Xuezhi Wang · Weihua Xu · Zhiyun Ouyang

Integrating population size analysis into habitat suitability assessment: implications for giant panda conservation in the Minshan Mountains, China

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Abstract Compared to conventional approaches, the integration of population size analysis with habitat suitability assessment on a large scale can provide more evidence to explain the mechanisms of habitat isolation and fragmentation, and thus make regional conservation plans. In this paper, we analyzed the habitat suitability for giant pandas in the Minshan Mountains, China, using the ecological-niche factor analysis (ENFA) method, and then evaluated the current conservation status of this endangered species. The results showed that (1) giant pandas were distributed in a narrow altitudinal range in which vegetation cover was dominated by coniferous forest, mixed coniferous and deciduous broadleaf forest, and deciduous broadleaf forest with scattered bamboo understory, and (2) roads and human settlements had strong negative effects on the panda habitat selection. According to habitat analysis, the total habitat area of giant panda in the Minshan Mountains was 953,173 ha, which was fragmented into 12 habitat units by major roads, rivers, and human settlements. The habitat of the mid-Minshan was less fragmented, but was seriously fragmented in the north. The panda population size estimation showed that 676 individuals inhabited the study area, and 94.53% of them were in the mid-Minshan, but small panda populations less than 30 individuals inhabited the isolated and fragmented habitat patches in the north. The nature reserves in the Minshan Mountains have formed three conservation groups, which covered 41.26% of panda habitat and protected 70.71% of panda population of the study area, but there still exists two conservation gaps, and the connectivity among these reserves is still weak. Due

to habitat isolation and extensive human disturbances, giant pandas in the north (i.e., Diebu, Zhouqu, and Wudou) are facing threats of local extinction. In order to protect pandas and their habitats in this area, some effective conservation approaches, such as establishing new reserves in gap areas, creating corridors among patches, and seasonally controlling traffic flux in key roads, should be implemented in the future to link these isolated habitats together.

Keywords Giant panda (*Ailuropoda melanoleuca*) · Ecological-niche factor analysis · Habitat suitability · Population size · The Minshan Mountains · Nature reserves

Introduction

Giant panda populations historically extended throughout most of southern and eastern China, northern Myanmar, and northern Vietnam, but habitat loss from deforestation during the 19th and 20th centuries rapidly reduced their numbers and distribution area (Schaller et al. 1985). Currently, their distribution range is reduced to approximately 24 isolated populations across six rugged mountain ranges of the eastern edge of the Qinghai-Tibetan Plateau in the provinces of Gansu, Shaanxi, and Sichuan, western China (SAFC 2006). Among their six major distribution areas, the Minshan Mountains is the largest and has nearly half of the entire wild giant panda populations. Although the total number of giant pandas has recently increased (SAFC 2006), their habitat is still seriously discontinuous and fragmented. If habitat fragmentation and population isolation continues, the long-term viability of the species will be significantly threatened because of inbreeding depression (Lu et al. 2001).

The habitat degradation and fragmentation of the giant panda has aroused many researchers' attention. Since the late 1970s, systematic research has been

X. Wang · W. Xu · Z. Ouyang (✉)
State Key Laboratory of Urban and Regional Ecology,
Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences, 2871, Beijing 100085, China
E-mail: zyouyang@rcees.ac.cn
Tel.: +86-10-62849191
Fax: +86-10-62943822

conducted on giant pandas, including studies on behavior ecology (Schaller et al. 1985; Reid et al. 1991), habitat requirements (Ouyang et al. 2002; Bearer et al. 2008), and habitat assessments (Liu et al. 1999, 2001; Loucks et al. 2003; Linderman et al. 2004, 2005; Xu et al. 2006a, 2006b; Viña et al. 2007) from the scale of individual nature reserves to the entire mountains. These studies have revealed that systematic research on giant panda habitat on a large scale is necessary to explain the mechanisms of habitat isolation and fragmentation (Loucks et al. 2003; Xu et al. 2006a). In such mechanisms, explanation of information about population size for each isolated patch is necessary, which will contribute to the actual regional conservation plan and habitat management for the conservation of the endangered species (Reed et al. 2002; Carlos et al. 2003). The current giant panda population was isolated into several sub-populations, and previous studies have found that a small panda population of less than 30 individuals in an isolated habitat has a high risk of local extinction because of low breeding efficiency and inbreeding depression (Wang et al. 2002). However, due to the lack of detailed information on giant panda distribution, most previous analysis focused on parts of the Minshan Mountains (Xiao et al. 2004; Wang et al. 2008), which cannot analyze the viabilities of giant panda populations in isolated habitat units. Therefore, an integrated study of population size analysis and habitat suitability assessment at the entire mountains scale is required for comprehensive conservation of the wild giant panda population.

With the advances in computer tools such as the geographic information system (GIS), remote sensing (RS), and statistical modeling techniques, predictions of species geographic distribution based on environmental conditions have gained much attention in ecology, and have been widely applied to habitat prediction (Li et al. 1997; Hirzel et al. 2002; Reutter et al. 2003) and habitat evaluation (Liu et al. 1999, 2001; Hirzel et al. 2004; Xu et al. 2006a; Sattler et al. 2007; Wang et al. 2008). Among some commonly employed statistical techniques, multiple regression models (e.g., generalized linear model [GLM] and generalized additive model [GAM]), which require both “presence” and “absence” data of species for model calculation, showed robust performances for interpreting species distributions (Hirzel et al. 2001, 2002). However, sometimes these methods are not useful in habitat modeling of large mammals due to the lack of reliable or meaningful “absence” data (Reutter et al. 2003). The niche-based habitat modeling, including ecological-niche factor analysis [ENFA] (Hirzel et al. 2002), maximum entropy modeling [MaxEnt] (Phillips et al. 2006) and DesktopGarp (Stockwell and Peters 1999) require only “presence” data of species during the process of model calculation. Such modeling is recommended when “absence” data is not available or is unreliable (Hirzel et al. 2002). Among these niche models, the ENFA model had gained wide application in many fields for its robust prediction power and the

ability to explain species niche requirements (Reutter et al. 2003; Soares and Brito 2007; Sattler et al. 2007; Viña et al. 2008; Wang et al. 2008).

In this paper, we applied ENFA model to build the habitat suitability map for the giant panda in the Minshan Mountains, and then evaluated the status of habitat and the panda population size in each isolated habitat unit of the entire mountains. The main objectives of this paper were: (1) to evaluate current habitat distribution and fragmentation; (2) to assess conservation status and population viability of each habitat unit; and (3) to identify conservation gaps and to present some conservation suggestions.

Methods

Study area

The Minshan Mountains are between Sichuan and Gansu Provinces, in southwest China (31°24′–34.34°N and 102°38′–105°64′E; Fig. 1). Situated northwest of Sichuan Basin and east of the Qinghai-Tibetan Plateau, this area is characterized by high mountains and deep valleys, with elevations between 496 and 5,561 m. In addition to the altitudinal gradient, there are enormous variations in topography, soils, climatology, and hydrology that produce the diverse flora and fauna, including a number of threatened species such as *Ailuropoda melanoleuca*, *Rhinopithecus roxellanae*, *Budorcas taxicolor*, *Davidia involucre*, and *Taxus celebica*. The Minshan Mountains are divided into several patches by four large rivers (Fig. 1), which are branches of the Yangtze River. The giant panda populations in Qionglai and Minshan Mountains are blocked by the Minjiang River. In the Minshan Mountains, Diebu is the northernmost county pandas inhabit, and Ruogai is the westernmost one. The climate in the east of the Minshan Mountains is north sub-tropical monsoon, and in the west (including the west of Ruogai, Songpan, and Maoxian) is Tibetan plateau monsoon.

Presence data collection and population estimation

Because individual giant pandas are difficult to be found in the field, fecal droppings and feeding remnants were taken as straightforward indicators for the “presence” of pandas during the field survey (Schaller et al. 1985; Viña et al. 2007). These “presence” points were acquired from the wild panda population surveys which were conducted across the Minshan Mountains using the transect-line sample method during the summers of 1999–2002 (SAFC 2006). A total of 2,280 panda “presence” points in the study area were collected and used in the ENFA model calculation. The number of panda individuals was calculated using the bamboo stem-fragment distinguishing method, which is the most effective way to

Fig. 1 The location and topography of the Minshan Mountains, China

survey giant panda populations in wild (Yin et al. 2005; Zhang et al. 2005). This method for distinguishing individuals is based on the evidence that the average intact stem length of consumed bamboo in the feces of pandas differs between age classes. The statistical analysis of stem lengths can differentiate individuals and estimate the population size when combined with home range estimation. In total, 674 panda individuals were identified using this method (SAFC 2006) in the study area.

Habitat modeling

A habitat suitability map for giant pandas was produced using the ENFA model, whose principle is to compare the distributions of environmental predictors between the “presence” data sets and the data sets of the whole study area. Similar to principal component analysis, ENFA summarizes all predictors from eco-geographical variables (EGVs) into several uncorrelated factors retaining most of the information (Hirzel et al. 2002). The first column of eigenvectors is termed “marginality”, which maximizes the multivariate distance of EGVs between cells occupied by species and cells within the whole study area. The marginality coefficients range from -1.0 to 1.0 and the positive values indicate that the focal species prefers values higher than the mean of the whole area, while the negative values indicate preference for lower-than-mean values. The higher the absolute value of marginality is, the larger the species departs from the mean available habitat. The second and

subsequent columns are termed “specialization”, which accounts for how restricted the species niche is compared to the available habitat. Eigenvectors and eigenvalues were used to build the habitat suitability map.

Besides panda “presence” points, bio-geographical factors and human disturbance factors were also included in the ENFA model calculation. Bio-geographical factors include elevation, slope, aspect, vegetation, bamboo, and water sources, all of which affect giant panda habitat selection. The human disturbance factors include roads, residential areas, and croplands. Some human disturbances (such as herding, herb collection, and mining) that affect panda habitat selection (SAFC 2006) were not considered in this study because they are seasonal in some local areas and cannot be interpreted in a large-scale habitat modeling. The bamboo distribution map was from the third national giant panda survey (SAFC 2006). The elevation, slope, and aspect were calculated from the digital elevation map (DEM, 1:50,000). The vegetation types and croplands were derived from the supervised classification of Landsat-TM images (acquired on June 2001) using Erdas Imagine 9.0. The vegetation was classified into seven types: barren land, alpine meadow, coniferous forest, mixed coniferous and deciduous broadleaf forest, deciduous broadleaf forest, shrubs, and croplands.

Topographical data (i.e., altitude, slope, and aspect) were quantitative and used directly in ENFA model, but land-cover and human disturbance factors were qualitative and were transformed into frequency and distance variables before calculation (Hirzel et al. 2002). Frequency variables described the proportion of cells from a

given category within a circle of 1,380 m (23 pixels) radius around the focal cell. This radius reflected the home range size of the giant panda, which is 3–6 km² depending on the season (Schaller et al. 1985). Because panda “presence” points were collected in summer, we chose the largest home range size of 6 km² in summer as the circle’s area. Distance variables expressed the distance between the focal cell and the closest cell belonging to a given category. The distances variables were calculated in ArcGis 9.0.

After the transformation of environmental factors, we obtained 24 EGVs (Table 1). EGVs and “presence” points were converted to raster grids (60 × 60 m per pixel) that were normalized through Box–Cox (Hirzel et al. 2002) transformations. Model analysis was performed in BioMapper 3.2 (Hirzel et al. 2006) with a geometric-mean distance algorithm, which provides a good generalization of the niche (Hirzel and Arlettaz 2003).

Model evaluation and reclassification

Model accuracy was evaluated through the Jake–Knife cross-validation (Fielding and Bell 1997). “Presence” points were partitioned into ten subsets of equal size, and nine of them were used to calibrate the habitat suitability map and the remaining one to evaluate the result. The absolute validation index (AVI) and contrast

validation index (CVI) were introduced into the model validation. AVI was defined as the ratio of predicted suitability index exceeding 0.5 of the validation cells, while CVI explained how well the model discriminates poor from good habitat. By replicating this process ten times, each subset was used in turn for validation. The means and standard deviations of the validation indices were calculated for modal validation.

According to MacArthur’s broken-stick distribution (Hirzel et al. 2002), the first five ENFA factors (Table 1) were selected for mapping the habitat suitability. Values of habitat suitability index (HSI) were 0–1, in which 0 means the least suitable habitat, and 1 the most suitable. By overlapping the habitat suitability map with the vegetation and human factor maps, a criterion for habitat classification was established as follows: (1) HSI < 0.1: these areas were mostly roads, human settlements, farmlands and barren land, and were not suitable for the giant panda; (2) 0.1 ≤ HSI < 0.4: these areas were mainly alpine meadows or zones of low elevation (< 2,000 m) dominated by shrubs. Giant panda could seasonally occur here but they were not very suitable areas; and (3) HSI ≥ 0.4: these areas were vegetative covered with coniferous forests, mixed coniferous and deciduous broadleaf forests, and deciduous broadleaf forests, and were suitable for the giant panda. In accordance with this criterion, the habitat was reclassified into three habitat classes: 0–0.1 for unsuitable, 0.1–0.4 for marginally suitable, and 0.4–1.0 for suitable.

Table 1 The correlations between ENFA factors and EGVs for giant panda

EGVs	Factor 1 (36%)	Factor 2 (20%)	Factor 3 (7%)	Factor 4 (7%)	Factor 5 (5%)
Aspect	0	0	0	0	0
Distance to bamboo	— — — —	*	*	*	*
Bamboo frequency	+ + + +	*	*	*****	**
Distance to BF	—	0	**	*	***
Frequency of BF	+	**	0	0	*
Distance to CF	— —	*	**	**	***
Frequency of CF	+ +	*	*	*	**
Altitude	0	*****	**	*	*
Distance to croplands	+	*****	*****	*	*****
Distance to large rivers	+	0	*	0	0
Distance to alpine meadow	0	*	*	*	***
Alpine meadow frequency	—	*	*	*	0
Distance to MB	— — — —	*	***	*	*****
Frequency of MB	+ + + +	*	****	*****	***
Distance to major roads	+ +	0	0	0	0
Distance to villages	+ +	0	**	0	***
Distance to bareness land	+	**	****	*	0
Frequency of bareness land	— —	*	**	0	0
Distance to shrub	0	*	***	*	***
Shrub frequency	—	0	**	0	*
Slope	+	0	0	0	0
Distance to secondary roads	+ +	*	*	0	*
Distance to small rivers	0	0	*	0	0
Distance to towns	+	0	0	*	**

Notes: BF Deciduous broadleaf forest; CF Coniferous forest; MB Mixed coniferous and deciduous broadleaf forest. Factor 1 explained 100% of the marginality. The *percentages in parentheses* indicate the amount of specialization accounted for by the factor. The sign of “+” indicates that the species was found in locations with higher values than the average cell, and “—” indicates the opposite. The sign of “*” means the species occupied a narrower range of values than available. The greater the number of symbols, the higher the correlation; with 0 indicating a very weak correlation

Results

Ecological-niche factor analysis

A high global marginality value of 1.653 (global tolerance 0.411) indicated that giant pandas live in very particular habitat compared with the whole study area. Giant pandas preferentially inhabited a narrow altitudinal range close to the average (2,663 m) of the whole area, while slope and aspect were not significantly correlated with niche preference. For vegetation, giant pandas preferred habitats in forests comprising coniferous forest, mixed coniferous and deciduous broadleaf forest, and deciduous broadleaf forest, especially the mixed coniferous and deciduous broadleaf forest; meanwhile, they avoided shrubs, alpine meadow, and barren lands. The distribution of understory bamboo to some extent determined the distribution of the panda habitat. In addition, giant pandas avoided habitats with human disturbances. Major roads, secondary roads and human settlements had significant negative impacts on the distribution of giant pandas habitat (Table 1).

The first five ENFA factors (Table 1) were used to make the habitat suitability map, which explained 87.5% of information, accounted for 100% of marginality, and 74.9% of the total specialization. The cross-validation gave an average AVI of 0.506 (SD = 0.10) and an average CVI of 0.434 (SD = 0.09), and showed good prediction performance.

Habitat distribution

The total habitat area of giant pandas in the study area was 953,173 ha (with 54.10% being suitable habitat; Table 2). These habitats had been fragmented

into 12 habitat units (labeled A–L; Fig. 2) by rivers (Fig. 1), major roads, and other human activities along these roads (Fig. 2). Habitat units D, E, and F were the major panda distributive regions, where the habitat area was 244,920, 152,462, and 152,163 ha, respectively, which in total accounted for 57.65% of the entire habitat of the study area. The habitat fragmentation status in these units was also low, with the mean patch size of 170, 208, and 171 ha, respectively (Table 2). Unit A was a part of the habitat units of the Jiuding Mountains inhabited by 31 pandas. Due to the high traffic flow of provincial road P302 and strong influences from surrounding human settlements, this unit was entirely separated from unit D. The minimum distance between habitat units A and D was 6.1 km. Units B and C were separated from the Minshan Mountains by the Minjiang River and the national road N213. The habitat of units G–L in the north was seriously fragmented with the maximum mean patch size of less than 70 ha. These habitat units were separated from units D, E, and F by the Baishuihe River, provincial road P301, and national road N212.

Pandas among patches

About 676 pandas were identified by the third national panda survey in the study area. The habitat units of mid-Minshan (units D–F) had 639 pandas, accounting for 94.53% of the total population in the mountains. Unit A had 6 pandas which belong to the panda populations of Jiuding Mountains. Units G and J had 16 and 13 pandas, respectively, but they scattered in several habitat patches. Separated from the Minshan Mountains by national road N205 (Fig. 2) and Bailong River (Fig. 1), the habitat in unit I was fragmented into 3 isolated

Table 2 Habitat areas and pandas within different habitat units and nature reserves

Habitat units	Habitat area (ha)	Number of patches	Mean patch size (ha)	Suitable habitat		Habitat in reserves		Suitable habitat in reserves		Number of Total pandas	Pandas in reserves	
				Area (ha)	Ratio to habitat area (%)	Area (ha)	Ratio to habitat area (%)	Area (ha)	Ratio to suitable habitat area (%)		Number of Pandas	Ratio to total pandas (%)
A*	21,025	136	155	13,429	63.87	8,262	39.30	6,499	48.40	6	6	100.00
B	58,101	287	202	32,869	56.57	0	0.00	0	0.00	0	0	—
C	39,913	429	93	14,846	37.20	0	0.00	0	0.00	0	0	—
D	244,920	1,439	170	147,969	60.42	150,428	61.42	100,304	67.79	297	232	78.11
E	152,462	733	208	90,448	59.32	108,293	71.03	65,579	72.50	195	148	75.90
F	152,163	888	171	88,543	58.19	81,228	53.38	53,709	60.66	147	78	53.06
G	41,190	693	59	14,720	35.74	600	1.46	17	0.11	16	2	12.50
H	11,384	194	59	3,477	30.55	8,045	70.67	3,347	96.24	0	1	100.00
I	22,410	318	70	11,556	51.57	14,328	63.94	9,674	83.71	2	1	100.00
J	182,684	3,155	58	92,849	50.82	20,427	11.18	7,399	7.97	13	10	76.92
K	4,404	435	10	355	8.05	1,701	38.62	304	85.69	0	0	—
L	22,517	1,426	16	4,599	20.43	0	0.00	0	0.00	0	0	—
Total	953,173	10,133	94	515,659	54.10	393,313	41.26	246,831	47.87	676	478	70.71

Notes: * The number of pandas and habitat area of unit A is incomplete because it belongs to the Jiuding Mountains

Fig. 2 The habitat suitability map and road networks in the Minshan Mountains. The habitat units separated by roads and rivers in the Minshan Mountains are labeled A–L from bottom to top. Habitat unit A belongs to the Jiuding Mountains. C1 and C2 are county roads; P301, P302, P205, P206, and P313 are provincial roads; N213 and N205 are national highways

sub-patches with only two pandas found in the wild. Units B, C, H, K, and L had no pandas.

but they are completely isolated from other habitat patches.

Conservation status and gap analysis

Twenty-one nature reserves (Fig. 3) were established across the study area by the end of 2005, which covered 393,313 ha of habitat (about 41.26% of the total habitat; Table 2) and protected 478 pandas (about 70.71% of the total pandas; Table 2). Although these reserves formed three conservation groups (labeled R1, R2, and R3; Fig. 3), two conservation gaps (L1 and L2; Fig. 3) existed among these habitat units. Gap L1, crossed by the provincial road P205, is the potential connection area between Xiaohogou reserve and the other reserves in the main body of the Minshan Mountains. The conservation groups R1 and R2 are actually separated by Jiuzhaigou and Huanglong, which are not only nature reserves but are also national scenic heavily used for tourism. Being located between conservation groups R2 and R3, Gap L2 is outside of the nature reserves, and is seriously fragmented by Baishuihe River (Fig. 1), provincial road P301 (Fig. 2), and residential areas and croplands that surround it. Although most pandas in unit J were inside nature reserves, only 12% of habitat in the gap L2 was protected by nature reserves (Table 1). The habitat of unit I (Fig. 2) is protected by Jianshan (16; Fig. 3) and Baishuihe nature reserves (12; Fig. 3),

Discussion

In this study, the habitat suitability map was produced with the ENFA model, which is robust when the species occurrence data have asymmetrical distributions (Hirzel and Arlettaz 2003). This procedure was preferred for the habitat modeling of species with large home ranges (Hirzel et al. 2004), because it does not assume any distribution of the species occurrence, and it can attain a highest prediction success even if the spatial resolutions of data sources were coarse (Viña et al. 2008). Owing to data availability, the bamboo distribution map from the third national panda survey was used in the present study. This map might overestimate bamboo distribution since only field sample points and the limit elevation of each bamboo species were considered when producing the map (Linderman et al. 2004, 2005; SAFC 2006). The accuracy of the bamboo distribution map can be improved by combining detailed bamboo information through extensive field surveys in the future with sufficient financial support, which will further improve the model accuracy.

The panda “presence” data were derived from the third national giant panda survey in China, which is the

Fig. 3 The giant panda habitat suitability map and conservation groups in the Minshan Mountains. The names of the nature reserves are: 1 Qianfoshan; 2 Baodinggou; 3 Xiaozhaizigou; 4 Piankou; 5 Baiyang; 6 Xuebaoding; 7 Xiaohegou; 8 Tangjiahe; 9 Dongyanggou; 10 Baishuijiang; 11 Maozhai; 12 Yuhe; 13 Jianshan; 14 Huanglong; 15 Wanglang; 16 Jiuzhaigou; 17 Wujiao; 18 Baihe; 19 Baozuo; 20 Axia, and 21 Duoer. Regions marked *R1*, *R2*, and *R3* are conservation groups, and regions *L1* and *L2* are conservation gaps. Jiuzhaigou and Huanglong are national scenic areas with a large number of tourists visiting each year

most detailed and authoritative data of panda distribution at the whole-mountains scale. Based on these data sources, individual pandas were identified through the bamboo stem-fragment distinguishing method (Yin et al. 2005; Zhang et al. 2005; SAFC 2006). This method can satisfactorily estimate the giant panda populations (Zhang et al. 2005; Yin et al. 2005), but it may underestimate the population size because giant pandas often have overlapping home ranges and pandas of different age classes can produce similar bite sizes (Schaller et al. 1985). Although genetic methods can provide more accurate results for panda population estimation (Zhan et al. 2006), it is not feasible to collect enough fecal DNA samples in the entire mountains now. Therefore, the giant panda individuals we used in this study provide a coarse evaluation of the spatial distribution of panda population, rather than a definite or accurate panda numbers.

In this study, the ENFA results showed that panda avoided staying at habitats with human disturbances, especially roads and human settlements. The habitat in the Minshan Mountains was isolated into 12 habitat units by rivers, major roads, and human settlements. Although pandas can cross heterogeneous landscapes to meet daily needs (Yin et al. 2006), there is no direct evidence that pandas have successfully crossed barriers that had extensive human influences. To alleviate the influences from human activities, the Chinese government increased its commitment to giant panda habitat

protection, and has established 21 nature reserves in the study area by the end of 2005. These nature reserves have formed three conservation groups, which covered 41.26% of panda habitat and protected 70.71% of the panda population of the study area, but the connectivity among these habitats is still weak. A large conservation gap existed among nature reserves in Pingwu County, which were influenced by provincial roads P205 and C120 with high vehicle flux, and by the increasingly intensive production activities of surrounding Tibetan residents. Moreover, habitat in units G and J (Fig. 2) was seriously fragmented, and was not well protected by nature reserves. To provide enough spaces for giant panda migration among habitat patches, new nature reserves should be established in these two gap areas.

Genetic studies have revealed that the current giant panda populations have conserved enough genetic diversity (Lu et al. 2001) to not fall into an evolutionary “dead-end” (Zhang et al. 2007), but some populations in fragmented landscapes are still facing threats of local extinction. According to previous studies (Wang et al. 2002; Yin et al. 2006), the minimum size for an isolated panda population to remain stable is 30 mature individuals, the panda population in the habitat units D–F in the mid-Minshan was sufficient to maintain stabilization, but small panda populations less than 30 individuals inhabited the isolated and fragmented habitat patches in the north (i.e., units G–L), which indicated that giant pandas

in these units are facing threats of local extinction. Because of habitat fragmentation and low breeding efficiency, giant pandas have difficulties coping with climate change, natural disasters, and human disturbances. In addition, periodic bamboo-blooming (Reid et al. 1991; Carter et al. 1999) and high-magnitude earthquakes (Williams 2008) are serious threats to isolated panda populations.

Implications for conservation

The current giant panda habitat in the Minshan Mountains was seriously fragmented and isolated. In order to protect giant pandas and their habitats, some conservation approaches are necessary. First, new nature reserves should be established in conservation gaps we identified (i.e., L1 and L2; Fig. 3) in the Minshan Mountains. Second, corridors between Jianshan and Baishuihe nature reserves (Fig. 3) in the habitat unit G should be created to enable panda migration. Third, the daily number of vehicles passing on the key roads (i.e., roads P205, C120, P301, and P302; Fig. 2) should be seasonally controlled, so that pandas can travel between habitat patches. Finally, measures such as ecological compensation need to be carried out for improving local residents' livelihood, which will decrease the influence of human activity and improve the quality of giant panda habitats.

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