Biological Conservation 192 (2015) 454–460

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/bioc

Distribution and conservation of threatened plants in China

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 17 September 2015
Accepted 27 October 2015
Available online xxxx

Keywords:
Conservation
Nature reserves
Pattern
Red list
Species richness
Threatened species

ABSTRACT

China is very rich in biodiversity, however, it is also characterized by a long history of civilization. As a result, China has a large number of threatened species. Recently the Chinese government evaluated the living status of plants, and published the China Biodiversity Red List: Higher Plants. However, little is known about how threatened plants are distributed and conserved in China. In this study, we developed a fine resolution distribution database for 3244 threatened plants, explored richness patterns and evaluated the in situ conservation status of the threatened plants by overlapping the species distribution with terrestrial national and provincial nature reserves (NNRs and PNRs) in China. We found the greatest richness of threatened plants in the southwestern region of mainland China (mainly Yunnan, southeastern Xizang and western Sichuan), northwestern Guangxi, northern Guangdong, Hainan Island and the mountainous region of Taiwan, while the lowest richness was found in Qinghai, Hebei, Shandong, Jiangsu and Chongqing Provinces. On average, NNRs covered 18.8%, and NNRs and PNRs together covered 27.5%, of threatened plant distribution areas. However, 827 threatened plants (including 627 species endemic to China) were not covered by NNRs and 397 threatened plants (including 293 endemic to China) were not covered by either NNRs or PNRs. We proposed that nature reserves specifically designed for threatened plants need to be established in South China, especially in the Yunnan, Guizhou, Guangxi, Xinjiang Hainan, and Zhejiang Provinces.

1. Introduction

Biodiversity is fundamental for the health of global ecosystems and human well-being (Rands et al., 2010; Brugiere and Scholte, 2013). However, due to land use/land cover change, resource overexploitation, climate change, and environmental pollution, biodiversity is increasingly faced with habitat destruction and confronted with the risk of extinction worldwide (Millennium Ecosystem Assessment, 2005; Monastersky, 2014; Teller et al., 2015). The past century witnessed a loss of biodiversity at a rate far more rapid than natural processes (Balmford et al., 2003). Meanwhile, the global conservation network has been enhanced to protect biodiversity across the world (Rabb and Sullivan, 1995; Kullberg and Moilanen, 2014). However, the coverage of the network is considered to be inadequate, and efforts need to be spent to optimize it step by step (Rodrigues et al., 2004; Grenyer et al., 2006; Wu et al., 2013b).

To efficiently allocate limited resources to the species most needed to be conserved, conservation scientists have paid enormous efforts setting priorities for biodiversity conservation (Roberts et al., 2002; Trizzino et al., 2015). One of the most successful steps is the evaluation of the Red List of Threatened Species initiated by the International Union for Conservation of Nature (IUCN), which provides information on population size and trends, geographic range as well as habitat needs for global biodiversity (IUCN, 1994; Rodrigues et al., 2006). The most recent evaluation of the threatened status of global biodiversity showed that, 10,896 plant species are threatened, including 2205 critically endangered (CR), 3381 endangered (EN), and 5310 vulnerable (VU) (www.iucnredlist.org). As defined, these threatened species face a higher risk of extinction, and are worthy of more conservation efforts (Orme et al., 2005; Schipper et al., 2008). In fact, threatened species have become one of the most effective surrogates for the identification and evaluation of conservation priority areas (Myers et al., 2000; Grenyer et al., 2006; Clough et al., 2010; Huang, 2011; Neel and Che-Castaldo, 2013).

China is exceptionally rich in biodiversity, due partly to its unique geographical and ecological characteristics (Chen, 1993; Tang et al., 2006; Wang et al., 2011; Ma, 2015). Moreover, China harbors more threatened species than other regions in the world, due to geographic and climatic variation as well as a long history of cultivation, etc. (Chen, 1997; Chen et al., 2002; Tang et al., 2006; Zhang and Ma, 2008b; Lenzen et al., 2009). As a result, the study of threatened plants in China is of great significance in conservation biology worldwide. Indeed, a recent biodiversity mapping study shows that China has

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http://dx.doi.org/10.1016/j.biocon.2015.10.019
0006-3207/

exceptionally high species richness of threatened vertebrate animals, even after taking into consideration the high overall species richness (Jenkins et al., 2013). Consensus has been reached among the government, academics, and the public that in situ conservation is the most feasible way to conserve biodiversity in China (Heywood and Dulloo, 2005; Huang, 2011; Wu et al., 2013a; Zhang et al., 2015). By the end of 2012, China has established more than 2600 (this number increased to 2729 at the end of 2014) nature reserves to protect its megabiodiversity, including 363 national nature reserves (NNRs) (this number increased to 427 at the end of 2014) and 872 provincial nature reserves (PNRs) (Zhao et al., 2013). However, the effectiveness and efficiency of those reserves in protecting threatened species have being challenged in the past decades (Wan et al., 2014; Ng et al., 2015). Based on the distribution of 302 threatened plant species (a preliminary checklist of the Chinese Species Red List, Wang and Xie, 2004), Zhang and Ma (2008a) found large conservation gaps between the distribution and conservation of threatened plant species in China. The fact that some gaps still exist among these nature reserves implies that the protection of threatened plants is facing tough challenges in China.

Recently, the Ministry of Environment Protection of the People's Republic of China (2013) assessed the living status of 34,450 plants in China and published the China Biodiversity Red List: Higher Plants. According to the assessment, 3767 species from 176 families were identified as threatened plants, including 583 CR species, 1297 EN species and 1887 VU species, which is a ten-fold increase from previous reports (Wang and Xie, 2004). It is, therefore, of critical importance to re-evaluate the status of the in situ conservation of the threatened plants in China (Rodrigues et al., 2004; Wu et al., 2014; Zhang et al., 2015).

In this study, we compiled a 10 × 10 km resolution distribution database for nearly all threatened plants and then analyzed the distribution patterns of threatened plants and further evaluated the in situ conservation status of threatened plants in China. There are already several studies on the patterns of threatened plants based on county level distribution of previously defined threatened plants (Tang et al., 2006; Zhang and Ma, 2008a). However, the distribution of threatened plants is still unclear because of limited data availability. Specifically, our study has the following four characteristics. Firstly, the number of threatened plants in the China Biodiversity Red List has been widely expanded to 3767 species because of the larger number of plants that have been evaluated (Qin and Zhao, 2014). By comparison, Zhang and Ma (2008a) included 302 species and Tang et al. (2006) included 388. Secondly, we refined the distribution to a resolution of 10 × 10 km, which is much higher than the county level distribution used in previous studies (Tang et al., 2006; Zhang and Ma, 2008a). Thirdly, we compiled a distribution dataset based on all sources, compared to the local flora and specimen records in previous studies (Chen et al., 2002; Tang et al., 2006; Zhang and Ma, 2008a). Lastly and most importantly, we evaluated the conservation status of each of the threatened plants by comparing its distribution with the spatial database of the nature reserves, and therefore were able to calculate the coverage of nature reserves for each species. Two specific questions were posed here: (1) Where were the threatened plants distributed? and (2) How were these threatened plants conserved in China?

2. Material and methods

2.1. Threatened plant species in China

The threatened plant species used in this study are from the China Biodiversity Red List (Ministry of Environment Protection of the People's Republic of China, 2013; Qin and Zhao, 2014). The evaluation was conducted by 294 authoritative experts across China according to the IUCN Red List Categories and Criteria (Version 3.1, IUCN, 2001) and Application of the IUCN Red List Criteria at Regional Levels (Version 3.0, IUCN, 2003). The base list of the evaluation is from the "Catalogue of Life China" (http://www.sp2000.cn/joacn/), which covers almost all the wild higher plants in China. Finally, the Red List assessed the status of 34,450 species (including infrataxa) from 437 families, resulting in 3767 threatened species, including 583 critically endangered (CR), 1297 endangered (EN), and 1887 vulnerable (VU) species. The assessment is based on expert knowledge, specimen records (4,816,050 available specimens in total), and a literature review (more than 4000 sources). Please refer to Qin and Zhao (2014) for a more detailed description of the evaluation.

2.2. Distribution of the threatened plants in China

Our data on the distribution of the threatened plants are based on three sources. First, for the woody plants, we extracted the county level occurrences from the Atlas of Woody Plants in China (Fang et al., 2011). Second, for the herbaceous plants, we compiled the county level occurrence based on all available literatures, such as national, provincial and local floras, checklists of nature reserves, monographs of field investigation, and peer reviewed articles. Third, we further searched the specimen records from the China Virtual Herbarium (www.cvh.ac.cn) for all the threatened plants, and the locations (towns and villages) where the specimen was collected were digitalized for biodiversity mapping.

For the first two sources (county level distribution of woody and non-woody plants), the county level occurrence might over-estimate the distribution of each species, therefore, we also collected the upper and lower elevation records and habitat type of each species to refine the distribution. Then we overlapped the county level occurrence with a vegetation map of China (1:1,000,000) (Editorial Committee of Vegetation Map of China, 2007) and a digital elevation model (DEM) obtained from the United States Geological Survey (at a resolution of 30 m, available at http://reverb.echo.nasa.gov/reverb/redirect/wist). We defined the distribution as grids containing the habitat types and any elevation between the upper and lower limit of the county where the species occur. Finally, the distribution based on all three sources was transformed into grids at a resolution of 10 × 10 km, as this resolution is widely used for species distribution modeling at regional or country scales (Zhang et al., 2014; Irannezhad et al., 2015). In total, we compiled 888,596 distribution records for 3244 threaten species of higher plants (86% of the total threatened plants in China) from 176 families, of which 483 are CR species, 1112 EN are species and 1649 are VU species. It includes 2175 endemic and 1069 non-endemic species to China (Qin and Zhao, 2014).

In the analyses, we also equally grouped the threatened plants into four types (811 species in each types) according to their distribution ranges, including most narrowly distributed (Q1), narrowly distributed (Q2), widely distributed (Q3) and most widely distributed (Q4). Q1 species included one quarter of species with the narrowest distribution ranges; Q2 species included one quarter of species with the second narrowest distribution ranges; Q3 species included one quarter of species with the second widest distribution ranges; and Q4 species included one quarter of species with the widest distribution ranges.

2.3. Spatial database of nature reserves in China

Among the ~2600 nature reserves established before the end of 2012 in China, 319 NNRs and 835 PNRs are terrestrial (Zhao et al., 2013). To evaluate the representativeness of threatened plants in those nature reserves, we compiled the spatial database on NNRs and PNRs by digitalizing all terrestrial NNRs and PNRs using geographical information system techniques, using ArcGIS 10.2 software (ESRI, Redlands, US). We only included the terrestrial NNRs and PNRs because of the following facts, first, NNRs and PNRs covered >92% of the total area of terrestrial nature reserves in China (Zhao et al., 2013), second, most prefectural and county level nature reserves were not well managed (Quan et al., 2009); third, boundaries of these prefectural and county level were not well defined (Zhao, 2013).

2.4. Representativeness of threatened plants in nature reserves

We evaluated the representativeness of each threatened plant by calculating the proportion of the distribution area covered by NNRs and by NNRs and PNRs combined for each species. To do this, we first overlaid the distribution map with the NNRs and PNRs maps for each species, and defined the protection rate of each species as the ratio of the area covered by either NNRs or NNRs and PNRs combined with the total distribution area of the species. As a result, we find some species not covered by any NNRs or PNRs and the distribution area was then classified as a conservation gap.

All statistical analyses were carried out in R (ver. 2.15.1) (http://www.r-project.org/).

3. Results

3.1. Geographical distribution of threatened plants richness in China

As a whole, threatened plants were distributed widely across China, among which, the southwestern region of the mainland (mainly in Yunnan, southeastern Xizang and western Sichuan), Hainan Island and the mountainous regions of Taiwan contain the highest levels of richness (Fig. 1a). Richness is also high in South China (mainly in Guangxi, Guangdong and Fujian), but low in Eastern China (mainly in Shanghai, Jiangsu, Anhui and Shandong), Northern China (mainly in Beijing, Tianjing, Hebei, Shanxi and Inner Mongolia), Northeastern China (mainly in Liaoning, Jilin and Heilongjiang) and Northwestern China (mainly in the northwestern Xizang and Xinjiang). In some regions in Qinghai, Hebei, Shandong, Jiangsu and Chongqing Provinces, no threatened species were recorded (Fig. 1a). The high richness of threatened plants endemic to China occurred in the Southern and Northern part of Yunnan Province and the Southwestern part of Hainan Island (Fig. 1b); whereas the non-endemic species mostly distributed along the country's territorial border in the Southwest comprised of the provincial border of southeastern Xizang, south Yunnan and southwestern Guangxi, and the meeting belt of Guangxi and Guizhou (Fig. 1c).

For different categories, the CR species were concentrated in Southwestern China (mainly in Yunnan, Guangxi, Sichuan and Hunan), but all with less than 20 species (Fig. 1d); richness of the EN species was high in the southern part of Yunnan Province and Southwestern part of Hainan Island (Fig. 1e). The richness of VU species showed similar patterns with that of the overall threatened species, which was high in the Southwestern part of the mainland (mainly in Yunnan, southeastern Xizang and western Sichuan), the Hainan Island and the mountainous region in Taiwan (Fig. 1f).

3.2. Representativeness of threatened plants in the NNRs and PNRs in China

On average, NNRs covered 18.8% (std = 21%) of the distribution areas for all threatened plants in China. The protection coverage for the most narrowly distributed threatened plants was higher (Q1, mean = 21.6%) than narrowly (Q2, 20.5%), widely (Q3, 18.3%) and most widely (Q4, 14.9%) distributed threatened plants. It is noteworthy that 827 threatened species were not covered by any NNR in China, among which 19 were most widely distributed (Q4), 125 were widely distributed (Q3), 260 were narrowly distributed (Q2), and 423 were most narrowly distributed (Q1) (Fig. 2a). Of all the unprotected threatened species, 627 were endemic to China. NNRs covered 18.5% (std = 24%), 20.3% (std = 22%) and 17.9% (std = 19%) of distribution areas for all CR, EN, VU species, respectively. In total, 183 CR, 263 EN and 381 VU species were not covered by any NNR in China (Fig. 2c).

NNRs and PNRs together covered 27.5% (std = 22%) of the distribution areas for all threatened plant species in China. The protection coverage was higher in the most narrowly (Q1, mean = 30.3) and narrowly distributed threatened plants (Q2, 28.7%) than the widely (Q3, 27.3%) and the most widely distributed threatened plants (Q4, 23.6%). In total, 397 threatened plants, including 293 endemic to China, were covered by neither NNRs nor PNRs, including four most widely distributed (Q4), 30 widely distributed (Q3), 107 narrowly distributed (Q2), and 256 most narrowly distributed (Q1) threatened plants (Fig. 2d). NNRs and PNRs together covered 27.0% (std = 25%), 28.7% (std = 22%) and 26.8% (std = 20%) of distribution areas for CR, EN and VU plants in China, respectively; while 93 CR, 121 EN and 183 VU plants were not covered by any NNR or PNR (Fig. 2c).

A large percentage of the unprotected threatened plants by NNRs were distributed in Southwest China (mainly in southern Xizang, the convergence of Yunnan and Sichuan, southwestern Yunnan, Guizhou and the country's territory border in Guangxi), with some distributed in the Southeast (mainly on the southeast coast of Guangdong and the southwest coast of Fujian), the South (mainly in North Hainan), Central (mainly in central Hubei) and Northwest China (mainly in the country's territory border in Xinjiang, Fig. 3a). When the PNRs were considered, the unprotected threatened plants were mostly distributed in Southwest China (mainly in Yunnan, Guizhou and Guangxi Provinces), central Hainan and East Zhejiang (Fig. 3b).

4. Discussion

4.1. Distribution patterns of threatened plants in China

Based on fine resolution distribution data, we explored the patterns of threatened plant richness in China. We found that South China has the most threatened plants, while East China, North China, northeastern and northwestern China have the least threatened plants (Fig.1a). The hotspots of threatened plants identified in this study are mostly located in the biodiversity hotspots identified in China (Tang et al., 2006), and this pattern is consistent with that in other plant groups in China, such as woody plants (Wang et al., 2011) and overall plants (Tang et al., 2006). The pattern is also consistent with the distribution of endemic plants in China (López-Pujol et al., 2006; Huang, 2011), partly because the threatened plants in China are mostly endemic to China (67.0% in our dataset). Compared to Zhang and Ma (2008a) and Tang et al. (2006), who found that the county-level distribution regions of threatened plants are mainly in Central and South China, while the distribution of threatened plants in our study show a broader and more continuous distribution. According to previous studies (Zhang and Ma, 2008a), hotspots of threatened plants only appeared in three small regions in Yunnan, including Hengduan Mountains, Xishuangbanna Region and southeastern Yunnan. In contrast, we identified the entire Yunnan province as a hotspot for threatened plants. Analogously, we also found northern Hainan, northwestern Guangxi and the southern part of Jiangxi as hotspots for threatened plants. Meanwhile, we also identified hotspots for plants with different threat levels, and for endemic and non-endemic threatened plants. This is partly because of the finer spatial distribution data, the large number of species analyzed, and increased data sources. Larger species size tends to illustrate more comprehensive results and better fit into the real world, while higher resolution significantly reduces spatial correlation errors and increases accountability (Pitt et al., 1997).

Previous studies have also showed that endangered vertebrates were mainly concentrated in the Hengduan Mountains, South Yunnan, the East China Mountains and Hainan Island (Chen et al., 2002; Tang et al., 2006; Huang, 2011). Hotspots of threatened plants in our study covered the distribution those of endangered vertebrates (excluding birds) in China, indicating their distribution regions are prioritized areas and need more attention (Zhao et al., 2015).

4.2. Conservation of threatened plants in China.

Threatened species are more vulnerable to extinction than other species because of their limited geographic ranges, population size,

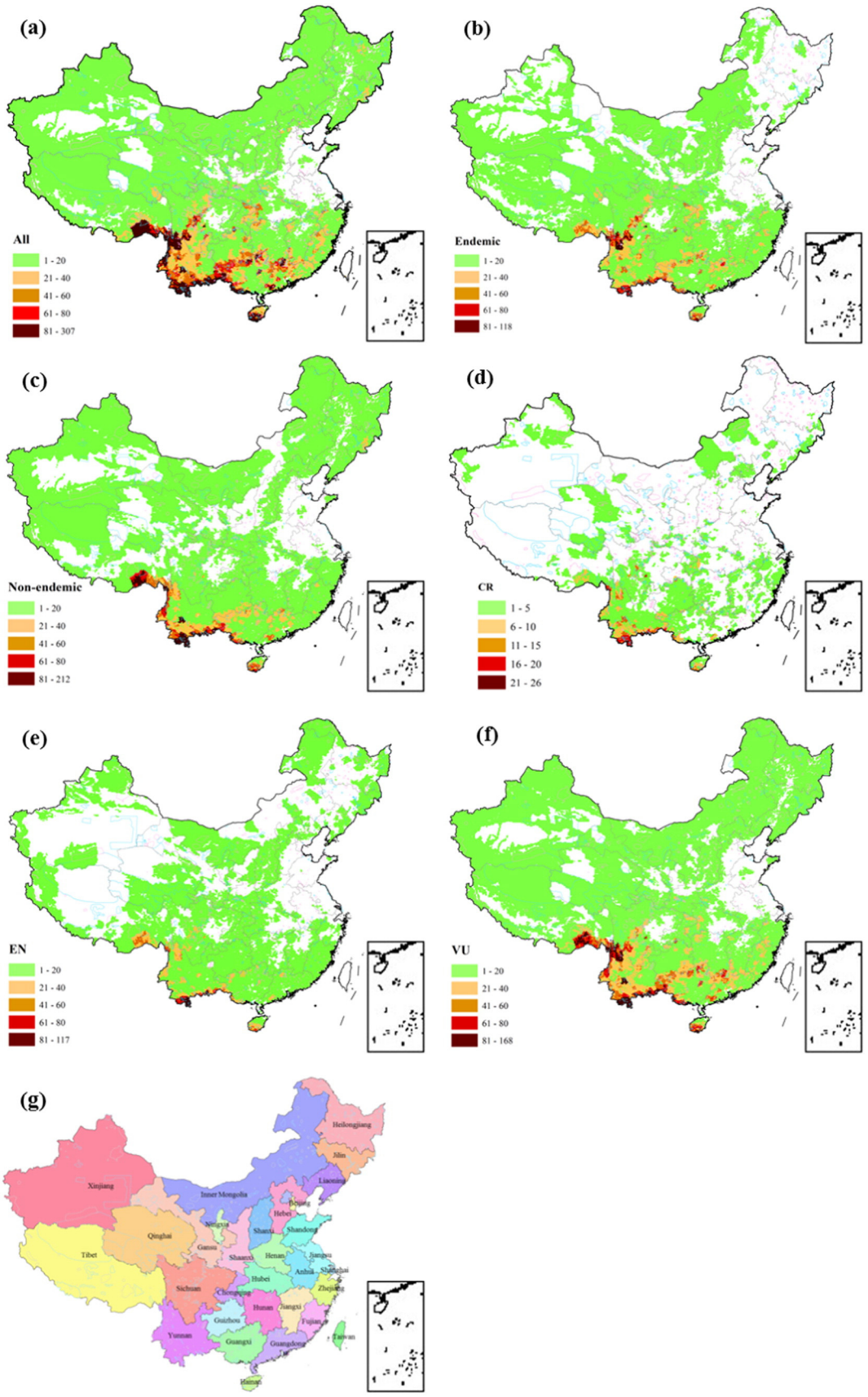

Fig. 1. Distribution of threatened plant richness in China and nature reserves: (a) all threatened plants, (b) threatened plants endemic to China, (c) threatened plants non-endemic to China, (d) critically endangered plants, (e) endangered (EN) plants, (f) vulnerable (VU) plants. The sub-figure (g) illustrated the provinces of China. Blue lines indicate the border of NNRs, the pink lines indicate that of PNRs and the gray lines indicate the provincial boundary.

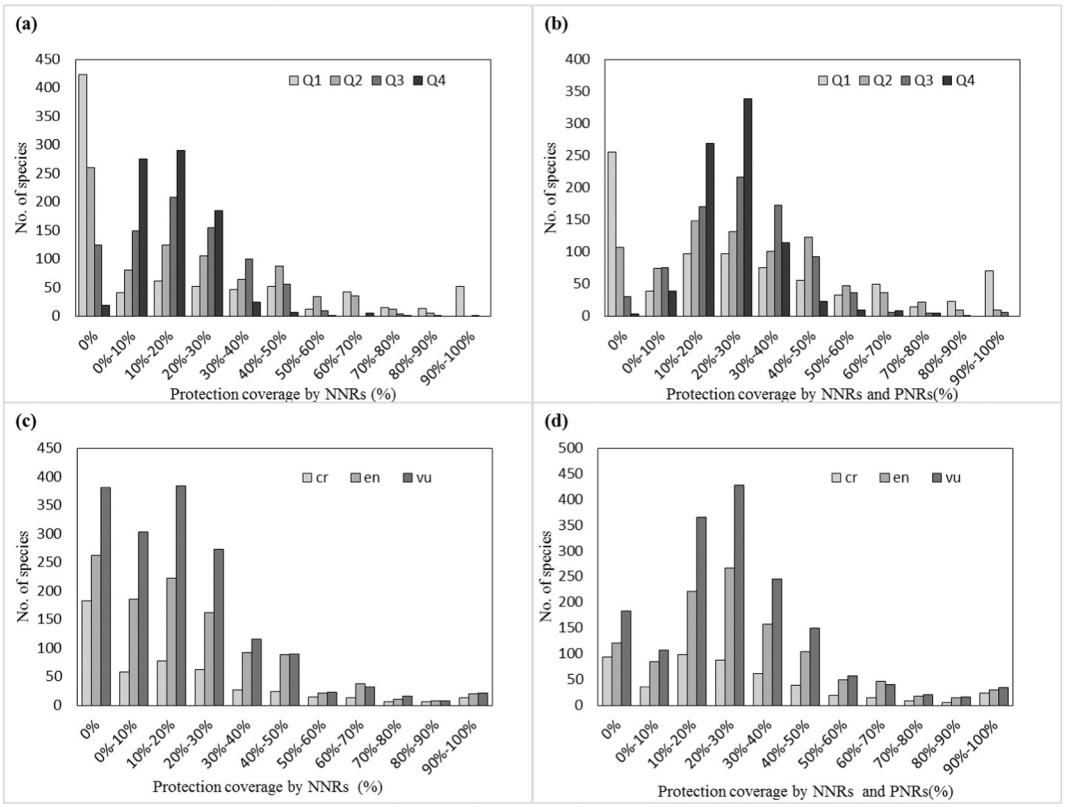

Fig. 2. Frequency distribution of percentage of threatened plants covered by national nature reserves (NNRs) (a & c) and by both national and provincial nature reserves (NNRs and PNRs) (b & d) in China for threatened plants with different range sizes (a & b) and different threatened level (c & d). Q1: most narrowly distributed quarter, Q2: narrowly distributed quarter, Q3: widely distributed quarter, and Q4: most widely distributed quarter; CR: critically endangered, EN: endangered, VU: vulnerable.

and vulnerability from external factors, such as anthropogenic activities and climate change (Myers et al., 2000; Huang, 2011). The ecological significance of threatened species has been confirmed in other studies, and focusing conservation efforts on endangered and threatened species could also help to conserve other species (Warman et al., 2004).

Regional and global studies have shown that the global protected area networks are not in a position to meet their protected goal to conserve biodiversity (Schipper et al., 2008; Tognelli et al., 2008). Our study reconfirmed this finding. The network of protected areas used in this study (including NNRs and PNRs) covers, approximately, 13.7% of the total land area of the country, and protection of threatened plants in China represents 36% of overall number worldwide (www.iucnredlist.org). There is no doubt that the present protection situation of threatened plants in China can act as a great supplement for the world's threatened plants. However, its spatial distribution is far from providing adequate coverage of threatened plants.

National nature reserves (NNRs) covered 75% and provincial nature reserves (PNRs) cover another 13% of the threatened plants. However, nearly 25% of the threatened plants, i.e. 827 species (of which 297 species are endemic to China) are still outside NNRs. Furthermore, around 12% of threatened species, i.e. 397 species (of which 293 are endemic), are still outside of both NNRs and PNRs. These unprotected species are distributed mostly in South China, consistent with the conservation gaps for orchids (Zhang et al., 2015). These results, together with the

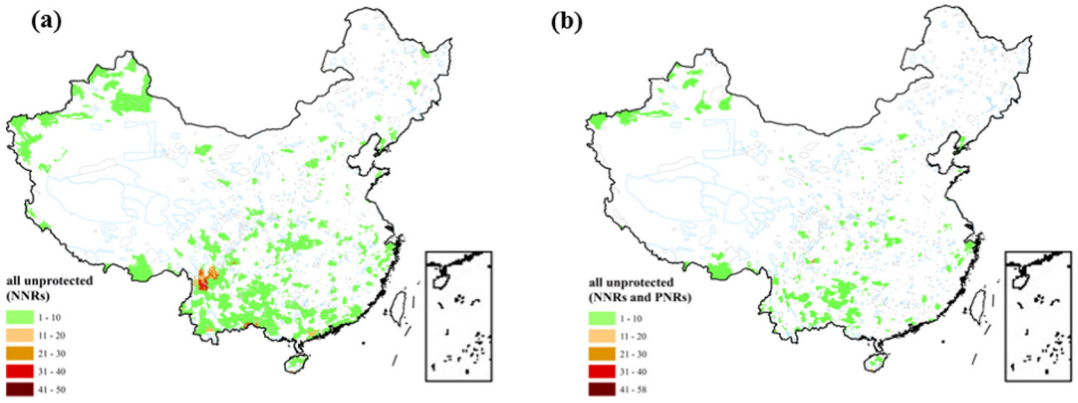

Fig. 3. Distribution of richness of threatened plants not covered by national nature reserves (a) and by either national or provincial nature reserves (b) in China. Blue lines indicate the border of NNRs, pink lines indicate that of PNRs, and gray lines indicate provincial boundaries.

fact that over half of threatened species in Yunnan are endemic to China, indicate the importance of setting up new nature reserves in Yunnan Province. We also identified many conservation gaps in some other regions in South China and Northwest China, for example, in Guizhou, Guangxi, Guangdong and Xinjiang Provinces (Fig. 3). This conservation gap is slightly different from a recent study by Zhang and Ma (2008a), partly because of the limited nature reserves and species number or species distributions used. For instance, only 265 nature reserves and 302 species were used in Zhang and Ma's study (2008a), while by comparison, this study used most of the terrestrial national (319) and provincial nature reserves (835) established before the end of 2012.

Our results highlight the significance of conservation of threatened plants species in overlapping areas with high species richness in South China, especially in Yunnan, Guizhou, Guangxi, Xinjiang Hainan, and Zhejiang provinces. Considering the current rates of human encroachment and the possibility of future land use changes, the existing nature reserves in China are not adequate to represent threatened plants diversity (Pauchard et al., 2006; Wilson et al., 2005). Strategic action is urgently needed to meet the management gap, especially in Eastern China where fast economic growth is the main driver of ecosystem degradation (Armesto, 1998; Zhao et al., 2013). We therefore propose prioritizing designated provincial reserves at the national level in these areas specifically designed for threatened plant species, and setting up natural reserves especially in Yunan, Hainan, Guangdong and Fujian provinces. At the same time, better management strategies should also be developed to ensure the efficiency of related nature reserves.

4.3. Uncertainty of the present study

Although the dataset is the best that can be compiled at current conditions, there are still some weaknesses in the present study. Firstly, although including a large number of species, the present China Biodiversity Red List is not perfect and the list for higher plants is still a 'work in progress'; there are still many endemic plant species with small populations, particularly those in southwestern China, that are not included on the list for some reasons (Chen et al., 2014). Secondly, the distribution data was not based on in situ investigations, but extracted from different sources including specimen records and county level records. Among these data sources, the overlaying of county level occurrences with elevation range and habitat types may slightly overestimate the distribution range of species. Thirdly, we assumed that nature reserves and species range may coincide when both occurred in the same grid (10×10 km), but without counting for other scenarios, therefore may slightly overestimate the conservation percentage. Lastly, the land cover data we used are based on the vegetation atlas of China (Editorial Committee of Vegetation Map of China, 2007), which is based on investigations in 1990s. Land use and land cover changed rapidly during the past few decades in China (Seto and Fragkias, 2005; Liu et al., 2010). Although this is the most updated, comprehensive and credible source available at the national scale under current conditions, it may influence the current distribution of threatened plants (Li et al., 2007). More studies based on in situ investigations and the most updated land use data are needed to design nature reserves specifically for threatened plants at local scales.

Acknowledgments

We are grateful to G.H. Zhao for assistance in data collection and we would also like to thank Alison Cassidy from the University of California at Davis for her assistance with English language and grammatical editing of the manuscript. This research was partly supported by the Special Research Funding for the Public Benefits of the Ministry of Environmental Protection (#201209028) and the National Natural Science Foundation of China (NSFC #31021001 & 31170499).

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