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Research trends on bats in China: A twenty-first century review

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ABSTRACT

In this century, China has sustained unparalleled economic development, leading to exponentially growing investments in scientific research. Yet, the demand for research-funding is large and tracing the current knowledge is a key step to define priority research topics. In this same span, studies on bats in China have uncovered an overlooked diversity and revealed novelties in bats' evolutionary history and life-history aspects. All this 21st-century knowledge, however, is scattered and a large part is concealed from most of the international scientific community in Mandarin-language articles. Here, we summarize the post-millennium (2000–2017) research on bats in China and point out trends and future directions based on neglected topics, groups, and regions. In addition, we provide an up-to-date list of bat species in China. We retrieved 594 publications related to bats in China, nearly half were written in Mandarin. At least 147 bat species are present in China, which places it among the most bat-rich countries in the world. There was a significant positive trend on the number of publications, from 12.5 annual average in 2000–2005 to 46.5 in recent years, reflecting the Chinese economic-scientific development in this century. We found marked taxonomic and spatial biases. Half of the studies in this century focused on *Rhinolophus*, *Myotis*, and *Hipposideros*, and the southern and eastern provinces were the most studied. Systematic/taxonomy and Ecology were the predominant topics post-millennium, whereas only 10 articles have clear conservation-driven goals. Our review shows that the majority of studies were focused on the least concern, cave-dweller species, and on bat-rich provinces. Future projects should address the effects of human-modified landscapes on bat community to define proper conservation actions. We discuss some priority actions and projects that will help to enhance bat protection in China.

Introduction

Bats represent one-fifth of the world mammal diversity and provide several ecosystem services that benefit diverse sectors of the society (Kasso and Balakrishnan, 2013; Kunz et al., 2011). For example, bats positively affect the economy by acting as insect pest suppressors saving billions of dollars annually on pesticides in agroecosystems (Boyles et al., 2011; Russo et al., 2018), pollinators of commercial plants (e.g. fruit bats are the major pollinators of durian, *Durio zibethinus*, a highly economic fruit crop in southeast Asia (Bumrungsri et al., 2008), and seed dispersers (maintaining and regenerating forests) (Kasso and Balakrishnan, 2013; Saldaña-Vázquez et al., 2019; Taylor et al., 2018). Bats can also be used as bioindicators of environmental pollutants (Heiker et al., 2018; Zukal et al., 2015), a well-known problem of the Chinese large cities. Their role as potential virus hosts of recent outbreaks (e.g. Ebola, Severe acute respiratory syndrome) has also highlighted their public health importance (Han et al., 2015; Moratelli and Calisher, 2015). Particularly in China, bat-borne viruses have drawn the focus of numerous studies in this century (Chu et al., 2008; Cui et al., 2007; Ge et al., 2012; Zhu et al., 2009).

In the 21st-century, China has sustained unparalleled economic development, leading to exponentially growing investments in scientific research (Cao et al., 2006; Wang et al., 2011). As a result, a massive amount of novelties has been published in the past two decades, making China the current largest producer of scientific papers. Following this trend, post-millennium studies on bats in China have uncovered an overlooked diversity and unveiled several aspects of bats' evolutionary history and life-history features (Lin et al., 2014; Peng et al., 2017; Tu et al., 2017). Recently, 135 bat species, of which 19% are endemic, were listed in the last national compilation (Jiang et al., 2017). This diversity represents 20% of the

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Chinese mammal fauna but is expected to be underestimated, as, on average, one new species has been described per year in the last decade and several taxa are known to represent species complexes (Mao et al., 2014; Sun et al., 2016). All this 21st-century knowledge about Chinese bats, however, is scattered in the literature, hampering a general understanding of the current status, and a large part of it is concealed from most of the international scientific community in Mandarin-language articles.

In this revision, we summarize the post-millennium research on bats in China and point out trends and future directions based on neglected topics, groups, and regions. Mapping the available knowledge is a key step to identify scientific gaps and define priority research topics and subjects to direct research efforts. We hope that our review provides this baseline for future studies. As we anticipated an uneven distribution of publications across taxa and provinces, we test a set of parameters (species distribution range, species threatened status, presence in caves, province area, and province bat diversity) that could be related to research biases. Additionally, we provide an up-to-date list of bat species in China with supporting references.

Material and methods

A systematic literature review of studies on bats in China published between 2000 and 2017 was carried out from August to September 2017. We searched the ISI Web of Science, Scopus, Google Scholar, PubMed, JSTOR, Elsevier, and Wiley Online Library databases for papers on "bat" OR "Chiroptera" AND "China". Articles published in Mandarin were searched in the Chinese Scientific database (http://www.cnki.net/) using the same keywords in Mandarin. In addition, we tracked the references cited in the articles to recover papers published in journals that are not indexed in any of these databases.

From each publication, we extracted the following information: year of publication, species studied, language (Chinese or English), collecting localities of bats in China (provinces), research topic, destination of voucher material, habitat where the study was conducted (cave, artificial roost, forest, laboratory), and methods used for species identification (morphology, molecular, and echolocation). All species, provinces, and research topics addressed in each paper were computed and treated as independent cases. We categorized the papers into seven main research topics: 'biogeography', 'conservation', 'ecology', 'genetic', 'parasitology/disease', 'physiology/anatomy', and 'systematic/taxonomy' (Table 1).

We update species names following Simmons (2005) and recent revisions. *Rhinolophus monoceros* and *R. cornutus* are treated as subspecies of *R. pusillus* following Li et al. (2006). *Myotis latirostris* is allocated in the genus *Submyotodon* and *Myotis ricketti* is considered a junior synonym of *Myotis pilosus* (Ruedi et al., 2015). *Myotis taiwanensis* is considered subspecies of *Myotis fimbriatus* following Ruedi et al. (2015). *Myotis watasei* is considered synonym of *M. rufoniger* and *Myotis flavus* is treated as subspecies of *M. formosus* (Csorba et al., 2014). Previous records of *Myotis daubentonii* in China refer to *Myotix petax* (Matveev et al., 2005). *Falsistrellus affinis* is allocated in the genus *Hypsugo* (Görföl and Csorba, 2018). *Thainycteris* is considered a valid genus (Francis et al., 2010; Guo et al., 2017) and all Chinese records of *Kerivoula titania* and *Kerivoula hardwickii* are attributed to *K. furva* (Yu et al., 2018). All Chinese records of *Hipposideros bicolor* and *Rhinolophus rouxii* are respectively attributed to *H. pomona* and *R. sinicus* (Zhang et al., 2009a). *Hipposideros terasensis* is considered subspecies of *H. armiger* (Thong et al., 2012).

Table 1
Number of publications (N) on bats in China from 2000 to 2017 per research topic. Note that some articles may include more than one category. See Supplementary Data SD1 for the full publication list.

Research topic	N	Remarks
Biogeography	**21**	Includes articles related to phylogeography and description of species range
Phylogeography	19	
Distribution limits	2	
Conservation	**10**	Includes only articles with clear conservation-driven goals. Cave exploitation, climate change, wind-farm effects.
Ecology	**164**	Includes studies related to any aspect of natural history at individual, population, species, and community levels.
Activity pattern	9	
Behavior	17	Includes mother-pulp recognition, feeding behavior, foraging behavior, sexual behavior, sleeping time
Diet	16	
Echolocation	92	
Niche modeling	3	
Niche partitioning	12	Includes studies on habitat use, resource partitioning, prey selection
Roost	5	Roost selection and monitoring
Ecosystem services	6	Fruit-bat interaction, pollination, seed dispersal
Community structure	2	
Population genetics	2	
Genetic	**74**	Studies on genes description and expression, and cytogenetics
Cytogenetics	18	
Epigenetics	2	
Gene(s) description	23	Genome, microsatellites
Gene(s) expression	31	Enzyme expression, hibernation-related genes
Parasitology/Disease	**115**	Includes studies related to viruses, bacteria, fungus and other endo/ectoparasites
Viruses	99	Alphacoronavirus, Astrovirus, Betacoronavirus, Bocaparvovirus, Coronavirus, Ebola-virus, Encephalitis-virus, Filovirus, Gammaretroviruses, Hantavirus, Lyssavirus, Orthoreovirus, Paramyxovirus, Parvovirus, Picornavirus, Reovirus, Rotavirus
Bacteria	3	Staphylococcus, Bartonella
Fungi	2	White-nose fungus
Ecto/endo Parasites	11	Mites, protozoans, ticks, trematodes, toxoplasma
Physiology/Anatomy	**62**	Articles related to description of external or internal morphology, histology, and physiology, including ontogenetic studies.
Anatomical description	10	Includes studies on heart anomaly, wing morphology, brain structure, phallic morphology
Brain activity	26	Mostly related to hibernation aspects
Histology	10	
Metabolism	5	
Postnatal development	9	
Sensory system	2	Studies on vision acuity and auditory function
Systematic/Taxonomy	**169**	Includes taxonomic revisions, species delimitations, species descriptions, inventories, and notes of distribution records of both fossil and extant taxa
Checklist	24	
Distribution records	56	
New species description	16	
Paleontology	3	
Phylogeny/Taxonomy	70	

The records of *Barbastella leucomelas* in China were treated either as *Barbastella beijingensis* or *Barbastella darjelingesis* depending on the collecting locality (Benda et al., 2008; Kruskop et al., 2019). The few records of *Miniopterus fuscus* and *Miniopterus australis* were considered misidentifications as these species have no reliable records in China. The Chinese records of *Miniopterus schreibersii* were treated as *M. fuliginosus* or *M. magnater* based on the collection locality (Li et al., 2015). We consider *Plecotus auritus* and *P. austriacus* restricted to Europe (Spitzenberger et al., 2006) and the records of *Plecotus* from Beijing and Henan provinces are tentatively assigned to *P. ognevi*.

To evaluate trends (proportion and number of publications) on studies of Chinese bats in the last 18 years in relation to research topics, Chinese provinces, and taxa, we used descriptive statistics, bar plots, and Kendall' Tau b coefficient. Pearsonś Chi-squared (X^2) was used to test the evenness distribution of the number of publications per research topic, per species, and per Chinese province. As we anticipated an unbalanced distribution of publications per species, we selected five parameters as explanatory variables to understand why some species are more studied than others using quasi-Poisson generalized linear models in R software (R Development Core, 2017). The parameters are: 1) total species distribution, 2) species distribution in China, 3) IUCN threatened status, 4) Chinese threatened status, and 5) presence in caves. Species distribution was calculated in square kilometers based on IUCN spatial data maps (http://www.iucnredlist.org/technical-documents/spatial-data) using ArcGIS 10.2. The threatened status was based on the most recent assessments of the International Union for the Conservation of Nature (IUCN, 2017) and the China Mammal Red List (Jiang et al., 2016). Species that were recently described or underwent recent taxonomic changes were not included in this analysis. Presence in caves was retrieved from Luo et al. (2013) and our own survey. Lastly, we assessed via quasi-Poisson generalized models, whether province area (in square kilometer), province bat diversity and the presence of a bat research unit (institute or university) are correlated with the number of publications per province. The number of species per province was calculated by overlapping the IUCN species geographic ranges using ArcGIS 10.2.

Results

Temporal trends across research topics

We retrieved 594 publications related to bats in China (see Supplementary Data SD1), nearly half (49%) were written in Mandarin. There was a significant positive trend on the number of publications along the last 18 years (Kendall's Tau-b coefficient = 0.65; z = 3.75; $p = 0.0001$) (Fig. 1, Supplementary Data SD2). Up to 2005, the annual average number of articles was 12.5, from 2006 to 2010 grew to 43.2, and the last seven years reached 46.5. By comparing research topics, we detected a marked heterogeneity on the number of publications (X^2 = 149.02, d.f. = 102, $p = 0.001$; Table 1). Systematic/Taxonomy and Ecology studies accounted for 27.3% and 26.5%, respectively, followed by Parasitology/Disease (18.6%), Genetic (12%), Physiology/Anatomy (10.1%), Biogeography (3.9%), and Conservation (1.6%). When analyzing temporal trends, we detected a shift in studied topics. Ecology was the predominant category up to 2005 with an average of 48.1% per year, reaching 70% of all publications in 2004. From 2006, there was a marked increase in Parasitology/Disease studies, which accounted for 43.2% all publications in 2016, and on Genetics, comprising 27.9% of all publications in 2008 (Fig. 1).

Geographic bias and correlated parameters

Bats from all thirty-four provinces of China (including Taiwan) were listed in at least one publication in the past 18 years, but with a very strong, uneven distribution across provinces (X^2 = 1106.1, d.f. = 33, $p < 0.0001$). The majority of studies was focused on the southern and eastern part of the country (Fig. 2). Most of the studies were conducted in Yunnan (12%), Guangdong (9.9%), Guangxi (8.3%), Guizhou (7.5%) and Beijing (5.6%), while the least studied provinces were Ningxia (0.1%), Xinjiang (0.2%), Shanghai (0.2%), Macau (0.3%) and Inner Mongolia (0.3%). Our models show that number of publications per province positively relates to local species diversity (estimate = 0.02; $t = 5.91$; standard error = 0.005; $p < 0.0001$) and negatively associates with province area (estimate= -0.000; t = -2.04; stand. error = 0.000; $p = 0.04$). The presence of a bat research unit (estimate= 0.38; $t = 1.47$; stand. error = 0.25; $p = 0.15$) has no effect on the number of publications across provinces.

Taxonomic bias and preferred studied taxa

A total of 135 bat species was listed in the 594 publications. We detected a very high unbalanced distribution of publications across species (X^2 = 2935.4, d.f. = 102, $p < 0.0001$). Three genera appeared in almost half of the publications (Fig. 3). *Rhinolophus* was by far the most studied, listed in 21.2% of all publications, followed by *Myotis* (13.3%), and *Hipposideros* (11.8%). Sixteen genera (45% of 35) were present in less than ten studies: *Megaderma*, *Barbastella*, *Hypsugo*, *Plecotus*, *Pteropus*, *Tadarida*, *Chaerephon*, *Harpiocephalus*, *Macroglossus*, *Scotomanes*, *Sphaerias*, *Submyotodon*, *Megaerops*, *Arielulus*, *Harpiola*, and *Thainycteris*. In terms of species, the most studied were: *Rhinolophus ferrumequinum* (mentioned in 5.8% of all publications), *Hipposideros armiger* (5.5%), *Rhinolophus pusillus* (5.5%), *Rhinolophus sinicus* (4.3%), *Myotis pilosus* (4.1%), *Rhinolophus affinis* (4%), and *Rousettus leschenaultia* (4%) (see Supplementary Data SD3 and SD4 for the complete species list). Our models reveal that bats with larger area of occurrence in China (estimate = 0.27; $t = 3.29$; stand. error = 0.08; $p = 0.001$), roosting in caves (estimate = 0.81; $t = 2.26$; stand. error = 0.35; $p = 0.02$), and nationally classified as Least Concern (estimate = 1.86; $t = 2.5$; stand. error = 0.74; $p = 0.01$) were more studied. The remaining parameters were not significant to explain the heterogeneous distribution of studies across species.

We also found that the most at-risk species have received the least attention, only 8.4% of all publications mentioned the 37 bat species nationally threatened or with deficient data (see Supplementary Data SD3, SD4, and SD5). Besides notes on geographic distribution, only four threatened species (*Coelops frithii*, *Eonycteris spelaea*, *Myotis formosus*, and *Rhinolophus yunanensis*) were the main focuses of the articles. Similarly, the 27 bat species endemic to China appeared in only 8% of the articles (see Supplementary Data SD3 and SD5). The 27 species pending evaluation of their national threatened status appeared in 4.2% of the publications.

Temporal trends by language

The majority (>55%) of the articles up to 2005 were published in Mandarin and by 2010 the cumulative number of publications in English overtakes that of Mandarin-language articles (Fig. 4). However, Mandarin papers still represent at least 40% of the annual production in recent years. It is noteworthy that 87% of English-language articles have a Chinese scholar as the first author. We also found a significant difference between English and Mandarin articles per research topic (X^2 = 18.69, d.f. = 6, $p = 0.004$). Ecology (28.8%) and Systematic/Taxonomy (31.3%) were the most explored topics among Mandarin-language articles. Ecology (24.2%), Parasitology/Disease (22.5%), and Systematic/Taxonomy (22.2%) were

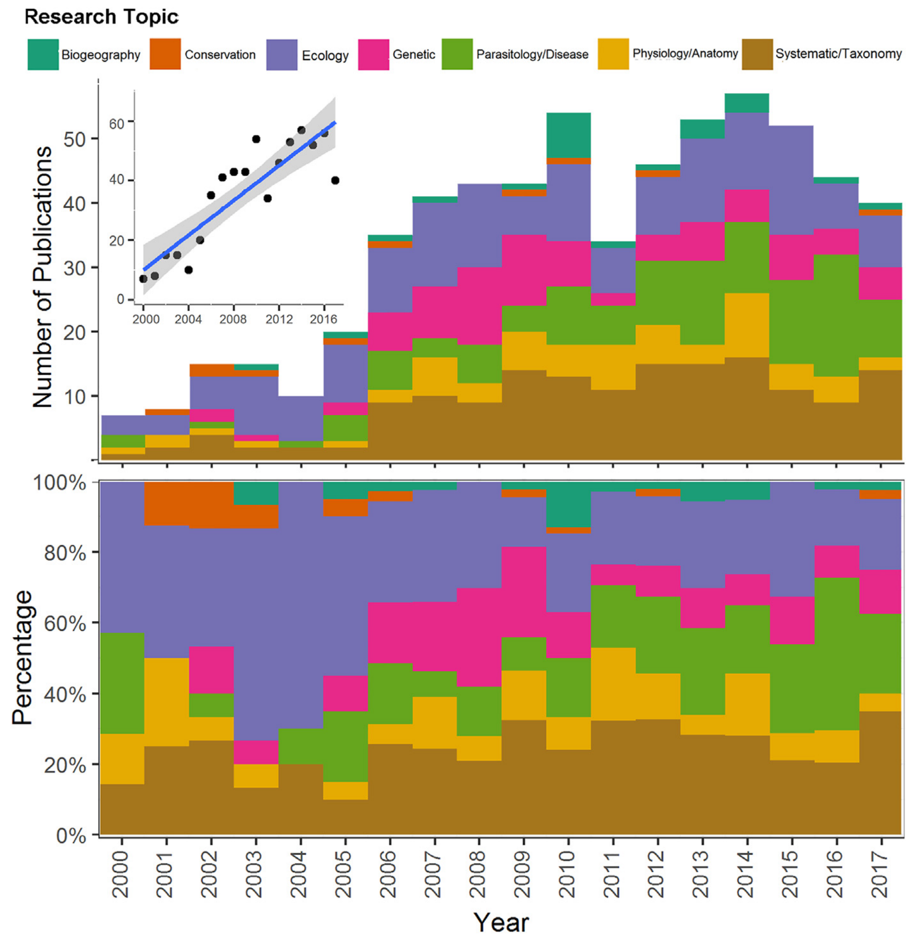

Fig. 1. Temporal research trend of studies on bats in China from 2000 to 2017. Number of publications (top) and percentage of publications (bottom) per year. Colored bars represent research topics. The upper-left insert shows the linear trend of the number of publications over the years.

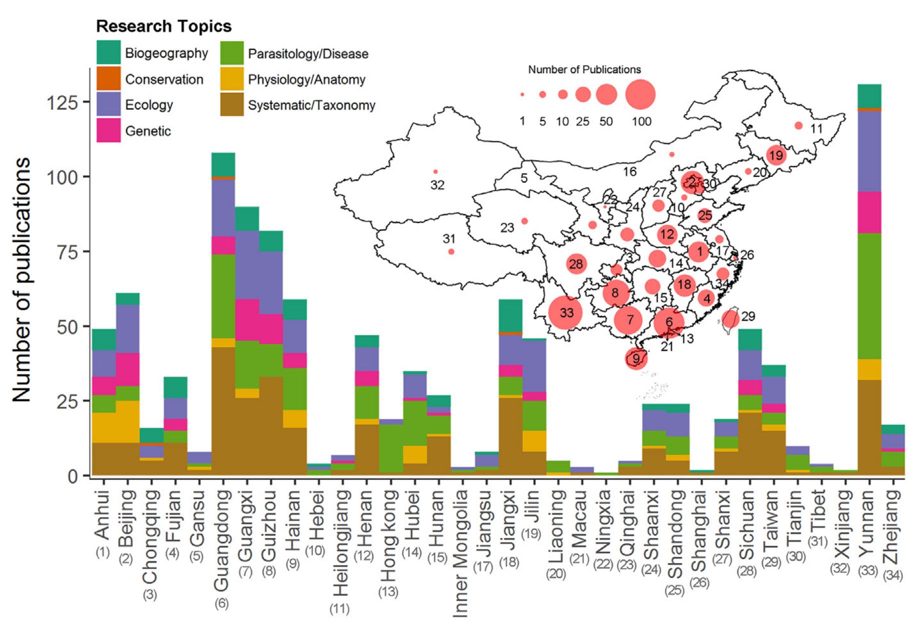

Fig. 2. Spatial distribution of the number of publications on bats per Chinese provinces from 2000 to 2017. Colored bars represent research topics. Numbers in parentheses refer to provinces codes.

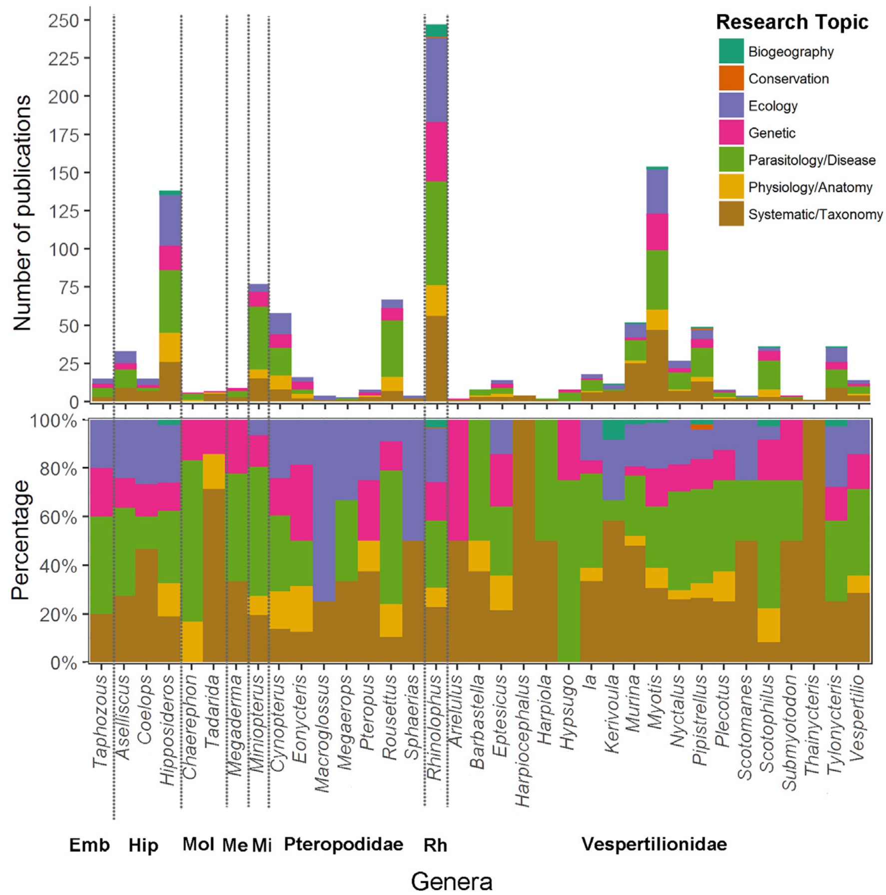

Fig. 3. Number of publications (top) and percentage of publications (bottom) on bats in China per genera from 2000 to 2017. Colored bars represent research topics. Genera are arranged in alphabetic order within families. Abbreviations: Emb (Emballonuridae), Hip (Hipposideridae), Mol (Molossidae), Me (Megadermatidae), Mi (Miniopteridae), Rh (Rhinolophidae).

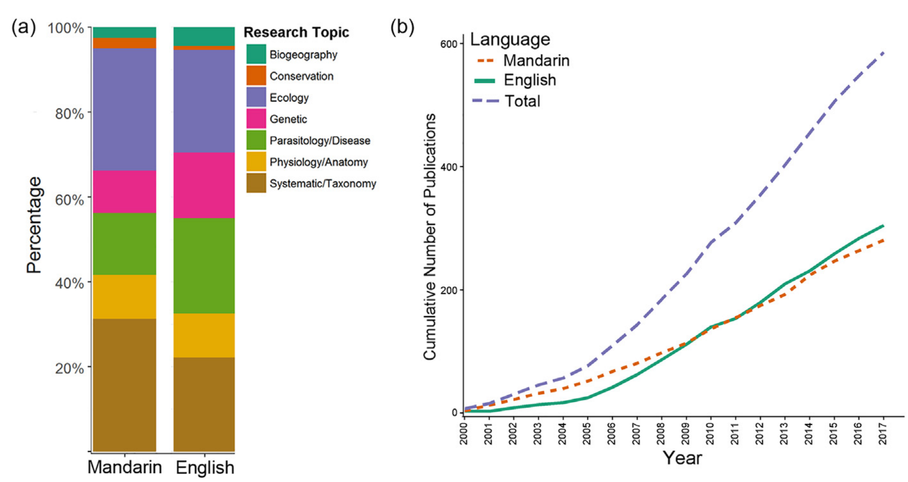

Fig. 4. Publication trends on bats in China by language from 2000 to 2017. Percentages of publications per research topic (a); cumulative numbers of publications per year (b).

the main topics among English-language papers. Interestingly, conservation-oriented studies were mostly published in Mandarin (Fig. 4).

Applied methods and the most studied habitats

Two-hundred and nine studies (35.2%) mentioned the methods used to identify species. The majority of the studies relied only on morphology (63.6%), while exclusively molecular-based methods were applied in 18.6% of the studies. Complementary methods were applied in 35 studies, including molecular and morphology (13.8%), morphology, echolocation, and molecular (1.4%), molecular and echolocation (0.9%). 274 papers mentioned the habitat where the bats were sampled, the majority was focused on caves (63.7%), followed by forests (17.2%), artificial roosts (10.8%) and captivity (8.1%). From the 182 publications that mentioned collecting of bats, only 21.4% listed the final destination (i.e., museum collection) of the voucher material.

Discussion

Over the 21st century, the number of publications on bats in China follows a significant upward trend, especially from 2006. This sharp increase can be mainly attributed to two events. First, it seems to be a direct effect of China's 15-years Science and Technology project launched in 2006 (Cao et al., 2006). Allied to a growing number of scientists and universities, this long-term plan has increased investments in priority research topics, including research on biodiversity and environmental protection. Not surprisingly, the trend in bat studies is congruent with the overall scenario of scientific production in China (Xie et al., 2014).

The second turning point was the discovery of bats as the natural reservoirs of the severe acute respiratory syndrome (SARS) coronavirus in 2005 (Lau et al., 2005; Li et al., 2005; Poon et al., 2005). Between 2002 and 2003, the global outbreak of the SARS, originated in Guangdong province, south China, infected 8096 people from 26 countries and caused 774 deaths according to the World Health Organization (http://www.who.int/csr/sars). Nearly 92% of the cases were from China, resulting in 685 deaths in eight months. Since 2005, a greater effort has been directed to uncover the association between bats and zoonotic viruses in China (Han et al., 2015; Lin et al., 2017; Wu et al., 2016; Yuan et al., 2009). The number of articles on Parasitology/Disease rose from 6.7% in 2002 to 43.2% in 2016, of which 85% focused on bat-borne viruses. By contrast, ecology studies have decreased its dominance, resulting in a more balanced distribution of research topics in recent years (Fig. 1). It is important to emphasize that zoonotic risks are often overemphasized at the expense of conservation and that the effective role of bats in most of the last human disease outbreaks has been largely based on speculation instead of direct evidence (Löpez-Baucells et al., 2018; Moratelli and Calisher, 2015). In fact, preserving bats' natural habitats and roosting sites (e.g. caves) is the most effective way to avoid human-bat interaction and reduces risk of exposure to pathogens (Patil et al., 2017; Plowright et al., 2011; White et al., 2018).

Chinese bat diversity and future targets

One hundred thirty-five bat species were recorded in our review, including 23 species that were not listed in the last national compilation (Jiang et al., 2017). In contrast, thirteen species listed by Jiang et al. (2017) were not retrieved in our review; however, for three of them (*Myotis nattereri*, *Scotozous dormeri*, *Pipistrellus kuhlii*) we could not find the original source to validate its occurrence in China. In sum, considering two newly recognized species after 2017, the current known diversity of bats in China reaches 147 species (see Supplementary Data SD3), an increase of 22% (including 23 new species) in the last 18 years (Wang, 2003). This new species discovery era reflects the increasing number of bat researchers in China (Luo et al., 2013), greater field survey efforts (Chen et al., 2017; Wu et al., 2012, 2008), and the growth of integrative taxonomic studies (Eger and Lim, 2011; Feng et al., 2008; Kuo et al., 2017).

China stands out among the most bat-rich countries together with Indonesia (221 species, Suyanto et al., 2002), Colombia (187 spp.,Solari et al., 2013), Brazil (183 spp., Feijó et al., 2015; Moratelli and Dias, 2015; Nogueira et al., 2014), Ecuador (171 spp., Tirira, 2016), Venezuela (165 spp.,Sánchez and Lew, 2012), and Peru (165 spp., Pacheco et al., 2009). The high diversity of bat species in China in relation to adjacent countries —Thailand (138 ssp., Soisook, 2011), India (127 ssp., Talmale and Saikia, 2018), Vietnam (120 ssp., Kruskop, 2013), Laos (90 ssp., Thomas et al., 2013), and Philippines (70 ssp., Tanalgo and Hughes, 2018)—may be explained by its marked topographic and habitat complexity, including four of the world's biodiversity hotspots (the mountains of Central Asia, Himalayas, Hengduan mountains, and part of Indo-Burma), and representing the transition between two biogeographic realms (Palaearctic and Indo-Malayan), harboring both tropical and temperate species.

Despite this remarkable growth, we anticipate a still overlooked diversity in Chinese bat fauna due to the taxonomy and spatial biases. Nearly half of the publications on systematics and taxonomy in the past decades focused on the three most species-rich genera *Rhinolophus*, *Myotis*, and *Murina*. Not surprisingly, 25 species were newly recognized in these genera. In contrast, the majority of genera (82%) was the focus of less than 3% of taxonomic studies (Fig. 3). Particularly for species with wide and disjunct geographic distributions (e.g. *Eptesicus serotinus*, *Nyctalus aviator*, *Nyctalus noctula*, *Pipistrellus pipistrellus*, *Plecotus ognevi*), we might expect future taxonomic discoveries. An apparent exception to this trend is *Hipposideros* that was the focus of 9% of the taxonomic studies but showed only minor species-level taxonomic changes in the last decades. Part of this stability can be explained by systematic practices applied by some authors. Marked geographic, morphological, and genetic variation within species of *Hipposideros* have led to subspecies recognition (Zhao et al., 2015; Zhou et al., 2016), largely defined on mitochondrial cytochrome b genetic distance (Bradley and Baker, 2001). However, the degree of genetic divergence should be used as complementary support to set taxonomic ranks, not as sole criteria (Bradley and Baker, 2001; Ferguson, 2002). For future works, we encourage authors to apply multiple lines of evidence in defining species boundaries.

Our study also revealed that endemic species or those at the highest risk of extinction have received the least attention. The 26% of the species treated as least concern at country level concentrated 54% of all publications, while the data deficient and threatened (endangered and vulnerable) species represent 25% of the entire Chinese bat fauna but was the focus of only 8.4% of the studies in the last two decades (Supplementary File SD5). There is therefore a clear need for more studies on threatened species in order to draw appropriate conservation actions (Mace et al. 2008).

Where have the bat studies been concentrated?

The spatial distribution of studies on bats in China shows a marked concentration in the southern and eastern regions of the country. Less than 4% of all publications in the past 18 years were conducted in the western and northern portions of China, which cover nearly half of the Chinese territory. Our models show that most of the bat studies were held in provinces with higher bat diversity (see Supplementary Data SD6). The core area of the Qinghai-Tibetan plateau, at the west, seems to impose abiotic constraints to bats' survival; thereby, no study on bats is expected from this region. In contrast, the north part of the country might have its diversity partially underestimated due to this spatial bias. For example, a new bat species from Beijing–the most studied province in the north of China–was described in this century (Zhang et al., 2007). Furthermore, studying bats living in harsh environmental conditions as in deserts and semiarid zones may help answer physiological adaptation questions (Geiser, 2004; Yuan et al., 2011). Among the 43 physiology-focused studies retrieved in this review, only two examined bats from north China (Jilin province).

Chinese bat studies have been concentrated on cave dweller species. Considering that subterranean habitats hold nearly 70% of China's bat diversity, that they can harbor large populations (>14.000 individuals), and also face high level of human disturbance, the conservation of these habitats should be treated as high priority (Luo et al., 2013; Niu et al., 2007; Zhang et al., 2009b). Long-term monitoring studies should also be conducted in these areas to assess population dynamics. However, neglecting other roosting habitats results in an incomplete understanding of the bat community structure (Feijó and Rocha, 2017; Flaquer et al., 2007). In addition, species inhabiting forest patches or human settlements near urbanized and agricultural areas are of public health concern due to the higher likelihood of bat-human contact, demanding regular surveillance programs (Nunes et al., 2016). Complementary sampling methods (ground and canopy mist nets, acoustic detectors) should be combined with cave roost surveys in future projects aiming to address community ecology questions.

The language barrier

Our study reveals that a large proportion of articles are still published in Mandarin and that the majority of those published in English have Chinese affiliated researchers as the first author. This shows that national scientists are the main leaders of the research conducted in China. Publishing in the country's native language has the advantage to make the information available to national policy-makers and local public (Bortolus, 2012; Di Bitetti and Ferreras, 2017; Superina et al., 2014). Although English-language papers represent the majority of publications in the last decade in China, their proportion is still much lower than in other non-English speaking countries (González-Alcaide et al., 2012). Non-English papers prevent the research findings from being accessed by a broader audience (Di Bitetti and Ferreras, 2017; González-Alcaide et al., 2012). This is particularly true for articles written in Mandarin, China's exclusive language. In addition, English-language papers tend to have a higher citation rate; thereby, higher international recognition [which does not necessarily reflect quality] than non-English articles (Di Bitetti and Ferreras, 2017). Perhaps in a way to partially overcome this language barrier, most of the recent Mandarin articles retrieved in this review have English abstracts. The pros and cons of publishing in non-English or English languages were addressed in more details by Bortolus (2012) and Di Bitetti and Ferreras (2017).

Where are the voucher specimens?

Another finding is the lack of information about the quantity and whereabouts of voucher specimens in most of the articles that mentioned collecting bats. Museum specimens are temporal and spatial snapshots of biodiversity and limitless source of information to address systematics, taxonomic, ecological, evolutionary, climate change, and public health questions (Suarez and Tsutsui, 2004). Failing to disclose the destination of voucher specimens impedes their use in future studies as well as to ascertain species taxonomic identity. This undesirable practice may lead to negative impacts on the bat community caused by oversampling of collecting sites (Russo et al., 2017). Particularly in Parasitology/Disease studies, collected specimens (if preserved or not) and their whereabouts are often omitted. As detailed by Suarez and Tsutsui (2004), voucher specimens are of major relevance to public health, as they can be used to identify hosts of zoonotic pathogens, trace back the origin and evolution of parasites, and identify potential agents or phenomena related to past and future outbreaks, providing guidance for rapid and efficient actions. Thus, we reinforce the recommendation of the American Society of Mammalogists (Sikes et al., 2016) that all individual collected in nature should be deposited with associated data into an official scientific collection and the museum voucher number should be clearly disclosed in the article.

Conservation-driven studies gap

In contrast to the global rising trend on conservation-oriented studies (Bakker et al., 2010; Di Marco et al., 2017), articles on bat conservation in China are scarce. Indeed, only ten articles in the past 18 years have clear conservation-driven goals. This is critical considering the accelerate rate of urbanization in modern China, which have already led to local extinctions (Chouteau et al., 2012; Wang et al., 2007; Zhao et al., 2006; Zheng and Cao, 2015).

Half of the bat studies conducted in this century were focused on ecology and systematics. Taxonomic revisions are paramount to reveal the actual diversity and to properly define species, the basic unit for conservation actions (Garbino et al., 2018; Mace, 2004; Tsang et al., 2016). In addition, the knowledge about species' life-history aspects (e.g. Cheng and Lee, 2002; Ho and Lee, 2003; Ma et al., 2006; Park et al., 2000) generated in this century helps to assess the threatened status of bat species and plan effective conservation strategies (Mickleburgh et al., 2002). However, conservation-driven research is needed to draw efficient conservation actions (Weeks and Adams, 2017). For example, although the majority of articles were related to ecological aspects of bats, long-term monitoring studies are still lacking. These studies can provide reliable information about community dynamics and how species respond to climate and human-induced changes (Ingersoll et al., 2013; Meyer et al., 2010). Future projects should also address the effects of human-modified landscapes (i.e., agricultural systems, urbanization, dams, deforestation) on the bat community, and which species are more susceptible to these alterations.

The knowledge gap on bat conservation aspects in China is even more critical when the available evidence regarding the decline of bat populations is considered. Zhang et al. (2009b) reported several cases of bat population declining in the past decades and listed four main threats: overexploitation of caves for tourism, extensive use of pesticide, replacement of old buildings used as roosts by bats, and the consumption of bat meat. Giam (2010) briefly discussed the potential impact of the increasing numbers of wind farms on the bat community, although no study had properly evaluated this impact in China. Hughes et al. (2012) predicted extensive losses of bat diversity in south China, the most bat species-rich region in the country, associated with future climatic and vegetation changes. Tian et al. (2015), studying the dietary composition of owl pellets in Beijing, suggested that the bat population declines as urbanization increases.

Based on findings and recommendations retrieved from papers during this review, we discuss some priority actions and projects that will help enhance bat protection in China:

(i) Strengthen protection of caves used as roosts by bats and their surroundings, in particular, those identified to harbor large colonies and threatened species (see Luo et al. (2013). Because cave tourism is a growing business in China, we should link it with bat conservation through educational events. For example, bat-watching programs have been attracting hundreds of millions of visitors annually to observe the evening emergence of large bat colonies in the United States (see http://www.batcon.org/resources/getting-involved/visit-a-bat-viewing-site). Similar activities can be developed in China to stimulate bat tourism.

(ii) The modernization of old buildings in China has restricted the number of available roosts for bats, which contributes to the decline in bat populations (Zhang et al., 2009b). Urbanization is an inevitable process, especially in rapidly developing countries as China, leading to deforestation and fragmentation, well-known major threats to wildlife (Imqvist et al., 2016; McDonald et al., 2013). Particular for bats, urbanization has an uneven effect across species, favoring some while leading others to local extinction (Jung and Threlfall, 2018; Nunes et al., 2016; Russo and Ancillotto, 2015). Nevertheless, in the absence of natural habitats, most of the urban bats seem to be dependent on man-made roosts to survive. Artificial roosts ("bat houses", "bat boxes") in urban areas can be used as a mitigation program to enhance roost availability (Mering and Chambers, 2014; Rueegger, 2016), as have been applied in Hong Kong (Chan, 2006; Shek et al., 2012). Additionally, monitoring programs should be coupled to assess bat-boxes effectiveness (Rueegger, 2016).

(iii) Increasing landscape connectivity to facilitate bats dispersion among forest fragments is a key factor to prevent massive biodiversity losses in the next decades (Hughes et al., 2012). In this century, multiple afforestation programs have increased 42% of the forest cover in China, the country with the highest greening rate in the world (Chen et al., 2019). China thus represents a model for other developing countries by showing that economic development can be successfully integrate with environmental protection. Liang et al. (2018) identified conservation priority areas and ecological corridors in China that, if preserved, will enhance the landscape connectivity and promote an efficient ecological network. Currently, about 19% of China's nature reserves are within those priority areas.

(iv) Our review shows that threatened and endemic species are those that have received the least attention. Even the basic information on general aspects of home-range, diet, population size, reproduction of threatened and endemic bats are lacking. Thus, we encourage future projects to focus on species with higher extinction risk (see Supplementary SD 3 and 4). Notably, population monitoring programs are particularly important as they can provide both ecological information and reveal the main threats.

(v) Successful conservation actions often rely on the engagement with policy-makers and the local population to ensure their long-term efficiency (Andrade and Rhodes, 2012; Superina et al., 2018). Strengthening publicity and education to raise public awareness of bat ecological and economic relevance is highly important, as well as to enroll government managers, policy-makers and private sectors in conservation actions. The ecological services provided by bats should be better quantified and monetized in future projects (e.g. Boyles et al., 2011; Taylor et al., 2018) to highlight their economic value for the Chinese private sector and governments.

Conclusions

China has experienced a truly scientific revolution in this century owing to a marked increase in research funding. Likewise, studies on bats have increased fourfold over the past two decades. Fifty percent of the post-millennium articles were focused on ecology and systematic aspects, resulting in a better understanding of the Chinese bat diversity and species ecological features. Harboring 147 species, China lies among the most bat-rich countries in the world. Nevertheless, the taxonomy and spatial research biases on Chinese bat studies predict a still overlooked diversity. Future systematic/taxonomic projects should target those groups and regions identified in this review as poorly studied, and apply integrative approaches to properly define species boundaries.

The discovery of bat-borne viruses related to the recent outbreaks in China is a landmark in "parasitology/disease" bat studies, boosting several projects to investigate the association of bats and zoonotic viruses. It is noteworthy that the risk of human exposure to pathogens is drastically reduced when bats' natural habitats and roosting sites are preserved. Therefore, efforts to preserve bats' habitats have large public health value. They also provide diverse economic services (e.g., suppressors of agricultural pest insects and insects that transmit pathogens to humans, pollinators and seed dispersers of highly economic fruit crop; reviewed by Kunz et al., 2011). Unfortunately, many of these ecosystem benefits remain largely neglected in Chinese studies. We encourage future projects to quantify and monetize bats' ecosystem services in a way to emphasize their importance for the Chinese private sector and governments.

Another finding of this review was the scarcity of studies with conservation-driven goals and on threatened and endemic species. The ongoing marked economic development in China has led to an accelerated rate of urbanization, and, ultimately, intensification of wildlife threats. As a consequence, severe decline of bat populations has been reported in recent years. At the bright side, national afforestation programs in this century have increased in about 42% of forest cover in China. The continuation and expansion of these nationwide programs is crucial for a sustainable development, integrating biodiversity preservation into socioeconomic plans.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.mambio.2019.09.002.

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