Predicting suitable habitat of the Chinese monal (*Lophophorus lhuysii*) using ecological niche modeling in the Qionglai Mountains, China

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Understanding the distribution and the extent of suitable habitats is crucial for wildlife conservation and management. Knowledge is limited regarding the natural habitats of the Chinese monal (*Lophophorus lhuysii*), which is a vulnerable Galliform species endemic to the high-montane areas of southwest China and a good candidate for being an umbrella species in the Qionglai Mountains. Using ecological niche modeling, we predicted current potential suitable habitats for the Chinese monal in the Qionglai Mountains with 64 presence points collected between 2005 and 2015. Suitable habitats of the Chinese monal were associated with about 31 mm precipitation of the driest quarter, about 15 ℃ of maximum temperature of the warmest month, and far from the nearest human residential locations (> 5,000 m). The predicted suitable habitats of the Chinese monal covered an area of 2,490 km^2, approximately 9.48% of the Qionglai Mountains, and was highly fragmented. 54.78% of the suitable habitats were under the protection of existing nature reserves and two conservation gaps were found. Based on these results, we provide four suggestions for the conservation management of the Chinese monal: (1) ad hoc surveys targeting potential suitable habitats to determine species occurrence, (2) more ecological studies regarding its dispersal capacity, (3) establishment of more corridors and green bridges across roads for facilitating species movement or dispersal, and (4) minimization of local disturbances.

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2   **niche modeling in the Qionglai Mountains, China**

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ABSTRACT

Understanding the distribution and the extent of suitable habitats is crucial for wildlife conservation and management. Knowledge is limited regarding the natural habitats of the Chinese monal (*Lophophorus lhuysii*), which is a vulnerable Galliform species endemic to the high-montane areas of southwest China and a good candidate for being an umbrella species in the Qionglai Mountains. Using ecological niche modeling, we predicted current potential suitable habitats for the Chinese monal in the Qionglai Mountains with 64 presence points collected between 2005 and 2015. Suitable habitats of the Chinese monal were associated with about 31 mm precipitation of the driest quarter, about 15 °C of maximum temperature of the warmest month, and far from the nearest human residential locations (> 5,000 m). The predicted suitable habitats of the Chinese monal covered an area of 2,490 km², approximately 9.48% of the Qionglai Mountains, and was highly fragmented. 54.78% of the suitable habitats were under the protection of existing nature reserves and two conservation gaps were found. Based on these results, we provide four suggestions for the conservation management of the Chinese monal: (1) ad hoc surveys targeting potential suitable habitats to determine species occurrence, (2) more ecological studies regarding its dispersal capacity, (3) establishment of more corridors and green bridges across roads for facilitating species movement or dispersal, and (4) minimization of local disturbances.

31 **INTRODUCTION**

32   Understanding the distribution of suitable habitats and its influencing factors are crucial for

33 wildlife conservation and management (Austin 2002). Ecological niche models have developed as

34 excellent tools for predicting habitat distribution of species that are difficult to investigate

35 (Peterson *et al.* 2002, Mota-Vargas *et al.* 2013), because they can predict the distribution of

36 species' habitats at a large spatial scale based on species presence data and environmental

37 variables, without the need for extensive surveys and detailed descriptions of physiological and

38 behavioral characteristics (Morrison *et al.* 2012). In particular, MaxEnt, a presence-only modeling

39 approach based on the maximum entropy principle (Phillips *et al.* 2006), outperforms other models

40 in prediction accuracy (Elith *et al.* 2006, Phillips *et al.* 2006), transferability (Tuanmu *et al.* 2011),

41 and performance with small sample sizes (Pearson *et al.* 2007, Costa *et al.* 2010). It offers great

42 potential for addressing endangered and poorly known bird species with scarce occurrence data

43 (e.g. Botero-Delgadillo *et al.* 2012, Marcondes *et al*. 2014, Tobón-sampedro *et al*. 2015).

44   The Chinese monal (*Lophophorus lhuysii*) is the largest Galliform species (with a mean length

45 of 76 cm and a mean weight of 3.18 kg) distributed in high-montane regions, mainly inhabiting

46 subalpine scrubs, as well as subalpine and alpine meadows at an elevation of 3,000–4,900 m

47 (MacKinnon *et al.* 2000, Madge *et al.* 2002). This species is endemic to southwest China, and is

48 found primarily in southeast Gansu, southeast Qinghai, western Sichuan, and northwest Yunnan

49 (Lei and Lu 2006, Lu 2015). It has been listed on appendix I of CITES since 1975 (CITES 2016)

50 and classified as a vulnerable species on the IUCN red list since 1994 (IUCN 2015). In 1989, the

51 Chinese government started to legally protect the species as a first-class, nationally-protected

52   wildlife species (Checklist of Wild Animals of National Priority Protection 1989). Recently, the

53   Chinese monal was identified as one of the endemic bird species in China with the highest

54   conservation values in terms of phylogenetic diversity (Chen 2013). Its population size, however,

55   remains small (10,000–25,000 individuals in total, BirdLife International 2015) and is inferred to

56   be in a state of continuous decline because of illegal hunting and on-going habitat degradation and

57   fragmentation (BirdLife International 2015). It is therefore necessary to establish effective

58   conservation programs targeting the Chinese monal.

59   However, knowledge of the natural habitats of the Chinese monal is limited, as cryptic behavior

60   and inaccessible habitats of the species make it difficult to survey the natural populations. Most of

61   the previous studies were conducted in the late twentieth century and only provided simple

62   descriptions of habitat use (Ma 1989, Zhang 1995), population density and structure (He and Lu

63   1985, Long *et al.* 1998), breeding ecology (He *et al.* 1986), activity pattern (Ma 1988), and feeding

64   habits (Lu *et al.* 1986). There has not been a quantitative analysis of the natural habitats of the

65   Chinese monal at a large spatial scale in any part of its geographical range and this limited

66   knowledge has constrained conservation development for the Chinese monal.

67   The Qionglai Mountains are a part of the biodiversity hotspot of the Mountains of Southwest

68   China (Mittermeier *et al.* 2011) that supports many endangered and endemic wildlife species. As

69   the geographical center of the distribution of the Chinese monal (Lei and Lu 2006, Lu 2015; Figure

70   1), this region is critical for the conservation of the species. In this study, we used the ecological

71   niche modeling approach, with species records and predictors selected from a large set of

72   environmental variables, to predict the current potential suitable habitats for the Chinese monal in

73 the Qionglai Mountains. Our objectives were to (1) delineate the distribution of suitable habitats

74 of the Chinese monal, (2) identify critical environmental factors influencing the species' habitat

75 suitability, (3) compare the prediction with existing nature reserve network and provide

76 conservation suggestions based on the results.

77 **MATERIALS & METHODS**

78 **Study area**

79   The Qionglai Mountains are the easternmost portion of the Hengduan Mountains, extending

80 approximately 250 km from north to south at the center of Sichuan Province, China (E: 102°01′–

81 103°46′, N: 29°27′–31°55′; Figure 1). The area covers 26,258 km^2 and incorporates 12 counties,

82 including Lixian, Xiaojin, Baoxing, Dayi, Lushan, Qionglai, and Tianquan. The areas west of the

83 Min River in Wenchuan, Dujiangyan and Chongzhou counties are also included in the Qionglai

84 Mountains (the east side of the River belongs to the Minshan Mountains). The areas east of the

85 Dadu River in Luding and Kangding counties are also included in the Qionglai Mountains (the

86 west sides of the River belong to the Daxueshan Mountains). Elevation ranges from 450 m in the

87 Sichuan Basin to 6,250 m at the Siguniang Mountain peak. The subtropical monsoon climate

88 predominates the region. There are diverse ecosystems and vegetation types, with many rare and

89 endangered wildlife species, such as the giant panda (*Ailuropoda melanoleuca*), golden snub-

90 nosed monkey (*Rhinopithecus roxellanae*), snow leopard (*Panthera unica*), takin (*Budorcas

91 taxicolor*), and dove tree (*Davidia involucrate*) (Hu 2001).

92 **Presence data**

93   In total, we gathered 103 current (2005-2015) presence records of the Chinese monal (Table

94   S1), including sightings, callings, feces, and feathers. The majority (86.4%) of the records was

95   from field surveys in recent years, including the authors' filed survey records, sympatric animal

96   database of the fourth national survey on giant panda, and biodiversity monitoring data from nature

97   reserves; the remaining data was from published literatures and network databases (for details, see

98   Table 1). To insure spatial accuracy, we only kept presence points with accuracies to three decimal

99   places of the coordinates. To avoid overfitting the model, we generated a 1 km² buffer around each

100   presence point and randomly selected one if the buffers overlap, as this area approximates the

101   minimum home range size maintained by the Chinese monal (He and Lu 1985). Finally, 64

102   remained presence points with geographic coordinates were used to build the ecological niche

103   model (Figure 1).

104   **Environmental data**

105   42 environmental variables (Table S2) summarizing five groups (bioclimatic data, vegetation,

106   phenological metrics, topographical attributes, and human impacts) potentially related to habitat

107   suitability of the Chinese monal were selected as candidate variables. We included 19 bioclimatic

108   variables from WorldClim 1.4 (http://www.worldclim.org/), which were interpolated based on a

109   large number of weather stations all over the world, integrating the effects of latitude, longitude,

110   and elevation (Hijmans *et al.* 2005). Bioclimatic data were frequently used in habitat modeling

111   due to direct effects on species distribution (Guisan and Zimmermann 2000). Vegetation and

112   phenology-related variables were derived from moderate resolution imaging spectroradiometer

113   (MODIS) remotely sensed data from LP DAAC (https://lpdaac.usgs.gov/). The International

114   Geosphere-Biosphere Programme (IGBP) classification of land cover within MCD12Q1 2014

115   product was used as a categorical variable of vegetation type (Loveland and Belward 1997). This

116   classification was derived from yearly MODIS data and 1860 training sites observations

117   distributed across the Earth's land areas (Friedl *et al.* 2010). We downloaded a time series of

118   MOD13Q1 16-day enhanced vegetation index (EVI) product over a three year period from 2013

119   to 2015 (23 layers per year). To reduce the potential noise caused by cloud remnants, we

120   reconstructed a clean and smooth EVI time series employing an adaptive Savitzky-Golay filter and

121   then generated 15 phenological metrics using TIMESAT 3.2 (Jönsson and Eklundh 2002, 2004).

122   These EVI derived metrics strongly correlate with vegetation primary productivity and its

123   seasonality (Jönsson and Eklundh 2002, Rahman *et al.* 2005, Alcaraz-Segura *et al.* 2013), and

124   could improve the performance of species habitat modeling (Requena-Mullor *et al.* 2014). The

125   topographical attributes included elevation, slope, aspect, and distance to rivers. Slope and aspect

126   were extracted from an ASTER GDEM V2 30 m resolution digital elevation model (DEM;

127   http://www.gscloud.cn/), using Surface Analyst Tool of ArcGIS 10.2 (ESRI, Redlands, CA, USA).

128   Aspect was recalculated as the absolute value of actual degree minus 180°, representing how close

129   the slope was to the adret facing the sun (Kalkhan 2011). We produced a layer of distance to the

130   nearest perennial river using the Euclidean Distance Tool of ArcGIS. Variables regarding human

131   impacts included Euclidean distance to residential locations (villages and rural settlements) and to

132   roads, and human influence index (HII). HII layer was downloaded from Last of the Wild (Data

133   Version 2, 2005) (http://sedac.ciesin.columbia.edu/), representing anthropogenic impacts spanning

134   1995-2004 that were calculated by integrating the data including human population pressure

135   (population density), human land use (built-up areas, nighttime lights, land use, and land cover),

136   and human accessibility (coastlines, roads, railroads, and navigable rivers). The basic vector layers

137   of rivers, roads, and residential locations were provided by National Geomatics Center of China

138   (NGCC). Each variable was projected to the UTM zone 48N coordinate system, and resampled to

139   the same pixel size as the EVI layers (about 250 m) using bilinear interpolation, except for the

140   categorical land cover that was resampled using nearest neighbor assignment.

141   **Model procedure**

142   We used MaxEnt to generate the habitat suitability model of the Chinese monal (MaxEnt 3.3.3k,

143   http://www.cs.princeton.edu/~schapire/maxent/). Ecological niche models with inappropriately

144   complex variables might be oversized, overfitted or redundant (Parolo *et al.* 2008, Swanepoel *et*

145   *al.* 2013). To increase abilities in building high accuracy predictions and in identifying the critical

146   predictors constraining the species' distribution, we implemented an optimized selection of 42

147   environmental variables based on sample-size-corrected Akaike information criteria (AICc)

148   (Akaike 1974, Warren and Seifert 2011, Warren *et al.* 2014). Firstly, we built a MaxEnt model

149   with the full set of 42 variables and removed variables with contribution < 1% or had Pearson's

150   correlation coefficients > $\lfloor 0.7 \rfloor$ with the highest contributed variable; then the retained variables

151   were used to build a new model, and the variables with low contribution (< 1%) or high correlation

152   coefficients (absolute values > 0.7) with the second highest contributed variable were removed

153   again; finally, a set of models with different set of variables were produced after repeating this

154   process, and AICc value was calculated for each model based on codes proposed by Warren *et al.*

155   (2010). The model with the lowest AICc was considered to have the most appropriate complexity

156   (Warren and Seifert 2011, Jueterbock *et al.* 2016), thus the variables included in this model were

157   selected to build the final model for Chinese monal habitat. The optimized variable selection was

158   processed in R 3.2.2 (R Development Core Team 2015) with package "MaxentVariableSelection"

159   (Jueterbock 2015, Jueterbock *et al.* 2016).

160   The regularization multiplier, maximum number of background points, maximum iterations,

161   and convergence threshold were set as default values, since these settings have been found to

162   achieve good performances (Phillips and Dudík 2008). To produce stable results, we ran 20

163   replicate bootstrap procedures for the final model. Each replicate used a randomly selected dataset

164   of 75% training data and 25% test data. The built-in functions: contribution of variables, response

165   curves, and jackknife test, were used to analyze the relative importance of each variable in

166   modeling, and their relation with the habitat suitability. We used an average output grid of 20

167   replicates as the final model prediction, with a logistic habitat suitability index ranging from the

168   lowest "0" to the highest "1."

169   Model performance was evaluated using three different measures, including area under the

170   receiver operating characteristic curve (AUC), Cohen's maximized Kappa, and the true skill

171   statistic (TSS). All three measures are calculated based on specificity and sensitivity of the

172   predictive model. Specificity and sensitivity represent the success rate for classifying absences and

173   presences, respectively. AUC is a threshold-independent evaluation measure obtained by plotting

174   sensitivity against 1-specificity (Fielding and Bell 1997). We used the built-in function of MaxEnt

175   program to produce the mean AUC values of the 20 replicates. The model accuracy can be judged

176   as excellent if AUC > 0.9, good if 0.9 > AUC > 0.8, fair if 0.8 > AUC >0.7, poor if 0.7 > AUC >

177   0.6, and failed if 0.6 > AUC > 0.5 (Swets 1988).

178   Kappa and TSS are threshold-dependent indices that measure the agreement between

179   predictions and known occurrences (presences and absences) at different binary thresholds. Kappa

180   index is obtained by plotting sensitivity and specificity against different thresholds (Cohen 1960),

181   while TSS equals sensitivity + specificity - 1 (Allouche *et al.* 2006). Another difference is that

182   Kappa index responds to species prevalence whereas TSS does not (Allouche *et al.* 2006). In this

183   study, we used maximized values of Kappa and TSS at their own optimal thresholds to evaluate

184   model performance. The standards for judging model performance are: excellent if Kappa > 0.75,

185   good if 0.75 > Kappa > 0.4, and poor if Kappa < 0.4 (Araújo *et al.* 2005); while good to excellent

186   if TSS > 0.8, useful if 0.8 > TSS > 0.5, and poor if 0.5 > TSS > 0.2 (Coetzee *et al.* 2009). Since

187   these two indices require the use of absence data, 200 additional pseudo-absence points were

188   generated within the study region. These pseudo-absence points were randomly located outside

189   the 1 km buffers of observed presence points for Chinese monals. The threshold-dependent

190   statistics were analyzed in R 3.2.2 (R Development Core Team 2015) with package

191   "PresenceAbsence" (Freeman and Moisen 2008).

192   **Habitat analysis**

193   For further analysis, we applied a threshold that maximizes the TSS for transforming the model

194   prediction with a continuous habitat suitability index to a binary suitable/unsuitable map.

195   Maximum TSS is a promising threshold criterion when only species presence data are available,

196   outperforming many other criterions in most cases (Liu *et al.* 2005, Jiménez-Valverde and Lobo

197   2007, Liu *et al.* 2013). We estimated total suitable habitat area of the Chinese monal in the Qionglai

198   Mountains and areas harboured in counties and nature reserves, respectively.

RESULTS

Optimized variable selection showed that the model with the lowest AICc was built with: maximum temperature of the warmest month (bioclim5), precipitation of the driest quarter (bioclim17), annual maximum of EVI (evi maximum), base level values of EVI (evi base level), slope, and distances to residential locations (d_resident) and to roads (d_road) (Table S3 and S4). The seven predictors were therefore selected for the final MaxEnt modeling. We obtained average values of model evaluation indices after 20 replicates: training AUC = 0.966, test AUC = 0.953, maximum Kappa = 0.813, and maximum TSS = 0.882. High scores of model evaluation indices, both the threshold-independent and threshold-dependent, indicated that the habitat suitability model produced by MaxEnt performed excellently (Manel *et al.* 2001, Araújo *et al.* 2005).

Relevant variables

Evaluation of percent contribution of each variable to the model illustrated that three predictors had over 10% relative contribution to the habitat suitability model of the Chinese monal, contributing 78% collectively (Table 2). Precipitation of the driest quarter (bioclim17) made the largest contribution, followed by maximum temperature of the warmest month (bioclim5) and distance to the nearest residential locations. Similarly, these three predictors received the highest AUC values when used in isolation in the jackknife test (Table 2), indicating they are better at discriminating suitable from non-suitable habitat as compared with the other variables. The response of logistic probability of monal occurrence on the two critical climatic predictors were both unimodal, that the probabilities were at the peak at 31 mm for precipitation of the driest quarter and at 15 °C for maximum temperature of the warmest month (Figure 2 a & b). The

220   response curve also showed that monals were more likely to occur at sites further away (> 5,000

221   m) from the nearest human residential locations (Figure 2 c).

222   **Habitat status**

223   We created a binary suitable/unsuitable habitat map after applying the maximum TSS threshold

224   (where habitat suitable index = 0.208). The suitable habitats for the Chinese monal covered an area

225   of 2,490 km^2, corresponding to 9.48% of the entire Qionglai Mountains region. The majority of

226   suitable habitats for the Chinese monal distributed in the central mountain regions, mainly

227   stretching along the boundaries of Lixian-Wenchuan, Wenchuan-Baoxing, Xiaojin-Baoxing, and

228   Baoxing-Tianquan (Figure 3, Table 3). Ten existing nature reserves are located in the Qionglai

229   Mountains, covering over a quarter of the entire region. Over 50% of the suitable monal habitats

230   were situated within nature reserves. Wolong Nature Reserve provided the largest area of suitable

231   habitats for the Chinese monal, while Heishuihe, Labahe, and Fengtongzhai Nature Reserve also

232   had high proportions of suitable habitat (Table 4). Two general regions with large areas of potential

233   suitable habitat were outside of any nature reserves: one in the northern region of Lixian County,

234   and the other in northwest Baoxing County (Figure 3).

235   **DISCUSSION**

236   Our study represents the first attempt at predicting the suitable habitat of the Chinese monal.

237   Variable analysis revealed that bioclimatic variables were the most influential predictors on the

238   habitat suitability of the Chinese monal. Higher habitat suitability was constrained in narrow

239   ranges of both precipitation of the driest quarter and maximum temperature of the warmest month,

240   suggesting that Chinese monal was highly sensitive to climate under extreme periods. The monals

241   appeared to prefer habitats far away from residential locations, suggesting human disturbance as a

242   crucial pressure for the species. Although roads represent remarkable sources of disturbance to

243   wildlife that could lead to road-kill (Mumme *et al.* 2000) and barrier effect (Shepard *et al.* 2008),

244   the impact of roads was relatively weak in our niche model (Table 2). It is likely that a greater part

245   of occurrence records were sampled in more easily accessible sites in proximity to roads (Figure

246   1), and such a sampling bias had decreased the importance of roads disturbance in the model.

247   Despite the sampling bias towards roads, we found an relation that habitat suitability increased

248   with increasing distance from roads in the niche model predictions (Figure 2 d). As an explanation,

249   we suggest that our predictive habitat suitability was more sensitive to bioclimatic conditions than

250   to human disturbance; sites with bioclimatic conditions preferred by the Chinese monal might be

251   infrequently crossed by roads.

252   The predicted suitable habitats for the Chinese monal were highly fragmented. Specialized niche

253   requirements (i.e. narrow climate preferences) constrained their suitable habitats to subalpine and

254   alpine regions. High mountain ridges and deep valleys throughout the Qionglai Mountains

255   separated the suitable haibtats into small and isolated patches, especially for those distributed in

256   the north of Lixian County, south of Baoxing County, and the boundary area of Lixian-Xiaojin-

257   Wenchuan County (Figure 3). As a strong disturbance, human residential areas further restricted

258   and separated the suitable habitats. The fragmentation might have negative effects on the Chinese

259   monal, which has low dispersal ability (With and Crist 1995), reducing the probability of genetic

260   exchange (Höglund *et al.* 2011) and colonizing suitable empty patches (Stamps *et al.* 1987) by

261   increasing the resistance to individual movement between isolated habitat patches.

262   Many subalpine meadows within the Qionglai Mountains are summer pasture for the grazing

263   yaks. Grazing could lead to direct disturbance, accelerating habitat degradation and fragmentation,

264   and increasing the probability of poaching (Lu *et al.* 1986, Ma 1988, Long *et al.* 1998).

265   Additionally, gathering of herbs for use in traditional Chinese medicine in spring and summer,

266   especially the collection of *Fritillaria* spp., an important food source of the Chinese monal, could

267   result in a reduction of food abundance and thus a direct disturbance to the Chinese monal (Fuller

268   2000, Lu 2015). Our study, however, failed to incorporate these remarkable local threats into

269   modeling due to the lack of data. If grazing and herb gathering are considered, the actual suitable

270   monal habitat might be even smaller, more fragmented, and more variable than our prediction.

271   Our results raise concerns for the status of the Chinese monal in the Qionglai Mountains, and

272   the species may be at greater risk than has previously been considered. As a typical high-montane

273   species with large home range, the Chinese monal has the potential to serve as an umbrella or

274   flagship species for high-montane ecosystems. Conservation of these ecosystems will likely

275   contribute to the maintenance of regional biodiversity, at least for the montane Galliformes

276   (Roberge and Angelstam 2004, Rowland *et al.* 2006, McGowan *et al.* 2009). Based on our results,

277   we have several conservation suggestions targeting the Chinese monal. Our prediction could guide

278   future field surveys for locating new populations in the areas that were predicted to be suitable

279   habitat but lack investigation (Raxworthy *et al.* 2003, Menon *et al.* 2010). The large and well-

280   connected habitat patches distributed in the boundary area of Wenchuan, Baoxing, Lushan, and

281   Dayi County appear to provide ideal and important habitats for the Chinese monal and should be

282   treated as a priority area for conservation. However, a large portion stretching along the northern

283   boundary of Baoxing County is unprotected by any nature reserves and lacks systematic survey

284   (Figure 3). Similarly, large ribbon-like patches of suitable habitats in northeast of Lixian County

285   and north of Wenchuan County was also lacking protection and survey (Figure 3). Our first

286   suggestion, therefore, is to conduct ad hoc surveys for determining the actual occurrence of

287   Chinese monal in these two areas. If there are indeed some populations in these two regions, we

288   suggest that new nature reserves should be designated in order to fill these two obvious

289   conservation gaps. The second suggestion is to study the dispersal capacity of the Chinese monal

290   for further assessing habitat quality and fragmentation. Such ecological knowledge could be

291   helpful for determining the actual distribution of animals in relation to the distribution of suitable

292   environmental habitats (Pulliam 2000, Lu *et al.* 2012). For instance, it will be useful to determine

293   whether the Zagunao river valley is a geographic barrier that Chinese monals cannot cross through,

294   and whether gene flow can occur between the monal populations isolated in the south and north

295   of Baoxing County (Figure 3).

296   Although human disturbance appeared to be a crucial pressure for Chinese monals (He *et al.*

297   1986), we found that Chinese monals did not respond avoiding roads. For instance, during our

298   survey at Wenchuan in 2015, we observed that two Chinese monal pairs, almost at a daily bases,

299   crossed provincial road 303 through the top of the Huayan tunnel (E102°58′, N30°51′; Figure 1),

300   a well-known location for shooting Chinese monal among wildlife photographers. Huayan tunnel

301   has a length of 570 m, and the large area of natural shrub and meadow preserved on its top serves

302   as a corridor for the monals. However, this does not mean that roads are not a significant threat for

303   the species, as road-kill of Galliformes are not uncommon (Clevenger *et al.* 2003, D'Amico *et al.*

304   2015). Our third suggestion, therefore, is to build more corridors and green bridges across roads

305   to facilitate road-crossing or dispersal by Chinese monals.

306   For the purpose of 'game food', Chinese monals had been often poached by local people before

307   1980s, which was considered as the main cause of a substantial decline of the species (He *et al*.

308   1986, Lu *et al*. 1986, Long *et al*. 1998, Lei and Lu 2006). Unfortunately, we found self-made traps

309   for capturing monals and other Galliformes during our surveys, both inside and outside nature

310   reserves, suggesting that poaching is still continuing nowadays. Even though we found little

311   evidence of human impact on monal habitat distribution, our field observation suggested that

312   illegal hunting potentially threaten survival of the Chinese monals and their sympatric Galliform

313   species. Moreover, other short-term and seasonal local disturbance such as yak grazing and herb

314   collection could increase the probability of poaching (Lu *et al*. 1986, Ma 1988, Long *et al*. 1998).

315   Therefore, our fourth suggestion is to limit local disturbances, such as poaching, yak grazing, and

316   herb collection, for maintaining existing populations and habitats of the Chinese monal as well as

317   other montane Galliformes.

318   **CONCLUSION**

319   This study used the ecological niche modeling approach to predict current suitable habitat of the

320   Chinese monal in Qionglai Mountains. Their suitable habitat was associated with about 31 mm

321   precipitation of the driest quarter, about 15 ℃ of maximum temperature of the warmest month,

322   and far from the nearest human residential locations (> 5,000 m). The predicted suitable habitats

323   of the Chinese monal was highly fragmented covering an area of 2,490 km^2. 54.78% of suitable

324   habitat was under the protection of existing nature reserve network, but there were obvious

325   conservation gaps as two regions with large area of well-connected suitable habitat were out of

326   any nature reserve. Finally, this study provide conservation management suggestions in terms of

327   ad hoc surveys targeting potential suitable habitats to determine occurrence of Chinese monals,

328   more ecological studies regarding its dispersal capacity, establishment of more corridors and green

329   bridges across roads in suitable habitats and limitation of local disturbances such as poaching, yak

330   grazing, and herb collection.

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524   **Table 1. Sources of Chinese monal presence data in the Qionglai Mountains used in the**

525   **suitable habitat modeling.**

Source	Elevational range and area of survey site	Survey technique and effort	Survey time	Used/total presence points
Global Biodiversity Information Facility (http://www.gbif.org/)	Network database	Bird-watching records	2005-2015	2/7
Shen *et al.* 2010	3,300-4,170 m; 35 km²	Published literature	Apr-Nov, 2007-2010	7/7
Comprehensive scientific survey on Anzihe Nature Reserve	1,638-3,868 m; 110 km²	Line transect; 29 3-4.9 km transects	Apr-Oct, 2010	3/3
Comprehensive scientific survey on Fengtongzhai National Nature Reserve	1,000-4,896 m; 403 km²	Line transect; 38 2-5 km transects	May-Oct, 2010-2011	15/28
Sympatric animal database of the fourth national survey on giant panda	1,000-4,400 m; 8,740 km²	Grid square; 4,370 2 km² squares	Mar-Dec, 2012-2013	22/24
Infrared-triggered camera monitoring in Heishuihe Nature Reserve	1,520-4,234 m; 234 km²	Infrared-triggered camera; 70 cameras	All year round, 2013-2014	5/15
Infrared-triggered camera	1,500-4,500 m; 170	Infrared-triggered	All year	4/5

monitoring in Labahe Nature Reserve	km^2	camera; 30 cameras	round, 2014-2015	
Montane bird survey in Wolong National Nature Reserve	3,600-4,400 m; 17 km^2	Line transect; 7 2-6 km transects	Jun-Jul, 2015	6/14

526

527 **Table 2. Relative importance of environmental variables in the habitat suitability model of**

528 **the Chinese monal**

529 Note: bioclim17: precipitation of the driest quarter, bioclim5: maximum temperature of the

530 warmest month, d_resident: distance to residential location, evi base value: annual base level value

531 of EVI, evi maximum: annual maximum EVI, d_road: distance to roads.

Variables	Percent contribution[a]	Jackknife of AUC[b]
bioclim17	36.2	0.856
bioclim5	31.0	0.840
d_resident	10.5	0.771
evi base level	8.8	0.689
evi maximum	6.0	0.683
slope	4.8	0.631
d_road	2.7	0.642

532 [a] The relative contribution of each variable to predictive model, shown as mean value of 20

533 replicates.

534 [b] Jackknife test of variable importance, expressed as AUC (area under the receiver operating

535 characteristic curve) for models using each variable alone. A higher gain indicates a variable with

536 more information for modelling when used in isolation, shown as mean value of 20 replicates.

537 **Table 3. Estimates of suitable habitat areas of the Chinese monal distributed in counties**

538 **within the Qionglai Mountains**

County	County area (km^2)	Suitable habitat area (km^2)	Proportion of suitable habitat (%)
Wenchuan[a]	3,589	852	23.74
Baoxing	3,124	544	17.41
Lixian	4,325	401	9.27
Xiaojin	5,568	235	4.22
Lushan	1,259	159	12.60
Tianquan	2,390	150	6.28
Dayi	1,207	80	6.63
Kangding[b]	1,666	37	2.22
Chongzhou[a]	803	19	2.37
Luding[b]	647	13	2.00
Qionglai	1,377	0	0
Dujiangyan[a]	303	0	0
Total	26,258	2,490	9.48

539 [a] Wenchuan, Dujiangyan and Chongzhou described here are only their west parts of Min River.

540 [b] Kangding and Luding described here are only their east parts of Dadu River.

541 **Table 4. Estimates of suitable habitat areas of the Chinese monal in nature reserves**

Nature reserve	Reserve area (km²)	Suitable habitat area (km²)	Proportion of suitable habitat (%)
Wolong	2,124	585	27.54
Miyaluo	1,951	181	9.28
Heishuihe	325	146	44.92
Siguniangshan	583	131	22.47
Caopo	517	128	24.76
Fengtongzhai	403	111	27.54
Labahe	239	69	28.87
Anzihe	110	18	16.36
Jintangkongyu	242	0	0
Zhailong	204	0	0
Total	6,698	1364	20.36

543 **Figure 1. Topographic map of the Qionglai Mountains, showing the location of the 64**
544 **presence points of the Chinese monal used in modeling**
545 **The black triangle shows the location of Huayan tunnel at which we observed monals**
546 **crossing the road daily (detailed in Discussion). The geographic range of Chinese monal was**
547 **delineated based on Lu (2015).**

Figure legend (within map):

Presence points
Main rivers
Major roads
Counties
Elevation
≤ 1,000
1,001 - 2,000
2,001 - 3,000
3,001 - 4,000
4,001 - 5,000
≥ 5,001

Study area
Provinces
Geographic range of Chinese monal

548

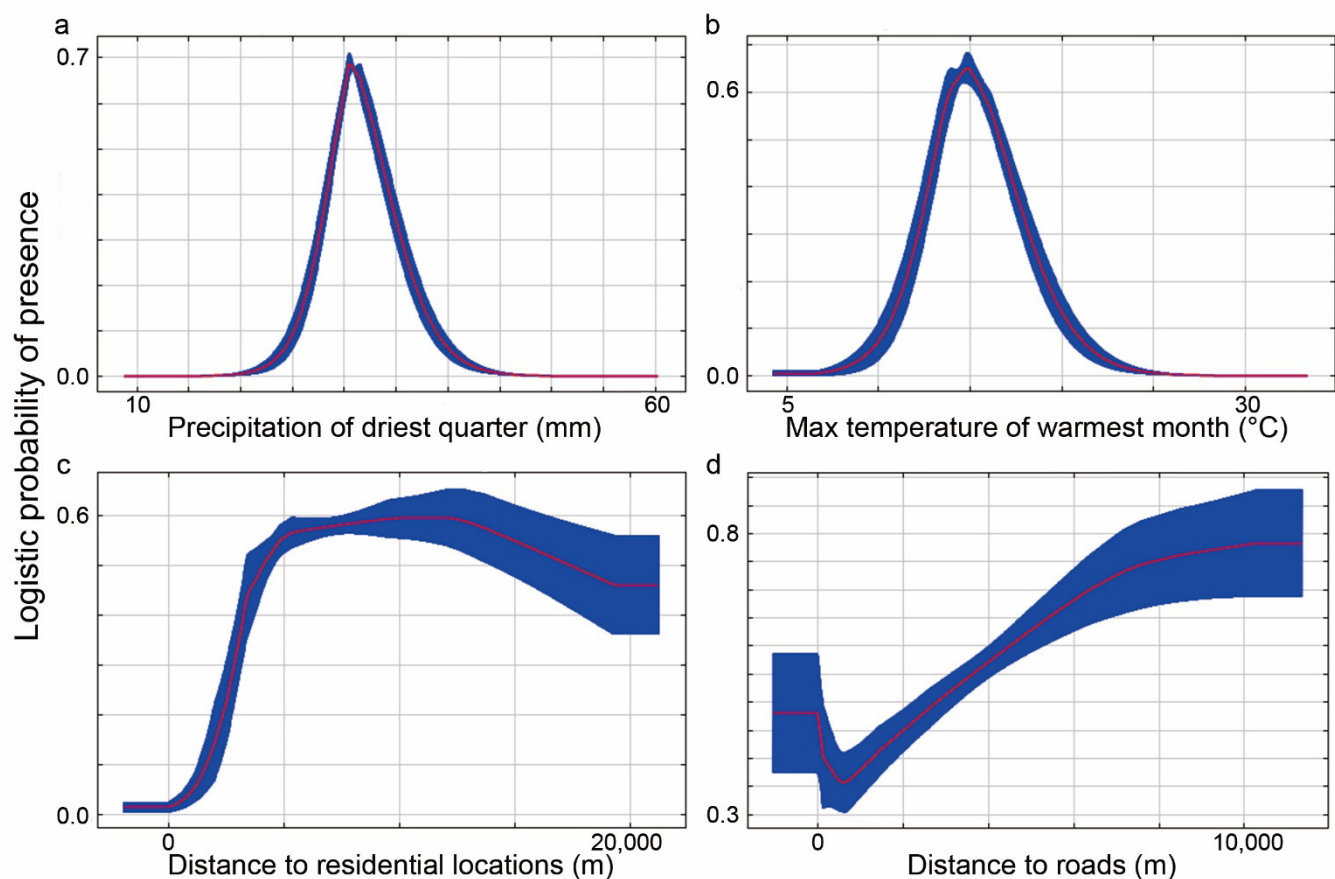
549 **Figure 2. Response curves of habitat suitability for the Chinese monal (vertical axis) to the**

550 **precipitation of the driest quarter (a), maximum temperature of the warmest month (b),**

551 **distance to residential locations (c), and distance to roads (d).**

552 **The red lines illustrate the mean responses of 20 replicates and the blue shades showed the**

553 **+/- standard deviation.**

554

555 **Figure 3. Predicted suitable habitat for the Chinese monal and existing nature reserves in**
556 **the Qionglai Mountains**
557 **The geographic range of Chinese monal was delineated based on Lu (2015).**

558