Received: 29 July 2022 | Revised: 11 January 2023 | Accepted: 12 January 2023

DOI: 10.1002/eap.2831

ECOLOGICAL APPLICATIONS
ECOLOGICAL SOCIETY OF AMERICA

ARTICLE

Special Feature: Management of biological invasions in China

Vulnerability of protected areas to future climate change, land use modification, and biological invasions in China

Yusi Xin[1,2] | **Zhixu Yang**[1,3] | **Yuanbao Du**[1] | **Ruina Cui**[1] | **Yonghong Xi**[1,4] | **Xuan Liu**[1,4]

[1]Key Laboratory of Animal Ecology and Conservation Biology, Institute of Zoology, Chinese Academy of Sciences, Chaoyang, China

[2]School of Landscape and Architecture, Beijing Forestry University, Haidian, China

[3]School of Ecology and Nature Conservation, Beijing Forestry University, Haidian, China

[4]University of Chinese Academy of Sciences, Beijing, China

Correspondence
Xuan Liu
Email: liuxuan@ioz.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 32171657, 32270549; The Grant of High Quality Economic and Social Development in South Xinjiang, Grant/Award Number: NFS2101; The National Undergraduate' Science and Technology Innovation Training Program, Grant/Award Number: 20204001018; The Third Xinjiang Scientific Expedition Program, Grant/Award Numbers: 2021xjkk0600, 2022xjkk0800; Youth Innovation Promotion Association of the Chinese Academy of Sciences, Grant/Award Number: Y201920

Handling Editor: Aibin Zhan

Abstract

Anthropogenic climate change, land use modifications, and alien species invasions are major threats to global biodiversity. Protected areas (PAs) are regarded as the cornerstone of biodiversity conservation, however, few studies have quantified the vulnerability of PAs to these global change factors together. Here, we overlay the risks of climate change, land use change, and alien vertebrate establishment within boundaries of a total of 1020 PAs with different administrative levels in China to quantify their vulnerabilities. Our results show that 56.6% of PAs will face at least one stress factor, and 21 PAs are threatened under the highest risk with three stressors simultaneously. PAs designed for forest conservation in Southwest and South China are most sensitive to the three global change factors. In addition, wildlife and wetland PAs are predicted to mainly experience climate change and high land use anthropogenetic modifications, and many wildlife PAs can also provide suitable habitats for alien vertebrate establishment. Our study highlights the urgent need for proactive conservation and management planning of Chinese PAs by considering different global change factors together.

KEYWORDS
biodiversity conservation, biological invasion, climate change, global change, land use change, protected areas

INTRODUCTION

Our global biodiversity is rapidly declining in response to accelerating anthropogenic global changes, such as climate change, land use modification, and alien species invasions (Johnson et al., 2017). Protected areas (PAs) are regarded as the cornerstone of local, national, and international biodiversity conservation (Maxwell et al., 2020), but it has been shown that approximately one-third of the world's PAs are under intense human pressures (Jones et al., 2018). Previous studies conducted at the continental scale have identified the strategic role of PAs in shielding native biodiversity by resisting global change impacts such as the risks of alien species establishment under climate change (Gallardo et al., 2017). Nevertheless, a comprehensive assessment of the vulnerability of PAs to different global change processes (i.e., climate change, land-use change, and biological invasions) is still lacking, which is crucial for future systematic conservation planning of PAs in the face of accelerating global change.

Climate change driven by greenhouse gas emissions has been regarded as one continuous major driver of global ecological community reorganization. The effect of climate change is not homogeneous across our planet, as there are some particularly sensitive areas, such as tropical areas and high latitudes (Burrows et al., 2011; Dillon et al., 2010). In addition, there may be climate debt for some types of ecosystems, as the effect of climate change is predicted to accumulate with time lags (Antão et al., 2020). Anthropogenetic habitat transformation is another major driver causing rapid declines in global biodiversity (Newbold et al., 2015). For instance, only one-fifth of global original forest cover remains as self-sustaining natural ecosystems, and many ecoregions, such as grasslands, were extensively converted to agriculture and pasture in the 20th century (WRI/UNDP, 1998). Many remaining lands have also been converted from natural habitats to smaller fragmented patches, which poses significant threats to species distributions and ecosystem functions (Fahrig, 2003). Furthermore, model projections have predicted that habitat loss will continue to increase (Powers & Jetz, 2019). Human-mediated alien species invasions are regarded as one of the greatest threats to biodiversity, economic development, and public health (Blackburn et al., 2019; Diagne et al., 2021; Zhang et al., 2022). Alien species introductions have steadily continued over the past 200 years worldwide (Seebens et al., 2017), and this trend is predicted to continue to increase by 36% from 2005 to 2050 (Seebens et al., 2021). Importantly, global ecosystems are commonly simultaneously exposed to combinations of these global change factors (Comte et al., 2021). It is thus critically important to evaluate their overall risks in PAs by combining different stressors to facilitate the implementation of timely and proactive conservation management strategies.

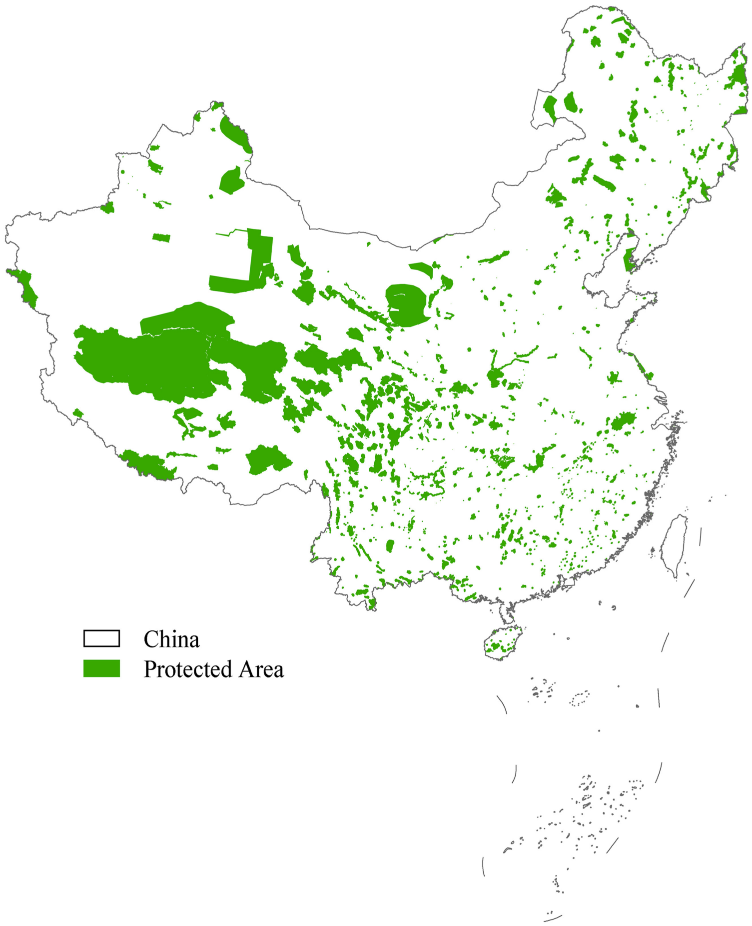
There are approximately 285,520 PAs covering approximately 15.8% of global land and 8.2% of marine areas according to the UNEP World Conservation Monitoring Centre (UNEP-WCMC) based on the November 2022 statistics in the World Database on Protected Areas (available at: www.protectedplanet.net). Traditionally, most PAs are established with a specific purpose or certain assumptions to conserve endangered species and distinctive ecosystems in geographically fixed and isolated spaces. Unfortunately, PAs are currently facing novel and significant threats from the global change processes mentioned above, which have been insufficiently appreciated and not fully incorporated into the designations of most PAs (Barber et al., 2004). For instance, climate change could influence the species conservation effectiveness of PAs by reducing habitat suitability and resulting in species range shifts (Hannah et al., 2007), which would be particularly important throughout low-latitude and tropical PAs (Bruno et al., 2018). Although PAs are generally established in remote areas with low levels of human deforestation, such as wilderness areas and natural monuments (Geldmann et al., 2014), natural habitat degradation usually occurs under increasing pressure from industrial development and local land use (Hernandez et al., 2015; Tesfaw et al., 2018), and this pressure is coupled with future climate change (Swingland et al., 2002). Concerns about the potential impacts of invasive alien species on PAs began 150 years ago and have increased rapidly since the 1980s (Foxcroft et al., 2017). A recent global study focusing on alien animal invaders found that terrestrial PAs are facing increasing risks from biological invasions (Liu et al., 2020). Importantly, PAs usually face different climate and anthropogenetic challenges simultaneously (Shrestha et al., 2021). Therefore, a comprehensive PA system must respond systematically to these global changes by considering the potential impacts of different emerging stressors together. It is thus necessary to evaluate the potential gaps in PAs in response to ongoing global change and to make a sound scientific basis for the future adjustment of PAs to address these new environmental pressures.

Here, based on different administrative level PAs with precise boundary information across China, we evaluate their vulnerability in response to global change factors by integrating the risks of future climate change, the projected anthropogenic land use modification, and the habitat suitability of 1421 alien vertebrate establishment under climate change scenarios. Chinese PA networks have been quantified as having a high representativeness of ecoregion coverage, high biodiversity, and natural vegetation types (Wu et al., 2011), although their conservation efficacy under predicted climate change, land use modification, and alien vertebrate establishment remains unknown. Our present study may not only help evaluate the overall vulnerability of Chinese PAs to environmental challenges but also facilitate the future adjustment of the PA boundaries to better prevent threats from growing global changes in the Anthropocene.

MATERIALS AND METHODS

PAs used in the study

Spatial data on the distributions and boundaries of 1134 PAs located in mainland China (Figure 1) were retrieved from the National Earth System Science Data Center, National



Serial no.	Province	No. protected areas	Area of protected areas (km^2)
①	Anhui	14	1686.5
②	Beijing	5	485.6
③	Chongqing	19	3165.1
④	Fujian	27	2147.7
⑤	Gansu	39	72443.9
⑥	Guangdong	71	3819.0
⑦	Guangxi	53	12311.7
⑧	Guizhou	39	3519.8
⑨	Hainan	23	2269.2
⑩	Hebei	14	2817.6
⑪	Heilongjiang	82	36638.0
⑫	Henan	16	24732.0
⑬	Hubei	28	5707.7
⑭	Hunan	49	8553.8
⑮	Inner Mongolia	44	58750.2
⑯	Jiangsu	11	3103.8
⑰	Jiangxi	83	3763.2
⑱	Jilin	26	11318.5
⑲	Liaoning	29	15142.1
⑳	Ningxia	8	4497.5
㉑	Qinghai	8	207485.2
㉒	Shaanxi	34	8074.6
㉓	Shandong	13	2440.0
㉔	Shanxi	10	2097.5
㉕	Sichuan	141	73770.8
㉖	Tianjin	2	17.6
㉗	Tibet	13	403653.5
㉘	Xinjiang	24	191997.2
㉙	Yunnan	79	21133.4
㉚	Zhejiang	16	896.4

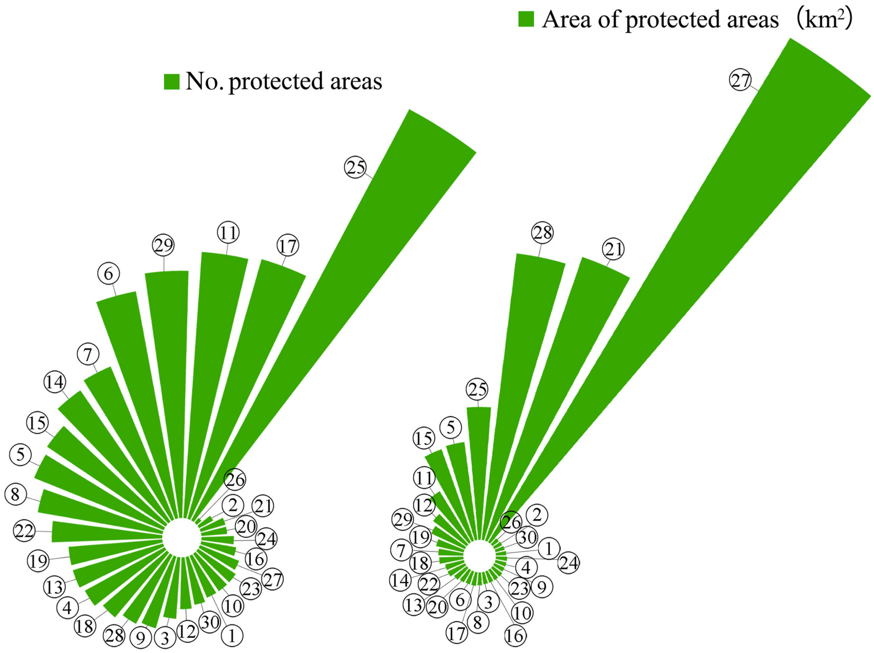


FIGURE 1 Geographic distributions of protected areas (PAs) used in the present study. The top three provinces with the largest number of PAs are Sichuan, Jiangxi, and Heilongjiang, and the top three provinces with the largest areas are Tibet, Qinghai, and Xinjiang.

Science & Technology Infrastructure of China (http://www.geodata.cn) (DOI: 10.12041/geodata.258874459422057.ver1.db), of which the precise PA boundaries were accessible. These PAs correspond to IUCN categories I, II, and IV, which include nature reserves, national parks, and species management areas with clear spatial boundary information. Based on the information from the National Earth System Science Data Center, these PAs can mainly be classified into three types: wetland PAs, forest PAs, and wildlife PAs, depending on different protected targets. We removed 114 marine and natural monument PAs or inland PAs with incomplete data. We also excluded PAs in Taiwan (China), Hong Kong (China), and Macao (China), where the precise spatial distribution data are not available. A total of 1020 PAs with different administrative levels were included for further analyses. These PAs were the most unmodified or slightly modified areas designated for protecting biodiversity and maintaining ecosystem functions. The average area of these PAs was 1165.14 km^2 (ranging from 0.02 to 298,000 km^2) calculated based on a Mollweide Equal Area projection. The top three provinces with the largest number of PAs are Sichuan, Jiangxi, and Heilongjiang, which account for 30% of the total number of all PAs, and the top three provinces with the largest areas of PAs are Tibet, Xinjiang, and Qinghai, which account for 67.6% of the total area of all PAs. The global change variables below were collected at a spatial resolution of 30 arc-second (approximately 1 km^2) to calculate the average environmental changes in PAs using ArcGIS version 10.6.

Global change factors

Climate change vulnerability

Our primary goal was to assess the degree to which projected future climate change may occur in each PA. To achieve this, we first collected present and future data on a total of six climate variables, including mean annual temperature (MAT), mean temperature of warmest quarter (MTWQ), mean temperature of coldest quarter (MTCQ), annual precipitation (AP), precipitation of driest quarter (PDQ), and precipitation of wettest quarter (PWQ) for current (1970–2000) and future (2050) periods from the Climate Research Unit (available at http://www.cru.uea.ac.uk/data). The current (1970–2000) period data were compiled monthly average climate data for weather stations from a large number of global, regional, national, and local sources (Fick & Hijmans, 2017). The future (2050) data are predicted in the MIROC5 mode based on RCP 8.5 scenarios, which have been widely used in global climate change studies (Cohen et al., 2020). These climate variables were chosen because they have been shown to be critically important to the physiological requirements of vertebrates (Araújo et al., 2008; Barbet-Massin & Jetz, 2015; Visconti et al., 2016). To reduce the multicollinearity among climate variables, a principal component analysis (PCA) was performed, and the first two components (i.e., PC1 and PC2) were extracted. The first two components (PC1 + PC2) explained a total of 99.89% and 98.36% of the variance in the present and future climates, respectively, indicating a good representation of the climatic variables. To measure climate vulnerability, we calculated the Euclidean distance between current and future distributions in the two-dimensional climate space (i.e., the PC1 and PC2 axes) (Shrestha et al., 2021). We then calculated the average climate vulnerability per grid for each PA in ArcGIS to account for the potential effect of PA area on climate vulnerability assessment. To better compare the magnitude of climate vulnerability for each PA, we used minimum–maximum normalization to transform the climate vulnerability values into 0–1. Values close to 1 indicate higher climate vulnerability, while values close to 0 indicate lower climate vulnerability (Shrestha et al., 2021).

Anthropogenic land use modification

For the anthropogenetic land use modification, we obtained data on the projected land use types in 2010 and 2050 at a spatial resolution of 1 km × 1 km under the RCP8.5 scenario (Quesada et al., 2018). This land use dataset uses a grid-based spatially explicit cellular automata (CA) model with a global 30 m land cover map (2010) as a base input after incorporating a variety of biogeographic and socioeconomic variables using an empirical analysis to downscale coarse-resolution land use information (specifically urban, crop, and pasture). The dataset accounted for spatial heterogeneity from topography, climate, soils, and socioeconomic variables (Li, Liu, et al., 2016; Li, Yu, et al., 2016). We selected four anthropogenic land use types, including cropland, grassland, impervious land, and urban greenspace, to represent the anthropogenic modified land use types during urbanization and agricultural development (Brovkin et al., 2013; Findell et al., 2017). Then, we performed PCA on the proportion of anthropogenically modified land use types along two different time dimensions and extracted the first two components that explained 97.6% and 97.04% of the variance for the present and future scenarios, respectively. We next calculated the Euclidean distance between the current and future distributions in two-dimensional climate space (i.e., the PC1 and PC2 axes) (Shrestha et al., 2021). Finally, we calculated the average of land-use types that were changed to a more anthropogenically influenced type in the unit raster of PAs to assess the extent to which potential land-use modification may occur within each PA (Zhang et al., 2022). We used minimum–maximum normalization to standardize the mean anthropogenic land use change for each PA to 0–1. Values close to 1 imply a higher risk of anthropogenetic land use modification, while values close to 0 imply a lower risk of modification.

Habitat suitability of alien vertebrate establishment

Habitat suitability is regarded as a fundamental factor in determining the risk of alien species establishment (Pyšek et al., 2010) and has been widely used to evaluate the risk of alien species establishment in both current and future climates (Bellard et al., 2013; Liu et al., 2019). Using keywords in English ((“alien” OR “introduc” OR “exotic” OR “non-native” OR “non native” OR “non-indigenous” OR “invasive”) AND (“vertebrate*” OR “mammal*” OR “reptile*” OR “amphibian*” OR “bird*” OR “fish*”) AND (“China” OR “mainland China” OR “China mainland”)) and Chinese ((“外来” OR “非本土” OR “外来入侵” OR “入侵”) AND (“脊椎动物” OR “哺乳动物” OR “鸟类” OR “两栖动物” OR “爬行动物” OR “鱼类” OR “淡水鱼类”) AND (“中国” OR “中国大陆”)), we reviewed literatures using Web of Science (https://www.webofscience.com/) and the Chinese Journal Full-text Database (National Knowledge Infrastructure, CNKI: https://www.cnki.net/), and extracted information of alien vertebrates that have been introduced to mainland China. In addition, we also checked all available open datasets to obtain alien or invasive vertebrates reported from mainland China. We obtained a total of 1421 alien vertebrates (83 amphibians, 369 reptiles, 334 birds, 416 fishes, and 219 mammals) (Data is available at Science Data Bank: https://www.scidb.cn/en). We conducted a cross-check of synonyms for all the alien vertebrates according to the taxonomy in the IUCN (https://www.iucnredlist.org/). Species names were also checked according to global open datasets for amphibians (The AmphibiaWeb, https://amphibiaweb.org/), reptiles (the reptile database, https://reptile-database.reptarium.cz/), birds (Avibase, https://avibase.bsc-eoc.org/avibase.jsp; Birdlife, https://www.birdlife.org/), and mammals (Mammal Species of the World 3rd edition, https://www.mammaldiversity.org/). We finally rechecked all the species names collected from different source databases according to “species-2000-China” (http://www.sp2000.org.cn/) to exclude those species native to China.

To be consistent with the temporal scale of the other two factors, we evaluated the alien vertebrate invasion risk by constructing species distribution models (SDMs) under current (1970–2000) and future (2050) periods in each of the PAs. We first collected occurrence records of each alien vertebrate from a number of online databases, including the Global Biodiversity Information Facility (GBIF, http://www.gbif.org/), Atlas of Living Australia (ALA, http://www.ala.org.au/), Biodiversity Information Serving Our Nation (BISON, https://bison.usgs.gov/), iNaturalist (iNat, https://www.inaturalist.org/), eBird (https://ebird.org/), Integrated Digitized Biocollections (iDigBio, https://www.idigbio.org/), with reference to Dyer et al's GAVIA database (Dyer et al., 2017), Biancolini et al's DAMA database (Biancolini et al., 2021), and Zhang et al. (2022). Occurrence data extraction was conducted with the scientific name of each alien vertebrate using the *spocc* (Chamberlain, 2021) and *rgbif* (Chamberlain et al., 2022; Chamberlain & Boettiger, 2017) packages in R (R Core Team, 2021). We then performed a data cleaning procedure to remove clustered records and invalid or duplicated records, and retained one record per 5 arc-minute grid cells to account for the potential biases from the data repositories (Kramer-Schadt et al., 2013). The species occurrence data were collected from both their native and invaded ranges considering the fact that alien vertebrates may occupy new realized climatic niches in invaded ranges (Broennimann et al., 2021; Cardador & Blackburn, 2020; Liu et al., 2017). Present-day and future climatic predictors at a resolution of 5 arc-minutes were extracted from the WorldClim/CHELSA database (WorldClim, https://worldclim.org/; CHELSA, https://chelsa-climate.org/). Based on the ecological requirements of our study species, we selected different bioclimatic predictors for the four taxonomic groups (Appendix S1: Table S1). The water variable reflecting the aquatic habitat of fish and terrestrial vertebrates' requirement for reproduction and food was obtained from the Global Lakes and Wetlands Database (GLWD, http://www.wwfus.org/science/data.cfm). The future water variable was not available yet and was thus assumed to be constant with the current conditions following previous studies (Li, Liu, et al., 2016; Li, Yu, et al., 2016).

We constructed SDMs using the maximum entropy algorithm (MaxEnt), which generally shows high predictive performance and has been extensively applied in macroecology and biogeography studies (Phillips et al., 2006). We did not include more modeling techniques, as a recent study suggested that there were no significant advantages of using multiple model ensembles compared with the single model approach (Hao et al., 2020). We built a number of candidate models with different feature classes and regularization multipliers, and selected the optimal one with a low 10% omission rate and a high AUC (area under the curve of the receiver operating characteristic) value to optimize model complexity when developing MaxEnt models (Radosavljevic & Anderson, 2014). The predictive ability of the optimal model was further evaluated using the continuous Boyce index (Hirzel et al., 2006), which represents a robust index for the presence-only model. The continuous habitat suitability SDM projections were converted into species presence (1) or absence (0) using 10% presence probability threshold (Zhang et al., 2021). We then evaluated the habitat suitability for establishment of each PA using the mean of the predicted richness of established alien species among grids in each of PA (Gallardo et al., 2017) considering the fact that there tended to be more established alien species in larger PAs (Liu et al., 2020). We used minimum–maximum normalization to standardize the average number of predicted richness of established alien vertebrate of each PA into 0–1. A value close to 1 indicates high alien vertebrate establishment risk, while a value close to 0 indicates low alien vertebrate establishment risk. To maintain the consistency of data accuracy, we resampled the predicted richness of established alien vertebrate to a 30 arc-second accuracy.

Combining three global change factors to calculate overall threats

We applied a three-level overlap analysis by assuming that a PA will be under the highest threat from the three global change factors when climate change, land use change, and habitat suitability for establishment of alien vertebrate are all predicted to be the highest in the future (Shrestha et al., 2021). We first quantified the ranking of each PA for each of the three global change factors by defining the PAs with the highest risks as the 25% of PAs with the highest climate change, the highest predicted richness of established alien vertebrates, and the highest proportion of anthropogenetic land use modifications. We then defined PAs with three-factor overlap as very high-risk, PAs with two-factor overlap as high-risk, PAs with only one single factor as medium-risk, and PAs with no high-risk factors as low-risk.

RESULTS

Risk assessment of different single global change factors

Most of the PAs with the highest climate change threats were located in Southwest, South, and Northeast China, following by PAs in some regions such as North of Xinjiang (Figure 2a). PAs with a very high risk of climate change accounted for 7.7% of the total area of PAs, with the top five provinces being Tibet, Sichuan, Yunnan, Liaoning, and Shaanxi. Provinces of Sichuan, Yunnan, Jiangxi, Guangdong, and Liaoning have the largest number of PAs with very high climate change risk. Forest PAs are most vulnerable to climate change with the number accounting for 29.5% of all the forest PAs, followed by wildlife PAs (21.4%) and wetland PAs (20.7%) (Figure 2a).

PAs facing very high anthropogenic land use changes were predicted in most regions, particularly in Southwest China and Northeast China (Figure 2b). These PAs accounted for 6.6% of the total area of the PAs. Among them, Sichuan, Heilongjiang, Liaoning, Jiangxi, and Yunnan ranked as the top five provinces with the highest number of PAs sensitive to land use change, and the area of PAs located in Inner Mongolia, Sichuan, Jilin, Liaoning, and Heilongjiang ranked as the top five provinces with the largest area of PAs facing very high land use anthropogenic changes. Wildlife PAs were most vulnerable to land use change, with the number accounting for 26.4% of all the wildlife PAs, followed by forest PAs and wetland PAs accounting for 25.5% and 22.5% of the corresponding PAs (Figure 2b).

Most PAs with a very high habitat suitability of alien vertebrate establishment were located in Central, southern, and southwestern China, and these PAs accounted for 2.6% of the total area of all PAs (Figure 2c). Among them, the number of PAs in Guangdong, Jiangxi, Yunnan, Guangxi, and Hainan were ranked as the top five provinces, and PAs located in Guangxi, Yunnan, Hunan, Guangdong, and Hainan had the largest area with very high habitat suitability of alien vertebrate establishment. Forest PAs could provide the highest proportion (35.6%) of PAs suitable for alien vertebrate establishment, followed by wildlife PAs (16.5%) (Figure 2c).

Overall threats of three global change factors

Based on the spatial distributions of the PAs with a very high risk of climate change, anthropogenic land use change, and alien vertebrate establishment, we quantified the overall risk of PAs to the three global change factors together (Figure 3a). We found that 21 PAs, mainly in Southwest and South China, were ranked as the most vulnerable PAs, with three very high-risk factors overlapping simultaneously. Nearly half of these PAs are located in Yunnan Province, and most were forest PAs (Figure 3). Additionally, 146 PAs were ranked as high-risk PAs with two overlapping very high-risk factors, and most were forest and wildlife PAs concentrating in Southwest, Central, and South China (Figure 3). Among them, 44 PAs with very high risks of climate change and anthropogenic land use change (Figure 4a), which were mainly concentrated in Southwest and Northeast China.

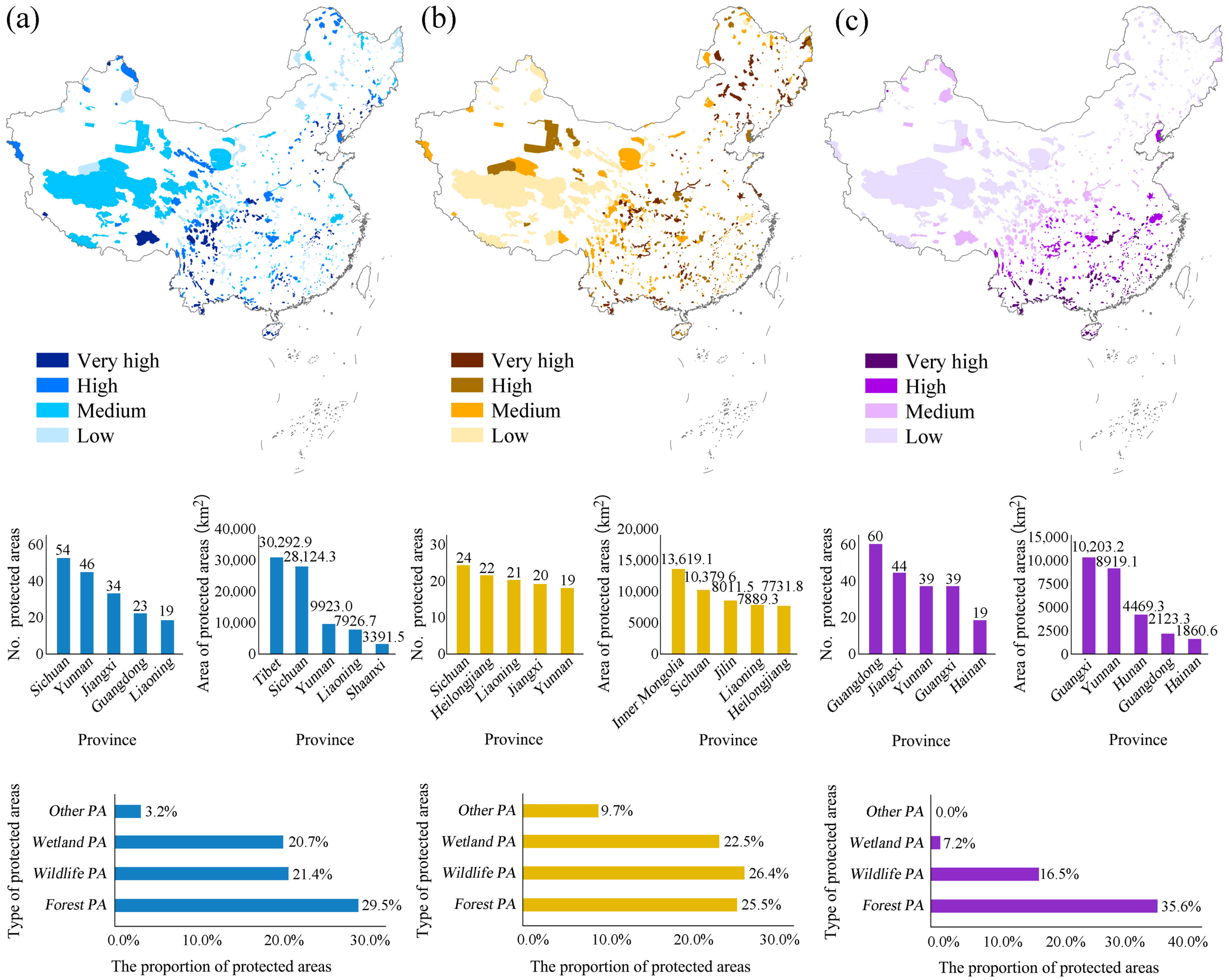


FIGURE 2 Different global change vulnerabilities of protected areas (PAs) in China. (a) Classification of PAs based on the climate change vulnerability. (b) Classification of PAs based on human-induced land use change vulnerability. (c) Classification of PAs based on alien vertebrate establishment vulnerability. The top 25% of PAs with the highest risk are considered as very high-risk PAs, the top 25%–50% PAs are considered as high-risk, the 50%–75% PAs are considered as medium-risk and the remaining 75%–100% PAs are considered as low-risk.

There were 62 PAs had overlapping climate change and habitat suitability for alien vertebrate establishment (Figure 4b), and these PAs were mainly located in Southwest and South China and Jiangxi Province. There were 40 PAs with a very high habitat suitability for alien vertebrate establishment and anthropogenic land use change (Figure 4c), most of which were located in Southwest, South, and Central China.

DISCUSSION

Our present study, to our knowledge, provides the first quantitative evaluation of the threats posed by three major global change factors (i.e., climate change, anthropogenic land use change, and biological invasions) together on PAs in China. We show that the vulnerable (167 very high-risk and high risk) PAs accounted for approximately 16.4% and 2.6% of the total number and area of all PAs, which are facing high risks of climate change, anthropogenic land-use change, and alien vertebrate establishment together. These PAs require the most stringent conservation measures to mitigate future potential global change impacts. We find that PAs in Southwest China will experience very high pressure from these three global change factors from the perspectives of both number and area. Previous studies have identified that PAs in these regions are biodiversity conservation

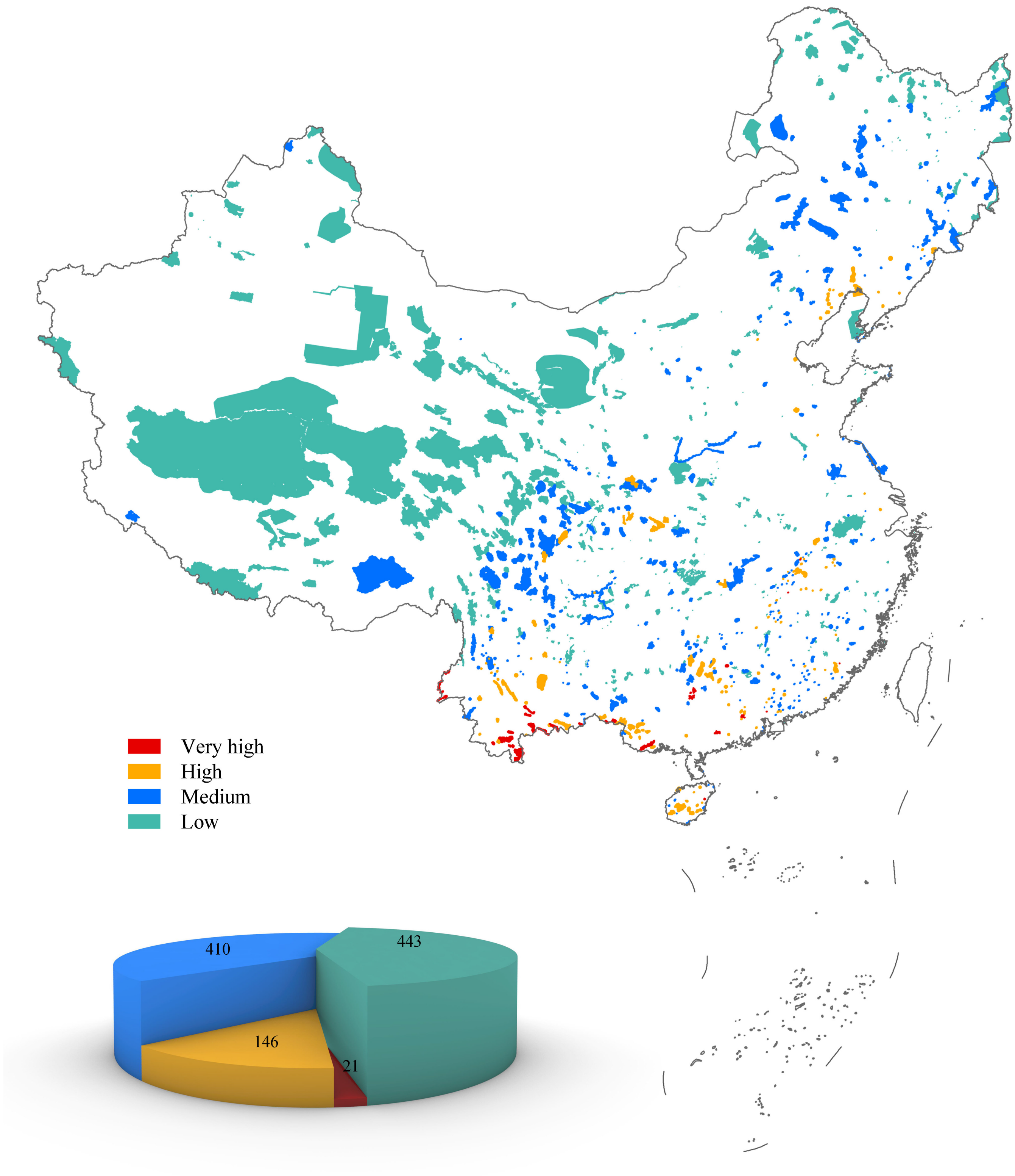


FIGURE 3 Classification of protected areas (PAs) in China based on three global change vulnerabilities, including climate change, anthropogenetic land use change, and habitat suitability of alien vertebrate establishment. PAs in red represent those that are at a very high risk for all three factors (very high risk, 21 PAs). PAs in orange represent those defined by two very high-risk factors (high risk, 146 PAs). PAs in blue represent those defined by only one very high-risk factor (medium risk, 410 PAs). PAs that are outside of the high-risk hotspots of these three factors were shown in green (low risk, 443 PAs).

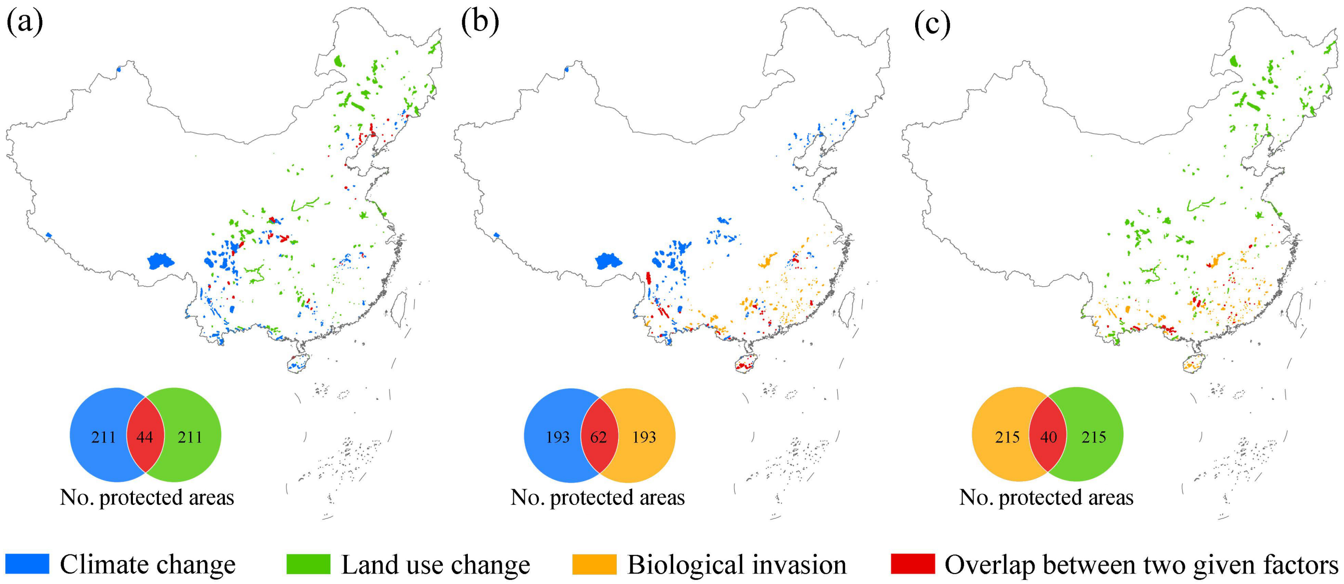


FIGURE 4 The overlap vulnerabilities of two global change factors. (a) Climate change and land use change. (b) Climate change and habitat suitability of alien vertebrate establishment. (c) Land use change and habitat suitability of alien vertebrate establishment. Colors indicate areas of very high vulnerability defined as the 25% of grid cells with (1) the highest climate change, (2) the highest anthropogenetic degree of land use change, and (3) the highest habitat suitability of alien vertebrate establishment.

hotspots under historical climate variability and anthropogenic pressures (Shrestha et al., 2021). Our present study provides further evidence of their vulnerability to future environmental changes. Considering that Southwest China is well known for its high biodiversity, we therefore suggest that PAs in this region should be a key area of conservation concern to fight the risks of different global change factors in the Anthropocene.

Our results show that several different types of PAs were generally vulnerable to the potential impacts of climate change. Climate change may thus pose an inevitable threat to Chinese PAs by affecting the ecosystems stability and wildlife survival through increasing temperatures, temperature and precipitation variability, and extreme climate events (Gross et al., 2016; Hoffmann & Beierkuhnlein, 2020). Climate change may also reshape the geographical distributions of wildlife and the resulting community structure and ecosystem functions (Pecl et al., 2017). This is especially true for species living close to their climatic tolerance and those that have low adaptation abilities to climate change (Garcia et al., 2014; Sinervo et al., 2010). PAs located at higher latitudes and altitudes may act as refuges to support more native species that disperse to these regions with climate change (Berteaux et al., 2018; Steinbauer et al., 2018). Therefore, sensitive PAs identified in our present study should be given priority attention through targeted measures to maintain their conservation effectiveness. We suggest that it may be helpful to expand existing PAs and establish new PAs in areas with less climate change (Elsen et al., 2020; Hoffmann et al., 2019).

With the increasing human population and process of urbanization, PAs are experiencing great pressure from the transformation of natural vegetation to residential zones and cropland (Martinuzzi et al., 2015). We find that PAs in Northeast, Southwest, South, Central, East, and North China have different degrees of sensitivity to anthropogenic land use change. In addition to wildlife and forest PAs, wetland PAs might be under great pressure from anthropogenic land use change that may disturb wildlife habitats. For instance, land use change may isolate crucial wildlife dispersal habitat corridors and reduce the ecological function of PAs to maintain biodiversity (DeFries et al., 2007). We suggest that it may be useful to establish buffer zones where local human populations can use PA resources and preserve migration corridors to help wildlife avoid the negative effects of habitat disturbances (Yang & Xia, 2008). Specifically, for wetland PAs, we recommend that the government consider proposing ecological recovery projects to resume lakes and ponds that provide essential habitats and wildlife food and water resources (Hawkins et al., 2003).

The issue of invasive alien species in PAs has been a concern for a long time (Usher, 1988). Compared with previous evaluations on the spatial patterns of alien species establishment under current climatic conditions (Liu et al., 2020; Shackleton et al., 2020), we still have a limited understanding of the future habitat suitability of alien species establishment under climate change in PAs

(Gallardo et al., 2017). Our present study supports a recent global evaluation stating that many PAs indeed may provide suitable habitats for alien vertebrate establishment under current climates (Liu et al., 2020). We provide further country-level insights that 36% of Chinese PAs will provide suitable habitat for the establishment of at least 60 alien vertebrates under future climate change, which is generally consistent with a continental study on the high risks of alien species establishment in Europe (Gallardo et al., 2017). This is especially true for forest and wildlife PAs in Southwest, Northwest, and Central China, which generally have higher elevations and latitudes, where has been predicted to increase habitat suitability for alien species establishment under future climate change (Bellard et al., 2013; Liu et al., 2011).

We acknowledge that our present study may still have some limitations. For instance, the vulnerability of each individual PA to global change factors may not only depend on the degree to which climate change, land use modification, and alien vertebrate establishment will occur but also be related to the resistance of PAs to these challenges (Dawson et al., 2011). The invasion risk of alien species is not only influenced by habitat suitability but is also closely associated with introduction factors related with human activities (Pyšek et al., 2010) and propagule pressures important for establishment (Lockwood et al., 2009), which are not yet available for future scenario modeling. Finally, the risk of Chinese PAs to global change may also be dependent on the exact policies that the government may carry out in the future. For example, in some regions, anthropogenic habitat disturbances may even be reduced under government intervention in the future (Zhang & Schwärzel, 2017). However, it is impossible to incorporate the policy effect into the predictive models, which needs more future studies when related information is available and can be quantified in modeling. The Chinese government has been paying close attention to the construction of national parks based on historical nature reserve systems. Our present study adds to previous research on the environmental challenges of Chinese PAs under historical and traditional environmental threats (Shrestha et al., 2021) and demonstrates that conservation planning for PAs also needs to incorporate future global change challenges by assessing the vulnerability of PAs to predicted future environmental changes. The map incorporating climate change, land use change, and habitat suitability for alien vertebrate establishment within PAs here provides the first step to achieve this goal by guiding spatial designation and zoning inside PAs for stakeholders and policy-makers.

Based on our findings, we propose some management suggestions to enhance the ability of Chinese PAs to cope with the future climate change, anthropogenic land use modification, and alien species invasion. In order to effectively adapt to climate change, it is necessary to establish an ecological corridor network among adjacent PAs with similar environmental conditions to facilitate dispersal of emigrants and arrival of colonists tracking climate change (Hole et al., 2011). It is especially for those small or isolated PAs that should be connected together to form a large PA network system. In addition, it is also needed to conduct specific evaluations on different native species in PAs to identify those highly vulnerable species for timely migration and ex situ conservation into climate-change refugia (Chen et al., 2017; Zhu et al., 2021). The anthropogenic land use change may further impede the dispersal of species especially for those taxa with weak dispersal abilities (Asamoah et al., 2021). Therefore, we suggest that natural resource disturbances should be avoided entirely in the core protection zones of PAs and it needs rigorous scientific guidance to conduct sustainable natural resource utilization in restricted areas of PAs. Some restoration and rewilding projects warrant future applications into the habitat recovery of those key wildlife species that are sensitive to land-use change (Pringle, 2017). Our results also show that there are some PAs that may be particularly suitable for alien vertebrate establishment. Because it is very difficult and often impossible to completely eradicate established populations (Blackburn et al., 2011; Simberloff et al., 2013), we recommend that strict prevention measures be taken against potential alien vertebrate introductions and establishment by strengthening the early detection and quarantine management of alien propagules within and around PAs.

ACKNOWLEDGMENTS

We thank two anonymous reviewers for their constructive comments on the manuscript. This work was supported by the Third Xinjiang Scientific Expedition Program (2022xjkk0800 and 2021xjkk0600), National Science Foundation of China (32171657 and 32270549), the Grant of High Quality Economic and Social Development in South Xinjiang (NFS2101), the grants from Youth Innovation Promotion Association of Chinese Academy of Sciences (Y201920) and the National Undergraduate' Science and Technology Innovation Training Program (20204001018).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

(1) Spatial data on the distributions and boundaries of PAs located in mainland China were retrieved from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn) using the keyword "protected area" ("自然保护区" in

Chinese) (DOI: 10.12041/geodata.258874459422057.ver1.db). (2) The list of 1421 alien vertebrates that have been introduced into mainland China, including detailed reference information, is available in Xin et al. (2023) in the Science Data Bank at https://doi.org/10.57760/sciencedb.07046. (3) Information of keywords and literature databases have been provided in *Materials and methods* section. Some occurrence data of alien vertebrates that have been introduced into mainland China and used for species distribution modeling were downloaded from Global Biodiversity Information Facility (GBIF, http://www.gbif.org/) from the link: https://doi.org/10.15468/dl.rm8rn8. Some occurrence data from Atlas of Living Australia (ALA, http://www.ala.org.au/), Biodiversity Information Serving Our Nation (BISON, https://bison.usgs.gov/), iNaturalist (iNat, https://www.inaturalist.org/), eBird (https://ebird.org/), and Integrated Digitized Biocollections (iDigBio, https://www.idigbio.org/) can be downloaded from the Science Data Bank at https://doi.org/10.57760/sciencedb.07577.

ORCID

Yuanbao Du https://orcid.org/0000-0003-1345-4127

REFERENCES

Antão, L. H., A. E. Bates, S. A. Blowes, C. Waldock, S. R. Supp, A. E. Magurran, M. Dornelas, and A. M. Schipper. 2020. "Temperature-Related Biodiversity Change across Temperate Marine and Terrestrial Systems." *Nature Ecology & Evolution* 4(7): 927–33.

Araújo, M. B., D. Nogués-Bravo, J. A. F. Diniz-Filho, A. M. Haywood, P. J. Valdes, and C. Rahbek. 2008. "Quaternary Climate Changes Explain Diversity among Reptiles and Amphibians." *Ecography* 31(1): 8–15.

Asamoah, E. F., L. J. Beaumont, and J. M. Maina. 2021. "Climate and Land-use Changes Reduce the Benefits of Terrestrial Protected Areas." *Nature Climate Change* 11(12): 1105–10.

Barber, C. V., K. Miller, and M. Boness. 2004. *Securing Protected Areas in the Face of Global Change: Issues and Strategies*. Gland, Switzerland: IUCN.

Barbet-Massin, M., and W. Jetz. 2015. "The Effect of Range Changes on the Functional Turnover, Structure and Diversity of Bird Assemblages under Future Climate Scenarios." *Global Change Biology* 21(8): 2917–28.

Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes, and F. Courchamp. 2013. "Will Climate Change Promote Future Invasions?" *Global Change Biology* 19(12): 3740–8.

Berteaux, D., M. Ricard, M.-H. St-Laurent, N. Casajus, C. Périé, F. Beauregard, and S. de Blois. 2018. "Northern Protected Areas Will Become Important Refuges for Biodiversity Tracking Suitable Climates." *Scientific Reports* 8(1): 4623.

Biancolini, D., V. Vascellari, B. Melone, T. M. Blackburn, P. Cassey, S. L. Scrivens, and C. Rondinini. 2021. "DAMA: The Global Distribution of Alien Mammals Database." *Ecology* 102: e03474.

Blackburn, T. M., C. Bellard, and A. Ricciardi. 2019. "Alien Versus Native Species as Drivers of Recent Extinctions." *Frontiers in Ecology and the Environment* 17(4): 203–7.

Blackburn, T. M., P. Pyšek, S. Bacher, J. T. Carlton, R. P. Duncan, V. Jarošík, J. R. U. Wilson, and D. M. Richardson. 2011. "A Proposed Unified Framework for Biological Invasions." *Trends in Ecology & Evolution* 26(7): 333–9.

Broennimann, O., B. Petitpierre, M. Chevalier, M. González-Suárez, J. M. Jeschke, J. Rolland, S. M. Gray, S. Bacher, and A. Guisan. 2021. "Distance to Native Climatic Niche Margins Explains Establishment Success of Alien Mammals." *Nature Communications* 12(1): 2353.

Brovkin, V., L. Boysen, V. K. Arora, J. P. Boisier, P. Cadule, L. Chini, M. Claussen, et al. 2013. "Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century." *Journal of Climate* 26(18): 6859–81.

Bruno, J. F., A. E. Bates, C. Cacciapaglia, E. P. Pike, S. C. Amstrup, R. van Hooidonk, S. A. Henson, and R. B. Aronson. 2018. "Climate Change Threatens the World's Marine Protected Areas." *Nature Climate Change* 8(6): 499–503.

Burrows, M. T., D. S. Schoeman, L. B. Buckley, P. Moore, E. S. Poloczanska, K. M. Brander, C. Brown, et al. 2011. "The Pace of Shifting Climate in Marine and Terrestrial Ecosystems." *Science* 334(6056): 652–5.

Cardador, L., and T. M. Blackburn. 2020. "A Global Assessment of Human Influence on Niche Shifts and Risk Predictions of Bird Invasions." *Global Ecology and Biogeography* 29(11): 1956–66.

Chamberlain, S. 2021. "Spocc: Interface to Species Occurrence Data Sources." https://CRAN.R-project.org/package=spocc.

Chamberlain, S., V. Barve, D. Mcglinn, D. Oldoni, P. Desmet, L. Geffert, and K. Ram. 2022. "Rgbif: Interface to the Global Biodiversity Information Facility Api." R Package Version 3.7.2. https://CRAN.R-project.org/package=rgbif.

Chamberlain, S. A., and C. Boettiger. 2017. "R Python, and Ruby Clients for Gbif Species Occurrence Data." *PeerJ PrePrints* 5: e3304v1.

Chen, Y., J. Zhang, J. Jiang, S. E. Nielsen, and F. He. 2017. "Assessing the Effectiveness of China's Protected Areas to Conserve Current and Future Amphibian Diversity." *Diversity and Distributions* 23(2): 146–57.

Cohen, J. M., E. L. Sauer, O. Santiago, S. Spencer, and J. R. Rohr. 2020. "Divergent Impacts of Warming Weather on Wildlife Disease Risk across Climates." *Science* 370(6519): eabb1702.

Comte, L., J. D. Olden, P. A. Tedesco, A. Ruhi, and X. Giam. 2021. "Climate and Land-Use Changes Interact to Drive Long-Term Reorganization of Riverine Fish Communities Globally." *Proceedings of the National Academy of Sciences of the United States of America* 118(27): e2011639118.

Dawson, T. P., S. T. Jackson, J. I. House, I. C. Prentice, and G. M. Mace. 2011. "Beyond Predictions: Biodiversity Conservation in a Changing Climate." *Science* 332(6025): 53–8.

DeFries, R., A. Hansen, B. L. Turner, R. Reid, and J. Liu. 2007. "Land Use Change around Protected Areas: Management to Balance Human Needs and Ecological Function." *Ecological Applications* 17(4): 1031–8.

Diagne, C., B. Leroy, A.-C. Vaissière, R. E. Gozlan, D. Roiz, I. Jarić, J.-M. Salles, C. J. A. Bradshaw, and F. Courchamp. 2021. "High and Rising Economic Costs of Biological Invasions Worldwide." *Nature* 592(7855): 571–6.

Dillon, M. E., G. Wang, and R. B. Huey. 2010. "Global Metabolic Impacts of Recent Climate Warming." *Nature* 467(7316): 704–6.

Dyer, E. E., D. W. Redding, and T. M. Blackburn. 2017. “The Global Avian Invasions Atlas, a Database of Alien Bird Distributions Worldwide.” *Scientific Data* 4: sdata201741.

Elsen, P. R., W. B. Monahan, E. R. Dougherty, and A. M. Merenlender. 2020. “Keeping Pace with Climate Change in Global Terrestrial Protected Areas.” *Science Advances* 6(25): eaay0814.

Fahrig, L. 2003. “Effects of Habitat Fragmentation on Biodiversity.” *Annual Review of Ecology, Evolution, and Systematics* 34: 487–515.

Fick, S. E., and R. J. Hijmans. 2017. “WorldClim 2: New 1-Km Spatial Resolution Climate Surfaces for Global Land Areas.” *International Journal of Climatology* 37(12): 4302–15.

Findell, K. L., A. Berg, P. Gentine, J. P. Krasting, B. R. Lintner, S. Malyshev, J. A. Santanello, and E. Shevliakova. 2017. “The Impact of Anthropogenic Land Use and Land Cover Change on Regional Climate Extremes.” *Nature Communications* 8(1): 989.

Foxcroft, L. C., P. Pyšek, D. M. Richardson, P. Genovesi, and S. MacFadyen. 2017. “Plant Invasion Science in Protected Areas: Progress and Priorities.” *Biological Invasions* 19(5): 1353–78.

Gallardo, B., D. C. Aldridge, P. Gonzalez-Moreno, J. Pergl, M. Pizarro, P. Pysek, W. Thuiller, C. Yesson, and M. Vila. 2017. “Protected Areas Offer Refuge from Invasive Species Spreading under Climate Change.” *Global Change Biology* 23(12): 5331–43.

Garcia, R. A., M. Cabeza, C. Rahbek, and M. B. Araújo. 2014. “Multiple Dimensions of Climate Change and their Implications for Biodiversity.” *Science* 344(6183): 1247579.

Geldmann, J., L. N. Joppa, and N. D. Burgess. 2014. “Mapping Change in Human Pressure Globally on Land and within Protected Areas.” *Conservation Biology* 28(6): 1604–16.

Gross, J. E., S. Woodley, L. A. Welling, and J. E. Watson. 2016. *Adapting to Climate Change: Guidance for Protected Area Managers and Planners*. Gland, Switzerland: IUCN.

Hannah, L., G. Midgley, S. Andelman, M. Araújo, G. Hughes, E. Martinez-Meyer, R. Pearson, and P. Williams. 2007. “Protected Area Needs in a Changing Climate.” *Frontiers in Ecology and the Environment* 5(3): 131–8.

Hao, T., J. Elith, J. J. Lahoz-Monfort, and G. Guillera-Arroita. 2020. “Testing Whether Ensemble Modelling Is Advantageous for Maximising Predictive Performance of Species Distribution Models.” *Ecography* 43(4): 549–58.

Hawkins, B. A., R. Field, H. V. Cornell, D. J. Currie, J.-F. Guégan, D. M. Kaufman, J. T. Kerr, et al. 2003. “Energy, Water, and Broad-Scale Geographic Patterns of Species Richness.” *Ecology* 84(12): 3105–17.

Hernandez, R. R., M. K. Hoffacker, M. L. Murphy-Mariscal, G. C. Wu, and M. F. Allen. 2015. “Solar Energy Development Impacts on Land Cover Change and Protected Areas.” *Proceedings of the National Academy of Sciences* 112(44): 13579–84.

Hirzel, A. H., G. Le Lay, V. Helfer, C. Randin, and A. Guisan. 2006. “Evaluating the Ability of Habitat Suitability Models to Predict Species Presences.” *Ecological Modelling* 199(2): 142–52.

Hoffmann, S., and C. Beierkuhnlein. 2020. “Climate Change Exposure and Vulnerability of the Global Protected Area Estate from an International Perspective.” *Diversity and Distributions* 26(11): 1496–509.

Hoffmann, S., S. D. H. Irl, and C. Beierkuhnlein. 2019. “Predicted Climate Shifts within Terrestrial Protected Areas Worldwide.” *Nature Communications* 10(1): 4787.

Hole, D. G., B. Huntley, J. Arinaitwe, S. H. Butchart, Y. C. Collingham, L. D. Fishpool, D. J. Pain, and S. G. Willis. 2011. “Toward a Management Framework for Networks of Protected Areas in the Face of Climate Change.” *Conservation Biology* 25(2): 305–15.

Johnson, C. N., A. Balmford, B. W. Brook, J. C. Buettel, M. Galetti, L. Guangchun, and J. M. Wilmshurst. 2017. “Biodiversity Losses and Conservation Responses in the Anthropocene.” *Science* 356(6335): 270–5.

Jones, K. R., O. Venter, R. A. Fuller, J. R. Allan, S. L. Maxwell, P. J. Negret, and J. E. M. Watson. 2018. “One-Third of Global Protected Land Is under Intense Human Pressure.” *Science* 360(6390): 788–91.

Kramer-Schadt, S., J. Niedballa, J. D. Pilgrim, B. Schröder, J. Lindenborn, V. Reinfelder, M. Stillfried, et al. 2013. “The Importance of Correcting for Sampling Bias in Maxent Species Distribution Models.” *Diversity and Distributions* 19(11): 1366–79.

Li, X., X. Liu, F. Kraus, R. Tingley, and Y. Li. 2016. “Risk of Biological Invasions Is Concentrated in Biodiversity Hotspots.” *Frontiers in Ecology and the Environment* 14(8): 411–7.

Li, X., L. Yu, T. Sohl, N. Clinton, W. Li, Z. Zhu, X. Liu, and P. Gong. 2016. “A Cellular Automata Downscaling Based 1km Global Land Use Datasets (2010–2100).” *Science Bulletin* 61(21): 1651–61.

Liu, X., T. M. Blackburn, T. Song, X. Li, C. Huang, and Y. Li. 2019. “Risks of Biological Invasion on the Belt and Road.” *Current Biology* 29(3): 499–505.e4.

Liu, X., T. M. Blackburn, T. Song, X. Wang, C. Huang, and Y. Li. 2020. “Animal Invaders Threaten Protected Areas Worldwide.” *Nature Communications* 11(1): 2892.

Liu, X., Z. Guo, Z. Ke, S. Wang, and Y. Li. 2011. “Increasing Potential Risk of a Global Aquatic Invader in Europe in Contrast to Other Continents under Future Climate Change.” *PLoS One* 6(3): e18429.

Liu, X., B. Petitpierre, O. Broennimann, X. Li, A. Guisan, and Y. Li. 2017. “Realized Climatic Niches Are Conserved along Maximum Temperatures among Herpetofaunal Invaders.” *Journal of Biogeography* 44(1): 111–21.

Lockwood, J. L., P. Cassey, and T. M. Blackburn. 2009. “The More You Introduce the More You Get: The Role of Colonization Pressure and Propagule Pressure in Invasion Ecology.” *Diversity and Distributions* 15(5): 904–10.

Martinuzzi, S., V. C. Radeloff, L. N. Joppa, C. M. Hamilton, D. P. Helmers, A. J. Plantinga, and D. J. Lewis. 2015. “Scenarios of Future Land Use Change around United States' Protected Areas.” *Biological Conservation* 184: 446–55.

Maxwell, S. L., V. Cazalis, N. Dudley, M. Hoffmann, A. S. L. Rodrigues, S. Stolton, P. Visconti, et al. 2020. “Area-Based Conservation in the Twenty-First Century.” *Nature* 586(7828): 217–27.

Newbold, T., L. N. Hudson, S. L. L. Hill, S. Contu, I. Lysenko, R. A. Senior, L. Börger, et al. 2015. “Global Effects of Land Use on Local Terrestrial Biodiversity.” *Nature* 520(7545): 45–50.

Pecl, G. T., M. B. Araújo, J. D. Bell, J. Blanchard, T. C. Bonebrake, I.-C. Chen, T. D. Clark, R. K. Colwell, F. Danielsen, and B. Evengård. 2017. “Biodiversity Redistribution under Climate

Change: Impacts on Ecosystems and Human Well-Being." *Science* 355(6332): eaai9214.

Phillips, S. J., R. P. Anderson, and R. E. Schapire. 2006. "Maximum Entropy Modeling of Species Geographic Distributions." *Ecological Modelling* 190(3–4): 231–59.

Powers, R. P., and W. Jetz. 2019. "Global Habitat Loss and Extinction Risk of Terrestrial Vertebrates under Future Land-Use-Change Scenarios." *Nature Climate Change* 9(4): 323–9.

Pringle, R. M. 2017. "Upgrading Protected Areas to Conserve Wild Biodiversity." *Nature* 546(7656): 91–9.

Pyšek, P., V. Jarosik, P. E. Hulme, I. Kuhn, J. Wild, M. Arianoutsou, S. Bacher, et al. 2010. "Disentangling the Role of Environmental and Human Pressures on Biological Invasions across Europe." *Proceedings of the National Academy of Sciences of the United States of America* 107(27): 12157–62.

Quesada, B., A. Arneth, E. Robertson, and N. de Noblet-Ducoudré. 2018. "Potential Strong Contribution of Future Anthropogenic Land-Use and Land-Cover Change to the Terrestrial Carbon Cycle." *Environmental Research Letters* 13(6): 064023.

R Core Team. 2021. "R: A Language and Environment for Statistical Computing." https://www.R-project.org/.

Radosavljevic, A., and R. P. Anderson. 2014. "Making Better Maxent Models of Species Distributions: Complexity, Overfitting and Evaluation." *Journal of Biogeography* 41(4): 629–43.

Seebens, H., S. Bacher, T. M. Blackburn, C. Capinha, W. Dawson, S. Dullinger, P. Genovesi, et al. 2021. "Projecting the Continental Accumulation of Alien Species through to 2050." *Global Change Biology* 27(5): 970–82.

Seebens, H., T. M. Blackburn, E. E. Dyer, P. Genovesi, P. E. Hulme, J. M. Jeschke, S. Pagad, P. Pyšek, M. Winter, and M. Arianoutsou. 2017. "No Saturation in the Accumulation of Alien Species Worldwide." *Nature Communications* 8(1): 1–9.

Shackleton, R. T., L. C. Foxcroft, P. Pysek, L. E. Wood, and D. M. Richardson. 2020. "Assessing Biological Invasions in Protected Areas after 30 Years: Revisiting Nature Reserves Targeted by the 1980s Scope Programme." *Biological Conservation* 243: 108424.

Shrestha, N., X. Xu, J. Meng, and Z. Wang. 2021. "Vulnerabilities of Protected Lands in the Face of Climate and Human Footprint Changes." *Nature Communications* 12(1): 1632.

Simberloff, D., J.-L. Martin, P. Genovesi, V. Maris, D. A. Wardle, J. Aronson, F. Courchamp, et al. 2013. "Impacts of Biological Invasions: What's What and the Way Forward." *Trends in Ecology & Evolution* 28(1): 58–66.

Sinervo, B., F. Mendez-de-la-Cruz, D. B. Miles, B. Heulin, E. Bastiaans, M. V. S. Cruz, R. Lara-Resendiz, et al. 2010. "Erosion of Lizard Diversity by Climate Change and Altered Thermal Niches." *Science* 328(5980): 894–9.

Steinbauer, M. J., J.-A. Grytnes, G. Jurasinski, A. Kulonen, J. Lenoir, H. Pauli, C. Rixen, M. Winkler, M. Bardy-Durchhalter, and E. Barni. 2018. "Accelerated Increase in Plant Species Richness on Mountain Summits Is Linked to Warming." *Nature* 556(7700): 231–4.

Swingland, I. R., E. C. Bettelheim, J. Grace, G. T. Prance, L. S. Saunders, R. A. Pielke, G. Marland, et al. 2002. "The Influence of Land-Use Change and Landscape Dynamics on the Climate System: Relevance to Climate-Change Policy beyond the Radiative Effect of Greenhouse Gases." *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 360(1797): 1705–19.

Tesfaw, A. T., A. Pfaff, R. E. Golden Kroner, S. Qin, R. Medeiros, and M. B. Mascia. 2018. "Land-Use and Land-Cover Change Shape the Sustainability and Impacts of Protected Areas." *Proceedings of the National Academy of Sciences of the United States of America* 115(9): 2084–9.

Usher, M. B. 1988. "Biological Invasions of Nature Reserves: A Search for Generalisations." *Biological Conservation* 44(1): 119–35.

Visconti, P., M. Bakkenes, D. Baisero, T. Brooks, S. H. M. Butchart, L. Joppa, R. Alkemade, et al. 2016. "Projecting Global Biodiversity Indicators under Future Development Scenarios." *Conservation Letters* 9(1): 5–13.

WRI/UNDP. 1998. *World Resources 1998–99: A Guide to the Global Environment*. Oxford: Oxford University Press.

Wu, R., S. Zhang, D. W. Yu, P. Zhao, X. Li, L. Wang, Q. Yu, J. Ma, A. Chen, and Y. Long. 2011. "Effectiveness of China's Nature Reserves in Representing Ecological Diversity." *Frontiers in Ecology and the Environment* 9(7): 383–9.

Xin, Y. S., Z. X. Yang, Y. B. Du, R. N. Cui, Y. H. Xi, and X. Liu. 2023. "Alien Vertebrates in Mainland China." Science Data Bank. https://doi.org/10.57760/sciencedb.07046.

Yang, Q., and L. Xia. 2008. "Tibetan Wildlife Is Getting Used to the Railway." *Nature* 452(7189): 810–1.

Zhang, L., J. Rohr, R. N. Cui, Y. S. Xin, L. X. Han, X. N. Yang, S. M. Gu, et al. 2022. "Biological Invasions Facilitate Zoonotic Disease Emergences." *Nature Communications* 13(1): 1762.

Zhang, L., and K. Schwärzel, eds. 2017. *Multifunctional Land-Use Systems for Managing the Nexus of Environmental Resources*. Cham: Springer International Publishing.

Zhang, Z., J. M. Kass, S. Mammola, I. Koizumi, X. Li, K. Tanaka, K. Ikeda, T. Suzuki, M. Yokota, and N. Usio. 2021. "Lineage-Level Distribution Models Lead to More Realistic Climate Change Predictions for a Threatened Crayfish." *Diversity and Distributions* 27: 684–95.

Zhu, G., M. Papeş, X. Giam, S. H. Cho, and P. R. Armsworth. 2021. "Are Protected Areas Well-Sited to Support Species in the Future in a Major Climate Refuge and Corridor in the United States?" *Biological Conservation* 255: 108982.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Xin, Yusi, Zhixu Yang, Yuanbao Du, Ruina Cui, Yonghong Xi, and Xuan Liu. 2023. "Vulnerability of Protected Areas to Future Climate Change, Land Use Modification, and Biological Invasions in China." *Ecological Applications* e2831. https://doi.org/10.1002/eap.2831