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Climate change threatens giant panda protection in the 21st century

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ABSTRACT

It is increasingly recognized that biotic interactions could play a significant role in species distribution modelling. To assess the conservation effectiveness of the giant panda (*Ailuropoda melanoleuca*) reserves in a changing climate, we combined both biotic variables (food availability) and abiotic (climatic and geographic) to project the potential changes of distribution and quality of giant panda habitats using the most recent IPCC-CMIP5 climate scenarios. Our results suggested that climate change would adversely affect giant pandas through habitat degradation, in that: (1) 52.9–71.3% of the current habitats could be lost; (2) the giant panda habitats could become more fragmented and isolated; and (3) both the quantity and quality of habitats in the current giant panda reserves could substantially contract, and approximately 20% of the reserves could lose all habitat representations in this century. Additionally, we found that climate change would make it increasingly necessary to translocate small populations of pandas from the southwestern to the northwestern part of the current distribution range to ensure population viability. Our results suggest the need for immediate change in current conservation policies and formulating adaptation plans for giant panda conservation in a changing climate.

1. Introduction

Rapid climate change has been widely recognized as a grave threat to biodiversity and is expected to interact with other environmental factors, leading to changes to species distributions, life histories, community compositions, and ecosystem functions (Thuiller, 2007; Bellard et al., 2012; Davies et al., 2014). Climate change may increase the extinction risk of already endangered species already threatened by small populations, low genetic diversity, habitat specialization or a limited geographic range (Moritz et al., 2008; Fordham et al., 2013). Most endangered species are specialists confined to restricted habitats, less physiologically tolerant to environmental change and less able to migrate/disperse to track climate change (Svenning and Skov, 2004; Maclean and Wilson, 2011). A major challenge in conservation planning for these species, in particular, is to incorporate climate change impacts into species conservation strategies (Araújo and Rahbek, 2006; Willis and Bhagwat, 2009; Strange et al., 2011).

The field of species distribution modelling has developed increasingly robust and sophisticated modelling approaches that can account for the dynamic ranges of species habitats. Numerous species distribution models (SDMs), including process-based and bioclimatic envelope approaches, have been widely used to explore the impacts of climate change on species ranges (Thuiller et al., 2009). Although some process-based models can successfully integrate dispersal and metapopulation dynamics into forecasts of species geographic ranges (Anderson et al., 2009; Fordham et al., 2013), most of the currently available models are too complex in parameterization and validation in model application (Pearson and Dawson, 2003). The bioclimatic envelope models have various limitations (such as the assumption of equilibrium, the assumption of complete sampling of species niche, and insufficient inclusion of adaptation, evolution, and dispersal), they are still used by many researchers (Hannah et al., 2002; Huntley et al., 2010; Araújo and Peterson, 2012). With a good understanding of the modelling techniques, careful choice of explanatory variables, and appropriate model validation and testing, these models can still provide important information on the potential impact of climate change on species range shifts, and help inform conservation decisions in a changing climate (Hijmans and Graham, 2006; Araújo and Peterson, 2012).

Most SDMs rely strongly on climatic data as predictor variables without taking into account any biotic interactions, such as

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competition with other species or other individuals, predation, and changes in food availability (Preston et al., 2008). However, some researchers have suggested that these biotic interactions may be critical to improve the predictive power of SDMs (Miska and Araújo, 2007; Preston et al., 2008; Boulangeat et al., 2012), especially those across trophic levels (Vander Putten et al., 2010; Barbet-Massin and Jiguet, 2011). It is known that climate change may alter biotic interactions, influencing species distributions both directly and indirectly. Therefore, biotic interactions must be included in SDMs for predicting long-term climate change impacts, such as species range shifts, particularly for species with specialized feeding habits (Bateman et al., 2012).

The giant panda (*Ailuropoda melanoleuca*), the only extant species of the panda lineage (Zhao et al., 2012) and one of the world's most treasured endangered species, now lives in six isolated mountain ranges in Sichuan, Shaanxi and Gansu provinces in south-central China. Its current distribution has been reduced to less than 1% of its historical range (Loucks et al., 2001). The endangerment mainly comes from anthropogenic activities, such as poaching and habitat destruction over the past the past 3000 years (Zhao et al., 2012). This impact is exacerbated by the biological constraints of the species, including dietary specialization, low reproductive rates and restricted gene flow (Liu et al., 1999; Lv et al., 2001). The giant panda was once a large carnivorous animal, after millions of years of evolution and adaptation to environmental change, it gradually evolved into a specialized species, 99% of its diet now consists of understory bamboos (Zhao et al., 2012).

In recent decades, the Chinese government and some conservation organizations have implemented many research and conservation programs aimed at preventing extinction and promoting the population recovery of giant pandas. For example, more than 60 nature reserves have been established that are designated as giant panda reserves within the current species range (Hu et al., 2011). As a result of all these conservation efforts, the giant panda population in the wild has steadily recovered from 1114 in the 1980s to 1596 at present (State Forestry Administration, 2006). Nevertheless, the population is thought to be vulnerable to the increasingly warmer and drier climate that is expected to occur in this century (Liu et al., 2004; Wang et al., 2010). Climate change may reduce significantly both the area of giant panda habitats (Songer et al., 2012; Fan et al., 2014) and food supplies (Tuanmu et al., 2013) in panda reserves, jeopardizing their effectiveness to safeguard giant panda populations in the future.

The aim of this study is to conduct the most comprehensive assessment to date on the impacts of climate change on the future distribution of giant pandas. Here, based on the comprehensive field survey on giant pandas and the latest climate projections, we applied both abiotic (climatic and geographic) and biotic variables (bamboo availability) to bioclimatic models to project the potential changes of the spatial distribution and quality of giant panda habitats in this century and assessed the implication of these changes on the conservation effectiveness of the giant panda reserves.

2. Materials and methods

2.1. Study area and data

The database used in the study was compiled during the Third National Survey on the Giant Pandas (State Forestry Administration, 2006). This large-scale survey was conducted using 11,174 transects, covering 57 counties in six mountain ranges——Qinling, Minshan, Qionglaishan, Daxiangling, Xiaoxiangling and Liangshan Mountains, situated in the Sichuan, Shanxi and Gansu Provinces of China. These data include the presence points of giant pandas as indicated by droppings, feeding remnants, and footprints ($N = 10{,}000$), a digital distribution map of bamboos, and nature reserve boundaries. The transects were selected on a topographic map of 1:50,000 or 1:100,000, and one transect was placed per 800 hectares in key areas and one per 2400 hectares in other areas. The transects extended from low to high altitudes on mountain slopes, taking into account of the distributions of bamboo species and the giant panda habitats of earlier records. Along each transect, no less than four 20 m × 20 m plots were set up and surveyed. The bamboo map was comprised of 16 bamboo species (Table A1) that contribute to more than 99% of the giant panda's diet. This was able to account for over 95% of the distribution area of all bamboo species in the giant panda habitats (State Forestry Administration, 2006). The bamboo species distributions were mapped on a topographic map of 1:50,000 based on the intensive field survey to produce a shape file. This bamboo distribution map was then converted to a one-kilometer presence grid to be compatible with other data. Finally, we randomly selected different grids from their distribution range as presence points for each of the 16 bamboo species. A total of 5981 presence points were selected and used to explore the relationships between these bamboo species and bioclimatic variables. The boundaries of 40 nature reserves were supplemented by data from Wu et al. (2011). Using this supplementary data we were able to analyze a total of 59 nature reserves. To accommodate potential species dispersal under future climate change, we extended the study area beyond six mountain ranges in the three provinces (Fig. 1). The elevation of this study area ranges from 273 m to 6298 m.

Nineteen bioclimatic variables at 30 s resolution were obtained from the Worldclim database (Hijmans et al., 2005) for current climate (1950–2000) and future climate scenarios for 2070 (average for 2061–2080). The data applied here are the recent IPCC-CMIP5 climate projections from five Global Circulation Models (GCMs) (Table A2) under three representative concentration pathways (RCP 2.6, 4.5 and 8.5). To minimize overfitting of the models, we calculated inter-correlations among 19 bioclimatic variables, and removed one of the two variables when correlation coefficient >|0.70| was obtained. Consequently, eight bioclimatic variables (Table A3) were used to construct species distribution models for bamboo and the giant panda.

Other environmental variables that are considered to be important drivers of giant panda distributions (Liu et al., 1999; Shen et al., 2008) were also used to build the giant panda habitat distribution model, including a biotic factor (bamboo availability) and topographical factors (slope, and aspect). We also incorporated the potential impact of human disturbance into our giant panda model, as human disturbance is known to intensify the negative impacts of climate change through habitat loss and fragmentation (Fan et al., 2014). The level of human disturbance was estimated based on habitat distance from residential areas and roads. Slope and aspect were derived from a DEM with a resolution of 90 m, which was obtained from USGS. Land cover maps were obtained from the Institute of Sichuan Forestry Investigation and Planning, which were interpreted from TM images taken in 2007. A road map (1:250,000) was obtained from the National Fundamental Geographic Information Center. The locations of all villages were acquired from the Institute of Geographic Sciences and Natural Resources of the Chinese Academy of Sciences. All spatial layers of these environmental variables were resampled to a resolution of 30 s to correspond to that of bioclimatic variables. Because reliable future projections of these variables (land cover, distance from residential areas, and roads) are not available, and because including static variables in SDMs alongside dynamic variables can improve model performance (Stanton et al., 2012), we kept these variables static in our projections.

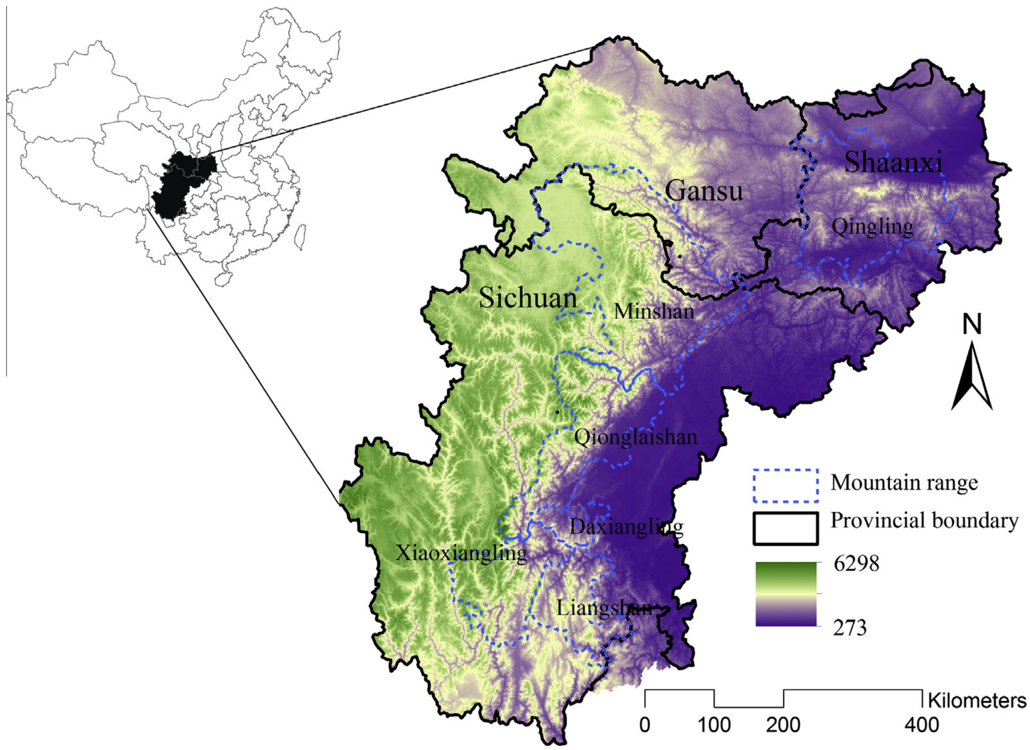

Fig. 1. The study area covering six mountain ranges (Qingling, Minshan, Qionglaishan, Daxiangling, Xiaoxiangling and Liangshan Mountains) in Sichuan, Shaanxi and Gansu Provinces of China. The elevation of this study area ranges from 273 m to 6298 m.

2.2. Species distribution modeling and testing

The maximum entropy approach (Phillips et al., 2006) was employed to project habitat suitability for both bamboo and giant pandas. This approach has shown to be one of the best performing models in predicting species distributions with presence-only data (Elith et al., 2006; Hijmans and Graham, 2006), and it has been extensively applied to project species range and vegetation shifts under climate change (Rebelo et al., 2010; Ponce-Reyes et al., 2012; Wong et al., 2013). The full extent of the study area was used to extract background (pseudo-absence) data to improve model performance (VanderWal et al., 2009). We performed 10 replications for each bamboo species and a maximum of 500 iterations for the giant panda, using a cross-validation procedure where we divided our dataset using 75% of the data for model calibration and retaining 25% of the data for evaluation. Climate change could affect the potential distributions of bamboo species that pandas feed on, and it could also affect pandas' behaviors and physiology. We first used eight bioclimatic variables to project the current and future distribution probability of 16 bamboo species. There is no adequate evidence that indicate which of these 16 species giant pandas prefer the most. We therefore compiled the outputs into a single map of bamboo forest suitability with the maximum probability of 16 species at each pixel (Fig. 2), assuming that pandas would feed on the different bamboo species equally. Inclusion of biotic interactions may improve both the explanatory and predictive powers of SDMs under climate change (Preston et al., 2008; Bateman et al., 2012), so we built the distribution model for the giant panda using bamboo suitability, the selected eight bioclimatic variables, and five environmental variables (slope, aspect, distance from residential areas, distance from roads, and land cover) as predictors. A total of five GCMs were used to produce probability outputs for each scenario. We used the average predicted probability of occurrence across the five GCMs for each grid as our consensus forecast, which was one of best methods for developing an ensemble forecast (Hole et al., 2009; Marmion et al., 2009). Subsequently, we applied the average predicted probability as the threshold to define the presence–absence distribution of giant panda habitats, as this method has been found to be a robust approach (Liu et al., 2005). Areas under the Operating Characteristic Curve (AUC) is a widely-used approach to evaluate model performance of species distribution models, but it is a threshold-independent measure that should not be applied to binary predictions (Lobo et al., 2008; Li and Guo, 2013). In this study, we adopted AUC to evaluate the model performance of our bamboo species models, whereas True Skill Statistic (TSS) was used to evaluate the model performance of our giant panda model. TSS is increasingly applied as a simple and intuitive measure for the performance of species distribution models that are built from presence-only data and binary predictions are produced by applying thresholds (Allouche et al., 2006).

2.3. Habitat suitability and classification

We adopted a habitat suitability technique (Dayton and Fitzgerald, 2006) to identify the distributions of different classes of habitat suitability for giant pandas. The habitat suitability model was constructed based on giant pandas' habitat selection criteria, including bamboo suitability, land cover, elevation, slope, aspect, distance from residential areas, and distance from roads (Liu et al., 1999; Shen et al., 2008). A suitability value of 1 (more resistance or less accessibility) to 50 (less resistance or high accessibility) was assigned at each pixel-cell to indicate suitability according to the previous study on giant panda and experts' views (Table A4) (Shen et al., 2008), then we developed an integrated habitat suitability map by determining the weights of all the layers with the Analytic Hierarchy Process (AHP) (Saaty, 1990) and combining the layers with the weighted linear combination approach. Finally, we reclassified panda habitats into marginally, moderately

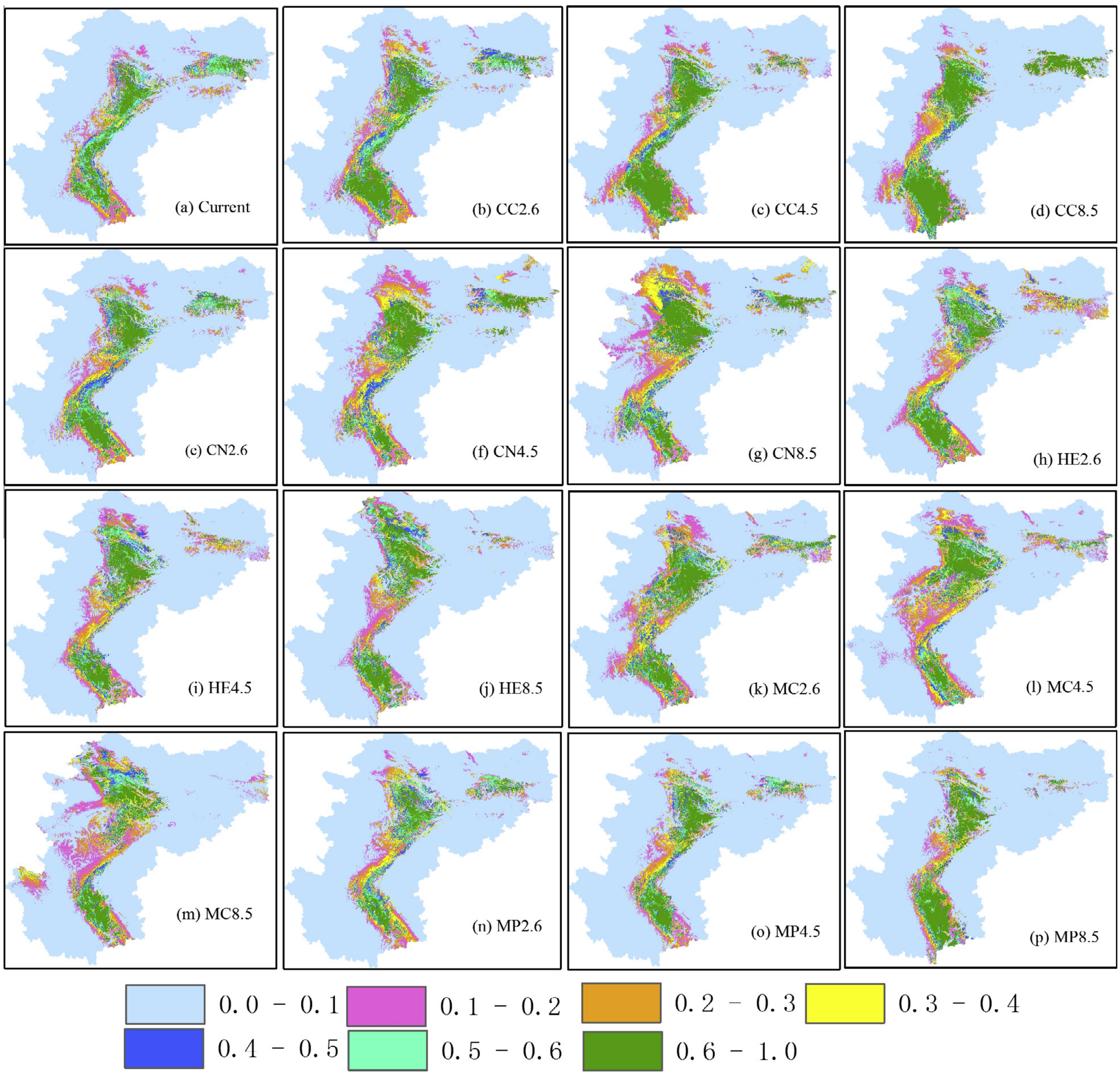

Fig. 2. Projected distributions of bamboo suitability extracted from the MAXENT model outputs of 16 bamboo species with the maximum probability for the current and 2070 in giant panda habitats in China: (a) current suitability; (b)–(p) suitability in 2070 projected by five GCMs (CC, CN, HE, MC, MP) for the three RCPs (2.6, 4.5, 8.5).

and highly suitable habitats using standard deviations classification (Liu and Li, 2008).

2.4. Spatial analysis of potential effects of climate change

We applied FRAGSTATS (version 4.2) (McGarigal et al., 2012) to calculate the mean patch index of different classes of giant panda habitats as a measure of habitat fragmentation. We also used the overlay analysis to assess the distribution patterns and potential changes of different classes of giant panda habitats. The potential change in habitat distribution under climate change was computed by overlapping current and future habitat distribution maps. This allowed us to identify areas of the habitat range that are projected to be lost, gain or remain under future climate scenarios. Subsequently, we overlaid the projected panda habitat maps with the boundary of 59 nature reserves to explore the conservation effectiveness of these reserves in protecting giant pandas under climate change.

3. Results

The high average AUC values (>0.96) for all models of the 16 bamboo species (Table A1) indicated that our models can reasonably capture bamboo-climate relationships, and thus can be used to project the future habitat suitability of bamboo species. The high TSS (0.71) for giant pandas also indicated that our model performs well in projecting giant panda habitat distributions. As determined by jackknife analysis in Maxent, the percent contributions of the variables in the panda model as ranked from highest to lowest were: Bamboo availability (46%), precipitation during the driest quarter of the years (11%), the mean temperature of the warmest quarter of the years (10%), precipitation seasonality (9%), slope (8%), mean diurnal range (7%), temperature seasonality (5%), and the other six variables (4%). We found that bamboo availability played an important role in modelling the spatial distribution of giant panda habitats.

Our results indicated that climate change would dramatically reduce the area of giant panda habitats (Fig. 3). Under the IPCC-CMIP5 representative concentration pathway (RCP) 8.5 climate change scenario, a high radiative forcing of ~8.5 W/m^2, the total habitat area for giant pandas (including the new climatically suitable habitats) would reduce from the current 2.89 million hectares to 1.31 million hectares by 2070, a reduction of 71.3%. Under RCP 4.5, a median radiative forcing of ~4.5 W/m^2, climate change would result in a habitat reduction of 55.9% by 2070. Even under RCP 2.6, the lowest radiative forcing, the habitat area would still reduce by 52.9% in the same period (Table A5).

In addition to a decrease in the area of suitable habitat, climate change would also degrade habitat quality. The highly suitable habitats are likely to be affected the most by climate change. Under RCP 2.6, the proportion of highly suitable habitats would decrease from the current 54.2% to 45.6% by 2070 (Fig. 4). Although moderately suitable habitats would increase in proportion, the total area would dramatically decrease (Table A6). Further reductions in habitat quality would result from an exacerbation of habitat fragmentation. Under RCP 2.6, the mean patch size of habitats would decrease from the current 652.5 hectares to 531.1 hectares by 2070. The highly suitable habitats would suffer the most severe fragmentation under future climate changes with the mean patch size decreasing by 30.1%. RCP 8.5 and RCP 4.5 would produce even more serious impacts on giant panda habitats than RCP 2.6 (Table 1).

Moreover, climate change would lead to both horizontal and altitudinal changes in giant panda habitat distribution, with the three RCPs producing similar trends of impact (Figs. 4 and 5). More specifically, in the Minshan Mountains, projected habitat area gains to the west and projected habitat losses in the central part would produce a westward shift of the overall habitat range. The Qingling and Qionglaishan Mountains would see a substantial contraction of habitat areas in all directions. Consequently, almost all suitable habitats for the giant panda would be lost under any of the three RCPs in the future. It should be noted that the disappearance of suitable habitats in the Qionglaishan Mountains would bisect the future habitat range into two isolated patches, creating a huge gap for animal movement, and hence, a major obstacle to gene flow. The suitable habitats in Daxiangling Mountains would also undergo significant contraction. Eventually, only a few fragments of suitable habitats would be left in the western part of the mountain later in the century (Fig. 4). The average altitude of the giant panda habitat range would increase from 2576 m to 2634 m, 2899 m, and 2997 m for RCP 2.6, RCP 4.5 and RCP 8.5 respectively. By the end of the century, the suitable habitats below 1500 m would almost vanish, while the proportion of the high-elevation habitats (>3100 m) would significantly increase (Fig. 4 and Table A7). The new suitable habitats projected for the future will likely be located in high-elevation areas in the Minshan and Liangshan Mountains. The rough and steep terrain in these areas

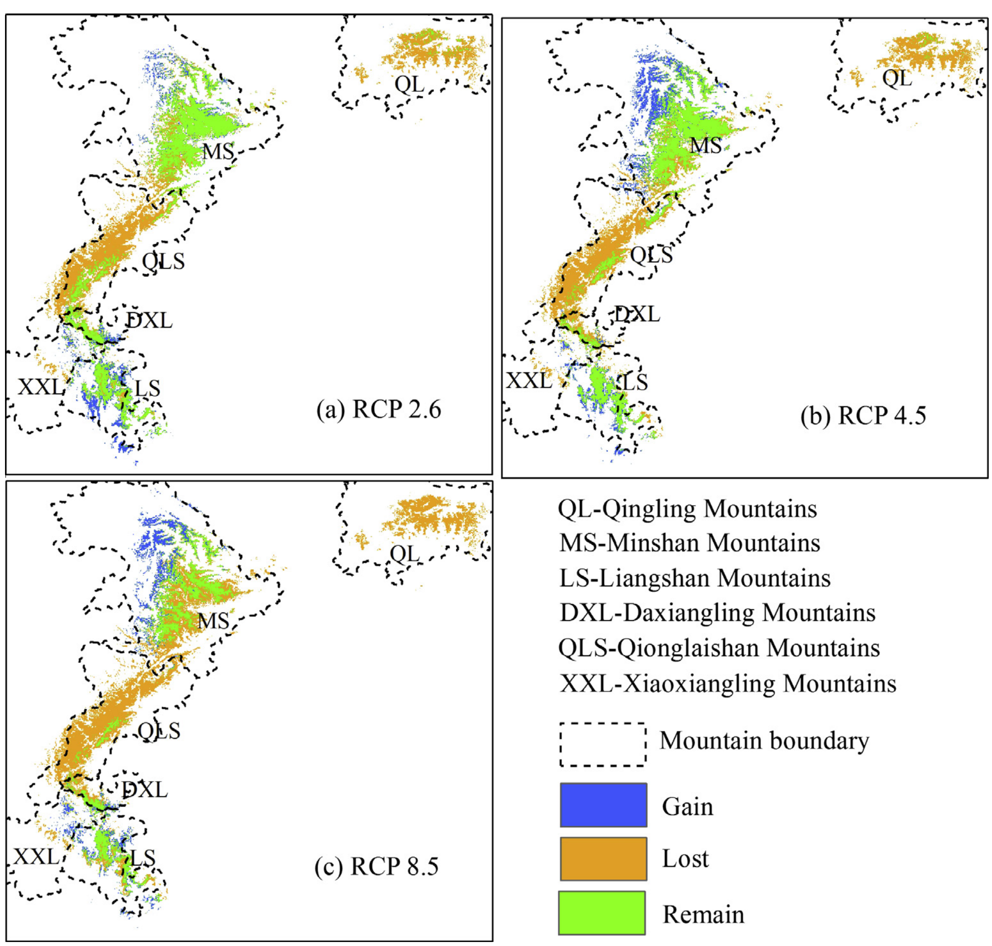

Fig. 3. Projected change of giant panda habitats in six mountain ranges based on consensus forecast from five GCMs by 2070 under CMIP5 (a) RCP 2.6, (b) RCP 4.5, (c) RCP 8.5. The projected current giant panda habitats were overlaid with future habitats to identify areas that would be lost, gain, or remain.

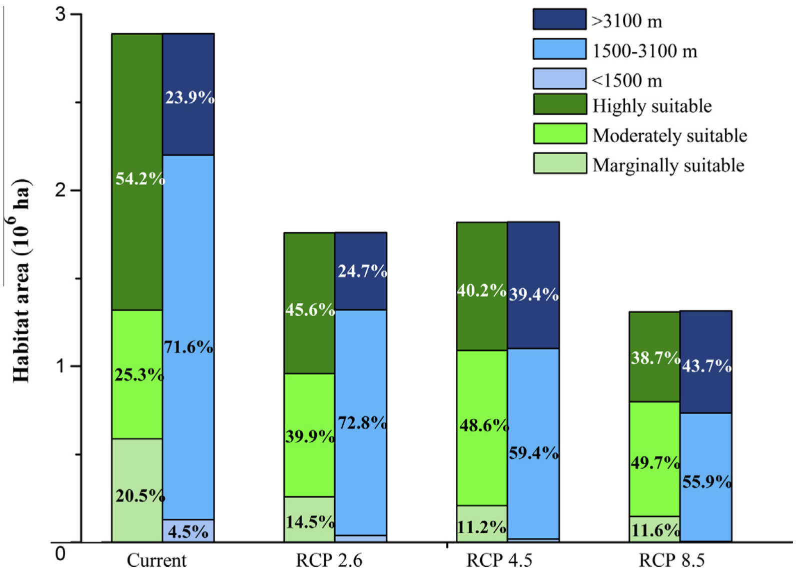

Fig. 4. Projected area (million hectares) and proportions of giant panda habitats in different suitability classes (marginally suitable, moderately suitable and highly suitable) and altitudes based on consensus forecast from five GCMs for the current and the three RCPs by 2070.

Table 1
The mean patch area (ha) of giant panda habitats in different suitability classes and the entire habitat landscape under the current and three RCPs by 2070.

Period/ scenario	Marginally suitable	Moderately suitable	Highly suitable	Overall
Current	325.1	305.4	1540.8	652.5
RCP 2.6	240.2	462.4	1094.9	531.1
RCP 4.5	206.3	677.6	1113.2	617.7
RCP 8.5	213.2	592.3	767.5	530.2

(Fig. 3) will cost giant pandas more energy to find food and mates (Wei et al., 1999), meaning that these areas are suboptimal for the giant pandas to inhabit.

The reduction and shift of giant panda habitats would profoundly impact the conservation effectiveness of the current giant panda reserves. Nevertheless, climate change would dramatically reduce the distributions of habitats in these reserves (Fig. 5). Under RCP 2.6, these reserves would be able to protect only 29.5% of the suitable habitats by 2070. Specifically, 33 of the current giant panda reserves would lose more than 50% of the habitats by 2070. Furthermore, giant panda habitats would lose all representation in 11 of the nature reserves by 2070. The number of nature reserves without suitable habitats would reach 12 and 20 by 2070 for RCP 4.5 and RCP 8.5 respectively (Table 2). The nature reserves that would experience most habitat loss under climate change are located in Qinling, Qionglaishan, and Daxiangling Mountains. Climate change would also create new habitats, but only 25.4–31.2% of the new habitats would be protected by nature reserves by 2070 if no additional reserves are established in these regions in the future.

4. Discussion

Effective conservation of giant panda habitats requires protection and restoration of bamboos, particularly for old-growth forests where bamboos form the understory (Zhang et al., 2011). Our model results indicated that these bamboo forests in the current panda habitats would contract rapidly during the 21st century with ongoing climate change (Fig. 2). Giant pandas historically lived in warmer regions at lower elevations and consumed many other species of bamboo that the giant pandas no longer feed on because they have moved to higher elevations to avoid anthropogenic stresses (Loucks et al., 2001). Presumably, as climate warms, those bamboo species at lower altitudes and more southern areas could move upwards and northwards and replace the bamboo species that giant pandas currently depend upon. However, all bamboo species have very limited dispersal ability; they reproduce mainly asexually by growing new shoots from their rhizomes that have a growth rate of less than 6 m per year (Fan, 1999). The slow dispersal ability of bamboo species due to special colonization would likely prevent them from fully colonizing new potential habitats. As a result, bamboo species outside the current panda habitats would be unlikely to become the stable food sources for giant pandas within the next 100 years – unless artificial measures are taken to facilitate dispersal. Protecting and introducing bamboos in climatically suitable areas, such as the northwest side of the Minshan Mountains, would likely assist giant pandas to adapt to future climate change. Sexual reproduction of bamboos occurs once every 60–120 years through mass flowering, i.e. simultaneous flowering of the same species in a region, and occasionally with other sympatric species, with most bamboos dying soon afterwards (Feng, 1991). There is strong evidence that mass flowering of bamboos poses an additional threat to the giant pandas' survival. For example, the mass flowering in the 1970s and 1980s caused more than 270 giant pandas in the Minshan Mountain alone to starve to death (Feng, 1991). A warmer and drier climate is considered to be a catalyst to bamboo flowering (Qing, 1989), therefore such catastrophic events could occur more frequently in the future. In this view, ensuring and increasing bamboo diversity may be an effective means to lowering the risk of simultaneous flowering and therefore ensuring the long-term food security of the giant panda in a changing climate.

Although the total area of future habitats may still be sufficient to support the current giant panda population size, climate change may lead to a local habitat shortage in some regions. In fact, the most severe threat may come from habitat fragmentation, which would reduce habitat connectivity. This would in turn prevent gene flow, thus decreasing critical genetic diversity and population viability (Lv et al., 2001; Zhu et al., 2010). Data indicate that habitat fragmentation would reduce habitat connectivity at the most highly suitable habitats in particular. This would lead to isolation

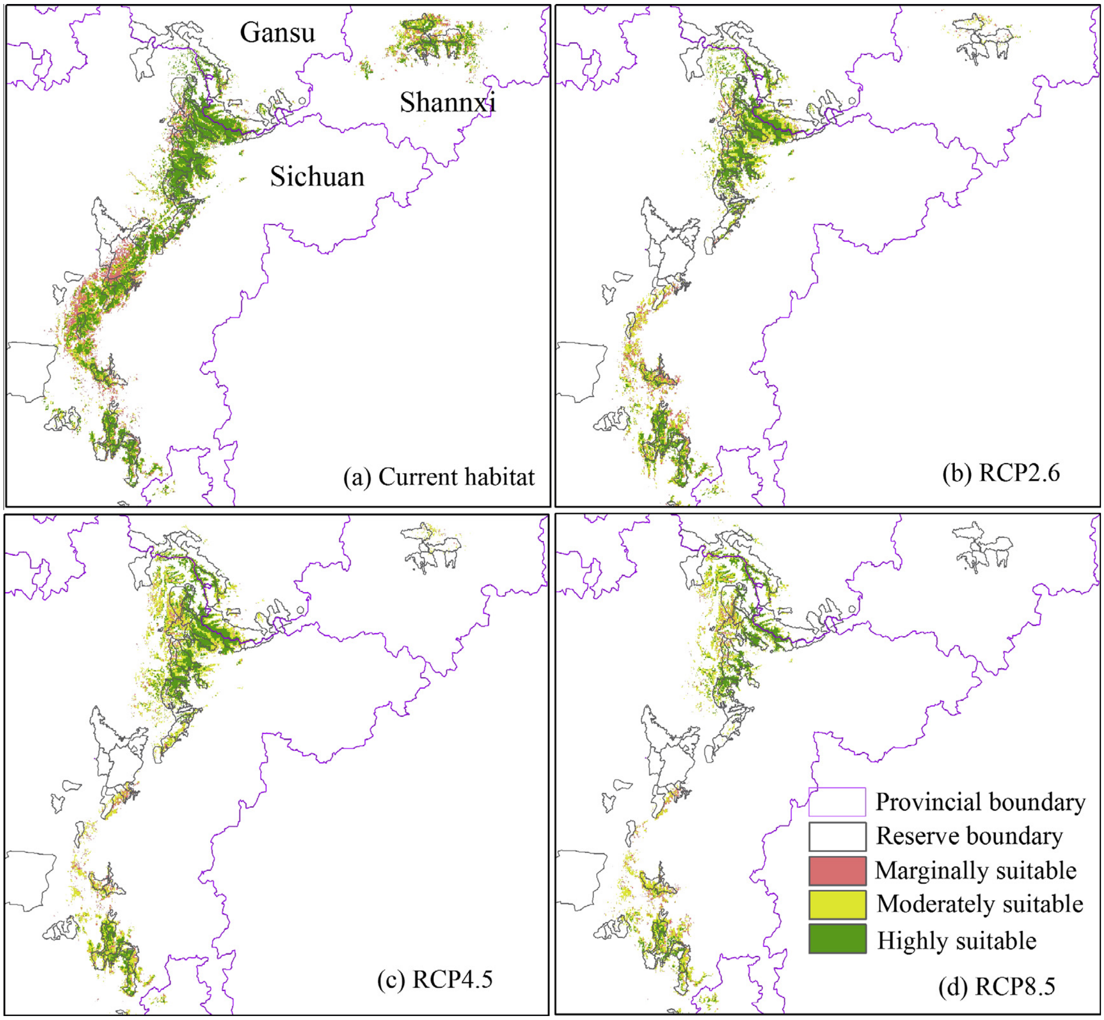

Fig. 5. Projections of giant panda habitats in three suitability classes (marginally suitable, moderately suitable and highly suitable) based on consensus forecast from five GCMs: (a) projected current distribution, (b) projected distribution by 2070 for RCP 2.6, (c) projected distribution by 2070 for RCP 4.5, and (d) projected distribution by 2070 for RCP 8.5.

Table 2
Projected numbers of giant panda reserves with different percentage of habitat loss (or gain) under the three RCPs by 2070 (*A* is the percentage change in habitat area. Negative values represent habitat loss within the reserves).

Percentage change of area	RCP 2.6	RCP 4.5	RCP 8.5
$A = -100$	11	12	20
$-100 < A \leqslant -50$	12	9	11
$-50 < A \leqslant 0$	26	22	19
$A > 0$	10	16	9
Total	59	59	59

within both populations and subpopulations, resulting in a decline of genetic diversity, thus weakening the species' potential to adapt to future climate change (Zhao et al., 2012). Thus the extinction risk of small populations, such as those in Xiaoxiangling and Daxiangling Mountains where the population size is only about 32 and 29, respectively would rise (State Forestry Administration, 2006).

Some additional points that have to be made for the modelling results: (1) it is projected that the new suitable habitats are likely to be located at high-elevation areas in the Minshan and Liangshan Mountains, where the terrain is both rough and steep (Fig. 3). This means that even though giant pandas may be able to utilize such new habitats in the future, the energy cost of giant pandas to find food and mates in such rough terrain might be too high for these areas to become *suitable habitats* (Wei et al., 1999). (2) Climate change is expected to profoundly impact the overall conservation effectiveness of giant pandas reserves. Because the giant panda reserves now cover about 85% of the suitable habitats, and host more than half of the wild giant panda populations (Hu et al., 2011), available habitats inside the current reserves would progressively decrease if these reserves are not modified or no new reserves are to be built in the future.

In a rapidly changing climate, there is a critical need to rethink the current conservation approach and incorporate climate change adaptation into our conservation planning (Game et al., 2011). It has been argued that some forest-dependent species (e.g. orangutans in Indonesia or giant pandas in China) may face a greater threat than others from climate change. This is because climate change will reduce and change the plants they eat, leaving them no option but to move further up into higher areas (Suhud and Saleh, 2007). In china, many recent eco-conservation programs that have been implemented in this region, such as the "grain-for-green" and the "carbon-sink forest" programs have focused on fast-growing tree species, without paying attention to the food availability of giant pandas. We suggest that food abundance and diversity of bamboo species should be considered for all forestry projects across the region. Habitat fragmentation threatens species conservation, and its impacts are expected to worsen under climate change. A recent study on orangutans in Sabah, Malaysian Borneo suggested that future habitat suitability projections can improve the efficacy of habitat corridors for long-lived, low-fecundity, philopatric species in rapidly changing environments (Gregory et al., 2014).

In view of the future diminishing habitats in the giant panda reserves, forestry planning and management should focus on enhancing habitat connectivity through establishing new reserves and habitat corridors, strengthening matrix management outside the reserves, and minimizing human disturbances in giant panda habitats. Increasing connectivity among nature reserves and habitats can promote habitat quality and gene flow among populations, which will effectively increase genetic diversity and population viability – both of which are vital to the long-term survival of giant pandas (Hu et al., 2011). Importantly, newly available climatically suitable habitats should also be protected and restored. For giant pandas, it is important to create new giant panda reserves in areas where future climate change is expected to produce new habitats, especially in the northwestern Minshan Mountains. These new reserves could potentially serve as stepping stones to facilitate giant panda migration to the emerging new habitats. Improving matrix management and establishing corridors between reserves could also assist giant panda migration across the landscape.

An adjustment of the existing reserves may be necessary where large habitat changes within the reserves and their vicinities are expected. These adjustments may involve manipulating the size, shape and spatial orientation of the reserves. For example, to maintain the current habitat size in the Huanglong National Nature Reserve, an increase of protected area to the west may be required. For those reserves that may lose most of their giant panda habitats, such as those in the Qionglaishan and Qinling Mountains, intensive management approaches may be required for the giant panda population and adjustment to their management strategies may be a necessary response to the change of biodiversity.

An intensive population management approach, such as translocation, may become necessary for the giant panda where the population is small and severe habitat loss is expected in the near future, as already suggested by some conservation ecologists and geneticists in recent years (Swaisgood et al., 2010; Zhu et al., 2010). Priority could be given to the population in Xiaoxiangling in particular, which is known to be the smallest, most isolated, and genetically vulnerable (Zhu et al., 2010; Li et al., 2010). Our results also indicate that climate change would seriously destroy the habitats in this area. The current population size in the southern part of the Qinling Mountains is much larger (273 giant pandas in 2004) (State Forestry Administration, 2006). However, the suitable habitat is projected to vanish in this area based on our projections. We think that the vanishing habitat could be due to the island effect of high elevations, and remarkable differences in climate, soil, and vegetation between the southern and northern slopes of the range. Accordingly, we suggest that translocation may be considered for the giant pandas living in the Xiaoxiangling Mountains and Qinling Mountains as well as those in the Qionglaishan Mountains. This of will naturally be based on intensive experimentation and careful planning.

In summary, based on concrete data and robust modelling approach, we projected that giant panda habitats would increasingly degrade and be fragmented in the coming decades. This would significantly reduce the size of protected habitats in the nature reserves. Intensive management strategies, including planting bamboos in new climatically suitable habitats, establishing new nature reserves and corridors, and translocating the most threatened populations, are suggested to be crucial to ensure the prosperity of wild giant pandas in the future.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2014.11.037.

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