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Amphibian diversity and conservation along an elevational gradient on Mount Emei, southwestern China

[1,2]Xiaoyi Wang, [1,3]Shengnan Yang, [1,2]Chunpeng Guo, [1,2]Ke Tang, [1,*]Jianping Jiang, and [1,3,*]Junhua Hu

[1]*Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, CHINA* [2]*University of Chinese Academy of Sciences, Beijing 100049, CHINA* [3]*Key Laboratory of Southwest China Wildlife Resource Conservation (China West Normal University), Ministry of Education, Nanchong 637009, CHINA*

***Abstract.*—Understanding the diversity, distribution, and threat status of species serves an important role in biodiversity conservation, particularly in regions with high species richness. Being a well-known Natural and Cultural World Heritage site, Mount Emei is seated on the transition zone between Qinghai-Tibetan Plateau and Sichuan Basin in southwestern China, and is of special significance to conservation and science due to its high biodiversity. Based on data from extensive field expeditions, the published literature, and museum specimens, this study documented a total of 35 species, belonging to 22 genera and nine families, along a 2,600 m elevational gradient on Mount Emei. Almost one-third of these species are in IUCN threatened categories. A majority of species occupied a narrower local elevation range size compared with their overall elevation range size, especially those that are threatened. Along the elevational gradient, both the total and threatened species richness showed hump-shaped patterns. These results provide insight into the species diversity, elevational distribution, and threat status for the amphibians on Mount Emei. These findings highlight the significance and urgent need to protect the amphibians in the focal region, provide support for further ecological studies, and will contribute to the conservation of this biodiverse region in the future.**

Keywords. Anura, biodiversity, Caudata, hump-shaped pattern, species richness, threatened species, World Heritage site

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Introduction

Elevational gradients provide one of the most powerful natural experiments for exploring the ecological and evolutionary responses of biota to the complex influences of geophysical and climatic changes (Korner 2007). In mountain regions, elevational gradients yield a large amount of environmental variation (e.g., in temperature and humidity) over a short spatial distance, and play a prominent role in shaping vertical species distribution (Korner 2007; Perrigo et al. 2019). Following in von Humboldt's footsteps, the importance of elevational gradients to biodiversity has motivated growing scientific interest in them over the last two centuries (Aynekulu et al. 2012; Frishkoff et al. 2019; Lomolino 2001). Along elevational gradients, a multitude of studies have focused on species diversity-elevation relationships across many different taxa worldwide (e.g., Frishkoff et al. 2019; Hu et al. 2011; Longino and Branstetter 2019; Peters et al. 2016; Quintero and Jetz 2018), often revealing monotonic decreasing, hump-shaped patterns or plateaus (Rahbek 2005). While varying degrees of evidence have supported different patterns, understanding the elevational patterns in biodiversity remains crucial for conservation in specific key biodiversity areas and in some taxa which are not well documented.

Among amphibians, the distribution range of a species is highly related to its adaptation to environmental variations and extinction risk (Chen et al. 2019; Cooper et al. 2008). Amphibians with a small geographic (e.g., latitudinal or elevational) range size may face higher extinction risk, since they are relatively less abundant, less mobile, and more easily influenced by local environment changes, compared with those with broad ranges (Botts et al. 2013; Chen et al. 2019; Cooper et al. 2008). Since each species has a unique ecological extension and environmental tolerance (Wells 2007), range size and its shifts along elevational gradients can be regarded as adaptive responses to environmental changes (Chen et al. 2009; Kusrini et al. 2017). Consequently, determining elevational range size

Correspondence. **jiangjp@cib.ac.cn* (JJ); *hujh@cib.ac.cn* (JH)

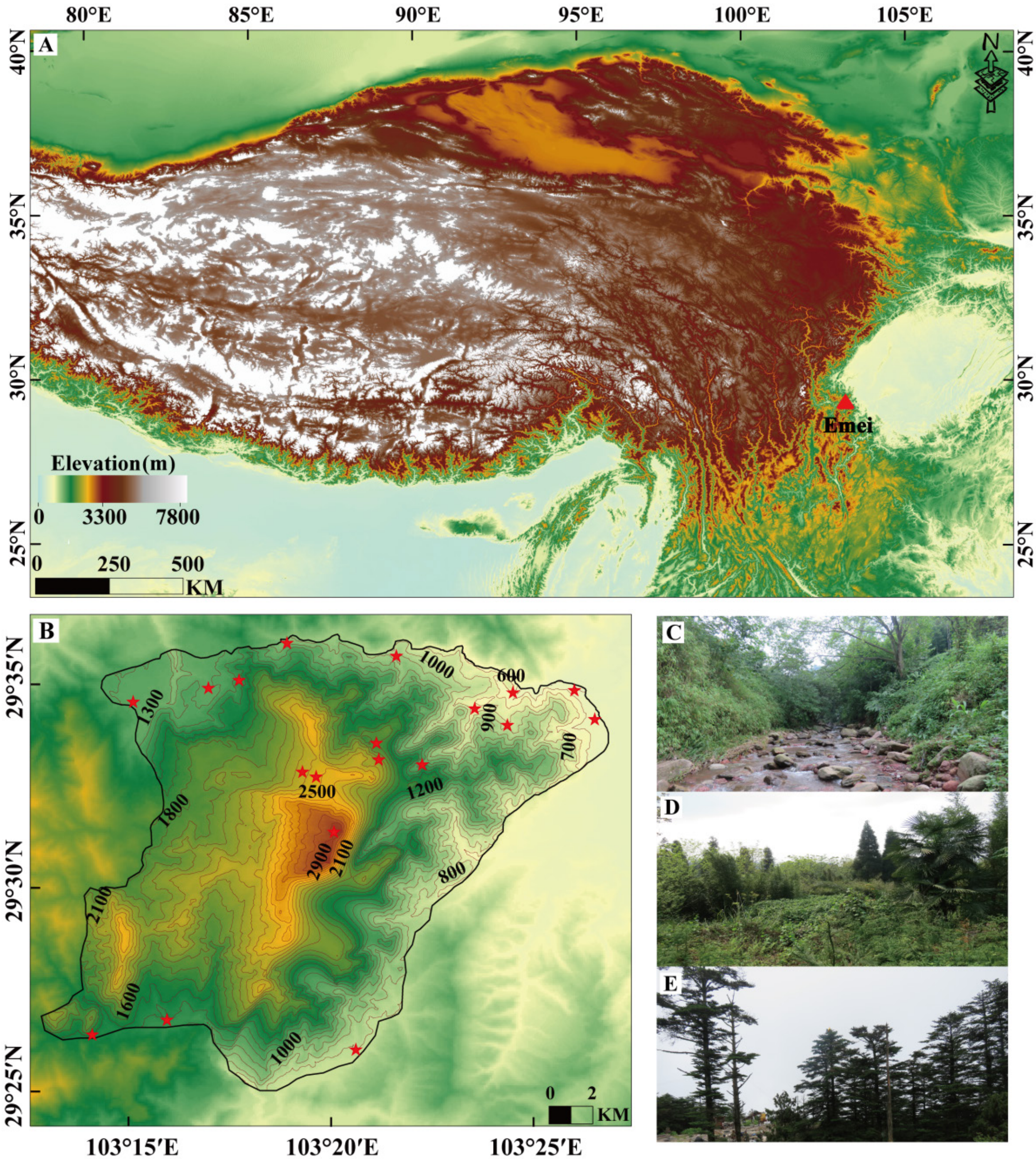

Fig. 1. (A) Geographic location of Mount Emei; **(B)** topographic overview of sample sites; and dominant vegetation types and typical habitats along the elevational gradient at **(C)** 500 m, **(D)** 1,300 m, and **(E)** 3,050 m. Sampling sites are indicated with red stars (see Appendix 1 for details).

under various environmental conditions is important for contributing to the conservation of amphibians with a narrow range (Chan et al. 2016).

Mount Emei (Omei Shan) is located in the transitional zone between the Sichuan Basin and Qinghai-Tibetan Plateau in southwestern China (Fig. 1A). It possesses various landscapes and a diversity of natural biological zones with high biodiversity (Li and Shi 2007; Zhao and Chen 1980). Mount Emei, together with the Leshan Giant Buddha Scenic Area, constitutes a Natural and Cultural World Heritage site due to the striking scenic beauty, and its exceptional spiritual and cultural significance in Chinese Buddhism (http://whc.unesco.org/en/list/779). In addition, the high biodiversity highlights its special significance to conservation and science (Zhao and Chen 1980). For amphibians, increasing attention has been paid to this region in the past several decades. Liu (1950) had conducted field surveys since 1938, and Fei et al.

(1976) roughly delineated the elevational distributions for 32 species. However, there were no scientific reports concerning amphibians on Mount Emei for nearly 40 years after these early studies, except for some scattered sightings and samplings. By recording 24 species, Zhao et al. (2018) recently documented the idiosyncratic contributions of individual species to the taxonomic, functional, and phylogenetic diversity on Mount Emei. While these studies presented different facets of diversity, efforts to provide a comprehensive inventory by integrating amphibian species diversity, distribution, and threat status on Mount Emei have remained severely limited.

This study aims to summarize and update data on amphibian species richness on Mount Emei, and also to delineate the distribution and threat status of each species based on extensive field expeditions, supplemented with data from the literature (Fei et al. 1976; Liu 1950; Zhao et al. 2018) and specimen records in the Herpetological Museum, Chengdu Institute of Biology (CIB), Chinese Academy of Sciences (CAS). This study will be helpful in the development of effective conservation strategies for the amphibians on Mount Emei and the surrounding areas.

Materials and Methods

Study Area

Mount Emei, a mountain in southwestern China which is known worldwide, was formed on the southwestern edge of Sichuan Basin, China, and dates from the late Cretaceous Period around 70 million years ago (Zhao and Chen 1980). From the base at about 500 m asl, the mountain rises to an altitude of 3,099 m (Fig. 1B). It is made up of deep canyons and narrow gorges (Tang 2006), which results in a variety of attractive landscapes and complex environments to support exceptionally rich flora and fauna (Li and Shi 2007; Zhao and Chen 1980). Mount Emei is characterized by a subtropical monsoon climate. The annual average temperature drops from 17 °C to 3 °C with the increasing elevation. The rainfall is abundant and concentrated during May–September, without a dry season (Tang 2006), and the highest rainfall occurs in the middle and high mountain areas (Li 1990).

The parent rocks in this region mainly include shale, dolomite, limestone, basalt, sandstone, and mudstone (Zhao and Chen 1980); and the following natural vertical soil zones have been described: yellow soil and mountain yellow soil sandwich a purple soil zone (below 1,800 m), mountain yellow-brown soil zone (1,800–2,200 m), mountain dark brown soil zone (2,200–2,600 m), and podzolic soil and meadow soil zone (above 2,600 m) [Li 1990; Tang 2006]. Additionally, Mount Emei is situated at the junction between the tropical and temperate zonation types in eastern Asia (Tang and Ohsawa 1997). There are three major vegetation types along the elevational gradient (from low to high): evergreen broad-leaved forest, evergreen deciduous broad-leaved mixed forest, and coniferous forest (Li and Shi 2007; Tang and Ohsawa 1997) [Fig. 1C–E].

Species Data

The field surveys included 23 line transects and three sampling points along the elevational gradient to comprehensively investigate the amphibian species composition on Mount Emei during the breeding seasons in 2017 and 2018 (Fig. 1B; Appendix 1). During the field surveys, line transects and sampling points were mainly placed near water resources according to habitat conditions, and locations were recorded by a global positioning system (GPS) app (Shenzhen 2bulu Information Technology Company). Observers (at least two persons) intensively searched for amphibians with an electric torch and searched systematically at a relatively steady pace (about 2.0 km h^{-1}) at night (1900–2400 h), with the locations of observed individuals being recorded by the GPS.

Complementary information was also collected from the literature (Fei et al. 1976; Liu 1950; Zhao et al. 2018), with useful information extracted on the taxonomy, species composition, and elevational distribution of amphibians. Species data were also supplemented with records from museum specimens in the CIB/CAS. The preserved specimen and recorded information were carefully authenticated and crosschecked, and records possibly representing missing species detections and/or misidentifications during sampling or secondary information compilation were removed. In total, there were 35 amphibian species scientifically recorded, with available elevation information for 34 of the species (all except *Amolops granulosus*).

Data Compilation and Analysis

Species nomenclature followed *Amphibian Species of the World* (Frost 2019). Referring to both the IUCN Red List (IUCN 2018) and the China Biodiversity Red List (MEP and CAS 2015), the threat status levels for each species were compared at the global and national scales. A database was generated with the species components, elevational distribution data (minimal and maximal elevations of occurrence), and threat status of each species.

The overall elevational range spanning 500–3,099 m was divided into 200 m band widths, and areas with elevation ranges between 500–1,299 m were defined as low elevations, ranges between 1,300–2,099 m as middle elevations, and ranges between 2,100–3,099 m as high elevations. For each species, the elevational distribution was assumed to cover a continuous range between the minimum and maximum documented elevations (Hu et al. 2011; Rahbek 1997). For example, a species with recorded elevation limits between 1,235 and 1,450 m can be classified into both the 1,100–1,299 m and 1,300–

1,499 m bands. Species richness was calculated from the total (cumulative) number in each band and each species' threat status was assessed for the different bands. In addition, three polynomial regressions (richness as a function of elevation, elevation^2, and elevation^3) were used to investigate the richness-elevation relationships for total species and threatened species (at both global and national scales) based on the smallest corrected Akaike information criterion (AICc) value.

Next, the overall range size (i.e., elevational range covering the whole distribution range of a species) was collected from the literature (Fei et al. 2006, 2009a,b, 2012) and the online database (*Amphibian Species of the World*, Frost 2019). Local elevational range size (maximal minus minimal elevation) observed on Mount Emei was plotted and compared with the overall range size for each species. The elevational range size values below the median value (i.e., 1,300 m) were considered "small," and they were considered "large" for those that were not less than the median.

Results

The 35 species belonged to 22 genera and nine families. Of special note, Mount Emei was the type locality of 14 species, including one endemic species (*Rana chevronta*; Table 1). At the family level, Megophryidae and Ranidae were the two most abundant families (each with 11 species) and they contributed approximately 63% of all amphibian species on this mountain; followed by Rhacophoridae (four species); Microhylidae, Dicroglossidae, and Hynobiidae (each with two species); and the other three families (Bufonidae, Hylidae, and Cryptobranchidae) were each represented by a single species (Table 1). According to the IUCN Red List, 13 of the 35 species were categorized as threatened, including two Critically Endangered (CR), five Endangered (EN), three Vulnerable (VU), and three Near Threatened (NT) species; while according to the China Biodiversity Red List, 16 of the 35 species were categorized as threatened, including one CR, three EN, nine VU, and three NT species (Table 1).

Along the elevational gradients, a cubic relationship was statistically favored over either a quadratic or linear relationship for the total species richness, while a quadratic relationship was favored over cubic or linear for the threatened species richness at the two scales (Fig. 2; Table 2). Both species richness and threatened species richness showed mid-elevation peak patterns (Fig. 2). Low and middle elevations (500–2,099 m) were found to harbor a majority of species with a maximum richness at the two elevational bands of 700–899 m and 1,500–1,699 m (Fig. 2). There was a sharp decrease between 1,900–2,099 m and 2,100–2,299 m, while species richness changed only slightly for elevations above 2,100 m (Fig. 2). Similar patterns were found for the threatened species, with a maximum in the band at 1,700–1,899 m (Fig. 2;

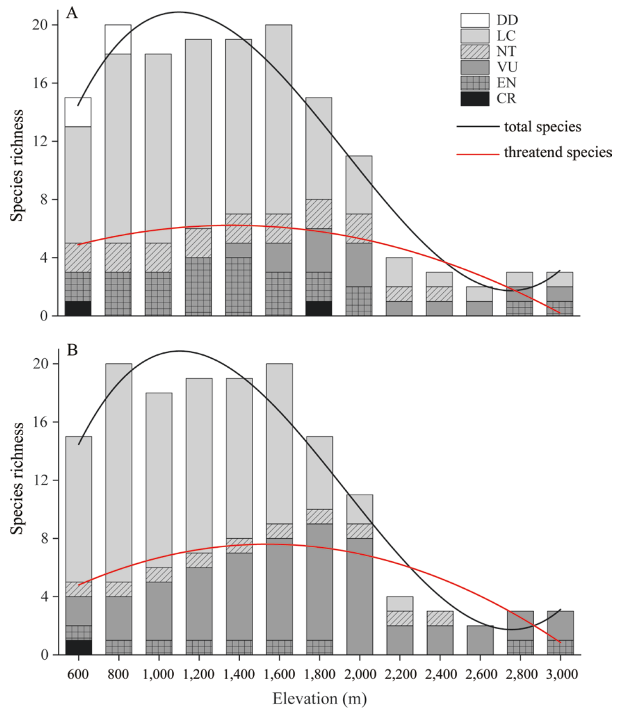

Fig. 2. The numbers of total and threatened species (bars) and elevational patterns of species richness (curves). Regression lines show total species richness (black) and threatened species richness (red) based on the polynomial regression models, with threatened status counts referring to the IUCN Red List **(A)** and the China Biodiversity Red List **(B)**.

Table 1). Referring to the IUCN Red List, 12 threatened species occurred in low and middle elevations, while three threatened species occurred in high elevations (Fig. 2A; Table 1); referring to the China Biodiversity Red List, 14 threatened species were in low and middle elevations, and four threatened species were in high elevations (Fig. 2B; Table 1).

Although the upper elevational limits of three species (i.e., *Scutiger chintingensis*, *Batrachuperus pinchonii,* and *Rhacophorus dugritei*) were higher than 3,000 m, and four species (i.e., *Xenophrys omeimontis*, *X. minor*, *Oreolalax omeimontis*, and *O. major*) were found to exceed the overall range size, 26 of the species have a small range size (< 1,300 m) on Mount Emei (Fig. 3; Table 1). In total, ten of the threatened species have a small range size on Mount Emei (Table 1). Notably, the Critically Endangered species (*Andrias davidianus*) and the endemic (*R. chevronta*) were each restricted to an extremely narrow range. The local range size was relatively wider than the overall range size for some of the threatened species (e.g., *B. londongensis*, *R. chevronta*, *O. omeimontis*), but the range size of these species were reasonably small (Fig. 3; Table 1).

Discussion

Knowing where the individual species occur and identifying which ones are threatened and their

Table 1. Amphibian species on Mount Emei, China, with their elevational distribution (minimal and maximal elevations of occurrence) and threat status.

Species	IUCN Red List	China Red List	Lower limit (m)	Upper limit (m)
I. Hynobiidae				
Batrachuperus londongensis[1]	EN	VU	1,200	1,400
Batrachuperus pinchonii	VU	VU	1,400	3,050
II. Cryptobranchidae				
Andrias davidianus	CR	CR	—	500
III. Megophryidae				
Oreolalax major[1]	VU	VU	1,500	2,000
Oreolalax schmidti[1]	NT	NT	1,580	2,340
Oreolalax multipunctatus[1]	VU	VU	1,800	1,920
Oreolalax omeimontis[1]	EN	VU	740	2,060
Oreolalax popei	LC	VU	950	2,010
Scutiger chintingensis[1]	EN	EN	2,890	3,050
Leptobrachium boringii[1]	EN	EN	650	1,650
Leptobrachella oshanensis[1]	LC	LC	760	1,810
Atympanophrys shapingensis	LC	LC	—	2,120
Xenophrys omeimontis[1]	NT	VU	610	1,920
Xenophrys minor	LC	LC	680	1,600
IV. Bufonidae				
Bufo gargarizans	LC	LC	500	1,910
V. Hylidae				
Hyla annectans	LC	LC	1,200	1,298
VI. Ranidae				
Rana chevronta[1,2]	CR	EN	1,750	1,850
Rana omeimontis[1]	LC	LC	500	2,080
Pelophylax nigromaculatus	NT	NT	500	1,300
Boulengerana guentheri	LC	LC	—	500
Nidirana daunchina[1]	LC	LC	750	1,660
Odorrana graminea	DD	LC	530	710
Odorrana schmackeri	LC	LC	530	790
Odorrana margaretae	LC	LC	500	1,810
Amolops chunganensis	LC	LC	720	1,600
Amolops granulosus	LC	NT	—	—
Amolops mantzorum	LC	LC	800	1,660
VII. Dicroglossidae				
Quasipaa boulengeri	EN	VU	500	1,900
Fejervarya multistriata	DD	LC	500	850
VIII. Rhacophoridae				
Polypedates megacephalus	LC	LC	740	1,600
Rhacophorus chenfui[1]	LC	LC	800	1,660
Rhacophorus omeimontis[1]	LC	LC	680	1,810
Rhacophorus dugritei	LC	VU	1,520	3,050
IX. Microhylidae				
Microhyla fissipes	LC	LC	500	530
Kaloula rugifera	LC	LC	700	900

[1]Species type locality is Mount Emei; [2]endemic species on Mount Emei. The threat status abbreviations refer to the IUCN Red List of Threatened Species and the China Biodiversity Red List: Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR).

Table 2. Results of polynomial regression models for assessing the total species and threatened species patterns along the elevational gradient.

Polynomial regressions	Total species richness	Threatened species (IUCN)	Threatened species (China)
First-order R^2	0.76***	0.22	0.39*
AICc	78.63	67.69	61.27
Second-order R^2	0.81***	**0.57***	**0.62****
AICc	79.90	**64.20**	**59.47**
Third-order R^2	**0.95*****	0.66*	0.70**
AICc	**68.64**	66.66	61.88

Tested effects were significant at: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Bold numbers indicate the models which best accounted for variation in the richness along the elevation gradient based on the smallest AICc value.

conservation status are critical for optimizing the conservation of species and communities in a given region. This study documented the species component, distribution, and threat status of amphibians along a 2,600 m elevational gradient on Mount Emei in China. Although Mount Emei is a Natural and Cultural World Heritage site with high richness in amphibians, their threat status is really severe overall, particularly since a majority of the species possess relatively narrow local range sizes. Taken together, these results can contribute to a better understanding and more effective conservation of the amphibian diversity on this mountain.

The higher amphibian diversity on Mount Emei documented in this study, relative to the published records in this region (Fei et al. 1976; Liu 1950; Zhao et al. 2018) and the neighboring regions (e.g., Mount Gongga and Mount Erlang; Xie et al. 2007), underlines its great significance in conservation and scientific studies. Megophryidae and Ranidae are the two most species-rich families, accounting for 63% of all species in the region (Table 1); and the extremely adaptable capacities and enhanced environmental tolerances of some species may contribute to the dominance of these two families (Fei et al., 2009a,b; Wells 2007). At the species level, the endemic species (*R. chevronta*) with a narrowly specified range is actually rare and threatened, and it should be urgently targeted for conservation (Hu et al. 2012). Although the data in this study were obtained from extensive field surveys combined with comprehensive data collection, the results provided here may be missing certain information. Anecdotal observations of *Odorrana hejiangensis* on Mount Emei have been reported (K. Jiang, pers. comm.), but they were not verified from any scientific publication or field expedition. Therefore, further surveys in the region are still necessary.

Elevation is often regarded as a surrogate for temperature and moisture, and is widely used to investigate distributional patterns of species richness in mountainous regions (Khatiwada et al. 2019; Peters et al. 2016; Rahbek 1995). Variations of climatic variables, land surface area, and geography along elevational gradients are among the hypothesized causal factors influencing species composition and distribution (Lomolino 2001). Amphibians, which tend to have complex life histories and relatively low mobility, are strongly restricted by the external environment (Hof et al. 2011; Wake and Vredenburg 2008). Climatic factors (mainly temperature and precipitation) are widely recognized as the key determinants that influence various aspects of amphibian biology, such as physiology, behavior, and ecological performance (Wells 2007). A habitat with a lower temperature and higher elevation is prone to support more species (Navas et al. 2013), and more abundant precipitation can support higher species richness and abundance (Rahbek 2005; Wells 2007). Under the influences of climatic, edaphic, and vegetation zones (Tang 2006; Tang and Ohsawa 1997), the vertical distribution pattern of amphibians on Mount Emei is obvious (Fig. 2). Indeed, low and middle elevations with higher temperatures (Tang 2006) and rainfall (Li 1990) are so suitable for amphibians that they support more species (Fig. 2). Additionally, it is well known that conserving a large number of species can provide the opportunity to conserve rare species and other undetected species (Aynekulu et al. 2012). That is, more conservation investment in the areas below 2,100 m on this mountain is needed because most of the amphibians and threatened species are restricted to the elevations below 2,100 m (Fig. 2). Even so, several species in high elevations (2,100–3,099 m) should also attract a great deal of attention because they can be considered as the indicators of environmental adaptation in the high elevations.

Range size is a critical factor that reflects the local assemblage structure (Gaston 1996) and a species' environmental niche (Pearson et al. 2006). It is recognized that species with different range sizes should be conserved with different strategies (Chen et al. 2019; Di Marco and Santini 2015). A small range size may be one of the strongest predictors of extinction risk (Chen et al. 2019; Rosenzweig 1995). In this study, some species have a larger local range size compared with the overall elevational range size but most species have a smaller local range size, especially among the threatened species (Fig. 3; Table 1). For instance, the range size is extremely narrow for *A. davidianus* (CR). Therefore, conservation priority should be given to these species with small range sizes (Chen et al. 2019). Range size can be influenced

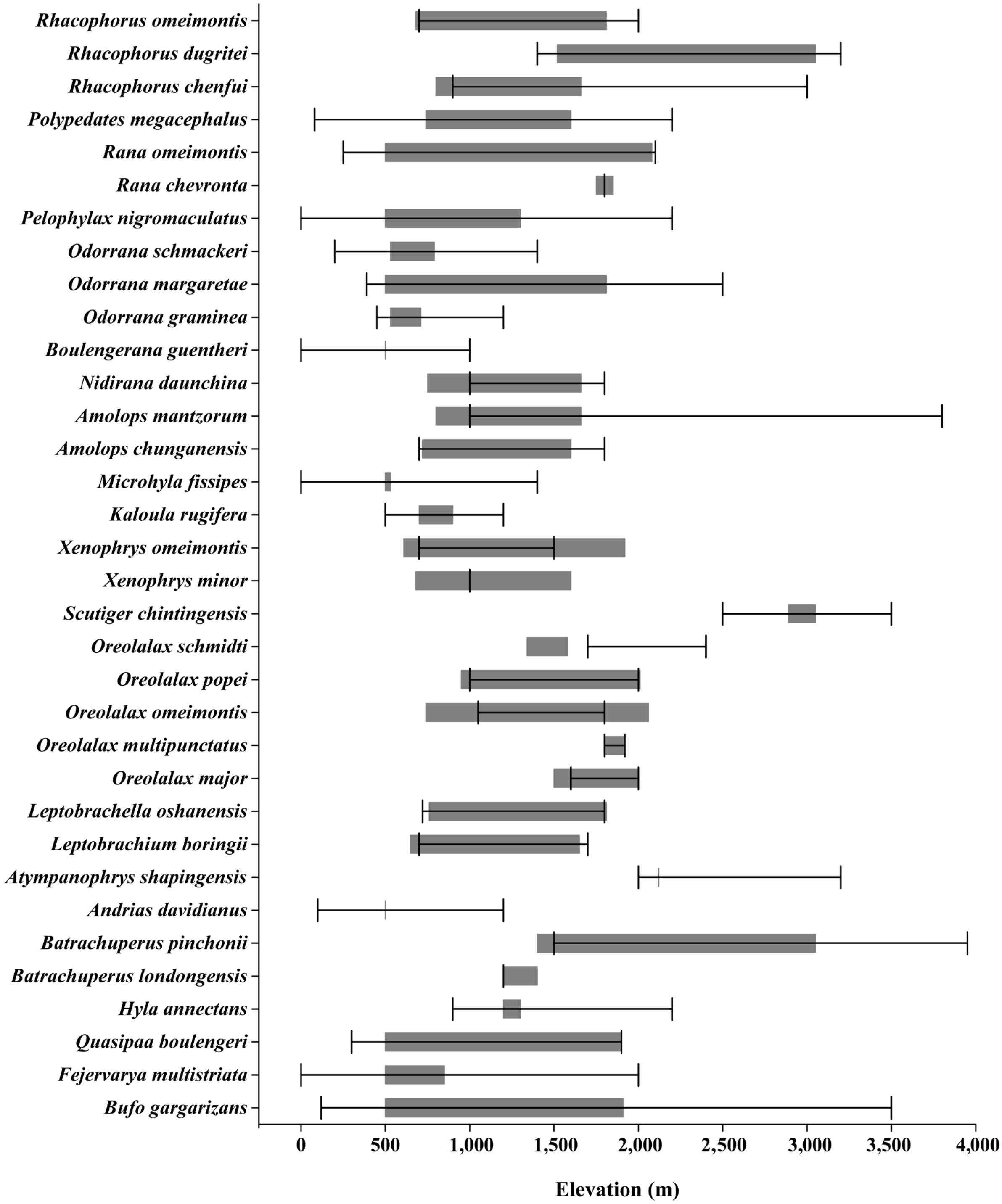

Fig. 3. Local and overall elevational ranges for each amphibian species. For each species, the local elevational range is the maximum minus minimum elevation on Mount Emei (gray box or vertical line), and the overall elevational range size is the published elevational range covering the whole distribution range (the horizontal line).

by environmental modification, as well as life-history and evolutionary traits (Gaston 1996). For example, increasing human activities and climate changes may lead to a range shift along the elevation (Chen et al. 2009; Kusrini et al. 2017). As a famous tourist attraction, the tourist season on Mount Emei overlaps with the breeding season of most amphibians, resulting in changes of the species' range size (Fei et al. 2009a,b; Liu and Yang 2012). On the other hand, individual intrinsic traits, such as dispersal abilities, habitat selection, and environmental tolerance, may indirectly contribute to a range shift under environmental changes (Fei et al. 2006, 2009a,b; Gaston 1996). For example, tadpoles and some stream-dwelling adults may be flushed downstream in running water, leading to a lower minimal elevation. Of course, one caveat must be applied to the results. Although this survey illustrated that a species' range size may be related to its threat status, it did not examine the extent of that correlation based on any statistical support. There is a need to further explore the influences of intrinsic traits (e.g., range size, body size, and clutch size) on extinction risk with more detailed data.

Amphibians are a major group that is currently at risk globally (Jiang et al. 2016; Wake and Vredenburg 2008), with declines which far exceed those of other vertebrate taxa (Hoffmann et al. 2010). Accumulating evidence indicates that amphibians are threatened by anthropogenic land-use changes, fatal chytridiomycosis, climatic changes, and over-exploitation (Blaustein and Kiesecker 2002; Hof et al. 2011). Mount Emei suffers from intense human disturbance (e.g., cultivation and tourism), and nearly one-third of the amphibian species are severely at risk as indicated by their currently threatened status (Table 1). As such, urgent conservation actions are necessary for amphibians. Although biodiversity conservation and environmental management awareness among local governments and the public have been strengthened, the conflict between conservation and socioeconomic development continues to make biodiversity conservation exceptionally difficult to achieve. In this context, understanding how species respond to human-disturbances and survive in the human-dominated landscape is critical to the conservation of amphibians in mountain systems. This study can be helpful for scientifically-based policy making and for implementing the regulatory measures to mitigate the potential disturbances on biodiversity caused by mass-tourism.

Conclusion

In summary, this study presents data on the species richness, distribution, and threat status for 35 amphibian species in a tourist attraction, Mount Emei in China, which is a site of special significance to conservation and to science. The results highlight the urgent need to manage and preserve the amphibians, especially the threatened species, and will be helpful in assisting with sustainable management and the development of effective conservation strategies. These findings can also provide a basis for further ecological studies, such as exploring intraspecific and/or interspecific responses to biotic and abiotic influences (Hu et al. 2019; Huang et al. 2020; Wang et al. 2019), not only for the focal mountain but also for other similar regions or high-profile areas of concern.

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Xiaoyi Wang is a Ph.D. candidate at Chengdu Institute of Biology, Chinese Academy of Sciences, whose work focuses on species diversity and community assembly mechanisms along environmental gradients, responses of traits to environmental changes, and the conservation of endangered species. Specifically, she aims to link biodiversity conservation with multidimensional insights, such as species function in the ecosystem, evolution and adaptation, to assess how biodiversity responds to environmental changes.

Shengnan Yang entered the laboratory at Chengdu Institute of Biology, Chinese Academy of Sciences and began her amphibian and reptile studies during her undergraduate work. She is interested in the ecology and conservation of amphibians and reptiles. Her current research topics include the impact of habitat transformation on these groups and the potential adaptability and plasticity of species.

Chunpeng Guo is a postgraduate student at Chengdu Institute of Biology, Chinese Academy of Sciences. His research interests include the road ecology, conservation biology, and natural history of reptiles and amphibians. His current studies focus on assessing the impacts of roads on amphibian and reptile assemblages in countryside landscapes.

Ke Tang is a postgraduate student at Chengdu Institute of Biology, Chinese Academy of Sciences. He studies the population ecology of amphibians and reptiles, and his current research focuses on the effects of environmental heterogeneity on amphibians and reptiles in the Three-River-Source (Sanjiangyuan) National Park in China.

Jianping Jiang is a herpetologist at Chengdu Institute of Biology, Chinese Academy of Sciences, with more than 25 years of professional wildlife and research experience. Currently, he is focusing on the taxonomy, systematics, ecology, evolution, and conservation of reptiles and amphibians.

Junhua Hu is a full professor at Chengdu Institute of Biology, Chinese Academy of Sciences. His research focuses on animal ecology and the conservation of endangered species in a changing world.

Appendix. Locations of sampling sites and the numbers of line transects (N) at each site along the elevational gradient on Mount Emei, China.

	Sampling site	Longitude (°E)	Latitude (°N)	Elevation (m)	N
Line transects	Huangwan Village	103.43	29.58	500	2
	Baoguo Temple	103.44	29.57	530	2
	Lianghekou	103.41	29.59	650	1
	Qingyin Pavilion	103.39	29.57	730	1
	Shenshui Pavilion	103.41	29.56	800	2
	Baiguo Village	103.34	29.43	860	1
	Chadi Village	103.36	29.59	914	1
	Weigan Village	103.31	29.60	1,100	1
	Longdong Village	103.28	29.58	1,250	2
	Qiliping	103.25	29.57	1,280	1
	Linggongli	103.29	29.58	1,340	2
	Kuhaoping	103.27	29.45	1,470	2
	Changshou Bridge	103.35	29.56	1,540	1
	Jinchuan Village	103.24	29.44	1,560	2
	Longqiaogou	103.35	29.55	1,900	1
	Jingding	103.33	29.52	3,050	1
Sampling points	Shouxing Bridge	103.37	29.55	1,280	
	Shuangshuijing	103.32	29.55	2,230	
	Leidongping	103.33	29.55	2,433	