Biological Conservation 274 (2022) 109715

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

The fate of giant panda and its sympatric mammals under future climate change

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ARTICLE INFO

Keywords:
Species vulnerability
Species sensitivity
Habitat exposure
Climate niche factor analysis
Extinction risk

ABSTRACT

Assessing the vulnerability of biodiversity under global climate change is one of the major tasks in ecology and conservation biology. Although species' vulnerability to climate change depends on habitat exposure, species sensitivity and adaptability, multifaceted studies on the impacts of climate change on biodiversity are still lacking. The aim of this study was to fill this gap by assessing the vulnerability of giant panda with its sympatric mammal species in Sichuan province of China, through the climate niche factor analysis. We found that species sensitivity plays a greater role than habitat exposure in determining the vulnerability of these species under future climate change, which doesn't closely match their current conservation status. Besides, these mammals were predicted to be more vulnerable at lower altitudes or latitudes. In particular, Daxiangling and Liangshan mountains emerge as the most vulnerable places to climate change. The conservation gap analysis demonstrated that the current protected area network covers no more than 5 % of the most vulnerable areas. Together, these results highlight the importance of using multifaceted analyses by integrating species sensitivity and habitat exposure to assess climate-related risks to better inform biodiversity conservation and management.

1. Introduction

Anthropogenic climate change has had profound effects on global biodiversity, and will likely have even stronger impacts in the future (Chen et al., 2011; Dawson et al., 2011; Bellard et al., 2012; Pacifici et al., 2015). A general result of these impacts is species' local extinctions (Sinervo et al., 2010; Wiens, 2016) and range shifts toward higher altitudes or latitudes (Chen et al., 2011). Nonetheless, it has been evidenced that species respond to climate change are highly varied and largely depend on the environmental characteristics of the habitats occupied (Jackson and Overpeck, 2000; Nolan et al., 2018; Rapacciuolo et al., 2014). For example, the species with low physiological tolerance to warming are more likely to loss more suitable habitats than the ones with high tolerance (Bonebrake and Deutsch, 2012; Deutsch et al., 2008), and are also more likely to become local extinct in low latitudes than in high latitudes (Brown, 2014; Wang et al., 2022). These realities pose a grave challenge to biodiversity conservation and resource management (Kling et al., 2020), which should be refined by scientifically sound predictions of which species will most likely be at risk from climate change and where the hotspots of the risks will be under future climate change (Soroye et al., 2020; Williams et al., 2007).

The degree of the climate-related risks posed to species (i.e. vulnerability) depends on the rate and magnitude of climate change within species' habitat (i.e. exposure), the ability to tolerate climate change (i.e. sensitivity) and the ability to adjust to these changes (i.e. adaptability) (Foden et al., 2019; Jamwal et al., 2021; Nadeau et al., 2017; Pacifici et al., 2015). In this context, several methods, including correlative, mechanistic and trait-based models, have been developed to assess species' vulnerability to climate change recently (Pacifici et al., 2015). However, the commonly used correlative approaches based on species distribution models neglect the relative contribution of exposure and sensitivity in determining vulnerability (Butt et al., 2016; Leclerc

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https://doi.org/10.1016/j.biocon.2022.109715
Received 28 April 2022; Received in revised form 15 August 2022; Accepted 31 August 2022
Available online 13 September 2022

et al., 2020), while mechanistic and trait-based approaches (i.e. using species' climate niche width and dispersal ability as predictors of climate-driven vulnerability) are often limited by the availability and quality of species' trait data and have thus only been used in a few studies (Pacifici et al., 2015). Recently, one comprehensive climate change vulnerability assessment framework, climate niche factor analysis (CNFA), was developed by Rinnan and Lawler (2019). CNFA uses species occurrence data and bioclimatic variables to quantify species vulnerability based on separated species sensitivity and habitat exposure, and can provide spatially explicit insights into spatial patterns of climate change vulnerability (Rinnan and Lawler, 2019). This method is a powerful tool for improving forecasts of species and regions that might be at risk, and has been used to assess species vulnerability to climate change for plants (Lakoba et al., 2021; Wang et al., 2021; Wang et al., 2022) and mammals (Jamwal et al., 2021; Khosravi et al., 2021).

Climate change vulnerability assessments are particularly crucial in biodiversity hotspots (Bellard et al., 2014; Trew and Maclean, 2021), as it is often suggested that the species in these regions, especially rare and endangered species, might be particularly vulnerable to climate change due to their narrow ranges and persistence in regions of climatic stability over evolutionary time scales (Ohlemüller et al., 2008). Located in one of 34 global biodiversity hotspots, China's Sichuan province are home to approximately 50 % of China's mammals (Myers et al., 2000). Of 204 mammals in Sichuan that have been assessed on the IUCN Red List, over 29 % are currently at risk of extinction (IUCN, 2016), primarily due to a combination of livestock grazing, deforestation, agriculture expansion, road construction, and other disturbances (Li et al., 2017a; State Forestry Administration, 2006, 2021). Furthermore, climate change is expected to exacerbate these current risks and could reorder the current ranking of the Red listed species, challenging the current conservation and management strategies implemented in this region (Rinnan and Lawler, 2019; Wang et al., 2021). However, existing conservation assessments mainly focuses on the climate-induced range shifts of individual threatened mammal species, such as the giant pandas (*Ailuropoda melanoleuca*) (e.g., Songer et al., 2012), the climate change vulnerability of other mammal species, especially non-threatened ones have not yet been evaluated. Moreover, although a network of 44 protected areas (PAs) were established in this region to protect the most iconic species (i.e., the giant panda) by assuming that providing protection for giant pandas could benefit its co-occurring species (Li and Pimm, 2016; State Forestry Administration, 2006), about half of mammal species' ranges are on average not located in current PAs. Additionally, some recent studies have shown that climate-driven species range shifts might have significant effect on the effectiveness of these PAs (Li et al., 2017a, 2017b). Therefore, the potential protection provided by these PAs needs to be examined under future climate change (Hannah et al., 2007; Lawler, 2009).

In this study, we aim to assess the vulnerability of giant panda and its sympatric mammal species in Sichuan Province, to a range of climate change scenarios and analyze their spatial vulnerability patterns to identify priority protected areas and conservation gaps to mitigate the impacts of climate change. Specifically, we formulated the following three hypotheses: (*i*) species sensitivity plays a greater role than habitat exposure in determining vulnerability of these mammal species; (*ii*) future climate change will affect the current ranking of the Red listed species; and (*iii*) these mammal species are more vulnerable at low latitude/altitude areas than high latitude/altitude areas. To test these hypotheses, we adopted the recent proposed CNFA framework (Rinnan and Lawler, 2019). Our study is the first to investigate how the giant panda and its sympatric mammal species will response to future climate change by using a multifaceted approach to mapping climate change vulnerability, and therefore offers new insights for policy decisions regarding the PA networks for giant panda and its sympatric mammal species.

2. Materials and methods

2.1. Study area and species occurrence data

This study was conducted in the giant panda distributional ranges of Sichuan province, China (102°29′36″–102°52′24″ E, 29°28′33″–29°43′54″ N) — home to about 75 % of the giant panda populations (Fig. S1). This region is mainly composed of five mountain ranges, including Minshan, Qionglai, Daxiangling, Xiaoxiangling and Liangshan, covering an area of ~127,438 km^2. This region is also an important global biodiversity hotspot that harbors a lot of rare and endangered species of animals and plants in the southwest China (Myers et al., 2000), which makes this region immensely suitable for evaluating the vulnerability of mammal species under climate change.

The occurrence records of mammal species were provided by the Fourth National Giant Panda Survey (State Forestry Administration, 2021), which was carried out from 2011 to 2014. Although this survey was designed primarily to census giant pandas, there were also instructions for how to identify and record signs (e.g., faeces, fur and signs of foraging) for its sympatric mammals (State Forestry Administration, 2021). To reduce the potential errors in species identification and ensure the quality of data, those signs that species can't not be accurately identified were not retained during the survey (State Forestry Administration, 2021). In total, we obtained 13,898 occurrence records of 44 mammal species during this survey (State Forestry Administration, 2021). To ensure the reliability of this study, we excluded species with fewer than 15 records from subsequent analysis. Finally, a total of

Table 1
Mammal species list, current conservation status and the number of records in the current study.

Order	Common name	Scientific name	IUCN status	Number of records
Primates	Sichuan snub-nosed monkey	*Rhinopithecus roxellana*	EN	207
	Rhesus macaque	*Macaca mulatta*	LC	51
	Tibetan macaque	*Macaca thibetana*	NT	330
Carnivora	Asiatic black bear	*Ursus thibetanus*	VU	580
	Gray wolf	*Canis lupus*	LC	19
	Red fox	*Vulpes vulpes*	LC	30
	Giant panda	*Ailuropoda melanoleuca*	VU	3406
	Chinese red panda	*Ailurus fulgens*	EN	734
	Hog badger	*Arctonyx albogularis*	VU	154
	Masked palm civet	*Paguma larvata*	LC	28
	Asiatic golden cat	*Catopuma temminckii*	NT	26
	Leopard cat	*Prionailurus bengalensis*	LC	535
Artiodactyla	Forest musk deer	*Moschus berezovskii*	EN	298
	Tufted deer	*Elaphodus cephalophus*	NT	830
	Sambar deer	*Rusa unicolor*	VU	322
	Reeves' muntjac	*Muntiacus reevesi*	LC	80
	Takin	*Budorcas taxicolor*	VU	1842
	Chinese serow	*Capricornis sumatraensis*	VU	914
	Chinese goral	*Naemorhedus griseus*	VU	1485
	Wild boar	*Sus scrofa*	LC	1526
Rodentia	Chinese bamboo rat	*Rhizomys sinensis*	LC	74
	Malayan porcupine	*Hystrix brachyura*	LC	121
	Himalayan marmot	*Marmota himalayana*	LC	18

EN: endangered; VU: vulnerable; NT: near threatened; LC: least concern.

13,610 records for 23 mammal species are available to use (Table 1).

2.2. Bioclimatic variables

We downloaded four bioclimatic variables at a ~1 km resolution averaged for the period 1970–2000 from the WorldClim (Fick and Hijmans, 2017): annual mean temperature (MAT), temperature seasonality (TEMP_Season), annual mean precipitation (MAP) and precipitation seasonality (PREC_Season), for these variables have low multicollinearity (all variables with variance inflation factor < 5) and have the greatest ecological relevance to mammal species in the study area (Tang et al., 2020). Similarly, the same four bioclimatic variables at a 2.5 arc-minutes resolution in 2070s (2061–2080) under two representative concentration pathways (RCPs) scenarios, RCP 2.6 and RCP 8.5, from three global circulation models (GCMs): BCC-CSM2-MR, CanESM5 and MIROC-ES2L, were also obtained from the WorldClim (Fick and Hijmans, 2017). Finally, all the bioclimatic variables were resampled at 1 km resolution using a bilinear interpolation.

2.3. Climate change vulnerability assessments

For each species, time periods, RCP scenarios and GCMs, species vulnerability to future climate change were assessed by using climate niche factor analysis (Rinnan and Lawler, 2019), through which two metrics were derived: (*i*) species sensitivity and (*ii*) habitat exposure to future climate change. Species sensitivity is defined as the degree to which the persistence ability of one species is determined by the climatic conditions of its current range (Hirzel et al., 2002). Generally, the more a species was constrained by the climatic conditions of its current range, the more sensitive it is to future climate change (Rinnan and Lawler, 2019). Specifically, sensitivity was quantified by the marginality, which reflects the distance between the niche centroid of climatic conditions in species' habitat and the whole study area, and the specialization, which is the ratio of size of the global niche to that of the species' niche (Hirzel et al., 2002). Habitat exposure is defined as the extent to which the species will experience climate change across its current range and can be calculated as a dissimilarity measure between present and future climatic conditions within its current range. The higher such dissimilarity, the larger the departure of its current range from current climatic conditions to future climatic conditions. Then, the vulnerability for each species was obtained as the geometric mean of sensitivity and exposure. All the vulnerability analyses were carried out using the R package CENFA (Rinnan and Lawler, 2019) under R v4.2.1 (R Core Team, 2022). Specifically, species sensitivity, exposure and vulnerability were calculated using the functions 'cnfa', 'departure' and 'vulnerability' in the CENFA package, respectively.

2.4. Spatial vulnerability analysis

To investigate the spatial vulnerability of the 23 mammal species, we calculated the sensitivity, exposure and vulnerability for each grid cell. To examine whether species are more vulnerability at low latitudes or altitudes under future climate change we used simple linear regression models to explore the relationship between latitude/altitude and the mean spatial vulnerability under RCPs 2.6 and 8.5, respectively. To investigate the effect of different potential future CO_2 emission pathways on the vulnerability of these species, we calculated the difference between the mean spatial vulnerability under RCPs 2.6 and 8.5 for each grid cell and used simple linear regression to explore the variations of these differences along latitudes and altitudes.

2.5. Identification of priority protected areas and gap analysis

To identify the priority areas for protection, we classified the mean spatial vulnerability in each grid cell into three levels: (1) 'Low', the mean spatial vulnerability in the grid cells was less than the 1/3 quantile of the mean spatial vulnerability in the whole study area; (2) 'Median', between the 1/3 and 2/3 quantiles; and (3) 'High', >2/3 quantiles (Wang et al., 2022). Accordingly, the areas of 'High' vulnerability are mostly in need of protection. To help inform and facilitate the development of climate change conservation strategies, we also assessed the percentages of the areas in each vulnerability category within the current PAs network. Finally, we conducted a gap analysis and search for the areas with 'High' vulnerability to climate change but not well protected by the current PAs.

3. Results

3.1. Overall sensitivity, exposure and vulnerability across species

The sensitivity of the 23 mammal species ranged from 1.411 for the Masked Palm Civet to 3.027 for the Himalayan Marmot (mean sensitivity across all 23 species, 1.991 ± 0.419 SD; Table 2). On the contrary, these species exhibited similar patterns in their exposure to climate change. For these mammal species, the exposure under RCP 8.5 (mean ± SD: 1.229 ± 0.047) was generally higher than for under RCP 2.6 (0.757 ± 0.061) (Table 2). Accordingly, compared with other mammal species, the Himalayan Marmot had the highest overall vulnerability, followed by Gray Wolf, Sambar Deer and Sichuan Snub-nosed Monkey, while the Masked Palm Civet had the lowest overall vulnerability (Table 2). The top three species with the highest vulnerability are all "least concern" species in the IUCN Red List. These results indicated that the vulnerability of these mammal species to climate change doesn't closely match their current conservation status in the IUCN Red List under all future scenarios.

The 23 mammal species exhibited similar patterns in their sensitivity, exposure and vulnerability as partitioned among each bioclimatic variable (Fig. 1; Tables S1–S5). Specifically, most of these 23 mammal species are mainly sensitive to MAP (Fig. 1a; Table S1). Moreover, the ranges of these species consistently exhibit high departure of MAT and PREC_Season, but low departure of MAP (Fig. 1b–c; Tables S2–S3). Finally, these 23 species generally exhibit equally high vulnerability to MAT and MAP under climate change (Fig. 1d–e; Tables S4–S5).

Table 2
Overall sensitivity, exposure and vulnerability of the 23 mammal species under RCPs 2.6 and 8.5 by the 2070s.

Species	Sensitivity	Exposure		Vulnerability	
		RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Sichuan snub-nosed monkey	2.501	0.854	1.291	1.687	1.737
Rhesus macaque	1.534	0.794	1.317	1.334	1.383
Tibetan macaque	1.836	0.813	1.279	1.461	1.510
Asiatic black bear	1.657	0.783	1.250	1.383	1.429
Gray wolf	2.627	0.692	1.265	1.714	1.786
Red fox	2.216	0.694	1.158	1.59	1.648
Giant panda	2.287	0.752	1.186	1.594	1.636
Chinese red panda	2.305	0.729	1.136	1.630	1.681
Hog badger	1.631	0.783	1.241	1.369	1.414
Masked palm civet	1.411	0.814	1.347	1.279	1.330
Asiatic golden cat	1.761	0.740	1.255	1.419	1.472
Leopard cat	1.602	0.769	1.216	1.348	1.390
Forest musk deer	1.847	0.722	1.174	1.448	1.495
Tufted deer	1.665	0.771	1.218	1.383	1.428
Sambar deer	2.585	0.665	1.104	1.713	1.766
Reeves' muntjac	1.817	0.808	1.292	1.451	1.501
Takin	2.087	0.741	1.184	1.534	1.579
Chinese serow	1.998	0.718	1.177	1.492	1.538
Chinese goral	2.282	0.731	1.181	1.597	1.642
Wild boar	1.620	0.818	1.276	1.362	1.407
Chinese bamboo rat	1.801	0.768	1.239	1.434	1.480
Malayan porcupine	1.688	0.745	1.192	1.387	1.432
Himalayan marmot	3.027	0.716	1.283	1.844	1.919

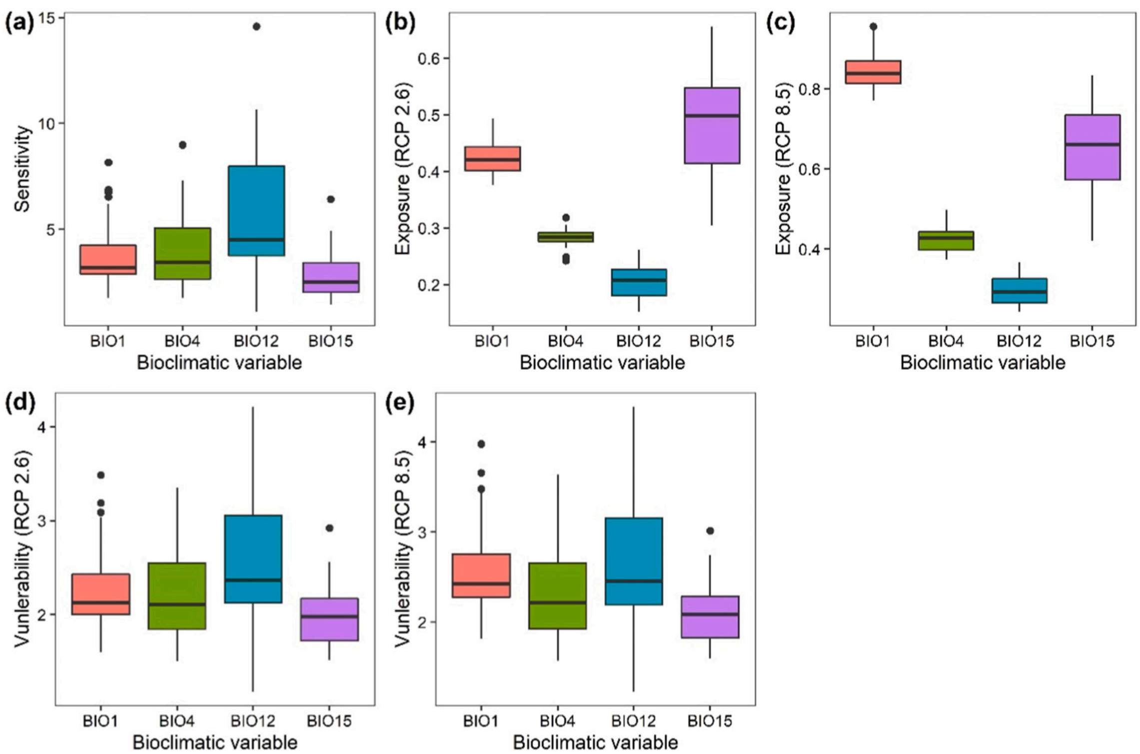

Fig. 1. The sensitivity factor (a), departure factor (b, c) and vulnerability factor (d, e) of 23 mammal species for four bioclimatic variables calculated under RCPs 2.6 and 8.5 by the 2070s.

3.2. Spatial patterns of sensitivity, exposure and vulnerability

As the standard deviation of spatial sensitivity, exposure, and vulnerability for the 23 species was relatively low (Figs. 2–3), the mean spatial sensitivity, exposure, and vulnerability represent common characteristics for these species. The mean spatial sensitivity shows that the high latitude areas (e.g., the western parts of Minshan and Qionglai mountains) are less sensitive to climate change for these species than the low latitude areas (e.g., the eastern parts of Daxiangling, Xiaoxiangling and Liangshan mountains) (Fig. 2a). Similarly, these mammal species will experience high climatic exposure and have high vulnerability in these areas under all future scenarios (Fig. 3a–b).

The vulnerability of the 23 species exhibited decreasing trends with increasing latitude and altitude under both RCP 2.6 ($R^2 = 0.240$, $p < 0.001$ for latitudes and $R^2 = 0.513$, $p < 0.001$ for altitudes; Fig. 3d, g) and RCP 8.5 ($R^2 = 0.265$, $p < 0.001$ for latitudes and $R^2 = 0.531$, $p < 0.001$ for altitudes; Fig. 3e, h). Besides, the increasement in mean spatial vulnerability from RCP 2.6 to 8.5 also decreased with the increase of latitude ($R^2 = 0.255$, $p < 0.001$; Fig. 3f) and latitude ($R^2 = 0.459$, $p < 0.001$; Fig. 3i).

3.3. Conservation gap analysis and priority protected areas

Under all future climate scenarios, the areas where these mammal species are in 'Low' vulnerability mainly occur in the western parts of the study area and at high latitudes (between 32°N and 34°N), while the areas where the species are in 'High' vulnerability mainly occur at low latitudes (between 28°N and 30°N) (Fig. 4a–b). In particular, these species are expected to face greater climate-related risks in Daxiangling and Liangshan mountains, for the percentage of the area of 'High' vulnerability in these mountains would be up to 80 % in Daxiangling and 50 % in Liangshan, respectively (Fig. 4c–d). However, our conservation gap analyses show that no more than 5 % of these high vulnerability areas would be covered by the current PAs (Fig. 4e–f). Moreover, although these species mainly distribute in the areas of 'Low' and 'Median' vulnerability, the current PA network covers < 25 % of these areas (Fig. 4e–f).

4. Discussion

Scientifically sound predictions of which species will most likely be at risk from climate change and where the risks will be the greatest is essential to guide conservation strategies, especially for rare and endangered species (Williams et al., 2007; Soroye et al., 2020). In this study, we evaluated the vulnerability of giant panda and its 22 sympatric mammal species to future climate change and showed that species sensitivity rather than habitat exposure (i.e. changes in climatic conditions) had a significantly preponderant effect in determining the vulnerability of these species (hypothesis *i*), which are not the same as those species that are currently vulnerable in the IUCN Red List (hypothesis *ii*), and that the vulnerability of these species decreased with increasing latitude (hypothesis *iii*). Besides, we found that the current PA network covers < 5 % of the most vulnerable areas and covers < 25 % of the median and low vulnerable areas, respectively. These findings provide insights into the status, trends and threats for giant panda and its sympatric mammal species by identifying risks and prioritizing conservation in a rapidly changing world.

Species sensitivity and habitat exposure have been evaluated separately in many previous studies (Dickinson et al., 2014; Garcia et al., 2014; Williams et al., 2008). However, habitat exposure alone is not sufficient to accurately represent the vulnerability of a species to future climate change (Foden et al., 2019; Pacifici et al., 2015), since the patterns of species' habitat exposure were not necessarily consistent with niche measures of species' sensitivity to climate change (Cianfrani et al., 2018; Jamwal et al., 2021). Consistent with these previous studies, our results show that, the contribution of habitat exposure in determining the vulnerability of giant panda with its sympatric mammal species is almost negligible, while species sensitivity contributes most to the vulnerability. For example, despite ranked as the highest exposure species, Masked Palm Civet was classified as the least vulnerable by

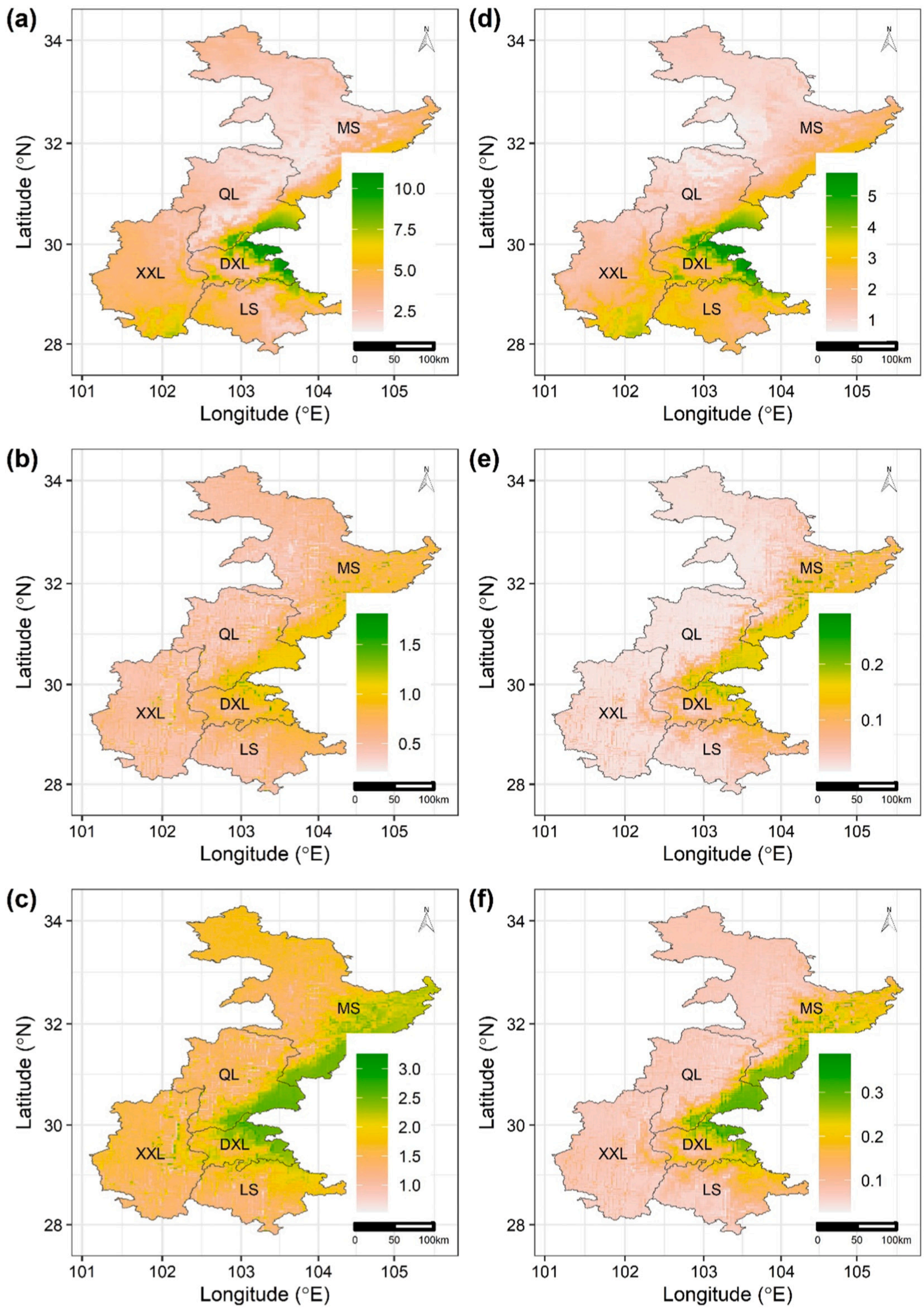

Fig. 2. The mean of predicted sensitivity (a), exposure across the 23 mammal species under RCP 2.6 (b) and RCP 8.5 (c) and the standard deviation of predicted sensitivity (d), exposure across all species under RCP 2.6 (e) and RCP 8.5 (f). The black lines in (a)–(f) are the boundaries of the five mountains in Sichuan provinces: Minshan (MS), Qionglai (QL), Daxiangling (DXL), Xiaoxiangling (XXL) and Liangshan (LS) mountains.

virtue of its lowest sensitivity. These findings highlight the importance of using the measures of niche width to assess species' vulnerability to future climate change (Foden et al., 2019; Jamwal et al., 2021).

The current threat status of species in the IUCN Red List do not always mean equally threats under future climate change in previous studies (e.g., Thomas et al., 2004; Thuiller et al., 2005). Similarly, we found that the vulnerability of some 'Least Concern' mammal species to future climate change was expected to be higher than that of all the 'Endangered', 'Vulnerable' and 'Near Threatened' mammal species, although these species also exhibited relatively high vulnerability. For example, two 'Least Concern' species, Himalayan Marmot and Gray Wolf, mainly distributed in high-elevation regions, are also highly vulnerable to climate change. Moreover, although their narrow habitat is highly fragmented due to intensifying human activities, no actions are

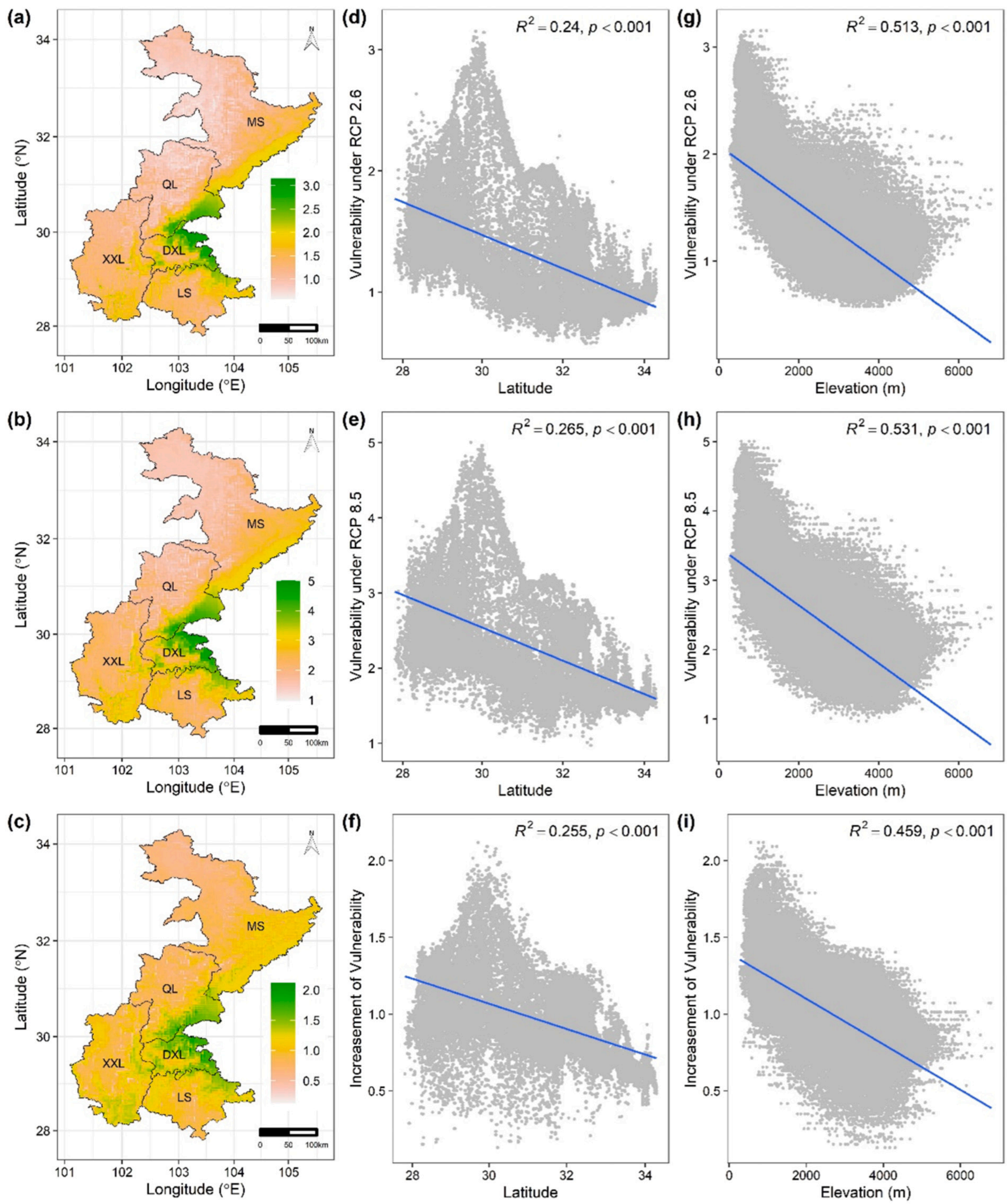

Fig. 3. The mean spatial vulnerability of all 23 mammal species under RCPs 2.6 (a) and 8.5 (b), the increase in mean spatial vulnerability from RCP 2.6 to RCP 8.5 (c) and their relationship with latitude (d–f) and altitude (g–i) under different future climate scenarios by the 2070s. The black lines in (a)–(c) are the boundaries of the five mountains in Sichuan provinces: Minshan (MS), Qionglai (QL), Daxiangling (DXL), Xiaoxiangling (XXL) and Liangshan (LS) mountains.

currently being implemented to protect them (IUCN, 2016). These findings indicate that future climate change may reorder the extinction risk of mammal species in the IUCN Red List of species and reveal the potential limitations of using umbrella species as a conservation tool in protecting mammal communities (Wang et al., 2021), highlighting the necessary to continuously monitor and update the Red List due to the intensifying human-driven climate change (Wang et al., 2021).

Furthermore, our results highlight that there is a significant negative correlation between the vulnerability of these 23 mammal species and latitude/altitude. These results are expected given prior patterns according to previous studies in *Meconopsis* species (Wang et al., 2021) and North American seed plants (Zhang et al., 2017). One possible explanation of these general patterns is that most of species (e.g., endemic, threatened or endangered species) are expected to face greater climate change in low latitudes altitudes than in high latitudes/altitudes (Yuan et al., 2018; Trew and Maclean, 2021), and consequently the appearance of novel climates and the disappearance of existing ones in these regions under future periods will lead to the rapid loss of its current suitable

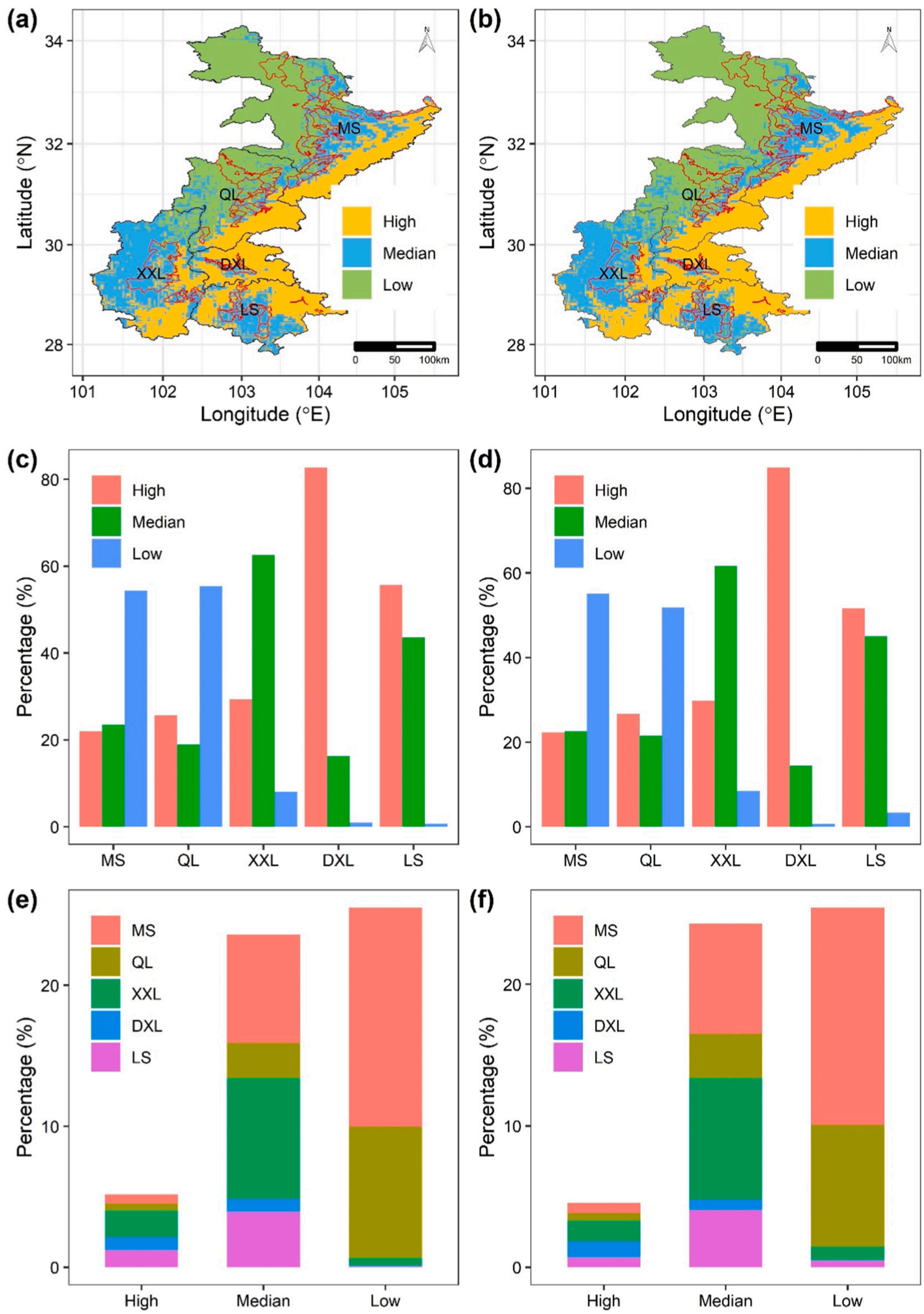

Fig. 4. The spatial distributions of the three levels of vulnerability of the 23 mammal species in the whole study area under RCPs 2.6 (a) and 8.5 (b), the percentage of their areas in each of the five mountains (c–d) and the percentage of their areas insides PAs in each of the five mountains (e–f) by the 2070s. The red lines in (a)–(b) are the boundaries of panda nature reserves. The black lines in in (a)–(d) are the boundaries of the five mountains in Sichuan provinces: Minshan (MS), Qionglai (QL), Daxiangling (DXL), Xiaoxiangling (XXL) and Liangshan (LS) mountains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

habitat and even become local extinction (Williams et al., 2007). Moreover, our results also highlight the Daxiangling, Liangshan mountains as the most vulnerable in low latitudes, along with up to 80 % and 50 % of their total area to have ‘high’ vulnerability by 2070s. Moreover, although the current protected area network has been proven to adequately cover critical landscapes for several sympatric species (Li and Pimm, 2016), no more than 5 % of these areas with ‘high’ vulnerability in these two mountains are situated within it. These conservation gaps, together with other threats such as livestock grazing and road construction (State Forestry Administration, 2006, 2021), poses severe challenges for the effectiveness of the current protected area network to ensure persistence of these mammal species, which also provide a practical starting point for incorporate multi-species conservation planning into future conservation and management strategies. However, although the Giant Panda National Park has been established with the aim to protect more endanger species and vulnerable areas than current PA network, the Liangshan mountains, the second most vulnerable areas identified by our analysis, has not been included in this park system (Xu et al., 2019).

Despite our comprehensive framework addressed some shortcomings of previous studies, our vulnerability assessments are subject to limitations common to the climate niche factor analysis framework (Foden et al., 2019; Jamwal et al., 2021). Specifically, we did not include species adaptability to climate change into the current work (Foden et al., 2019). It is impractical to consider such ability to adjust to climate change at this moment for these data are often unavailable for many species. Additional studies are required to further improve the vulnerability assessment presented here by incorporating species adaptability into the research framework. Specifically, we need to further understand the role that species-specific dispersal ability plays in coping with climate change and how species' evolutionary history confers adaptive potentials to future climate change (Zhang et al., 2017). Moreover, due to potential survey bias and highly variable detectability among species, the detection of these sympatric mammals might be imperfect (Dorazio, 2014), which is likely have an impact on the estimation of species sensitivity and habitat exposure. Therefore, future researches are also needed to assess to what extent species' vulnerability is related to the imperfect detection of species.

In conclusion, we assessed the vulnerability of giant panda and its sympatric mammal species to climate change by using the recently proposed climate niche factor analysis framework within a global biodiversity hotspot. Notably, species sensitivity, rather than habitat exposure, plays a dominant role in determining species vulnerability, highlighting the importance of using multifaceted analyses by integrating species sensitivity and habitat exposure to assess climate-related risks to better inform biodiversity conservation and management. Besides, the vulnerability of mammal species has a negative correlation with latitude, highlighting a disproportionate extinction risk along a latitude gradient. Importantly, the identified areas with 'high' vulnerability and conservation gap analysis suggests conservation planning needs to more directly focus on those not well protected areas with high risks to avoid species losses from climate change. In addition, our estimations of the vulnerability of the 23 major mammal species could be used to improve the future assessments of the current conservation status of biodiversity in the distributional ranges of giant pandas.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The occurrence records data used in this study belong to China's State Forestry and Grassland Administration and are available upon request and approval. The climate and land-use data were detailed and summarized in this paper and Supplemental Information.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (32100401), the Second Tibetan Plateau Scientific Expedition (2019QZKK05010502), and the Fundamental Research Funds (17E067, 17E068, 17C044 and 17C045) and the Innovation Team Funds (KCXTD2022-7) of China West Normal University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109715.

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