Conservation status of threatened land plants in China and priority sites for better conservation targets: distribution patterns and conservation gap analysis

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Received: 4 January 2022 / Revised: 10 March 2022 / Accepted: 1 April 2022 / Published online: 2 June 2022 © The Author(s) 2022

Abstract
There are about 10% of the world’s land plants in China, of which 11% are threatened species. Here, we used China as a proxy to identify hotspots of threatened species, evaluate the effectiveness of current conservation networks and assess the correlations between distribution patterns of different groups. We built the most complete database of 3,881 species of threatened land plants in China (TLPCs) to date, based on 43,710 occurrence records at county level. A total of 467 counties identified as hotspot by species richness, complementarity, and weighted algorithms, mostly confined to the mountainous areas in southern China, which account for 15.58% of land area, however, hold 95.34% of the total TLPCs. The correlation analysis revealed weak to moderate relationship between the distribution patterns of three groups (bryophytes, ferns, and gymnosperms) and angiosperms of TLPCs. We found 86.34%, 84.05% and 95.77% of TLPCs protected by NNRs, PNRs and NRs [nature reserves, including both national NRs (NNRs) and provincial NRs (PNRs)], respectively. Besides, there were 41.11% and 18.84% of hotspots identified as conservation gaps of NNRs and NRs, respectively. In conclusion, the NNRs do not play a more dominant role in conserving TLPCs diversity in comparison to PNRs. We proposed that conservation planning need to be established in the periphery of Yunnan-Guizhou Plateau due to a large number of hotspots and conservation gaps located in this area. Since a large proportion of unprotected TLPCs are critically endangered and narrow-ranged species, it is urgent to set priorities for their conservation in the nearest future.

Keywords Complementarity · Conservation gaps · Distribution patterns · Narrow-ranged species · Species richness · Threatened land plants
Introduction

Plants are integral part of biodiversity, playing two important roles in maintaining global environmental balance and ecosystem stability (CBD 2010). However, biodiversity is declining at an accelerated rate due to habitat loss and fragmentation, over-exploitation of resources, climate change and invasion of alien species (Miller et al. 2012; Monastersky 2014; Pimm et al. 2014; Teller et al. 2015; Johannes et al. 2019). In 2020 the IUCN (International Union for Conservation of Nature) enlisted ~35,500 species which are threatened to extinction (IUCN 2021). China is one of the countries, holding significant higher plant diversity in the world due to its unique geography and climate (Sang et al. 2011; Liu et al. 2015). There are ~35,000 land plant species (bryophytes and vascular plants) recorded in China, accounting for about 10% of the world’s total records, with about 50% endemics (Huang et al. 2011; Wang et al. 2015b; Qin et al. 2017a). However, due to population growth and rapid urbanization pressures, the number of threatened plant species in China has increased significantly (Ren et al. 2019). China has up to 3,879 TLPCs threatened to extinction, accounting for 10.84% of the total land plants in China (Qin et al. 2017a). However, very little is known about the conservation status of these TLPCs.

The Convention on Biological Diversity (CBD) in 2010 proposed 20 different targets called the Aichi Biodiversity Targets. One of the crucial among the Aichi Biodiversity targets was to conserve at least 17% of terrestrial areas by 2020. To achieve this target, it is necessary to consider effective management, ecological representation, and a system that can connect protected areas and other area-based conservation measures (CBD 2010). In addition, in situ conservation is one of the great significances to national ecological security and the most feasible way to conserve biodiversity (Heywood and Dulloo 2005; Huang 2011). In consonance with the Aichi Biodiversity targets, China has established a large number of protected areas, which cover over 17% of its terrestrial areas (Zhang et al. 2017). Nature reserves (NRs), including national nature reserves (NNRs) and provincial nature reserves (PNRs), are a vital part (over 80%) of these protected areas and have been well managed (Zhao et al. 2013; Zhang et al. 2017; Xu et al. 2017a). For effective conservation of these nature reserves, China has conducted nationwide assessments on vegetation (Wu et al. 2011; Sun et al. 2020), amphibian (Luo et al. 2015; Chen et al. 2016), and ecosystem services (Xu et al. 2017a). In all these studies, researchers found that these nature reserves are still facing severe challenges associated to their structural and management issues (Zhang et al. 2017). Similarly, there is still a lack of systematic assessments of conservation effectiveness for TLPCs at species level due to the absence of high-resolution species occurrence records. Therefore, it is very urgent to comprehensively investigate the distribution pattern of TLPCs and identify conservation gaps in the existing nature reserve networks.

Identification of biodiversity hotspots and gap analysis are the most common analytical tools to identify priority areas for biodiversity conservation, evaluate the conservation effectiveness, and maximize the conservation outcomes (Myers 1988; Scott et al. 1993; Myers et al. 2000; Xu et al. 2017b). In the past, hotspot areas were mainly identified based on species richness (the number of species within a defined region: Prendergast et al. 1993; Brooks et al. 2006; Jenkins et al. 2013; Zhang et al. 2015b). However, beside species richness, biodiversity conservation priority is also closely related to species distribution and biogeography (Huang et al. 2012; Huang et al. 2016). Moreover, the use of species richness alone as a criterion to identify conservation areas leads to huge losses in the coverage of biodiversity.
(Veach et al. 2017). To overcome this issue, analytical tools for complementarity are used to cover as many species as possible in a small area when identifying biodiversity hotspots (Prendergast et al. 1993; Dobson et al. 1997). Similarly, the weighted algorithm can also be used to prioritize the conservation of species with narrow distribution (Williams et al. 1996; Williams 2000; Crisp et al. 2001; Huang et al. 2013; Huang et al. 2016; Veach et al. 2017). So far, there are very few reports, where the conservationists integrated multiple algorithms to identify hotspots and ensure the comprehensiveness as well as the accuracy of conservation priority planning (Huang et al. 2012; Zhang et al. 2015c; Chi et al. 2017; Veach et al. 2017; Xie et al., 2022).

Threatened plant species have been of great concern due to their narrow distribution, small sizes of viable population, and high social, economic, and scientific values (Bean 2009; Wang et al. 2015a; Rejmánek 2018; Xu et al. 2019b; Fig. S1). Till to date, most of the studies only focused on the conservation status of several important taxa, such as orchid species and threatened medicinal plants (Zhang et al. 2015a; Chi et al. 2017; Liu et al. 2020) or threatened plants within very limited areas (Cao et al. 2013; Wan et al. 2014). There are very few nationwide studies where the researchers considered both the distribution and conservation priorities of TLPCs (Tang et al. 2006; Zhang and Ma 2008; Sun et al. 2013; Zhang et al., 2015b; Zhao et al. 2016; Xu et al. 2019b), however, again here majority research only focused on few number of species, avoiding representativeness of the distribution patterns and conservation status of the total TLPCs. In addition, the use of outdated and different red lists of threatened land plant species in previous studies is an insufficient argument for the conservation of TLPCs. In general, there are two commonly used red lists in the above studies, including China Species Red List (including 3,782 threatened species made assessment of 4,408 species, a part of the China flora; Wang and Xie 2004) and China Biodiversity Red List (including 3,767 threatened species made assessment of 34,450 species, the whole China flora; Ministry of Environment Protection of the People’s Republic of China 2013). However, Qin et al. (2017a) compiled an updated Threatened Species List of China’s Higher Plants, which contained 3,879 TLPCs made assessment of 35,784, the whole flora. Comparing it with the 2004’s Red list and 2013’s Red list, we found a discrepancy in species composition as well as endangered species categories, where only 40% and 93% of TLPCs species remain consistent, respectively (Qin et al. 2017b; Table S1). Beside these discrepancies, most of the recent studies on the conservation status and conservation priority planning of TLPCs are based on the outdated red lists (Li 2016; Zhang et al. 2015b). Therefore, it is necessary to study the distribution patterns of all TLPCs and evaluate their conservation status based on the updated red list.

Here, we built the most comprehensive database on occurrences/distributions of all the TLPCs to date, with more extensive information than in any previous study, accessed their distribution patterns based on species richness, complementarity, and weighted ranged size rarity for the first time. We then identified diversity hotspots using different indicators and uncovered conservation gaps. Lastly, we evaluated the conservation effectiveness of the existing conservation networks and provided feasible suggestions for developing countermeasures to set conservation priority for TLPCs in the future.
Materials and methods

Development of species occurrences database

We evaluated a total of 3,881 TLPCs (namely, bryophytes and vascular plants) from 1,215 genera and 206 families, listed as threatened on the Threatened Species List of China’s Higher Plants (Qin et al. 2017a). Out of these 3,881 TLPCs, 63.82% (2,477 TLPCs) are endemic to China belong to 802 genera and 206 families (Huang et al. 2012; Qin et al. 2017a). We also considered the narrow-ranged TLPCs, defined as the species native to China with no more than three occurrences at county level, including species endemic to China and species partly distributed in China (Qin et al. 2017b). There are 1,916 narrow-ranged TLPCs, from 788 genera and 227 families, where again 1,309 species are endemic to China (Table S1). In developing the occurrence database, we adopted the threatened categories and criteria of TLPCs following Qin et al. (2017a), and in accordance with the IUCN Red List Categories (Version 3.1; IUCN Standards and Petitions Subcommittee 2011; IUCN 2012). The threatened categories included VU (Vulnerable), EN (Endangered), and CR (Critically endangered).

We used county as a basic spatial unit to analyze the distribution patterns of TLPCs (Huang et al. 2016; Chi et al. 2017). For occurrences data, we used specimen records provided by Chinese Virtual Herbarium (CVH, http://www.cvh.ac.cn/) and county-level distribution information from Flora of China and provincial as well as local floras. We geo-referenced and standardized all the records into county levels and built a county-level occurrence database of all TLPCs. We consulted the Global Biodiversity Information Facility (GBIF) and other open-access databases as well for relevant information on TLPCs, however, there are limited information out there. The final occurrence database includes 43,710 entries of county-level distribution information on 3,881 TLPCs, including bryophytes, ferns, lycophytes, gymnosperms, and angiosperms (Table S1).

Identification of hotspots areas

We used three different algorithms, including species richness algorithm, complementary algorithm, and weighted algorithm, to analyze the distribution pattern of TLPCs. We calculated species richness for each county as a total number of species in the county. This approach defines the regions with highest species richness as hotspot (Prendergast et al. 1993; Richard et al. 2006). The complementary algorithm defines biodiversity hotspots, selecting the minimum area that can cover all the species, focusing on species irreplaceability (Dobson et al. 1997; Zhang et al. 2015a). For complementary algorithm, we assigned TLPCs from the database to counties in a hierarchical fashion, for example first, we selected a county had the highest abundance of TLPCs, excluded the TLPCs recorded for that county from the database, again run the algorithm to select the next county with the highest number of remaining TLPCs and again removed the TLPCs recorded in that second county from the database. This process was iterated until all the TLPCs were assigned to the counties and the database with zero TLPCs (see details in Chi et al. 2017). The weighted algorithm assigns different weights to species according to the inverse of the value of its range (Williams et al. 1996; Williams 2000). The weighted values of all the species in a county were
added together to obtain the weighted index of a particular county applying the following equation:

$$\text{Rarity score} = \sum_{i=1}^{n} W_i$$

where $n$ is the number of species in the spatial analysis unit, i.e., the number of species in the county, and $W_i$ is the weight of species $i$, is the reciprocal of the species range.

We identified diversity hotspot areas for conservation priority of TLPCs by considering results generated by the above three algorithms. First, we analyzed the distribution patterns of three groups (all TLPCs, endemic TLPCs, and narrow-ranged TLPCs) using three algorithms. Next, we standardized each value per county by calculating the ratio of species richness of each county to the total number of their corresponding group (Xue et al. 2021). Then, we summed all the standardized values (the ratios) of all three groups of each county corresponding to the three algorithms and selected the top 17% of the total land area with higher summed value as hotspots of each algorithm, respectively. Finally, we treated those hotspot counties identified by two or three algorithms as final hotspot counties, which were considered to be diversity hotspot areas of TLPCs.

**Conservation effectiveness and gap analysis**

China has established a total of 2,750 NRs, covering approximately 15% of land surface at the end of 2017 (Ministry of Ecology and the Environment 2019). We only considered the network of NNRs and PNRs for conservation effectiveness and gap analysis as the most prefectural- and county-level NRs are not well managed (Quan et al. 2009) and their boundaries are not well defined (Zhao et al. 2013; Zhang et al. 2015b). To evaluate the conservation effectiveness of the existing NRs and identify conservation gaps, first, we compiled geo-document layers of the nature reserve network based on the list of nature reserves (http://www.mee.gov.cn) and using the documents of the World Database on Protected Areas (https://www.protectedplanet.net/), which included 464 NNRs and 806 PNRs. Then, we calculated the number of species in counties which had established NNRs and PNRs to evaluate the conservation effectiveness of existing conservation networks (NNRs, PNRs and both). Conservation gap analysis was performed by overlapping the final diversity hotspots of TLPCs with the range of NRs. If hotspot counties without established NNRs or PNRs, we treated these counties as conservation gaps (Chi et al. 2017; Zhang et al. 2021).

**Species composition of TLPCs and correlations of distribution patterns**

We statistically analyzed the species composition of different taxonomic groups contained in the hotspots and existing NRs (including both NNRs and PNRs) as well as the conservation effectiveness and gaps of NRs. We illustrated the results using chord diagram and circular barplot as implemented in the R package “circlize” (Gu et al. 2014) and “tidyverse” (Wickham et al. 2019). We classified all the species into three groups according to priority of conservation, namely narrow-ranged TLPCs, endemic TLPCs (excluding narrow-ranged TLPCs), and the remaining species (excluding narrow-ranged and endemic TLPCs, Table S8) to have a better resolution of illustration.
To reveal the factors influencing threatened land plants in China, we further accessed the distribution patterns of TLPCs in different threatened categories and criteria. For this purpose, we performed the spatial correlation of TLPCs (all, endemic and narrow-ranged TLPCs) on different algorithms, threatened categories (CR, EN, VU), criteria (A, B, C, D), and groups (bryophyte, fern, lycophyte, gymnosperm, and angiosperm) as implemented in R package “corrplot” (Wei and Simko 2017). To check upon the confidence and degree of correlations between different distribution patterns, we calculated Pearson’s coefficient. Different categories used for correlation statistics include \(|r|\) value (0.90 \(\leq |r| < 1\), very strong correlation; 0.70 \(\leq |r| < 0.90\), strong correlation; 0.40 \(\leq |r| < 0.70\), moderate correlation; 0.10 \(\leq |r| < 0.40\), weak correlation; and 0 \(\leq |r| < 0.1\), negligible or no correlation, see details in Wei and Simko 2017; Schober et al. 2018). To run the correlation analysis smoothly, we filled the counties without occurrence or absence value with zero (value 0).

**Results**

**Distribution patterns of TLPCs**

According to the species richness algorithm, counties with high species richness are mostly confined to southwestern part of China in all TLPCs, especially two apparent diversity ranges, one is southwest of Sichuan and border areas of western Yunnan and southeastern Xizang, the other is border areas of southern Yunnan, southwest of Guangxi, border area of Guangxi and Guizhou, and northern Guangdong (Fig. 1a). Distribution pattern of the complementary algorithm is congruent with the former but appeared more scattered, and most counties with higher species richness also confined to the two regions (Fig. 1b). For the weighted algorithms, the distribution pattern, and counties with high value of rarity are also coincided with the first one but the two regions with high rarity score were not as apparent as the species richness algorithms (Fig. 1c). In addition, the bryophytes are mostly

![Fig. 1](image-url)
concentrated in southern Hainan, northwestern Yunnan, and southern Xizang (Fig. S8a). The fern (including lycophytes) are mostly aggregated to the south of Qinling Mountain-Huaihe River, notably Taiwan, Hainan, and southern Yunnan (Fig. S8b). The gymnosperms are distributed near the political boundary between Hubei and Chongqing, Taiwan, northern Fujian, the boundary between Hunan, Guangxi and Guizhou, and northwestern Yunnan (Fig. S8c). Contrary to the gymnosperms, angiosperms are mostly distributed in southeastern Xizang, the border between Sichuan and Yunnan, and southern Hainan (Fig. S8d).

The correlation analyses indicate distribution patterns of all, endemic and narrow-ranged TLPCs showed strong to very strong correlations (r = 0.74–0.95, r = 0.82–0.92, p < 0.01), according to species richness algorithms and complementary algorithm, respectively (Fig. 2). However, there are moderate correlations (r = 0.47–0.61, p < 0.01) between distribution pattern of the weighted algorithm and species richness algorithm or complementary algorithms. Furthermore, according to the species richness algorithm, except distribution patterns of bryophytes, ferns and gymnosperms, there are apparent strong to very strong correlations (r = 0.88–0.99, p < 0.01) between other plant groups regardless of different threatened categories and criteria. There are weak to moderate correlations (r = 0.49–0.7, p < 0.01) between the distribution patterns of three groups (bryophytes, ferns and gymnosperms) and angiosperms.

**Fig. 2** Correlogram of distribution patterns of all TLPCs (TH), endemic TLPCs (TH_E), narrow-ranged TLPCs (NA_R), bryophytes (Bryo), ferns and lycophytes (Fern), gymnosperms (Gymn), and angiosperms (Angi), species under Criterion A, species under Criterion B, species under Criterion C, species under Criterion D, endangered (EN), vulnerable (VU), and critically endangered (CR) of TLPCs according to species richness algorithm, and distribution patterns of all TLPCs (TH_C), endemic TLPCs (TH_E_C), narrow-ranged TLPCs (NA_R_C) using the complementary algorithm as well as distribution pattern of species range of rarity score of all TLPCs (RS) according to weighted algorithm.
Distribution pattern of diversity hotspots for TLPCs

There are 500 counties (accounting for 17.01% of land area) recognized as hotspot counties of species richness algorithm (Table S3), which are distributed mainly in the southwestern and southern parts of China (Fig. 3a). These hotspot counties contain 3,640 TLPCs (accounting for 93.79% of all TLPCs), belonging to 1,158 genera and 273 families (Table S9). According to the complementary algorithm, only 276 counties (13% of land area) identified as hotspot counties (Table S4) with most of them confine to the northwestern and southwestern parts of China (Fig. 3b). Hotspot counties of complementary algorithm also harbor 3,640 TLPCs (93.79%), belonging to 1,159 genera and 271 families, with 2,303 endemics and 1,705 narrow-ranged species (Table S9). For the weighted algorithm, there are a total of 597 hotspot counties (accounting for 17.01% of land area, Table S5), which were mainly confined to the southwestern and southern parts of China (Fig. 3c). In these hotspot counties, there are 3,762 species (96.93%) belonging to 1,182 genera and 275 families, with 2,402 endemics and 1,816 narrow-ranged species (Table S9).

Finally, we determined a total of 467 counties as diversity hotspots, where 206 are first-class hotspots (identified by three algorithms) and 261 are second-class hotspots (identified by two algorithms; Table S7). These hotspot counties account for 15.58% of the land area, closer to 17% (a goal of the global protected land in Aichi Target 11), and were divided into 18 diversity hotspot areas for TLPCs, including (1) Tianshan-Altai Mountains, (2) South-eastern Himalayas, (3) Qilian Mountains, (4) Three-river Headwater Region, (5) Hengduan Mountains, (6) Southern Yunnan, (7) The mountains areas in western Guangxi, southeast-

Fig. 3 Hotspot counties of TLPCs identified by (a) species richness algorithm, (b) complementary algorithm, (c) weighted algorithm, and (d) the above three algorithms. The red color shows counties identified as hotspot by all the three algorithms used, orange by only two algorithms, and green with only one
ern Yunnan and southwestern Guizhou, (8) Qinling Mountains, (9) Bashan-Wushan Mountains, (10) Daloushan-Wuling Mountains, (11) Nanling Mountains, (12) Hainan Island, (13) Northeastern Taihang Mountains, (14) Changbai Mountains, (15) Dabie-Mufu-Luoxiao Mountains, (16) The hilly Region of Southeastern China, (17) Taiwan Island, and (18) The mountains areas of western Guangdong and eastern Guangxi (Fig. 4a; Table 1). The final hotspots harbor 3,700 (95.34%) TLPCs, belonging to 1,176 genera and 274 families, with 2,353 (94.99%) endemics and 1,760 (91.86%) narrow-ranged species. And most importantly, these areas include 582 species of CR (94.48%), 180 ferns (including lycophytes, 98.36%) and 146 gymnosperms (97.99%, Table S9).

**Conservation effectiveness of the existing conservation network focusing on the whole country**

Based on the distribution of NNRs, we recovered a total of 901 counties covered by NNRs, accounting for 58.92% of the total land area. These counties harbor 3,351 species, accounting for 86.34% of TLPCs, with 473 species of CR (76.79%) and 137 ferns (including lycophytes, 74.86%, Fig. 5; Table S10). Besides, we found 1,182 counties covered by PNRs, accounting for 59.50% of the total land area. Counties with the network of PNRs harbor 3,262 (84.05%) TLPCs, consist of 2,059 endemics and 1,335 narrow-ranged species (Fig. 5; Table S10). These counties harbor 485 species of CR (78.73%) and 133 bryophytes (71.12%). For the distribution of national and provincial nature reserves (NRs), a total of 1,560 counties have established NRs, accounting for 79.41% of the total land area. These counties harbor 3,717 species (accounting for 95.77% of all TLPCs), where 2,354 and 1,757 species were endemics and narrow-ranged TLPCs, respectively. For different taxonomic groups, 179 bryophytes, 179 ferns (including lycophytes) and 148 gymnosperms record in these counties (Table S10).

**Conservation effectiveness of the existing conservation networks focusing on hotspots**

The conservation effectiveness analysis revealed a total of 275 out of 467 (58.89%) hotspot counties covered by the NNRs, which are mainly distributed in the northeastern, eastern, northwestern, and southwestern parts of China (Fig. 4b). These protected hotspots contain 3,246 species (83.64% of all TLPCs), including 2,037 endemic species (82.24%), 1,386 narrow-ranged species (72.34%), 462 species of CR (75.00%), and 135 ferns (including lycophytes, 73.77%, Table S9). There are 272 of 467 (58.24%) hotspot counties covered by PNRs, which mainly distributed in the southern, southwestern, and northeastern parts of China (Fig. 4c). These hotspots account 3,131 species (accounting for 95.77% of all TLPCs), with 1,975 endemic, 1,258 narrow-ranged species, 466 species of CR, and 120 bryophytes (Table S9). Taken together, 379 of 467 (81.16%) hotspot counties are in the existing conservation network of NRs, and most of them are distributed in the southern, southwestern, northeastern, and northwestern part of China (Fig. 4d). These hotspots include 3,590 species (accounting for 92.50% of TLPCs), with 2,272 endemics and 1,661 narrow-ranged species. There have 553 species of CR and 162 bryophytes in these hotspot counties (Table S9).
Table 1  The final diversity hotspot areas and their identification in the three algorithms of TLPCs

| Comprehensive approaches | Species richness algorithm | Complementary algorithm | Weighted algorithm |
|--------------------------|----------------------------|-------------------------|-------------------|
| Diversity hotspot areas | Species richness algorithm | Complementary algorithm | Weighted algorithm |
|                          | All TLPCs                  | Endemic TLPCs           | All TLPCs         | Endemic TLPCs | Narrow-ranged TLPCs (17%) | Narrow-ranged TLPCs (17%) | Narrow-ranged TLPCs (17%) |
| Tianshan-Altai Mountains | +                          | -                       | +                 | +             | +                         | +                         | +                         |
| Southeastern Himalayas   | +++                        | ++                      | +++               | +++           | +++                       | +++                       | +++                       |
| Qilian Mountains         | +                          | +                       | -                 | +             | +                         | +                         | +                         |
| Three-river Headwater Region | +                        | +                       | -                 | +             | +                         | +                         | +                         |
| Hengduan Mountains       | +++                        | +++                     | +++               | +++           | +++                       | +++                       | +++                       |
| Southern Yunnan          | +++                        | +++                     | +++               | +++           | +++                       | +++                       | +++                       |
| The mountains areas of western Guangxi, southeastern Yunnan and southwestern Guizhou | +++ | +++ | ++ | +++ | + | ++ | ++ | +++ |
| Qinling Mountains        | ++                         | +                       | +                 | +             | +                         | +                         | +                         |
| Bashan-Wushan Mountains  | ++                         | +++                     | ++                | +             | +                         | +                         | +                         |
| Daloushan-Wuling Mountains | +                     | +++                     | ++                | +             | +                         | +                         | +                         |
| Nanling Mountains        | +++                        | +                       | +                 | +             | +                         | +                         | +                         |
| Hainan Island            | +++                        | +++                     | +++               | +++           | +++                       | +++                       | +++                       |
| Northeastern of Taihang Mountains | +                      | -                       | -                 | +             | +                         | +                         | +                         |
| Changbai Mountains       | +                          | -                       | +                 | +             | +                         | +                         | +                         |
| Dabie-Mufu-Luoxiao Mountains | +                     | +                       | +                 | +             | +                         | +                         | +                         |
| The hilly Region of Southeastern China | ++ | ++ | + | +++ | + | ++ | + | +++ |
| Taiwan Island            | +++                        | +++                     | +++               | +++           | +++                       | +++                       | +++                       |
| The mountains areas of western Guangdong and eastern Guangxi | + | ++ | + | ++ | + | + | + | +++ |

Note: Threatened land plants in China (TLPCs). “+++” represents the main distribution area; “++” represents the medium distribution area; “+” represents the minor distribution area; “-” represents almost not distribution area.
Fig. 4 Distribution patterns of hotspots and conservation gaps. (a) Eighteen diversity hotspot areas of TLPCs detected in this study, (b) conservation effectiveness of national nature reserves (NNRs), with hotspot counties shown in red or orange, networks of NNR in grey, and conservation gaps of NNRs in black, (c) conservation effectiveness of provincial nature reserves (PNRs), with hotspot counties shown in red or orange, networks of PNR in grey, and conservation gaps of PNRs in black, (d) conservation effectiveness of national nature reserves (NNRs) and provincial nature reserves (PNRs), with hotspot counties shown in red or orange, networks of NNR in grey, PNR in whitish grey, and conservation gaps of NRs in black, (e) species richness of all unprotected TLPCs which out of the range of national nature reserves, and (f) unprotected TLPCs out of the range of NRs.
Conservation gaps in the existing conservation network

The conservation gap analysis indicates that 41.11% (192 of 467) of hotspot counties were out of NNR networks, mostly distributed in the southwestern and western parts of China (Fig. 4b). The gaps contain 2,260 species (accounting for 58.23% of TLPCs), including 1,382 endemics and 661 narrow-ranged species. Conservation gaps of PNRs indicate 41.76% (195 of 467) of hotspot counties were beyond the range of PNR networks, mostly confined to the southwestern, southeastern, and northwestern parts of China (Fig. 4c). The gaps of PNRs contain 2,624 species (accounting for 67.61% of TLPCs), including 1,598 endemics and 894 narrow-ranged species. There are 88 out of 467 hotspot counties identified as conservation gaps of NRs, which located in the southwestern and central parts of China (Fig. 4d). The gaps of NRs contain 1,210 species (accounting for 31.18% of TLPCs), share by 90 gymnosperms (60.40%), 738 endemics and 199 narrow-ranged species (Table S9).

Moreover, in the extent of the whole country there are still 530 species, accounting for 13.66% of TLPCs, outside NNRs completely, of which 15.26% (378 species) endemics and 24.59% (455 species) of narrow-ranged species, including 143 species of CR and 443 angiosperms (Table S10). These species distribute in 282 counties, mostly concentrate in the southwestern, northwestern, and eastern parts of China (Fig. 4e). In addition, there are also 164 species, accounting for 4.23% of TLPCs are not protected by NRs, of which 123 endemics and 159 narrow-ranged species, 42 CR and 151 angiosperms (Table S10). These species distributed in 116 counties, which located in the southwestern, northwestern, and
eastern parts of China (Fig. 4f). The detailed relationships between species composition and the proportion of different taxa in each area (hotspots, NNRs, PNRs, effectiveness, and gaps) are shown in Tables S9 and S10; Figs. 5 and 6.

**Discussion**

**Hotspots and conservation priorities for TLPCs**

Hotspots identified in this study contain all hotspots recognized in previous studies (Zhang and Ma 2008; Sun et al. 2013; Huang et al. 2012; Zhang et al. 2015b; Li 2016; Zhao et al. 2016). However, due to limited sampling or outdated plant checklist a few hotspots confirmed in previous studies (Sun et al. 2013; Li 2016) are also characteristic of high species richness but of unremarkable comparing with hotspots identified here in this work. In this study, both the complementary and weighted algorithm identified some areas as hotspots for conservation priority which have been undervalued in previous studies and based on a comprehensive analysis, we further confirmed several hotspots for TLPCs that are previously identified occasionally due to limited occurrence data of the threatened plants (Tang et al. 2006; Zhang and Ma 2008), such as Tianshan-Altai Mountains, Qilian Mountains, and northeastern Taihang Mountains. It’s worth noting that Deng et al. (2019) identified genetic
diversity hotspot and refugia based on multi-plant species haplotype diversity in China, which further demonstrated to understand distribution patterns and hotspot of threatened species. Therefore, to guarantee hotspots identified more robust and reliable, more general evidence and comprehensive approaches are highly appreciated.

The common consensus is that a hotspot should represent a considerable number of endemic and threatened species, undergoing through exceptional loss of habitat (Myers et al. 2000). We extensively investigated the distribution patterns and conservation status of TLPCs in whole China using the newly updated list of threatened plants integrated with state-of-the-art statistical toolkits. We critically evaluated the conservation effectiveness of the existing conservation networks and identified hotspots for TLPCs. These hotspots are of high conservation value with 15.58% of land area coverage, which is closed to 17%, a proportion of the terrestrial area that should be protected by 2020 according to IUCN (CBD 2010). In particular, these hotspots have high taxonomic representation of TLPCs, almost contain 95% of Chinese endemic TLPCs, and more species of CR and narrow-ranged than NRs (Figs. 5 and 6; Table S10). Therefore, to conserve the most threatened species at the least cost, it is necessary to identify diversity hotspots featuring extremely high species richness and exceptional concentrations of endemic and threatened species (Olson and Dinerstein 1998; Mittermeier et al. 1998; Myers et al. 2000; Novacek and Cleland 2001).

Optimization and strengthening of conservation networks

Although the conservation networks of NNR in China play a dominating role in biodiversity conservation (Wu et al. 2011; Zhang et al. 2017), our results indicate the role of NNRs in conservation appear unapparent comparing to PNRs. Comparing with PNRs, the NNRs covered 901 counties (vs. 1,182 counties covered by PNRs) which occupied 58.92% of the total land area (vs. 59.50% of the total land area occupied by counties associated with PNRs), however, both NNRs and PNRs protected approximate number of TLPCs (86.34% of NNRs vs. 84.05% of PNRs) (Fig. 5; Table S10). Therefore, focusing on conservation of TLPCs, the NNRs appear limited advantage in either the land area or conservation effectiveness and should be pay more attention to the construction and management of NNRs. In particular, PNRs showed higher conservation effectiveness for some specific taxonomic groups than NNRs, such as ferns (including lycophytes), gymnosperms, and CR species, though they showed similar conservation effectiveness for other groups (Table S10). Furthermore, the conservation effectiveness of NNRs varied from 74.86 to 89.3% regardless of different groups, whereas the conservation effectiveness got a significant promotion (91.70–99.33%) when taking PNRs into account (Fig. 5; Table S10). This suggests that PNRs play an important complementary role in biodiversity conservation to NNRs. Given nature reserves are the most important elements and play a key role to conserve biodiversity (Watson et al. 2014), we recommend that more attention should be paid on strengthening establishment of NNRs when setting conservation priorities in future.

Our conservation gaps analysis indicates that a considerable number of TLPCs are unprotected, and most of them concentrate in the inter-provincial boundary among Guangxi, Guizhou, Yunnan, Sichuan, and Chongqing, i.e., the surrounding areas of Yunnan-Guizhou Plateau (Fig. 4b-d). However, based on large precise occurrence data the distribution patterns of conservation gaps in this study regardless of NNRs or PNRs occurred more clustered comparing to the scattered distribution patterns presented in previous study by
utilizing resampled distribution data (Zhang et al. 2015b). In addition, our results also indicate that the periphery areas of Yunnan-Guizhou Plateau have highly concentrated hotspots unprotected (Fig. 4), which has been overlooked in previous studies. Though the conservation gaps of NRs covered only 1.88% of the total land area of China, they contain 31.18% of TLPCs with an exceptional high proportion of gymnosperms (60.4%, Fig. 6; Table S9). According to distribution patterns of conservation gaps, nature reserves either NNRs or PNRs should be considered and more conservation measures should be apt to this area in the future. Given different groups received varying conservation effectiveness, further conservation countermeasures should be considered, including ecological corridors, and establishing Micro-Reserves (Fos et al. 2014; Laguna et al. 2016; Munemitsu et al. 2017; Xu et al. 2017a; Zhang et al. 2017).

**Species-specific conservation planning**

One important principle to set conservation priorities is to maximize the conservation of threatened biodiversity through allocation of limited funds and human efforts to species conservation and the critical challenge is to prioritize the taxa and regions for conservation (Vane–Wright et al. 1991; Olson and Dinerstein 1998; Myers et al. 2000; Brummitt and Lughadha 2003). As indicate in the correlation analyses, there are apparent mismatch of distribution patterns between different groups, notably bryophytes, ferns (including lycophytes), and gymnosperms (Fig. 2), even comprehensive conservation strategy would not provide high conservation efforts to each taxonomic group. Furthermore, the proportions of ferns (including lycophytes) and bryophytes unprotected by NNRs are higher than angiosperms’, even though angiosperms are a large proportion of TLPCs (Table S10), which indicates that the existing NNRs mainly focused on the protection of total TLPCs, however, neglected some specific groups. Therefore, based on systematically evaluated the conservation effectiveness and gaps of the TLPCs by using an integrated approach, we recommend that more specific conservation actions should be implemented on some specific groups associated with the apparent incongruence of their distribution patterns and the varying extent of the conservation effectiveness. Specifically, research and conservation actions for some groups of ecological and economic importance should be intensified, such as Oaks (*Quercus* spp.) and Magnoliaceae (Sara and Eastwood 2007; Daniele et al. 2007).

Similarly, high proportions of narrow-ranged TLPCs are not protected by NNRs, PNRs, and both (Fig. 5; Table S10). This can be explained by the fact that narrowly distributed species are more likely to be unrepresented in protected areas (Gove et al. 2008; Watson et al. 2011; Gruber et al. 2012; Munemitsu et al. 2017), and it might also be due to their low population abundances (Wilsey and Polley 2004; Rejmánek 2018). Nevertheless, it is also reported that the geographic range of plant species is important for the identification of hotspots (Huang et al. 2012; Huang et al. 2013; Huang et al. 2016; Veach et al. 2017), and narrow-ranged species concentrated in particular geographic areas are high susceptibility to environmental stochasticity and could be potentially replaced by widespread species (Xu et al. 2019a). Besides, the threatened category of critically endangered (CR) species received an insufficient protection compared to EN and VU species (Tables S9 and S10), possibly because a large proportion of narrow-ranged species assessed as CR species (424 narrow-ranged species out of 616 CR species, Table S1). Given most narrow-ranged and CR species unprotected by NRs are distributed in the surrounding area of Yunnan-Guizhou Plateau and
western Xinjiang (Fig. 4e & f), more specific conservation countermeasures should be trend to these areas for which play a key role to improve the conservation effectiveness of existing conservation networks and protect narrow-ranged TLPCs. However, Yunnan-Guizhou Plateau, where are dominated by ethnic minorities, with a long history and rich cultural tradition of utilization of wild plant (Liu et al. 2020), so the harmony between local biodiversity and ethnic minority cultures is of importance in maintaining the sustainable use of biodiversity. Therefore, more conservation policies at national and regional levels should be developed toward the well-being of local people to resolve the contradiction between development and utilization for the improvement of effective conservation in the existing conservation networks, especially for TLPCs.

Conclusions

Threatened species data are a valuable and important indicator for the identification of hotspots and priority areas. We identified the hotspots for TLPCs based on total evidence and multiple indices, and the results indicate that NNRs did not play a more dominant role in conserving TLPCs biodiversity compared to PNRs due to the areas and species number of TLPCs protected. We also found that PNRs play important complementary role when it comes to conserve the TLPCs. Nevertheless, a large proportion of CR and narrow-ranged TLPCs species were unprotected by existing in situ conservation networks, and some conservation gaps were found in the periphery of Yunnan-Guizhou Plateau. Therefore, to achieve sustainable development, it is necessary to set the periphery of Yunnan-Guizhou Plateau as priority areas for conservation to adjust and improve current NRs network, particularly NNRs. And it is wise to develop specific conservation plans in policymaking based on the correlations between distribution patterns of different groups of TLPCs.

Supplementary Information  The online version contains supplementary material available at https://doi.org/10.1007/s10531-022-02414-9.

Acknowledgements  We thank the Chinese Virtual Herbarium (CVH) and Global Biodiversity Information Facility (GBIF) for permission to access species distribution data. We thank Lei Wu and Changying Xia for their helpful comments on the earlier draft of the manuscript. This study was supported by the National Natural Science Foundation of China [32071654], Biodiversity Survey, Observation and Assessment Program of Ministry of Ecology and Environment of China [8-3-7-20-9] and The Biodiversity Survey and Assessment Project of the Ministry of Ecology and Environment, China [2019HJ2096001006].

Author contributions  All authors contributed to the study conception and design. Material preparation and investigation were performed by Fei Qin and Wendi Zhang. Methodology and software were performed by Fei Qin, Tiantian Xue and Xudong Yang. The first draft of the manuscript was written by Fei Qin and all authors commented on previous versions and reviewed of the manuscript. All authors read and approved the final manuscript. Material preparation, methodology, manuscript revision and supervision were performed by Shengxiang Yu, Gulzar Khan and Yunfeng Huang.

Funding  Open Access funding enabled and organized by Projekt DEAL.

Data availability statement  Supporting data and all the findings of this study are available within the article [and/or] as supplementary materials.
Statements and Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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