (Aycrigg et al., 2013; Heinen, 2012; Joppa & Pfaff, 2009; Oldfield, Smith, Harrop, & Leader-Williams, 2004; Paudel & Heinen, 2015; Scott et al., 2001; Sergio & Pedrini, 2007; Shrestha, Shrestha, Chaudhary, & Chaudhary, 2010).

4.2. Estimates of climate change velocity

We based calculations of climate change velocity index on variable of temperature, because compared to precipitation, there is less uncertainty regarding the future projection of this variable (Loarie et al.,

Table 3
Proportions of the Isfahan province exposed to different vulnerability classes under the three temperatures - related climate variables.

Vulnerability class	% of the province occupied by the vulnerability class based on bio1	% of the province occupied by the vulnerability class based on bio10	% of the province occupied by the vulnerability class based on bio11
Low	33.7	33.8	34.1
Medium	33.2	33.0	32.9
high	33.1	33.1	33.1

2009). Furthermore, it has been well documented that changes in temperature are enough to predict the extent of altitudinal and latitudinal shifts in species range under climate change (Chen, Hill, Ohlemüller, Roy, & Thomas, 2011; Dobrowski & Parks, 2016; Kelly & Goulden, 2008; Lenoir, Gegout, Marquet, De Ruffray, & Brisse, 2008; Moritz et al., 2008).

For the Isfahan province, under all three temperature variables similar results were obtained regarding the geographic distribution of climate change velocity and exposure ranking of PAs. Although the value of the velocity index predicted for a given pixel varied regarding the used temperature variable, the estimated differences among the indices were not significant. We found only three PAs with different vulnerability ranking under the mean temperature of the coldest quarter, however, the share of moderate to high vulnerability classes from the PAs was similar among all the variables. Here, vulnerability assessment was performed using univariate algorithm introduced by Hamann et al., 2015. The univariate algorithm approach has also been used for similar evaluations at regional and global scales with mean annual temperature and precipitation as widely used climatic variables (see Ackerly et al., 2010; Chen, Zhang, Jiang, Nielsen, & He, 2017; Dobrowski & Parks., 2016; Loarie et al., 2009; Vale & Brito, 2015). Incorporating more than one climatic variable into velocity analysis would deliver different estimates of the index (Hamann et al., 2015). However, it has been shown to have no effect on spatial arrangement and vulnerability ranking of the PAs because of high robustness of the output maps (Hamann et al., 2015).

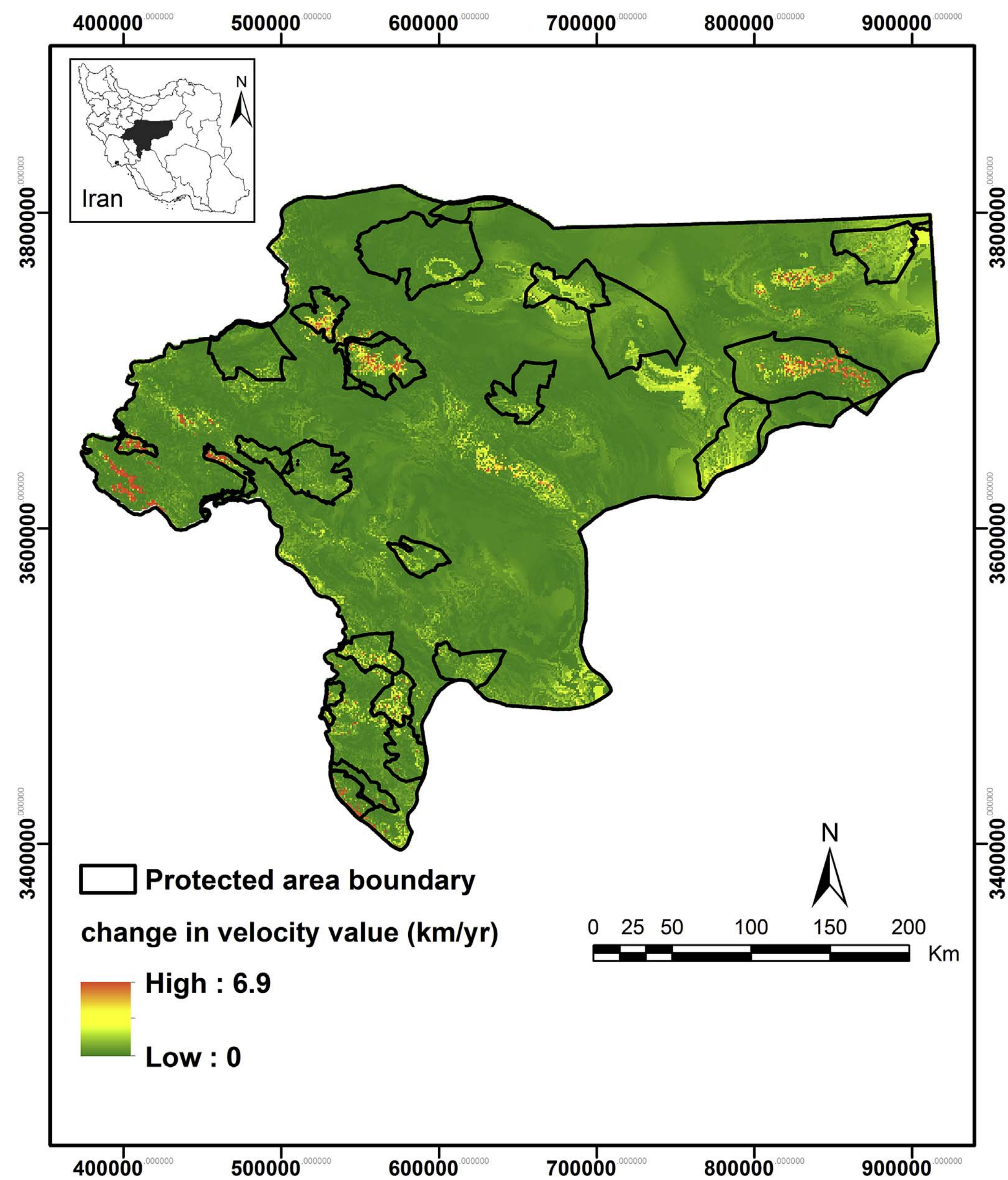

Fig. 4. Variation among estimated velocity values (km/yr) derived from three climate variables, i.e. the Mean Annual Temperature, the Mean Temperature of the Warmest Quarter and the Mean Temperature of the Coldest Quarter across Isfahan province.

Such robustness also includes the spatial resolution of the climate data. We performed a coarse sale analysis using grid size of 1 × 1 km, which is a suitable scale for investigating impacts of climate change on large species such as mammals. These species are affected by climatic conditions at large scales and at the same time are also more flexible to move large distances. However, regarding smaller vertebrates or even more so invertebrates, conducting finer resolution assessment is suggested, particularly in mountainous areas. Because, even in highly exposed PAs in Isfahan province, some of these species may only limit their range into the microrefugia within the sites (Batllori et al., 2017). Coarse scale analysis may ignore much of the local diversity and thus may fail in identifying such critical microhabitats (Batllori et al., 2017).

4.3. Vulnerability of Isfahan PAs to climate change

Our results demonstrated that altitudinal heterogeneity is an influential factor on climate change velocity influencing their vulnerability of PAs to climate change. Within the PAs network, the sites most vulnerable to climate change (Shannon values lower than 2) were located in the east and north. In contrast, PAs on in the west and south were predicted to be less affected by future climate change. Higher altitudinal heterogeneity of western and southern PAs will provide their species with more opportunities for upslope movement than those in east and north. However, their small size means that they may not be able to support upward movements for a long time or for big enough populations to survive. Eastern and northern PAs on the other hand are large, but the larger part of their area may be exposed to medium to high velocities. The abiotic velocity estimates reflect the upper limit of species' migration requirements, because it assumes that species have limited climate tolerances or lack any adaptive ability to warming climate (Carroll et al., 2015). In other words, for some species the abiotic velocity may overestimate their exposure to climate change. For example, some of the highly vulnerable areas in Isfahan are semi-arid and arid plains that make up the main habitats for desert-adapted ungulates such as Indian gazelle (*Gazella bennettii*) and Persian gazelle (*Gazella subgutturosa*) (Hemami and Groves, 2001). Because of their high thermal tolerance (Hetem et al., 2012), these species are likely to adapt to even increasing temperatures in their presently protected habitats. For such species, more realistic estimates of migration rate could be obtained through calculating biotic velocity which is based on species climatic niche models (Carroll et al., 2015). Biotic velocity indicates the lower end of migration rate because it assumes that a given species is able to adapt to a wide range of climate conditions (Carroll et al., 2015). Although biotic velocity might be higher than the actual migration rate for a given species, it delivers closer approximation than the abiotic velocity which includes no biological data.

Contribution of altitudinal heterogeneity to the vulnerability or the resiliency of the protected species could be well demonstrated comparing important montane species (such as wild goat and wild sheep as the important species in the region) in low and high altitudes PAs. These species are prone to climate change because of their geographic isolation, limited range, and highly specific environmental adaptations (La Sorte & Jetz, 2010). If the magnitude of climate change exceeds the local spatial gradient in climate, these species are forced out of the PAs to search for suitable climate niches in future (Dobrowski & Parks, 2016). Concerns over the particular vulnerability of mountain species within eastern PAs are justified for two reasons: 1) limited altitudinal gradients (up to 2700 m) which may not provide them with adequate opportunities for upward movements in response to climate change. 2) mountains in these PAs are like islands surrounded by less complex landscapes. If these species have to shift their range beyond the borders of the PAs, they have to traverse topographically homogeneous unsuitable and unprotected landscapes to reach the closest climate analogue. Across these landscapes, there is little chance to find a functioning corridor along similar climate gradients to the source habitat. Even if the geographical distance might be short, high climate resistance in intervening landscape would result in long exposure to unsuitable climate (Dobrowski & Parks, 2016).

In contrast, in west and south of the province, the unprotected landscape within and surrounding most PAs is more heterogeneous and less exposed to climate change. Although in these parts of the province velocity index may underestimate exposure of mountain species to climate change (Dobrowski & Parks, 2016), these species will still be less vulnerable when moving between the PAs. Because, they are more likely to find similar climates in unprotected heterogeneous landscape than those in the east of the province. The only threats to these species is associated with lower security outside the PAs. Even in such areas of the landscape.

4.4. Conservation implications

Our assessment revealed that many of Isfahan's PAs do not include sufficient habitat heterogeneity to cope with future climate change. As a result, some conservation dependent species may become seriously threatened by increasing negative impacts of climate change. We discussed our results with respect to the large ungulates in Isfahan province, because, boundaries of PAs in the province have been stablished based on the distribution of these species at that time. Accordingly, as far as it is possible, necessary conservation actions have to be planned to conserve their population and reduce their risk of extinction due to climate change in future. For desert adapted ungulates such as Indian gazelle and goitered gazelle extinction will be less likely because of species high adaptive ability to survive in harsh climate conditions. Furthermore, as large and highly mobile mammals they may cope with the negative impacts of climate change through migration. For these species we recommend expansion of PAs in the eastern parts of Isfahan province with mostly homogenous surrounding landscapes. For isolated mountain species such as wild goat, the best management approach is to connect the problematic PAs with areas containing sufficient habitat heterogeneity at higher altitudes. Due to their different topography, the west and south of the province provide more and better opportunities for improving the overall heterogeneity of the network especially on mountain ranges. Thus, enlarging these sites to include larger altitudinal gradients is highly recommended. The feasibility of increasing size of these sites and their connectivity between them is best achieved if expansion of human land uses in the vicinity and in potential corridors between these sites is prevented or stopped in future. In east of the study area, where the topography has formed isolated mountains with considerable distance from each other, suitable habitats may be available to populations of wild goat only at far distances. As a result, there is higher concern over local extinction of these species under future climate change in Isfahan province, because compared to other ungulates, wild goat has a very limited movement ability due to their affinity to steep terrain. An effective conservation strategy for this specialized species in eastern habitats would be transferring its populations to areas where they will be less threatened by the climate change. Areas presumably exposed to lower velocity of climate change could be considered as suitable for this species buffering its populations against effects of climate change for a longer time.

Isfahan PAs are only one example of many PAs in Iran and further west Asia that may be negatively affected by climate change. The present network of PAs in Iran includes more than 300 sites with the majority of them distributed across arid and semi-arid regions. Similar to central Iran, many other Iranian PAs represent similar characteristics regarding size, topography and altitudinal range. For example, approximately 46% of the PAs are smaller than 500 km^2 and only 31% are larger than 1000 km^2. Many of these PAs, however, do not include high enough variety of altitudinal gradients in order to be efficiently buffered against climate change. In this regard, only around 16% of the sites extend over a gradient of more than 2000 m altitude. This is even true for some of the largest PAs (larger than 1000 km^2) where only 29% of them span the same altitudinal gradient. Iran's largest mountain ranges, Alborz and Zagros, contain the highest topographical diversity. However, at present both of these mountainous ecosystems include only relatively small PAs protecting limited altitudinal diversity. Accordingly, it is expected that many small and even some large PAs and species within them face serious threat from future climate change. Thus, we suggest performing similar assessments for other sites within the present system of PAs in Iran and, if necessary, considering additional abiotic features such as slope and aspect. Condition and potential for connectivity between existing and new PAs and the region should also be considered in order to complement such assessments.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2018.02.006.

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