

## ASSESSING THE DISTRIBUTIONS AND POTENTIAL RISKS FROM CLIMATE CHANGE FOR THE SICHUAN JAY (*PERISOREUS INTERNIGRANS*)

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**Abstract.** The effects of global climate change have attracted increasing attention, especially concerning the Arctic, and Antarctic. However, montane/alpine areas are also quite sensitive to climate change. Animals endemic to these areas are distributed within restricted elevational ranges, and many of them are also reliant on the harsh climate, a change of which may affect them as disastrously as it may affect polar species. Here we used MaxEnt software to construct models and make predictions for the rare Sichuan Jay (*Perisoreus internigrans*), which is known only from isolated fragments of high-elevation coniferous forest on the Qinghai–Tibet plateau of west-central China. Our model suggests that potentially suitable areas are concentrated in northern Sichuan and southern Gansu provinces, and they are fragmented generally, because of the mountainous terrain. It also predicts severe risks from climate change, even more than for the other two species of the genus, *P. canadensis* and *P. infaustus*: (1) both of the extent of suitable habitat and the suitability of that habitat will decline significantly under climate change; (2) climate change will compel this bird to shift northward and upward, but areas left for such compensatory extension are quite limited, and (3) the suitable habitat will become much more fragmented, which may exacerbate the effects of climate change indirectly by slowing or halting gene flow and increasing the rate of extinction of isolated local populations.

**Key words:** climate change, Qinghai–Tibet plateau, Sichuan Jay, *Perisoreus internigrans*, MaxEnt, fragmentation.

### Evaluando las Distribuciones y los Potenciales Riesgos del Cambio Climático para *Perisoreus internigrans*

**Resumen.** Los efectos del cambio climático global han atraído cada vez más atención, especialmente en lo referido al Ártico y a la Antártida. Sin embargo, las áreas montañosas y alpinas también son bastante sensibles al cambio climático. Los animales endémicos de estas áreas están distribuidos dentro de rangos restringidos de altitud y muchos de ellos también dependen de climas severos. Cambios en estos climas pueden afectar tan severamente a las especies montañosas como a las polares. En este estudio usamos el programa MaxEnt para desarrollar modelos y hacer predicciones sobre la especie rara *Perisoreus internigrans*, la cual se distribuye únicamente en fragmentos aislados de bosques de conífera ubicados a gran elevación en la planicie de Qinghai–Tibet del centro oeste de China. Nuestros modelos sugieren que las áreas potencialmente adecuadas están concentradas en el norte de la provincia de Sichuan y en el sur de la provincia de Gansu, las que están generalmente fragmentadas debido a la topografía montañosa del terreno. También predicen severos riesgos derivados del cambio climático, con mayor intensidad que para las otras dos especies del género, *P. canadensis* y *P. infaustus*: (1) tanto la extensión como la calidad del hábitat adecuado disminuirán significativamente por el cambio climático; (2) el cambio climático obligará a esta especie a desplazarse hacia el norte y arriba, pero las áreas para esta extensión compensatoria son muy limitadas, y (3) el hábitat adecuado se volverá mucho más fragmentado, lo que puede exacerbar indirectamente los efectos del cambio climático disminuyendo o deteniendo el flujo génico e incrementando la tasa de extinción de las poblaciones locales aisladas.

## INTRODUCTION

There is now overwhelming evidence that an increase in the concentration of greenhouse gases in the Earth's atmosphere has caused global temperatures to increase by 0.6°C since 1900 (Houghton et al. 2001), and further increases of between 1.4

and 5.8 °C are predicted over the next century (Easterling et al. 1997, Leech and Crick 2007). Climatic change has already affected the population dynamics and distribution of numerous taxa across a broad range of landscapes and habitats (e.g., Walther et al. 2002, Root et al. 2003) and is likely to have even more

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severe consequences over the coming century (Easterling et al. 2000, Thomas et al. 2004). The entire distributional ranges of many bird species are predicted to shift north (e.g., Thomas and Lennon 1999), a pattern which is also mirrored for a suite of other taxa, particularly butterflies (e.g., Parmesan et al. 1999). These patterns emerge from changes in the ratio of colonizations and extinctions of populations at both the northern and southern margins of the species' range (Parmesan et al. 1999).

Montane ecosystems are generally considered to be especially sensitive to the effects of climate change (Pounds et al. 1999, Colwell et al. 2008). Across the globe, montane forests and species (e.g., Chen et al. 2009, Feeley and Silman 2010) have migrated on average 6.1 m higher up mountain slopes per decade in response to increased temperatures (Parmesan and Yohe 2003). Montane forest birds are, on average, predicted to shift their elevational range around 500 m upslope (Gasner et al. 2010), as caused by analogous changes to the ratio of net colonizations and extinctions of populations at both the lower and upper limits of their elevational ranges. Less certain, however, are the effects of climate change on the distributional ranges of globally threatened montane bird species. The ability of these species, of priority for conservation, to migrate northward and/or upslope may be more severely constrained by the fact that they are often habitat-restricted endemics susceptible to a range of anthropogenic threats that have already affected the extent and quality of their limited habitat. Predicted responses may vary by threatened species, with some likely to benefit whereas others more likely to be severely reduced (Hamer 2010). What is certain, however, is that making such predictions could have significant implications for maintaining biological interactions, designing networks of protected areas, and other conservation measures proposed for montane ecosystems.

The purpose of this study is to predict the effects of climate change on the distributional range of a habitat-restricted, globally threatened montane bird to determine whether such species-specific responses reflect what is currently predicted for other species. Our target species is the Sichuan Jay (*Perisoreus internigrans*), a medium-sized corvid restricted to high-elevation boreal and subalpine coniferous forests (2800 to 3500 m) on the Qinghai–Tibet plateau, west-central China (Sun et al. 2001). The Sichuan Jay is currently listed as vulnerable because of extensive habitat loss and fragmentation throughout its restricted range (BirdLife International 2001). Typically, these coniferous forests are regularly exposed to harsh winter conditions during which permanent territory holders of all species of *Perisoreus* use a winter cache of food (arthropods, berries, mushrooms, and vertebrate flesh) stored in trees during the previous summer and autumn (Blomgren 1964, Ekman et al. 1994, Strickland and Ouellet 1993, Jing et al. 2009). This life-history strategy of storing easily perishable food items may be critically dependent on colder high-elevation temperatures, and this alone may place these species at considerable risk from climate

change. In addition, the decline of the southernmost population of the congeneric Gray Jay (*P. canadensis*) has previously been linked to the increasing warmer autumnal temperatures in its range (Waite and Strickland 2006).

We use a method of maximum-entropy modeling (Phillips et al. 2006) to create ecological niche models for the Sichuan Jay in western-central China. Our objectives were twofold: (1) to describe the climatic conditions prevailing at known localities of the Sichuan Jay and to use these data to evaluate the species' potential distribution across the Qinghai–Tibet plateau; (2) to predict the future prospects of this species under reasonable scenarios of global climate change, and assess changes in both habitat suitability and spatial configuration. Our hope is that these models can be used to help frame an appropriate conservation agenda for globally threatened avifauna in forested montane regions, especially the “third world pole,” the Qinghai–Tibet plateau.

## METHODS

Ecological niche modeling (ENM) is a powerful analytical method with which the predicted effects of climate change on changing bird distributions can be examined (Crick 2004). ENM provides robust predictions of the current and future distributions of rare and endangered species (Thomas et al. 2004), selecting high-priority areas for conservation (Gottschalk et al. 2007) and identifying sites with high potential for future colonization (Engler et al. 2004) by linking occupancy data with landscape and abiotic variables (Gutiérrez et al. 2009). We used MaxEnt (version 3.3.1; Phillips et al. 2006) a machine-learning method to estimate the Sichuan Jay's distribution by finding the probability distribution of maximum entropy (Elith et al. 2006, Fouquet et al. 2010). MaxEnt uses presence-only occurrence data and is particularly well suited for the small sizes that are typical of many sets of species-occurrence data (Pearson et al. 2007, Wisz et al. 2008). Within the maximum entropy approach, the unknown probability distribution denoted as  $\pi$ , is over a finite set of  $X$ . Another set of known real-valued functions  $f_1, \dots, f_n$  on  $X$  represents environmental predictors or functions. Each feature  $f_j$  assigns a real value  $f_j(x)$  to each point  $x$  in  $X$ . The feature expectations

$\pi[f_j] = \sum_{x \in X} \pi(x) f_j(x)$  can be approximated by using a set

of sample points  $x_1, \dots, x_m$ .

Subsequently, the MaxEnt calculates the entropy of the approximation of  $\pi$  to each pixel throughout the study area (denoted by  $\pi_2$ , which represents the probability distribution) as

$$\pi_1[f_j] = \frac{1}{m} \sum_{i=1}^m f_j(x_i)$$

$$H(\pi_2) = - \sum_{x \in X} \pi_2(x) \ln \pi_2(x),$$

and then estimates the probability distribution through maximizing  $H(\pi_2)$  under a certain constraint  $\beta_j$  for each feature,

$$\text{i.e., } \left| \pi_1[f_j] - \sum_{i=1}^m \pi_2[f_j] \right| \leq \beta_j \quad (\text{Phillips et al. 2006}).$$

#### MODEL CONSTRUCTION

We obtained six climatic layers from the WorldClim database (Hijmans et al. 2005). We assumed that the maximum temperature of October and November is significantly related with preservation of the species' stored food items and so represents a specific life-history requirement (see Waite and Strickland 2006). We also included the mean temperature of spring and summer (i.e., from April to September) because of the possible relationship with food-resource abundance. Other climatic variables represent both general climatic trends (annual mean temperature and annual precipitation), and variations (precipitation seasonality and annual temperature range). The Sichuan Jay is associated with high elevation, dense coniferous and subalpine forest (Sun et al. 2001, Jing et al. 2009), therefore we also incorporated elevation (obtained from <http://www.worldclim.org/current>) and percentage forest cover >30% in China (obtained from Data Center for Resources and Environmental Sciences, Chinese

Academy of Sciences, <http://www.resdc.cn/>) as environmental layers into the predictive models. For future climate projections, we used data on the climate predicted for 2050 by three models, HadCM3, CCCMA, and CSIRO, available from the WorldClim dataset (<http://www.worldclim.org/futdwn.htm>). These climate models include two emissions scenarios from the Intergovernmental Panel on Climate Change Special Report (SRES; A2a and B2a; IPCC 2001). From field surveys and historical documents, we compiled 24 locations of the Sichuan Jay's occurrence (Table 1). We chose to include the Gongbo'gymdo location, which has previously been reported as erroneous (see Birdlife International 2001), but this is disputed by other authors (see Sun et al. 2001 Gongbo'gymdo location, which has previously, Martens and Sun 2003).

Using ArcGIS (version 9.1, ESRI, Redlands, CA), we transferred all climatic and environmental-data layers into a 1-km spatial resolution, with the same spatial references as WGS1984. To calculate correlations between the seven parameters we used the Band Collection Statistics in the Spatial Analyst extension of ArcGIS (Table 2). We eliminated the mean temperature April–September and annual mean temperature because of the high correlations with maximum temperature October–November ( $r > 0.8$ ; e.g., Fouquet et al. 2010). We used a logistic output of MaxEnt, with suitability

TABLE 1. The known localities of the Sichuan Jay on the Qinghai–Tibet plateau.

Location	Longitude	Latitude	Sources <sup>a</sup>
Wolong	102.972	30.858	China Ornithological Society (2007)
Mengbishan	102.303	31.708	China Ornithological Society (2007)
Zhuoni_mr	103.432	34.456	Sun et al. (2001)
Zhuoni_dayu	103.677	34.379	Jiang Y. X. (pers. obs.)
Luqu	102.683	34.467	Jing (2005), Sun et al. (2001)
Zhuoni_m	103.395	34.490	Jing (2005), Sun et al. (2001)
Diebu	103.317	34.050	Jing (2005), Bangs and Peters (1928)
Zhouqu	104.020	33.717	Jing (2005), Birdlife International (2001b)
Ruoergai	103.317	33.567	Jing (2005), Birdlife International (2001b)
Jiuzhaigou	103.700	33.050	Jing (2005), Birdlife International (2001b)
Songpan	103.731	32.995	Sun et al. (2001)
Shiqu	97.950	32.400	Jing (2005), Birdlife International (2001b)
Banma	100.917	32.850	Jing (2005), Sun et al. (2001)
Maoergai	103.167	32.533	Jing (2005), Stone (1933)
Maerkang	101.783	32.117	Jing (2005), Stone (1933)
Dege	98.783	31.950	Jing (2005), Sun et al. (2001), Tang (1996)
Jiangda	98.250	31.533	Jing (2005), Birdlife International (2001b)
Daofu	101.267	30.933	Jing (2005), Sun et al. (2001), Tang (1996)
Yajiang	100.617	29.833	Jing (2005), Sun et al. (2001), Thayer and Bangs (1912)
Gongbujiangda	93.233	29.833	Jing (2005), Stone (1933)
Site 1 <sup>a</sup>	103.432	34.442	Jing (2005)
Site 2 <sup>a</sup>	103.704	33.057	Jing (2005)
Site 3 <sup>a</sup>	103.717	33.071	Jing (2005)
Site 4 <sup>a</sup>	103.731	33.048	Jing (2005)

<sup>a</sup>Flock studied by Y. J., 2000–2004.

TABLE 2. Correlation coefficients among the seven environmental variables used in modeling the effects of climate change on the Sichuan Jay<sup>a</sup>.

	MA_ON	ME_AS	AMT	AP	PS	ATR	ELE	PFC
MA_ON								
ME_AS	0.96 <sup>b</sup>							
AMT	0.99 <sup>b</sup>	0.94						
AP	-0.36	0.49	-0.46					
PS	0.59	-0.49	0.65	-0.67				
ATR	-0.50	-0.13	-0.54	0.33	-0.47			
ELE	-0.74	0.88	-0.70	-0.21	-0.38	0.35		
PFC	0.16	0.15	0.16	-0.10	0.45	-0.17	-0.23	

<sup>a</sup>Abbreviations for variables: MA\_ON, maximum temperature in October and November; MA\_AS, mean temperature from April to September; AMT, annual mean temperature; AP, annual precipitation; PS, precipitation seasonality; ATR, annual temperature range; ELE, elevation; PFC, percentage forest cover >30%.

<sup>b</sup>ME\_AS and AMT removed from the model because of high correlation with MA\_ON ( $r > 0.8$ ).

values ranging from 0 to 1 (Phillips and Dudik 2008), to represent the cumulative probabilities of occurrence. We used the recommended default parameters for the convergence threshold ( $10^{-5}$ ), regularization multiplier (1), and the maximum number of iterations (500) (Phillips and Dudik 2008). To assess the robustness of each model we used cross-validation with five replicates, i.e., 20% of presence localities as test data during each replicate (Fouquet et al. 2010).

We based validation and interpretation on the area under the curve (AUC) of the receiver operating characteristics (ROC; Fielding and Bell 1997). An AUC value of 0 indicates a model with discrimination no better than chance, whereas an AUC value of 1 indicates perfect (100%) discrimination, and an AUC value >0.8 indicates excellent discrimination (Pearce and Ferrier 2000). We projected future climate-change scenarios and obtained suitability outputs during each replicate. Subsequently, we used ArcGIS to transform the predicted results from ASCII type into raster type for further analyses. We used the Ensemble-forecasting approach to decrease the predictive uncertainty and applied a basic mathematical function of mean ensembles (Araújo and New 2007, Marmion et al. 2009).

#### ASSESSING RISKS FROM CLIMATE CHANGE

We transformed the habitat-suitability results into a presence-absence distribution first by using the threshold of the average predicted probability of the model-building data (Liu et al. 2005, Hu et al. 2010). Subsequently, we calculated the dynamics of the area potentially suitable under six different climate-change scenarios. For conservation management, we illustrated the stable potential suitable habitat, habitat loss, and habitat gain. We calculated the mean, minimum, and maximum suitability values, latitudes, longitudes, and elevations of the presence grids of both five current and the corresponding 30 future scenarios. In addition, we calculated the total and mean

size of the potentially suitable forest patches to evaluate habitat fragmentation quantitatively. We applied a square lattice to identify the forest-patch size for which we considered the target grid to be connected with four neighboring grids in vertical and horizontal directions. We categorized forest patches by size as 1–10, 10–100, 100–500, or >500 km<sup>2</sup>. Since all climate-change scenarios were projected from the corresponding current replicates, we calculated the relative values of variables listed above for 30 climate-change scenarios, then calculated divergence from zero by the one-sample *t*-test in SPSS 15.0 to assess the differences. To assess forest fragmentation quantitatively, we applied methodology derived by Riitters et al. (2000) to identify the functional categories of potential areas of the jay's occurrence under current climate and six future climate-change scenarios. We assigned each grid of  $9 \times 9$  pixels in which the species was present to one of six categories: interior, patch, transitional, edge, perforated, or undetermined. These we illustrate graphically as figures to enhance their usefulness in conservation management.

## RESULTS

### MODEL PERFORMANCE AND PREDICTOR VARIABLES

The ROC analysis revealed that our model performed well with a high predictive accuracy ( $AUC = 0.984 \pm 0.007$ ). Cross-validation suggested that the model was quite robust, because of the relatively high AUC values for both training data (ranging from 0.990 to 0.993) and test data (ranging from 0.976 to 0.994). The variables that contributed most to model development and predicting the Sichuan Jay's distribution were elevation (45.1%), percentage of forest cover >30% (20.8%), mean annual precipitation (20.8%), and mean annual temperature range (10.4%). The presence thresholds (i.e., the average probabilities predicted from the model-building data) of five replicates were 0.712, 0.681, 0.689, 0.725, and 0.712, respectively.

### PREDICTED DISTRIBUTION OF THE SICHUAN JAY

The point-wise mean occurrence probability of 5-fold cross-validation outputs of the current situation is shown in Fig. 1. The model's outputs predicted that the Sichuan Jay is restricted primarily to the southeastern edge of the Qinghai–Tibet plateau, in northern Sichuan and southern Gansu provinces, especially to the larger patches of continuous forest within each province. In addition, the model predicted a number of grids in eastern Tibet and along the southeastern edge of Qinghai to have habitat of relatively high suitability (areas shown in dark red in Fig. 1).

### POTENTIAL RISKS FROM CLIMATE CHANGE

Although the suitability of some grids in southwestern and central China was predicted to be higher than the presence threshold, we excluded these grids from the subsequent analysis of climate-change risk (and included only the principal areas of the species' distribution shown in Fig. 1b and



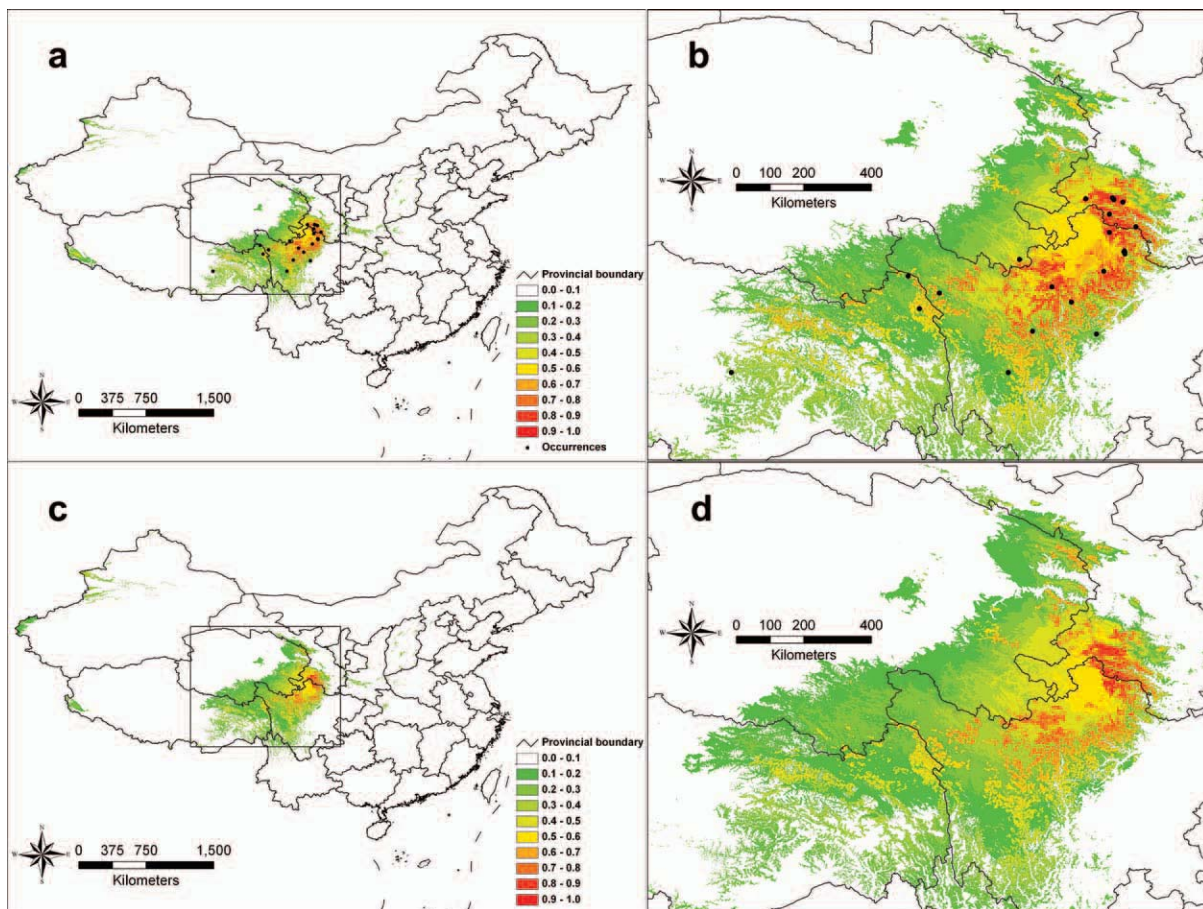


FIGURE 1. Mean predicted probability of occurrence of the Sichuan Jay under five scenarios of current climate and 30 of future climate change. (a, b) Current situation; (c, d) projected future situation. Black dots (b), the occurrence records on which the models are based.

1d) because of the Sichuan Jay's known poor capability for dispersal and the lack of verified observations of this species from these regions.

The predicted effect of climate change on the range of the Sichuan Jay was clearly evident. The extent of areas where jays were predicted to persist declined from 60 615 km<sup>2</sup> to 44 132 km<sup>2</sup> (Fig. 2), and the mean reduction of 16 484 km<sup>2</sup> in the extent of suitable areas was significant ( $P < 0.001$ ). Habitat loss and gain under different climate change scenarios clearly indicated that the potential habitat on the southern, western and eastern margins of the species' distribution would be lost, while new habitat gained was located mainly on the northern margin (Fig. 3). Areas lost were generally larger in extent than those newly gained under all climate-change scenarios. Patterns of habitat loss and gain were similar under different climate-change scenarios; however, the size of the areas varied considerably. The loss of suitable areas was greatest under the CSIRO scenario, followed by HadCM3 and CCCMA, respectively. The gain of suitable areas was largest under the CCCMA-A2a scenario, followed by HadCM3-B2a, CCCMA-A2a, CSIRO, and HadCM3-A2a, respectively (Fig. 3).

Many areas in the Sichuan Jay's range were on average, predicted to become significantly less suitable for the species (decrease in mean suitability value = 0.0110,  $P < 0.001$ ), with even the very best areas also predicted to become significantly less suitable (decrease in maximum suitability value = 0.0146,  $P < 0.001$ ; Fig. 4a). Overall, areas suitable for the Sichuan Jay were predicted to shift northward. Mean, maximum, and minimum latitudes for suitable areas all significantly shifted by 0.490° ( $P < 0.001$ ), 0.637° ( $P < 0.001$ ), and 0.844° ( $P < 0.001$ ) respectively (Fig. 4b), but significant longitudinal shifts were less apparent, with only the minimum longitudinal value shifting by 0.712° ( $P = 0.002$ ; Fig. 4c). Both the higher and lower elevational limits for the species were predicted to increase significantly by 153 m ( $P < 0.001$ ) and 80 m ( $P < 0.001$ ), respectively, but the mean value did not change significantly ( $P = 0.398$ ) (Fig. 4d).

Suitable Sichuan Jay habitat became increasingly fragmented under predicted climate-change scenarios. Not only were there significant increases in the proportion of smaller 1- to 10-km<sup>2</sup> (2.6%,  $P = 0.001$ ) and 10- to 100-km<sup>2</sup> (3.7%,  $P < 0.001$ ) forest patches across the region, the proportions

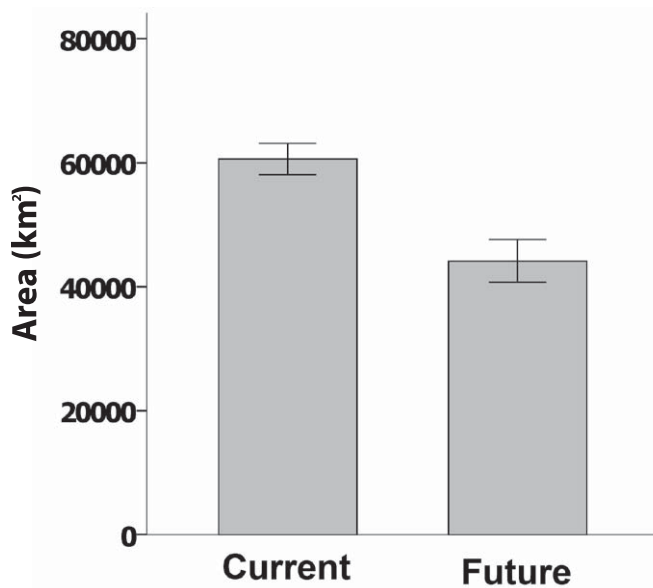


FIGURE 2. Mean extent of range of the Sichuan Jay under current climate and projected future climate, with SE values. The areas are identified from the threshold of the average predicted probability of the model-building data.

of patches of 100–500 km<sup>2</sup> and >500 km<sup>2</sup> declined significantly by 1.2% ( $P = 0.044$ ) and 5 % ( $P < 0.001$ ), respectively (Fig. 5a). Across all size categories, the mean size of a forest patch declined significantly, (2.5%, 2.6%, 2.5% and 27.5%, respectively; Fig. 5b), but perhaps most noticeably for patches of 10–100 km<sup>2</sup> ( $P = 0.006$ ) and >500 km<sup>2</sup> ( $P < 0.001$ ). Functional habitat categorization revealed that forest predicted to be most suitable for the Sichuan Jay was composed almost entirely of the categories patch, transitional, edge and perforated, while interior constituted only 0.3% (Table 3). The proportions of interior and patch areas were predicted to increase, whereas that of perforated areas was predicted to decrease under all climate-change scenarios. Areas of perforated and interior habitat were heavily concentrated along the boundary of Sichuan and Gansu provinces, all at the southern margins of the species' distribution, under all climate-change scenarios (Fig. 6).

## DISCUSSION

### EFFECTS OF CLIMATE CHANGE

We sought to use environmental data relating to known locations of the Sichuan Jay to develop a predictive niche-distribution model to assess the effects of future climate change on this rare and threatened Chinese endemic. According to the results of our modeling, dense high-elevation forests are of critical importance for the Sichuan Jay, with some indication that higher precipitation is also an important

environmental factor, perhaps related to food abundance (Dunning and Brown 1982). Alarming, our model suggests that the Sichuan Jay populations may be severely affected by climate change through loss and fragmentation of suitable forest, particularly at the southern margins of the species' distribution. Although some new areas were predicted to become potentially suitable, many other suitable areas would be lost under climate-change scenarios (Figs. 2 and 3).

Our model also predicted that the potential range of the Sichuan Jay will shift northward (Figs. 1, 3), driven primarily by changes in the southern portion of the species' range (Fig. 4c). Similar climate-related population declines have been previously reported for southern populations of another member of the genus, *P. canadensis* (Waite and Strickland 2006). Currently, the northern limit of the Sichuan Jay's range is constrained by extensive areas of arid habitat so the expansion and persistence of high-elevation coniferous forests in these arid landscapes is unlikely (Fig. 3). The significant loss of suitable habitat from the southern portion of its range is coupled with a low probability of any significant northward extension, unlike that for some European bird species (Thomas and Lennon 1999). In addition, our models also predict that the Sichuan Jay will shift to higher elevations at both margins of its elevational range (Fig. 4d), a pattern that has been predicted for other montane avifauna (e.g., Peh 2007, Gasner et al. 2010). The loss of suitable habitat at lower elevations is accompanied by a limited area available at higher elevations for dispersal and range expansion (e.g., Jetz et al. 2007).

Our model predicted further effects on the Sichuan Jay from increased forest fragmentation, further reductions in the overall extent forest, further reduction of forests' spatial structure, and a significant reduction in the number of patches of forest suitable for the species (Table 3, Fig. 5). Generally, the Sichuan Jay is observed gliding from high branches, and it appears to be a weak flier (J.Y., unpubl. data). Increased habitat fragmentation caused by climate change may severely affect the survival of such a bird, through slowing or halting gene flow and increasing the rate of extinction of isolated local populations. These factors may be further exacerbated by the complex topography of its montane environment, but further research is needed. What is clear, however, is that the scenario faced by the Sichuan Jay should be of concern to conservationists since it is of greater severity than what is currently predicted for its two better-known congeners, *P. canadensis* and *P. infaustus*, both of which also hoard food. The area of suitable forest available to both these wider-ranging congeners for compensatory extension is significantly larger and more continuous than that predicted for *P. internigrans* (Sun et al. 2001).

Although Both et al. (2010) proposed that climate change may affect principally long-distance migrants, mostly because of trophic mismatches, we suggest that it may also be quite serious for bird species with restricted ranges and limited dispersal abilities, because the risks from climate change

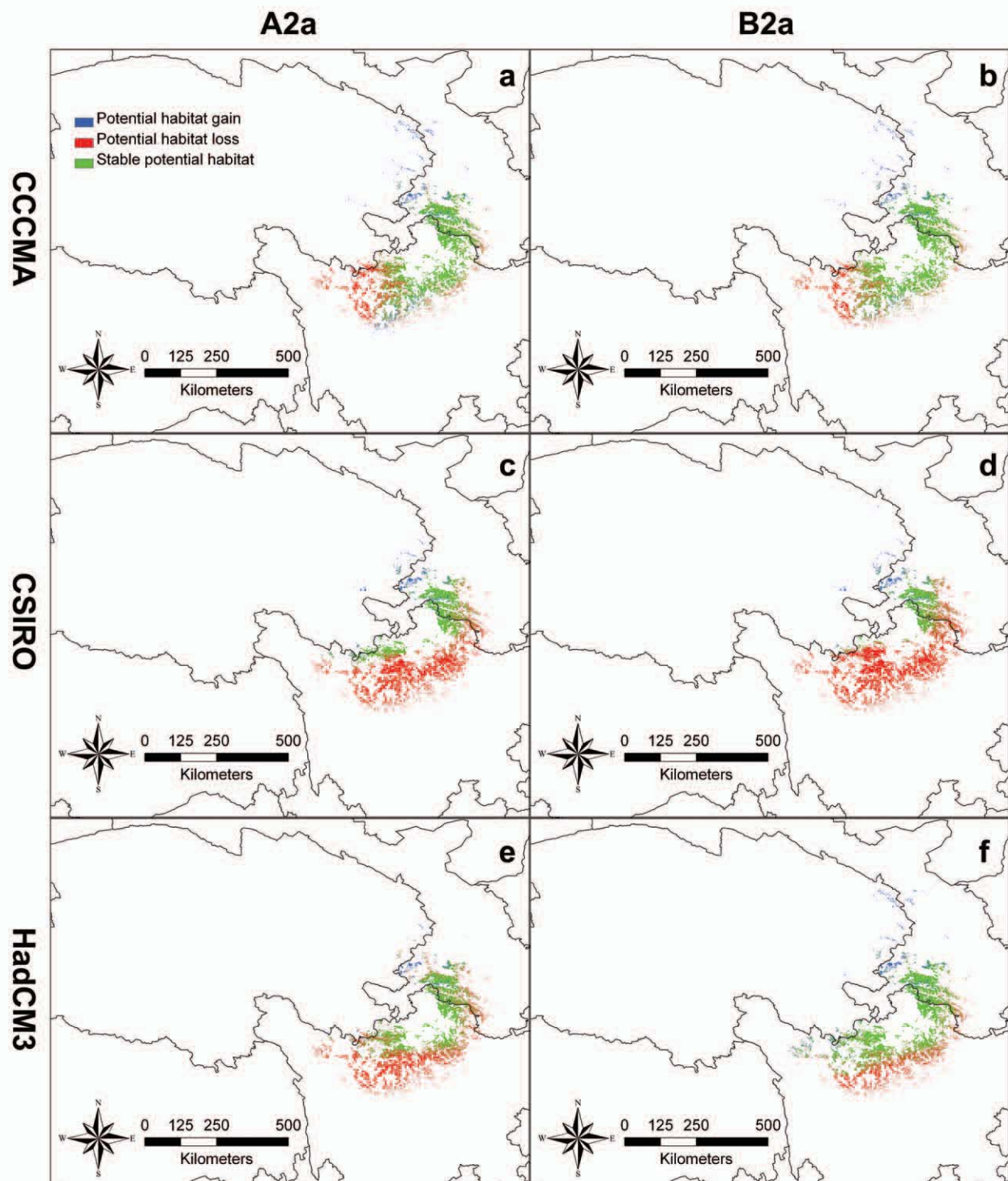


FIGURE 3. Predicted potential loss and gain of Sichuan Jay habitat under climate change, based on six different climate-change scenarios, CCCMA(A2a), CCCMA (B2a), CSIRO (A2a), CSIRO (B2a), HadCM3 (A2a), and HadCM3 (B2a).



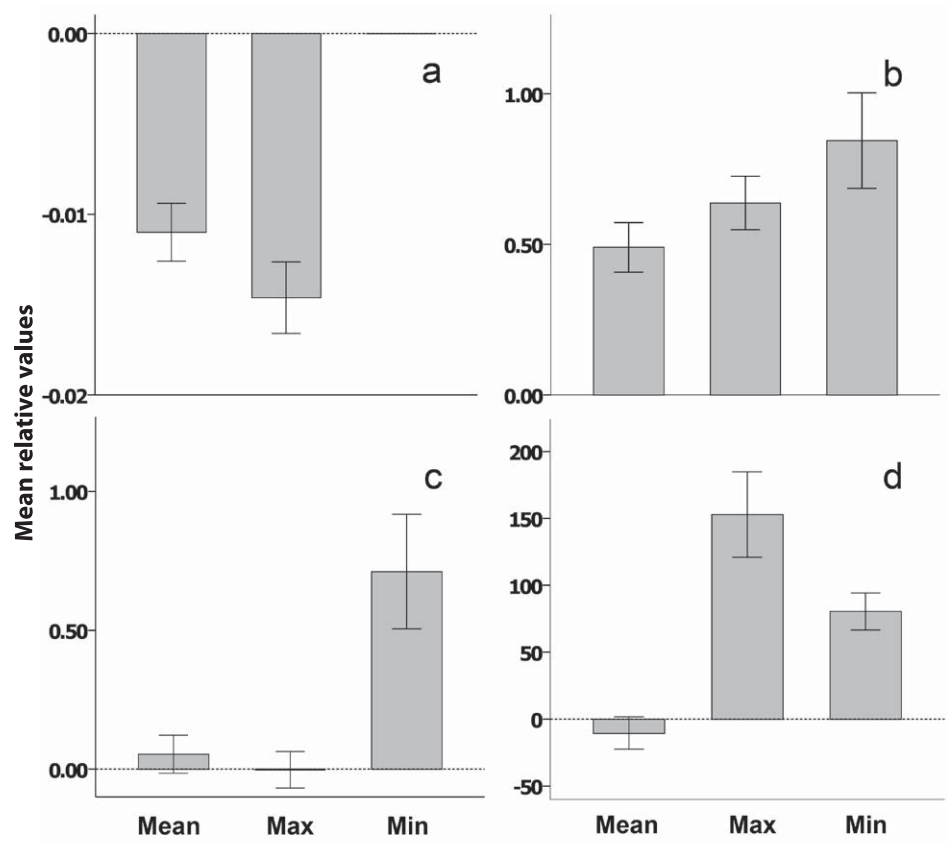


FIGURE 4. The differences between current and projected future climate in the mean, maximum, and minimum of suitability (a), latitude (b), longitude (c), and altitude (d) for the distribution of the Sichuan Jay, with SE values.

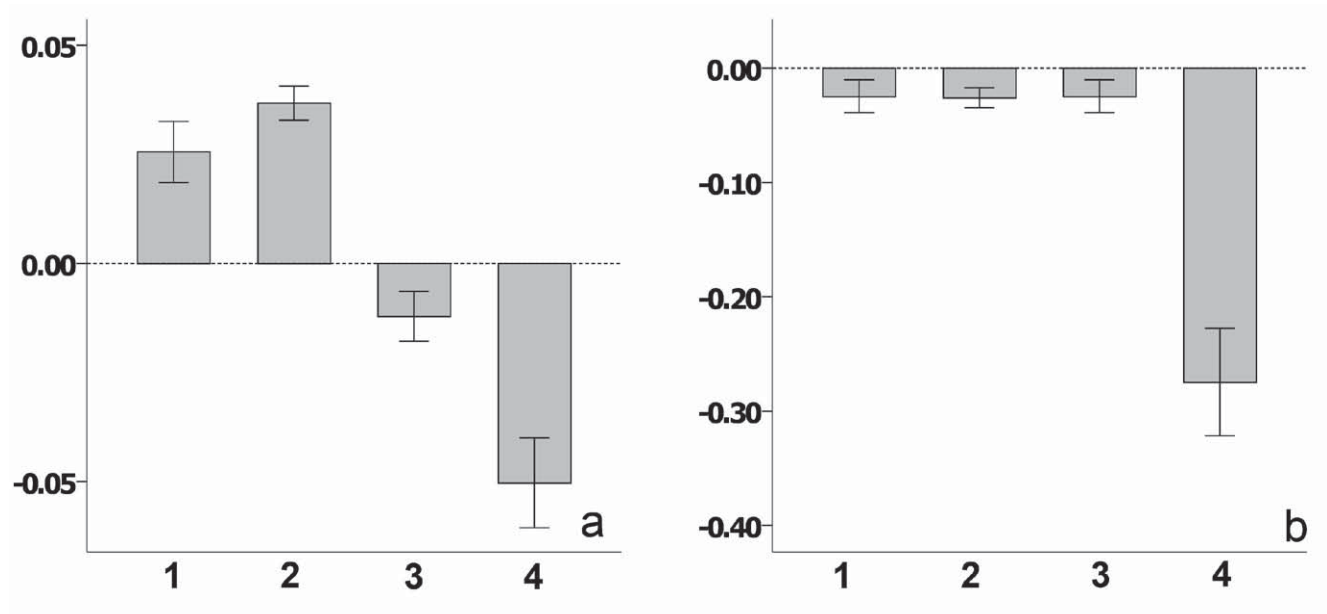


FIGURE 5. The relative proportions of total extent (a) and mean size (b) of patches of habitat suitable for the Sichuan Jay by four categories: (1) 1–10 km<sup>2</sup>, (2) 10–100 km<sup>2</sup>, (3) 100–500 km<sup>2</sup>, and (4) >500 km<sup>2</sup> under current climate and projected future climate, with SE values. The patches were calculated under the condition that the grids are connected with four neighbors of vertical and horizontal direction.



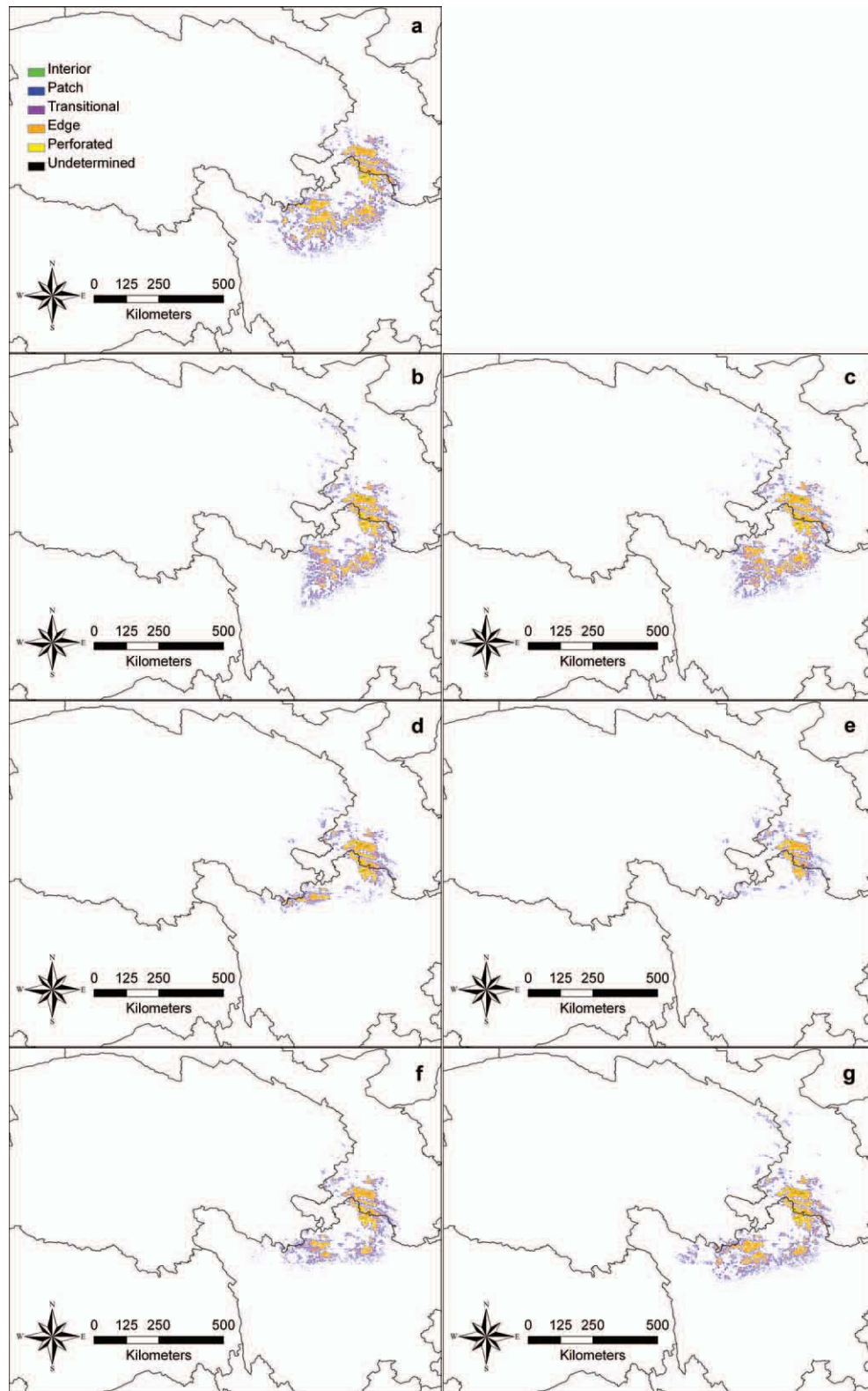


FIGURE 6. Areas of six habitat categories identified according to the model of Riitters et al. (2000) under current climate (a) and six scenarios of projected future climate: (b) CCCMA-A2a; (c) CCCMA-B2a; (d) CSIRO-A2a; (e) CSIRO-B2a; (f) HadCM3-A2a; (g) HadCM3-B2a.

TABLE 3. Extent (number of grids) and the corresponding proportion of categories of Sichuan Jay habitat defined according to the model of Riitters et al. (2000) under current climate and six scenarios of future climate change<sup>a</sup>.

Scenario	Interior (%)	Patch (%)	Transitional (%)	Edge (%)	Perforated (%)	Undetermined (%)
Current	126 (0.33)	9899 (25.60)	9604 (24.84)	10068 (26.04)	8927 (23.09)	38 (0.10)
CCCMA-A2a	238 (0.74)	9103 (28.21)	8480 (26.28)	7808 (24.20)	6615 (20.50)	21 (0.07)
CCCMA-B2a	252 (0.75)	8962 (26.82)	8479 (25.37)	8682 (25.98)	7024 (21.02)	19 (0.06)
CSIRO-A2a	209 (1.15)	4731 (26.09)	3897 (21.49)	5544 (30.57)	3745 (20.65)	10 (0.05)
CSIRO-B2a	80 (0.65)	3577 (29.15)	2495 (20.33)	3726 (30.36)	2389 (19.47)	6 (0.05)
HadCM3-A2a	111 (0.51)	6614 (30.42)	5563 (25.59)	5385 (24.77)	4059 (18.67)	9 (0.04)
HadCM3-B2a	293 (0.94)	9117 (29.15)	7526 (24.07)	8152 (26.07)	6161 (19.70)	22 (0.07)

<sup>a</sup>Values within the brackets are the corresponding proportions of different categories.

may arise not only through reducing the suitability of a species' habitat directly but also through the spatial structure changing the suitable areas indirectly (Suárez-Seoane et al. 2008). Kruess and Tscharntke (1994) identified changing spatial structure as one of the major causes of global biodiversity loss and local extinction, but it has not attracted enough attention by researchers in ecological modeling.

#### CONSERVATION-RESEARCH PRIORITIES AND RECOMMENDATIONS

The high-elevation coniferous forest located at the eastern and southern rim of the Qinghai–Tibet plateau is unique, but little conservation attention has been paid to the potential effects of climate change on these areas (but see Ni 2000, Klein et al. 2004), especially for the birds restricted to this area. Many endemic taxa living on the Qinghai–Tibet plateau have evolved specific survival strategies for the harsh high-elevation climate, such as unique incubation behaviors of the Blood Pheasant (*Ithaginis cruentus*) (Jia et al. 2010), physiological adaptations of the pulmonary circulation to cope with chronic hypoxia in the wild yak (*Bos grunniens*) (Durmowicz et al. 1993), and food-hoarding strategies by the Sichuan Jay (Jing et al. 2009). Under rapid climate change, such unique adaptive behaviors may become a severe constraint for individual survival or adaptation (Rankin and López-Sepulcre 2005). Such taxa therefore should be the priority focus for similar ecological-modeling research in the Qinghai–Tibet plateau to determine any similarities in vulnerability to climate change.

Until recently, very little was known regarding the ecology of the Sichuan Jay (Jing et al. 2009). Today we still lack basic data concerning many aspects of its ecology such as habitat preferences and distribution. Results of our modeling demonstrate that the endemic Sichuan Jay is under severe risk from increased forest fragmentation and other potential effects of climate change. A few conservation measures are underway, most noticeably the cessation of cutting of mature forest in Gansu and Sichuan since the disastrous floods there in 1998 (Sun et al. 2003), and replanting has been expanded and enforced into neighboring regions. However, data that would enable Chinese

policy-makers to frame a much broader conservation agenda for the species throughout the region are sorely lacking.

We suggest that more detailed surveys for the Sichuan Jay and its population status should be undertaken throughout the coniferous forest of the Qinghai–Tibet plateau, especially along the boundary of Gansu and Sichuan provinces, which may be the only viable refuge for the Sichuan Jay under climate change (Fig. 3, 6). All known populations within the regional network of protected areas should be monitored, and priorities for future protected areas should be established. Particular attention should be given to populations at the northern and southern margins of the species' known range, so that future changes can be monitored when they occur. Detailed habitat studies and modeling of dispersal probabilities would help develop suitable strategies for replanting previously logged forest and other areas at the northern and southern margins of the species' known distribution, to offset climate-related fragmentation and loss of habitat, especially near the boundary of Sichuan and Gansu provinces. Finally, one might even envisage contingency measures to breed and reintroduce this species to currently unoccupied but otherwise suitable or newly gained habitat fragments in the areas identified as potentially most suitable.

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#### LITERATURE CITED

- ARAÚJO, M. B., AND M. NEW. 2007. Ensemble forecasting of species distributions. *Trends in Ecology & Evolution* 22:42–47.
- BANGS, O., AND J. L. PETERS. 1928. Birds collected by Dr. F. J. Rock in western Kansu and eastern Tibet. *Bulletin of the Museum of Comparative Zoology* 68: 313–381.
- BIRDLIFE INTERNATIONAL. 2001a. Threatened birds of the world. Lynx Edicions, Barcelona.

- BIRDLIFE INTERNATIONAL. 2001b. Threatened birds of Asia. The Birdlife International red data book. Birdlife International, Cambridge, UK.
- BLOMGREN, A. 1964. Lavskrikan. Albert Bonniers Boktryckeri, Stockholm.
- BOTH, C., C. A. M. VAN TURNHOUT, R. G. BIJLSMA, H. SIEPEL, A. J. VAN STRIEN, AND R. P. B. FOPPEN. 2010. Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society B* 277:1259–1266.
- CHEN, I.-C., H.-J. SHIU, S. BENEDICK, J. D. HOLLOWAY, V. K. CHEY, H. S. BARLOW, J. K. HILL, AND C. D. THOMAS. 2009. Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National Academy of Sciences of the U.S.A.* 106:1479–1483.
- CHINA ORNITHOLOGICAL SOCIETY. 2007. China bird report 2006. China Ornithological Society, Beijing.
- COLWELL, R. K., G. BREHM, C. L. CARDELÚS, A. C. GILMAN, AND J. T. LONGINO. 2008. Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science* 322:258–261.
- CRICK, H. Q. P. 2004. The impact of climate change on birds. *Ibis* 146:48–56.
- DUNNING, J. B., AND J. H. BROWN. 1982. Summer rainfall and winter sparrow densities: a test of the food limitation hypothesis. *Auk* 99:123–129.
- DURMOWICZ, A. G., S. HOFMEISTER, T. K. KADYRALIEV, A. A. ALDASHEV, AND K. R. STENMARK. 1993. Functional and structural adaptation of the yak pulmonary circulation to residence at high altitude. *Journal of Applied Physiology* 74:2276–2285.
- EASTERLING, D. R., B. HORTON, P. D. JONES, T. C. PETERSON, T. R. KARL, D. E. PARKER, M. J. SALINGER, V. RAZUVAYEV, N. PLUMMER, P. JAMASON, AND C. K. FOLLAND. 1997. Maximum and minimum temperature trends for the globe. *Science* 277: 364–367.
- EASTERLING, D. R., G. A. MEEHL, C. PARMESAN, S. A. CHANGNON, T. R. KARL, AND L. O. MEARN. 2000. Climate extremes: observations, modeling, and impacts. *Science* 289:2068–2074.
- EKMANN, J., B. SKLEPKOVYCH, AND H. TEGELSTROM. 1994. Offspring retention in the Siberian Jay (*Perisoreus infaustus*): the prolonged brood care hypothesis. *Behavioral Ecology* 5:245–253.
- ELITH, J., C. H. GRAHAM, R. P. ANDERSON, M. DUDIK, S. FERRIER, A. GUIBAN, R. J. HIJMAN, F. HUETTMANN, J. R. LEATHWICK, A. LEHMANN, J. LI, L. G. LOHMANN, B. A. LOISELLE, G. MANION, C. MORITZ, M. NAKAMURA, Y. NAKAZAWA, J. M. OVERTON, A. T. PETERSON, S. J. PHILLIPS, K. RICHARDSON, R. SCACHETTI-PEREIRA, R. E. SCHAPIRE, J. SOBERON, S. WILLIAMS, M. S. WISZ, AND N. E. ZIMMERMANN. 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29:129–151.
- ENGLER, R., A. GUIBAN, AND L. RECHSTEINER. 2004. An improved approach for predicting the distribution of rare and endangered species from occurrence and pseudo-absence data. *Journal of Applied Ecology* 41:263–274.
- FEELEY, K. J., AND M. R. SILMAN. 2010. Land-use and climate change effects on population size and extinction risk of Andean plants. *Global Change Biology* 16:3215–3222.
- FIELDING, A. H., AND J. F. BELL. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24:38–49.
- FOUQUET, A., G. F. FICETOLA, A. HAIGH, AND N. GEMMELL. 2010. Using ecological niche modelling to infer past, present and future environmental suitability for *Leiopelma hochstetteri*, an endangered New Zealand native frog. *Biological Conservation* 143:1375–1384.
- GASNER, M. R., J. E. JANKOWSKI, A. L. CIECKA, K. O. KYLE, AND K. N. RABENOLD. 2010. Projecting the local impacts of climate change on a Central American montane avian community. *Biological Conservation* 143:1250–1258.
- GOTTSCHALK, T. K., K. EKSCHMITT, S. ISFENDIYAROGU, E. GEM, AND V. WOLTERS. 2007. Assessing the potential distribution of the Caucasian Black Grouse *Tetrao mlokosiewiczii* in Turkey through spatial modelling. *Journal of Ornithology* 148:427–434.
- GUTIERREZ, A. P., L. PONTI, AND Q. A. COSSU. 2009. Effects of climate warming on Olive and olive fly (*Bactrocera oleae* (Gmelin)) in California and Italy. *Climatic Change* 95:195–217.
- HAMER, K. C. 2010. The search for winners and losers in a sea of climate change. *Ibis* 152:3–5.
- HIJMAN, R. J., S. E. CAMERON, J. L. PARRA, P. G. JONES, AND A. JARVIS. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965–1978.
- HOUGHTON, J. T., Y. DING, D. J. GRIGGS, M. NOGUER, P. J. VAN DER LINDEN, D. XIAOSU, K. MASKELL, AND C. A. JOHNSON. 2001. Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, UK.
- HU, J. H., H. J. HU, AND Z. G. JIANG. 2010. The impacts of climate change on the wintering distribution of an endangered migratory bird. *Oecologia* 164:555–565.
- IPCC. 2001. Intergovernmental Panel on Climate Change third assessment report—climate change 2001. IPCC, Geneva, Switzerland.
- JETZ, W., D. S. WILCOVE, AND A. P. DOBSON. 2007. Projected impacts of climate and land-use change on the global diversity of birds. *PLoS Biology* 5: e157.
- JIA, C. X., Y. H. SUN, AND J. E. SWENSON. 2010. Unusual incubation behavior and embryonic tolerance of hypothermia by the Blood Pheasant (*Ithaginis cruentus*). *Auk* 127:926–931.
- JING, Y. 2005. Life history, cooperative breeding, foraging competition, and distribution of the Sichuan Jay (*Perisoreus internigrans*). Ph.D. thesis, Institute of Zoology, Chinese Academy of Sciences, Beijing.
- JING, Y., Y. FANG, D. STRICKLAND, N. LU, AND Y. H. SUN. 2009. Alloparenting in the rare Sichuan Jay (*Perisoreus internigrans*). *Condor* 111:662–667.
- KLEIN, J. A., J. HARTE, AND X. Q. ZHAO. 2004. Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan Plateau. *Ecology Letters* 7:1170–1179.
- KRUESS, A., AND T. TSCHARNTKE. 1994. Habitat fragmentation, species loss, and biological control. *Science* 264:1581–1584.
- LEECH, D. I., AND H. Q. P. CRICK. 2007. Influence of climate change on the abundance, distribution and phenology of woodland bird species in temperate regions. *Ibis* 149:128–145.
- LIU, C. R., P. M. BERRY, T. P. DAWSON, AND R. G. PEARSON. 2005. Selecting thresholds of occurrence in the prediction of species distributions. *Ecography* 28:385–393.
- MARMION, M., M. PARVIAINEN, M. LUOTO, R. K. HEIKKINEN, AND W. THUILLER. 2009. Evaluation of consensus methods in predictive species distribution modelling. *Diversity and Distributions* 15:59–69.
- MARTENS, J., AND Y. H. SUN. 2003. *Perisoreus internigrans* (Thayer et Bangs, 1912) China-Unglückshäer. Atlas der verbreitung palaearktischer Vögel 20:1–5.
- NI, J. 2000. A simulation of biomes on the Tibetan Plateau and their responses to global climate change. *Mountain Research and Development* 20:80–89.
- PARMESAN, C., N. RYRHOLOM, C. STEFANESCU, J. K. HILLK, C. D. THOMAS, H. DESCIMON, B. HUNTLEY, L. KAILA, J. KULLBERG, T. TAMMARU, W. J. TENNENT, J. A. THOMAS, AND M. WARREN. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399:579–583.

- PARMESAN, C., AND G. YOHE. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37–42.
- PEARCE, J., AND S. FERRIER. 2000. Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling* 133:225–245.
- PEARSON, R. G., C. J. RAXWORTHY, M. NAKAMURA, AND A. T. PETERSON. 2007. Predicting species' distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography* 34:102–117.
- PEH, K. S.-H. 2007. Potential effects of climate change on elevational distributions of tropical birds in southeast Asia. *Condor* 109:437–441.
- PHILLIPS, S. J., R. P. ANDERSON, AND R. E. SCHAPIRE. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190:231–259.
- PHILLIPS, S. J., AND M. DUDIK. 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31:161–175.
- POUNDS, J. A., M. P. L. FOGDEN, AND J. H. CAMPBELL. 1999. Biological response to climate change on a tropical mountain. *Nature* 398:611–615.
- RANKIN, D. J., AND A. LÓPEZ-SEPULCRE. 2005. Can adaptation lead to extinction? *Oikos* 111:616–619.
- RIITTERS, K., J. WICKHAM, R. O'NEILL, B. JONES, AND E. SMITH [ONLINE]. 2000. Global-scale patterns of forest fragmentation. *Conservation Ecology* 4(3). <<http://www.consecol.org/vol4/iss2/art3>>.
- ROOT, T. L., J. T. PRICE, K. R. HALL, S. H. SCHNEIDER, C. ROSENZWEIG, AND J. A. POUNDS. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421:57–60.
- STONE, W. 1933. Zoological results of the Dolan west China expedition of 1931. Part 1. Birds. *Proceedings of the Academy of Natural Sciences of Philadelphia* 85:165–222.
- STRICKLAND, D., AND H. OUELLET. 1993. Gray Jay (*Perisoreus canadensis*), no. 40. *In* P. Poole, P. Stettenheim and F. Gill [EDS.], *The birds of North America*. Academy of Natural Sciences, Philadelphia.
- SUÁREZ-SEOANE, S., E. L. G. DE LA MORENA, M. B. M. PRIETO, P. E. OSBORNE, AND E. DE JUANA. 2008. Maximum entropy niche-based modelling of seasonal changes in Little Bustard (*Tetrax tetrax*) distribution. *Ecological Modelling* 219:17–29.
- SUN, Y. H., C. X. JIA, AND Y. FANG. 2001. The distribution and status of Sichuan Grey Jay (*Perisoreus internigrans*). *Journal für Ornithologie* 142:93–98.
- SUN, Y. H., J. E. SWENSON, Y. FANG, S. KLAUS, AND W. SCHERZINGER. 2003. Population ecology of the Chinese Grouse, *Bonasa sewerzowi*, in a fragmented landscape. *Biological Conservation* 110:177–184.
- TANG, C. 1996. *Avifauna of the Hengduan Mountains*. Science Press, Beijing.
- THAYER, J. E., AND O. BANGS. 1912. Some Chinese vertebrates. *Aves. Memoirs of the Museum of Comparative Zoology* 40:137–200.
- THOMAS, C. D., AND J. J. LENNON. 1999. Birds extend their ranges northwards. *Nature* 399:213–213.
- THOMAS, C. D., A. CAMERON, R. E. GREEN, M. BAKKENES, L. J. BEAUMONT, Y. C. COLLINGHAM, B. F. N. ERASMUS, M. F. DE SIQUEIRA, A. GRAINGER, L. HANNAH, L. HUGHES, B. HUNTLEY, A. S. VAN JAARSVELD, G. F. MIDGLEY, L. MILES, M. A. ORTEGA-HUERTA, A. T. PETERSON, O. L. PHILLIPS, AND S. E. WILLIAMS. 2004. Extinction risk from climate change. *Nature* 427:145–148.
- WAITE, T. A., AND D. STRICKLAND. 2006. Climate change and the demographic demise of a hoarding bird living on the edge. *Proceedings of the Royal Society B* 273:2809–2813.
- WALTHER, G., E. POST, P. CONVEY, A. MENZEL, C. PARMESAN, T. J. C. BEEBEE, J. FROMENTIN, O. HOEGH-GULDBERG, AND F. BAIRLEIN. 2002. Ecological responses to recent climate change. *Nature* 416:389–395.
- WISZ, M. S., R. J. HIJMANS, A. T. PETERSON, C. H. GRAHAM, A. GUISAN, AND NPSDW GROUP. 2008. Effects of sample size on the performance of species distribution models. *Diversity and Distributions* 14: 763–773.