

## Research paper

## Plant diversity in Yunnan: Current status and future directions

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## ABSTRACT

Yunnan, located in southwestern China, harbors more than 19,000 higher plants, which represents the highest plant diversity in the country. However, plant diversity in Yunnan faces enormous threats today, including habitat destruction and fragmentation, environmental pollution, and over-exploitation of natural resources. Despite recent efforts to protect biodiversity, there are still thousands of threatened species, some of which have become extinct. We analyzed available data to gain a greater understanding of plant diversity and the status of plant conservation in Yunnan. We found that southern, southeastern, and northwestern Yunnan are hotspots of total species, endemic species, specimens, new species and threatened species, whereas southeastern Yunnan is a hotspot for plant species with extremely small populations. Moreover, we found that there are still conservation gaps and poorly protected areas in central, eastern, and northeastern Yunnan. We conclude that conservation of plant diversity in Yunnan requires modern field investigation, systematic research, the development of comprehensive databases, and government support. We recommend that conservationists pay more attention to building and improving functional protection systems and popularizing science.

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## 1. Introduction

Yunnan is located in southwestern China from 21°08'35"N to 29°15'03"N and 97°31'41"E to 106°11'45"E, where it borders Guizhou, Guangxi, Sichuan and Tibet in China and the countries of Myanmar, Laos and Vietnam. Yunnan covers a total area of 394,000 km<sup>2</sup> (Yang et al., 2008) with terraced terrain and an average elevation of 2000 m (Cheng et al., 2019; Li et al., 2013). Yunnan has six river systems, as well as 11 major and 19 small plateau lakes (Wang and Dou, 1998; Yang and Li, 2010). The highest peak is Kawakarpo, Mt. Meili in NW Yunnan, with an elevation of 6740 m and the lowest point is in SE Yunnan at the Nanxi River, which is 76 m above sea level (Yang et al., 2008).

Yunnan's climate is dominated by a large elevational range and the seasonal alternation of the southwest and southeast monsoons, which cause a wet (May to October) and dry season (November to

April) (Yang et al., 2008). The topographic configuration of Yunnan and its distinct dry and wet seasons are thought to have been critical to the development of biodiversity in this region, which is both a cradle and a museum of plant diversity.

Yunnan accounts for only 4.1% of the total land area of China, but contains more than half of all higher plants, or 19,333 species, which belong to 3,084 genera and 440 families. Furthermore, Yunnan harbors the most plant species endemic to China. To date, 160 nature reserves have been established in Yunnan (Yunnan Forestry and Grassland Bureau, 2016), and are classified into four levels: National, Provincial, Municipal and County. In 2018, the *Management Standard of Nature Reserves* was implemented, providing a basis for assessment of standardized construction and management of these nature reserves. In the same year, the first local regulations to protect biodiversity in China, *Regulations of Yunnan Province on Biodiversity Conservation*, were issued. These regulations made Yunnan a pioneer of biodiversity conservation legislation in China (Ministry of Ecology and Environment of the People's Republic of China, 2018). Consequently, research on plant diversity, assessment, and conservation in Yunnan has attracted worldwide attention and emphasized the importance of protecting national biodiversity and biological resources (Bao et al., 1995; Ma, 2020; Yang et al., 2008).

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In this work, our objectives are (1) to provide information on plant diversity and the status of plant conservation in Yunnan, (2) to evaluate the status of plant diversity surveys and research in Yunnan, and (3) to provide recommendations regarding future challenges to biodiversity in Yunnan.

## 2. Materials and methods

We integrated plant distribution data in Yunnan into a county-level distribution database of all seed plants species, specimens, new species, threatened species, and Plant Species with Extremely Small Populations (PSESPs). The distributional data were derived from latest released catalogues, published articles and online herbarium database resources, including Flora of China, Flora of Yunnan, The Checklist of Biological Species from Yunnan (2016), Species Red List of Yunnan Province (2017) (<http://bio360.kun.ac.cn/index/redlist>), Program outline of saving and protecting the species of minimal population in Yunnan Province (<http://lcj.yn.gov.cn/yunnanwz/pub/cms/2/8407/8415/8494/8497/92486.html>), Annual Report of Yunnan Nature Reserve 2016 (<http://lcj.yn.gov.cn/8415/8419/8660/8669/114841.html>), NSII (<http://www.nsii.org.cn>), Kingdonia (<http://kun.kingdonia.org/>) and Chinese Virtual Herbarium (CVH) (<http://www.cvh.ac.cn/>). We also analyzed the numbers, locations, and areas of nature reserves in Yunnan. Distribution maps were created by ArcGIS 10.4.1.

## 3. Results and discussion

### 3.1. Plant diversity in Yunnan

#### 3.1.1. The composition of plant diversity

Yunnan harbors more than half of the plant species in China (Fig. 1A). The Checklist of Biological Species from Yunnan (2016) recorded 19,333 higher plant species belonging to 3,084 genera and 440 families (Fig. 1B) (Sun and Gao, 2016). Forty-three main families (>100 species) account for more than 77% (11,662 species) of all angiosperm species in Yunnan, and nearly half of all angiosperms in Yunnan are represented by three families: Orchidaceae (995 sp.), Poaceae (936 sp.), Asteraceae (914 sp.) (Table 1). Thirteen main genera comprise over 100 species, including *Rhododendron* (349 species, 54% of China) and *Pedicularis* (196 species, 59% of China) (Table 1). However, most of the angiosperm genera in Yunnan (1989/2361) have fewer than 10 species.

#### 3.1.2. Distribution of species hotspots in Yunnan

Species richness hotspots are located in counties in SE and NW Yunnan; in contrast, counties in E and C Yunnan have relatively low levels of species richness (Fig. 2A). Gongshan County has the largest number of total species (3,985). Five additional counties (Shangrila, Jinghong, Pingbian, Jingdong and Deqin) have more than 3,000 species. Several counties (Weixi, Dali, Xichou, Jinping, Menghai, Malipo, Fugong, Luquan, Hekou and Longling) have 2,000–3,000 species (Fig. 2A).

Recent studies suggest that the most phylogenetically important regions are located in E and C Yunnan (Li et al., 2015). Specifically, although species and genera richness and phylogenetic diversity ( $\alpha$  diversity) are correlated and indicate that NW and SE Yunnan are hotspots (Li and Yue, 2019), phylogenetic analyses show that eastern regions are similar to western and southern regions, which have higher phylogenetic turnover than expected. Furthermore, phylogenetic  $\beta$  diversity indicates that floristic assemblages in C and NW, E and W Yunnan have closer relationships than traditional taxonomic approaches have shown (Li et al., 2015).

#### 3.1.3. Composition of plant diversity in different climatic zones

From south to north, Yunnan contains three climatic zones: the tropical zone in the southwest, south, and southeastern border; the subtropical zone in the west, middle and east; and the temperate zone in the high-elevation area in the northwest (Yang et al., 2008). The subtropical climatic zone, which has the largest area, harbors the largest numbers of plants: 11,452 species belonging to 2,012 genera in 250 families (Fig. 3A). The tropical zone has 7,199 species belonging 1,778 genera in 240 families. The alpine-temperate area has 4,655 species belonging to 1,024 genera in 241 families.

#### 3.1.4. Tanaka-Kaiyong line and floristic divisions

Yunnan is the intersection zone of the Sino-Japan flora and Sino-Himalaya flora. The significant floristic subkingdoms line, the “Tanaka-Kaiyong Line” (TK Line), is not only important for the dividing the Sino-Japan flora to the east from the Sino-Himalaya flora to the west, but also because it separates critical species and provides an opportunity to study vicariance (Fan et al., 2013; Li and Li, 1997; Zhu, 2019). Our findings indicate that species diversity is higher to the west of the TK line than to the east, with the west side having 255 families, 2,227 genera, 13,657 species, and 392,441 specimens and the east side having 251 families, 1,872 genera, 9,657 species, and 167,358 specimens (Fig. 3C). Previous research has shown that more endemic genera are distributed to the east of the TK line than to the west, suggesting that the TK line may be a geographical boundary of endemic Chinese seed plant genera in Yunnan (Feng and Zhu, 2010).

Wu et al. (2011) proposed that Yunnan contains the Eastern Asiatic Kingdom and Paleotropic Kingdom and can be categorized into nine floristic subregions (Wu et al., 2011). Our analysis of the composition of plant diversity of these subregions (Fig. 3B) found that the Central Yunnan Plateau subregion has the largest area and contains the largest number of total species (8,090 species belonging to 1,690 genera in 248 families). The total number of species for the remaining subregion varied from 1,454 to 7,255.

#### 3.1.5. Endemism in the flora of Yunnan

According to Yang et al. (2008), 180 plant genera endemic to China occur in Yunnan. These endemic genera are mostly concentrated in two endemic centers of biodiversity in NW (47) and SE (48) Yunnan. Of these genera, 20 are endemic to Yunnan and the Hengduan Mountains, including *Shangrilaia* Al-Shehbaz, J.P. Yue & H. Sun, *Gaoligongshania* D.Z. Li, Hsueh et N.H. Xia, and *Tsaiodendron* Y.H. Tan, H. Zhu & H. Sun (Al-Shehbaz et al., 2004; Liu and Peng, 2016; Wu and Peter, 1994; Yang et al., 2008; Zhou et al., 2017) (Table 2).

Earlier studies reported that Yunnan harbors 2,605 species endemic to China, or 18.4% of all Chinese endemics, and that these endemic species are distributed in Yunnan and in adjacent regions with similar environments (Wu and Peter, 1994). More recent evidence suggests that Yunnan contains 4,008 endemic species (Chen et al., 2013). Furthermore, 1703 species, which can only be found in Yunnan within China, are also distributed in neighboring regions of the Indochina Peninsula.

The distribution patterns of endemic plant species are highly congruent with those of total plant species (Fig. 2B). The counties with the greatest endemic species richness include Yulong (Lijiang) (549 sp.), Shangrila (Zhongdian) (483 sp.), and Gongshan (465 sp.). Thirty-two counties, most of which are located near Qujing, Yuxi, and Chuxiong, have fewer than 30 endemic species. Hotspots of endemism may have arisen for different reasons. For example, NW Yunnan has likely become a neo-endemic center due to ecological and geomorphological reasons. In contrast, S and SE Yunnan are paleo-endemic centers largely because of their geological history (Li, 1995). These regions may be long-term stable refugia because of

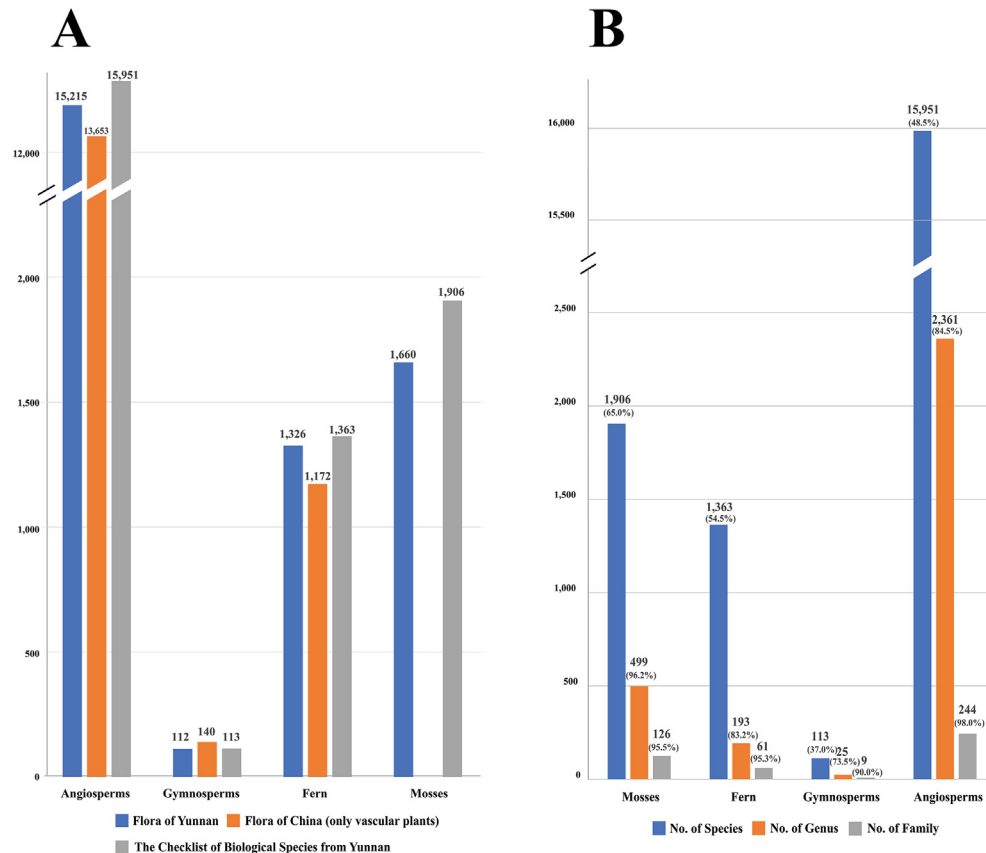


Fig. 1. (A) Number of plant species in Yunnan based on different criteria. (B) Updated composition of plant diversity in Yunnan.

the climatic stability provided by the mountains of Yunnan (Tang et al., 2018).

### 3.1.6. Diversity and distribution of vegetation

Ecosystems in Yunnan range from tropical to alpine zones (Yang et al., 2008). Despite a recent revisions to the vegetation classification system in China (Guo et al., 2018, 2020), research on the vegetation of Yunnan at a province-wide scale is still inadequate (Zhu, 2018). Previous research on vegetation in Yunnan identified 12 vegetation classes, 169 forms, and 209 associations (Wu et al., 1987). More recently, the *Ecosystem List of Yunnan Province 2018* (<http://bio360.kun.ac.cn/index/ecology>) identified 13 vegetation types, 37 vegetation subtypes, and 474 forms (Table 3). The additional vegetation types identified is Desert Vegetation, which is found in the periglacial zone of NW Yunnan. This vegetation type is characterized by several special features, including extreme elevation, rapid speciation, and extreme environments (Yang et al., 2019b). Notably, the subtype Aquatic Community has the largest number of associations (61), due to the variable wetland ecosystem in Yunnan.

### 3.1.7. Hotspots, new species, and opportunities

Yunnan has long attracted attention from botanists not only in China, but from around the world (Bao et al., 1995; Ma, 2020). This attention increased after the identification of biodiversity hotspots in Yunnan; however, collection activities have been uneven. Our analysis of 526,501 specimen records of the Herbarium of Kunming Institute of Botany, Chinese Academy of Science (KUN) and NSII indicate that current research efforts are insufficient (Fig. 2C). Specifically, the most-collected county is Gongshan with 38,203 specimens; second is Shangrila with 35,288 specimens; and more

than 20,000 specimens have been collected in Deqin, Weixi, Jinghong, Jingdong, and Pingbian. This collection pattern is consistent with species distribution patterns, namely that S and SE Yunnan are heavily-collected regions; however, C, E and NE Yunnan are poorly collected.

From 2013 to 2019, 163 new higher plant species (an average of 23 species per year) were reported from 53 counties in Yunnan (Fig. 2 D). These newly reported species include two new genera: *Mawenzhangia* Enroth, Shevock & Ignatov in Shangrila and *Tsaio-dendron* in Yuanjiang (Enroth et al., 2018; Zhou et al., 2017). The distribution of these newly reported species is consistent with total species and specimen distribution patterns. Most new species are distributed in NW, W, S and SE Yunnan in species hotspots in the following counties: Malipo (17 sp.), Gongshan (17 sp.), Mengla (14 sp.), and Yingjiang (11 sp.). However, these new species are not evenly distributed in all families and genera. Most newly reported species are concentrated in Gesneriaceae (22 sp.), Orchidaceae (12 sp.), Dryopteridaceae (12 sp.), Urticaceae (11 sp.) and Liliaceae (10 sp.). Furthermore, only two genera contain more than 10 new species: *Polystichum* (11 sp.) and *Elatostema* (10 sp.). One potential reason for this pattern may be that hotspots still contain undiscovered species, and that new species will be discovered upon further investigation. Another reason is that regions that have been relatively fully-investigated have yielded more specimens and information to be studied.

The distribution patterns of collected specimens may reflect the inadequacy of current research (Chen et al., 2013). For example, *Vegetation of China* (<http://nsii.org.cn/chinavegetaion>), reports relatively small numbers of recorded species and collected specimens (several hundred) in C, E and NE Yunnan. Cities in these regions (e.g., Qujing, Yuxi, and Chuxiong) are known to have high

**Table 1**  
The 43 main families and 13 main genera in Yunnan.

Family	Species (% of China)	Genus	Species (% of China)
Orchidaceae	995 (71%)	<i>Rhododendron</i>	349 (54%)
Poaceae	936 (57%)	<i>Pedicularis</i>	196 (59%)
Asteraceae	914 (48%)	<i>Carex</i>	158 (28%)
Fabaceae	776 (57%)	<i>Rubus</i>	146 (52%)
Rosaceae	637 (57%)	<i>Primula</i>	144 (43%)
Lamiaceae	530 (59%)	<i>Saxifraga</i>	143 (63%)
Ericaceae	514 (55%)	<i>Impatiens</i>	139 (59%)
Rubiaceae	441 (65%)	<i>Elatostema</i>	125 (73%)
Ranunculaceae	413 (40%)	<i>Gentiana</i>	117 (44%)
Primulaceae	331 (49%)	<i>Begonia</i>	115 (63%)
Cyperaceae	303 (36%)	<i>Ilex</i>	110 (49%)
Apiaceae	278 (55%)	<i>Salix</i>	109 (31%)
Urticaceae	275 (72%)	<i>Berberis</i>	101 (47%)
Apocynaceae	256 (70%)		
Orobanchaceae	239 (49%)		
Gesneriaceae	236 (61%)		
Lauraceae	235 (52%)		
Gentianaceae	221 (50%)		
Acanthaceae	193 (67%)		
Malvaceae	193 (93%)		
Fagaceae	191 (64%)		
Saxifragaceae	173 (59%)		
Celastraceae	170 (74%)		
Zingiberaceae	164 (85%)		
Salicaceae	164 (33%)		
Caryophyllaceae	156 (51%)		
Araceae	149 (89%)		
Euphorbiaceae	148 (78%)		
Brassicaceae	148 (51%)		
Papaveraceae	146 (34%)		
Balsaminaceae	139 (59%)		
Araliaceae	138 (77%)		
Asparagaceae	137 (57%)		
Polygonaceae	135 (73%)		
Berberidaceae	131 (44%)		
Moraceae	126 (81%)		
Cucurbitaceae	120 (77%)		
Begoniaceae	115 (63%)		
Vitaceae	113 (63%)		
Rutaceae	111 (82%)		
Aquifoliaceae	110 (49%)		
Sapindaceae	106 (60%)		
Rhamnaceae	105 (63%)		

levels of human activity and cultivated vegetation. Also, other counties, such as Jiangcheng and Ning'er in southern Yunnan and Wenshan on southeastern Yunnan, which are surrounded by several strongly-collected and species-rich counties, show inconsistent specimen and total species numbers. A fuller investigation of counties previously counted by CVH (<http://www.cvh.ac.cn/>) increased the total number of species reported by 100%–1000% (Chen et al., 2013; Wu et al., 2016). Species diversity in these areas may be underestimated because researchers pay less attention to counties where human activity is common, traffic conditions are poor, and wild regions are inaccessible due to frequent natural disasters (such as debris flow and landslide) (Chen et al., 2013).

### 3.1.8. Research and available online databases on plant diversity

As the basic information of species diversity in Yunnan Province, widely used and highly reliable checklists, flora, or monographs are helpful references in management of government departments and social organizations (Christenhusz and Byng, 2016). However, most research focuses on the relationship between biodiversity loss and protection, large scale patterns and formation mechanisms, as well as the mechanisms of community maintenance. Comprehensive studies of systematics are scarce. Major taxonomic advances at

Kunming Institute of Botany (KIB) have been summarized for 32 families, including Boletaceae, Poaceae, Begoniaceae, and Theaceae (Feng and Yang, 2018; Tian et al., 2018; Yu et al., 2018). Although there are some available checklists and investigation reports (Table 4), most are related to nature reserves in Yunnan, which cover only a limited area (Yang et al., 2008).

Online biodiversity resources and data sharing have advanced considerably in China and Yunnan (Wang et al., 2017) (Table 5). The most recent comprehensive database specifically focused on biodiversity in Yunnan is the Holographic Database of Plants (<http://bio360.kun.ac.cn/index>), which includes a database of The Checklist of Biological Species from Yunnan (2016). In addition, various public science projects, such as the Chinese Natural Herbarium (<http://www.cfh.ac.cn/>) and Biotracks (<http://www.biotracks.cn/>), have provided massive data for biodiversity research. Citizen scientists provide a wide range of observational data, but much of this data may also be inaccurate (Lv et al., 2015; Zhang et al., 2013).

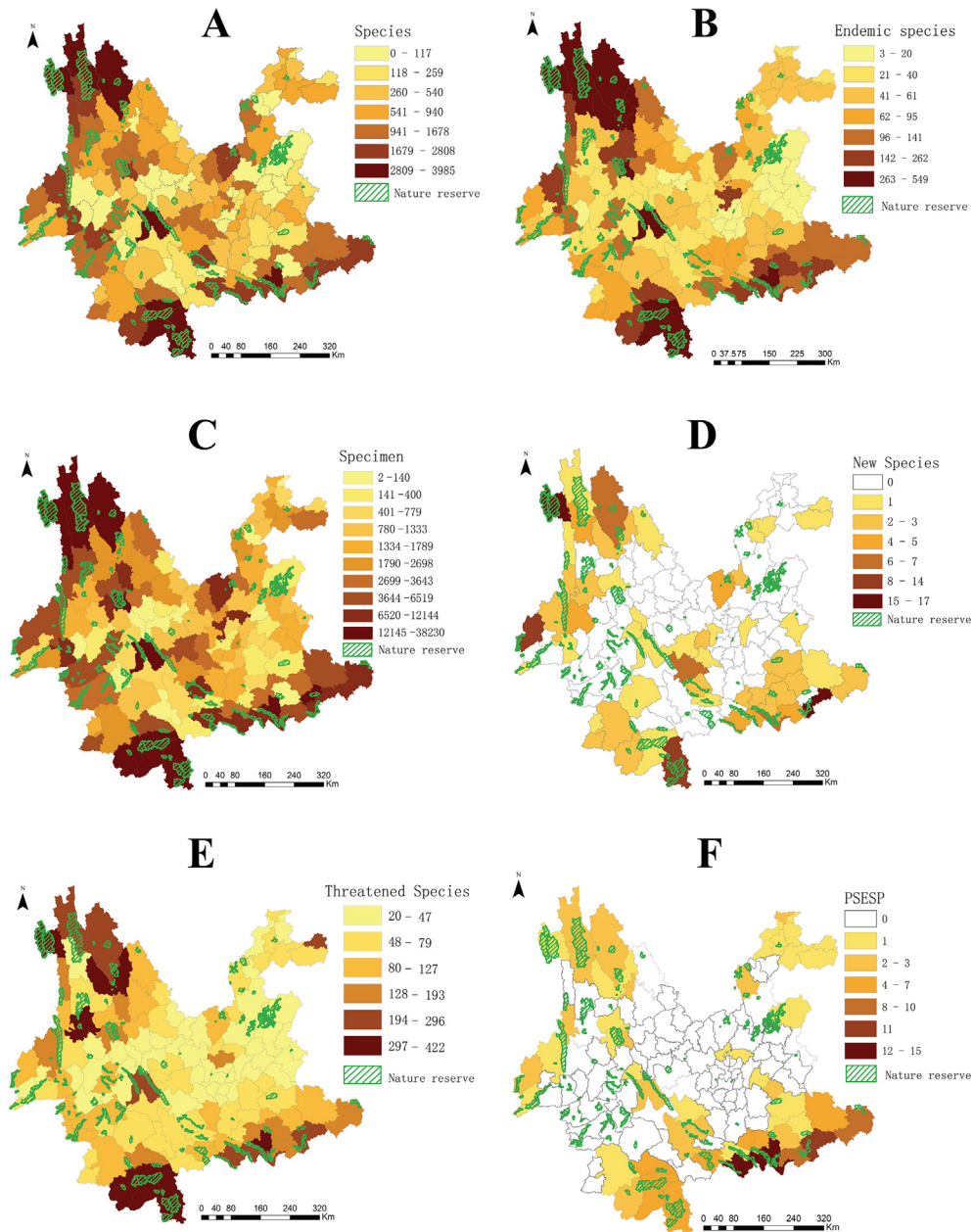
## 3.2. Threatened and conservation status in Yunnan

### 3.2.1. Status of the Red List and threatened species

In 2017, the first Red List of a province in China, the *Species Red List of Yunnan Province* (2017) (<http://bio360.kun.ac.cn/index/redlist>), was released, providing a more comprehensive picture of the conservation status of species in Yunnan than previous work (*Red list of China's biodiversity - Volume of higher plants*, [http://www.mee.gov.cn/gkml/hbb/bgg/201309/t20130912\\_260061.htm](http://www.mee.gov.cn/gkml/hbb/bgg/201309/t20130912_260061.htm)). Of 3,767 threatened species (IUCN Threatened Categories include Critically Endangered, Endangered, and Vulnerable) in China, 1,426 species are distributed in Yunnan (Table 6). The distribution patterns of threatened species in Yunnan is consistent with those of total species and endemic species (Fig. 2E). “Hotspots” of threatened species are located in NW, S and SE Yunnan. Specifically, most threatened species are in Mengla (442), Jinghong (393), Gongshan (360) Lijiang (358), and Pingbian (337).

Two important points must be noted. First, the number of threatened species in every category has remained high in China since the red list was published in 2013. Second, the number of species categorized as Data Deficient (DD) is very high. Furthermore, assessing the current conservation status of two types of species poses challenges: (1) newly described species for which basic biological and ecological information is lacking and (2) species with doubtful taxonomic status (Zang et al., 2016). Researchers have paid more attention to economic and protected species and less attention to the narrowly distributed species. However, categorizing species DD does not mean that the species is not endangered; in contrast, its survival status is not clear at all, and many of these species may even be extinct.

A recent example of the unclear survival status of a species is the re-discovery of *Hemilophia serpens* (O. E. Schulz) Al-Shehbaz, which was ‘re-found’ in 2019 near the Type location after first being discovered by Handel-Mazzetti in 1915 in Zhongdian (Shangrila) (Fig. 4A). For 104 years, there were no records or specimens of this ‘type-only’ species. Other ‘type-only’ species have also been re-discovered (Fig. 4B, C, D), for example, *Paraisometrum mileense* W. T. Wang, which was first collected in 1906 in Mile, and *Brachymeniopsis gymnostoma* Broth., which was first collected in 1916 in Lijiang (Chen et al., 2014; Jia, 2017). Both species were regarded as extinct in the wild until their recent re-discovery in Shilin (Yunnan) and Yadong (Tibet) confirmed that the species exist in the wild (Chen et al., 2014; Jia, 2017). These discoveries emphasize that species categorized as DD may be among the most threatened species and require increased attention from researchers in the future.



**Fig. 2.** County-level distribution of plant diversity in Yunnan. (A) Total species distribution patterns. (B) Endemic species distribution patterns. (C) Specimen distribution patterns. (D) New species distribution patterns (from 2013 to 2019). (E) Threatened species distribution patterns. (F) Distribution patterns of Plant Species with Extremely Small Populations (PSESP).

### 3.2.2. Conservation status for all plants and Plant Species with Extremely Small Populations (PSESP)

#### (1) Traditional and modern *in situ* conservation

China has a long history of nature conservation. Traditional conservation is based on plant and mountain worship, and relies on traditional culture and morality for enforcement. In contrast, modern conservation is based on the scientific method, and has established nature reserves with monitoring and management systems (Liu et al., 2000; Yang et al., 2019a; Zou et al., 2005). Historically, areas important to local minorities, such as Meili Snow Mountain in Yunnan, have been designated as “sacred mountains” (Wang, 2000; Yang et al., 2019a). More than half of China's ethnic minority groups reside in Yunnan, and fifteen of these 25 ethnic

minorities reside only in Yunnan (People's Government of Yunnan, <http://www.yn.gov.cn>). Local traditional culture plays an important role in biodiversity conservation (Liu et al., 2000; Yang et al., 2019a; Zou et al., 2005). However, traditional cultures are generally constricted to limited areas and much traditional knowledge of ecology is increasingly being lost (Zou et al., 2005). Thus, modern conservation systems are urgently needed.

#### (2) *In situ* conservation in Yunnan

*In situ* conservation has practical significance for maintaining the reproduction and evolution of organisms in the ecosystem, and is the most effective measure in biodiversity protection (Ma et al., 2012). The first nature reserve of Yunnan, the Xishuangbanna Nature Reserve, was established in 1958 and covers more than 10% of

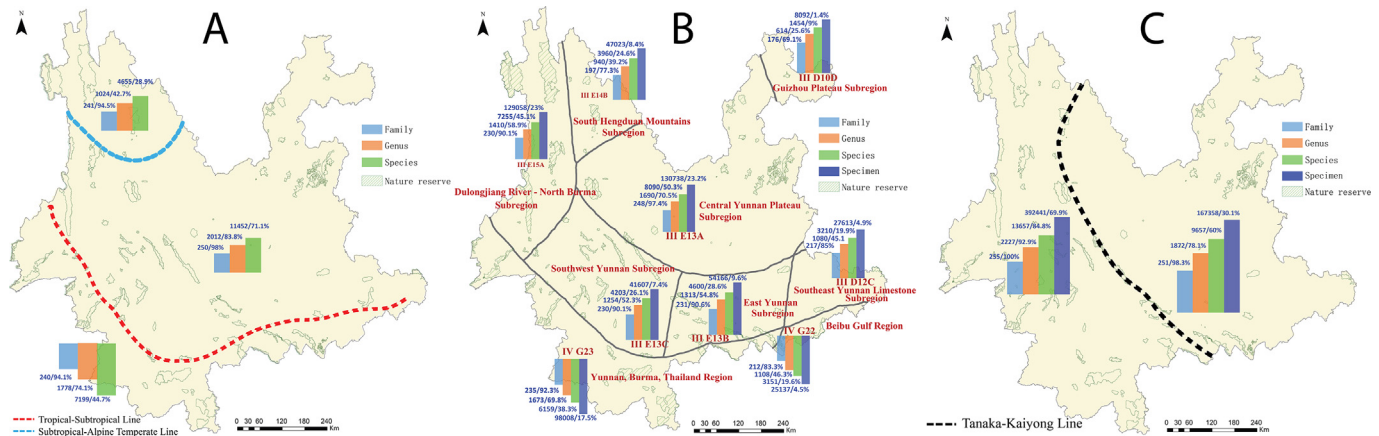


Fig. 3. Diversity composition of (A) three climate zones, (B) nine subregions of floristics division, and (C) different sides of the Tanaka-Kaiyong Line.

Table 2

Endemic genera in Yunnan and the Hengduan mountains.

N	Family	Genus	Species number	Distribution in Yunnan
1	Orchidaceae	<i>Smithorchis</i>	1	NW
2	Zingiberaceae	<i>Pyrgophyllum</i>	1	NW-C
3	Zingiberaceae	<i>Siliquamomum</i>	1	SE
4	Musaceae	<i>Musella</i>	1	C-W
5	Asteraceae	<i>Formania</i>	1	NW
6	Asteraceae	<i>Nouelia</i>	1	NW
7	Ranunculaceae	<i>Metanemone</i>	1	NW
8	Rubiaceae	<i>Trailiaedoxa</i>	1	NW
9	Melastomataceae	<i>Cyphotheca</i>	1	S-SW
10	Melastomataceae	<i>Sporoxeia</i>	2	S-SW
11	Gesneriaceae	<i>Hemiboeopsis</i>	1	SE
12	Apiaceae	<i>Chaerophyllopsis</i>	1	NW
13	Lamiaceae	<i>Holocheila</i>	1	C-SW, S, SE
14	Lamiaceae	<i>Skapanthus</i>	1	NW
15	Apocynaceae	<i>Parepigynum</i>	1	SE
16	Poaceae	<i>Ferocalamus</i>	2	S
17	Poaceae	<i>Gaoligongshania</i>	1	NW
18	Brassicaceae	<i>Shangrilaria</i>	1	NW
19	Euphorbiaceae	<i>Tsaiodendron</i>	1	SE
20	Lembophyllaceae	<i>Mawenzhangia</i>	1	NW

Xishuangbanna Prefecture, harboring about 3,500 higher plants (López Pujol et al., 2006). As of 2016, a total of 160 nature reserves have been established, accounting for 7.3% of the province's land area. Furthermore, the number and area of nature reserves ranks sixth and ninth in China, respectively (Yunnan Forestry and Grassland Bureau, 2016). In Yunnan, there are 21 National Nature Reserves, 38 Provincial Nature Reserves, 56 Municipal Nature Reserves, and 45 County Nature Reserves. Out of 129 counties in Yunnan, 109 have at least one nature reserve (Fig. 5). The higher-level nature reserves (e.g., National and Provincial Nature Reserves) cover almost all the biodiversity hotspots in Yunnan, whereas the lower-level nature reserves (e.g., Municipal and County level Nature Reserves) are more concentrated in the C, E and NE Yunnan. For example, the county with the largest number of nature reserves in Yunnan is Huize County (7), which is located in NE Yunnan (Fig. 5E). However, the total area of nature reserves in Huize County is below average (Fig. 5J). Because human activity increasingly fragments natural habitats, it is difficult to conserve large areas; thus, establishing small conservation areas may be an important strategy to protect local biodiversity. Moreover, even though 84.5% of counties in Yunnan have nature reserves, there are still many conservation gaps or unprotected areas that harbor threatened species (Wang et al., 2018; Yang et al., 2013; Ye et al., 2020).

### (3) *Ex situ* conservation in Yunnan

Botanical gardens play the most important role of scientific research and conservation in terms of *ex situ* protection (Chen and Sun, 2018). There are 10 botanical gardens and arboretums in Yunnan, eight of which are members of the Union of Chinese Botanical Gardens, which consists of 116 botanical gardens in China, including Xishuangbanna Tropical Botanical Garden (XTBG) and Kunming Botanical Garden (KBG). XTBG covers an area of about 1,125 hm<sup>2</sup>, contains more than 12,000 kinds of living plants, has 38 special collection botanical areas, and preserves a piece of original tropical rain forest with an area of about 250 hm<sup>2</sup>. It is the largest botanical garden in China with the most species collected and the most special theme areas. The KBG is a comprehensive botanical garden with an open area of 44 hm<sup>2</sup>, 18 special collection areas, and a collection of more than 8,700 species. Other botanical gardens, such as Kunming Arboretum of Yunnan Academy of Forestry Sciences, also play important roles in preserving the threatened and endangered plants (Botanical Garden Committee of Chinese Academy of Sciences, 2019).

In addition to botanical gardens, the Germplasm Bank of Wild Species in Kunming is also an important organization for *ex situ* conservation. To date, the germplasm bank has collected wild seeds

**Table 3**  
Vegetation type, vegetation subtype and number of associations in Yunnan.

Vegetation Type	Vegetation Subtype	Number of Associations
Tropical Rainforest	Seasonal Rainforest	19
Tropical Rainforest	Montane Rainforest	12
Monsoon Forest	Deciduous Monsoon Forest	7
Monsoon Forest	Semi-evergreen Monsoon Forest	3
Monsoon Forest	Tropical Seasonal Evergreen Moist Forest	4
Evergreen Broadleaf Forest	Monsoon Evergreen Broadleaf Forest	26
Evergreen Broadleaf Forest	Wet-dry Evergreen Broadleaf Forest	6
Evergreen Broadleaf Forest	Moist Evergreen Broadleaf Forest	8
Evergreen Broadleaf Forest	Middle-Mountain moist Evergreen Broadleaf Forest	20
Evergreen Broadleaf Forest	Mountain bryophyte Evergreen Broadleaf Forest	7
Evergreen Broadleaf Forest	Mountain top bryophyte Dwarf Forest	2
Sclerophyllous Evergreen Broadleaf Forest	Cold-temperate Montane Evergreen Oak Forest	4
Sclerophyllous Evergreen Broadleaf Forest	Dry and Hot Valley Sclerophyllous Evergreen Broadleaf Forest	5
Deciduous Broadleaf Forest	Subtropical Deciduous Broadleaf Forest	20
Deciduous Broadleaf Forest	Temperate Deciduous Broadleaf Forest	8
Subtropical Needleleaf Forest	Subtropical-tropical Needleleaf Forest	3
Subtropical Needleleaf Forest	Subtropical-temperate Needleleaf Forest	12
Temperate Needleleaf Forest	Temperate-cool Needleleaf Forest	9
Temperate Needleleaf Forest	Cold-temperate Needleleaf Forest	14
Bamboo Forest	Tropical Bamboo Forest	16
Bamboo Forest	Temperate Bamboo Forest	4
Bamboo Forest	Cold-temperate Bamboo Forest	3
Savanna-like Shrubby Grassland	Dry and Hot Savanna-like Shrubby Grassland	30
Savanna-like Shrubby Grassland	Tropical Savanna-like Shrubby Grassland	10
Savanna-like Shrubby Grassland	Subtropical-tropical Savanna-like Shrubby Grassland	5
Savanna-like Shrubby Grassland	Subtropical-temperate Savanna-like Shrubby Grassland	14
Scrub	Dry and Hot Valley Scrub	18
Scrub	Tropical River Beach Scrub	1
Scrub	Subtropical Limestone Scrub	12
Scrub	Temperate-cool Scrub	3
Scrub	Cold-temperate Scrub	56
Meadow	Cold-temperate Meadow	11
Meadow	Alpine Meadow	2
Meadow	Forb Meadow	12
Desert	Alpine Desert	17
Swamp	Aquatic Community	61
Swamp	Swampy Meadow	10

**Table 4**  
Published books, checklists, and reports on plants of Yunnan Province.

Title	Year
Flora of Yunnan	1977–2006
Forest of Yunnan	1986
Vegetation of Yunnan	1987
Vascular Plants of the Mts. Hengduan	1994
List of Plants in Xishuangbanna	1996
The Seed Plants from Mt. Wuliang in the South-Central Yunnan, China	1998
Seed Plants of Honghe Region in SE Yunnan, China	2003
Yunnan Mt. Luchun Huanglianshan Natural Reserve	2003
Ferns of Mt. Ailao	2007
List of Seed Plants in the Mt. Ailao of Yunnan Province, China	2009
Vascular Plants of the Dali Cangshan Erhai National Natural Reserve	2010
Research on the Seed Plants and Forest Vegetation in Mt. Yongdedaxueshan	2010
A Checklist of the Flowering Plants in Southeast Yunnan	2010
Checklist of Seed Plants of Mt. Yaoshan NE Yunnan	2010
Plants in Dabaoshan Black-Necked Crane Nature Reserve, China	2010
List of wetland plants in Yunnan	2010
Native Seed Plants in Xishuangbanna of Yunnan	2012
Seed Plants of the Alpine Subnival Belt from the Mts. Hengduan, SW China	2013
Yunnan Mt. Jiaozishan National Natural Reserve	2015
Seed Plants of Mt. Xilongshan, the First Peak in South Yunnan, China	2016
The Checklist of Biological Species from Yunnan (2016)	2016
Checklist of Seed Plants in the Karst Regions in China	2017
Species Red List of Yunnan Province	2017
Integrated Scientific Reports of Mt. Daweishan National Nature Reserve of Yunnan, China	2018
Ecosystem List of Yunnan Province 2018	2018
Catalogue of Seeds 2018 Germplasm Bank of Wild Species	2018
Invasive Species List of Yunnan Province	2019
Study and Conservation of Plant Species with Extremely Small Populations (PSESP) in Yunnan Province, China	2019

**Table 5**  
Available databases about biodiversity in Yunnan.

Database Name	Website	Description
Holographic Database of Plants	<a href="http://bio360.kun.ac.cn/">http://bio360.kun.ac.cn/</a>	Comprehensive database of plant diversity in Yunnan
Kingdonia	<a href="http://kun.kingdonia.org/">http://kun.kingdonia.org/</a>	Specimen database of KUN, 810,718 plant specimens of Yunnan, developed by KIB
Biotracks	<a href="http://www.biotracks.cn">http://www.biotracks.cn</a>	Biodiversity on the map, exhibiting combined information of plant digit specimen, collection information, photos, expedition tracks, developed by KIB
Germplasm Bank of Wild Species	<a href="http://www.genobank.org">http://www.genobank.org</a>	The Germplasm Bank of Wild Species (Information on germplasm resources of ca. 10,096 collected), developed by KIB
iFlora	<a href="http://www.iflora.cn/if/default.aspx">http://www.iflora.cn/if/default.aspx</a>	Information on plant taxonomy, distribution, identification, and resources, developed by KIB
Plant Introduction and Conservation Database	<a href="http://sdb.xtbg.ac.cn/page/index.vpage">http://sdb.xtbg.ac.cn/page/index.vpage</a>	Comprised by plant phenology and plant growth records, and other information, created by XTBG
NSII (National Specimen Information Infrastructure)	<a href="http://www.nsii.org.cn">http://www.nsii.org.cn</a>	National database that contains information on biodiversity of Yunnan
Species 2000 China Node	<a href="http://www.sp2000.org.cn/">http://www.sp2000.org.cn/</a>	National database that contains information on biodiversity of Yunnan
Subject Database of China Plant	<a href="http://www.plant.csdb.cn/">http://www.plant.csdb.cn/</a>	National database that contains information on biodiversity of Yunnan
Scientific Database of China Plant Species	<a href="http://db.kib.ac.cn/">http://db.kib.ac.cn/</a>	National database that contains information on biodiversity of Yunnan
Plant Plus of China	<a href="http://www.plantplus.cn/">http://www.plantplus.cn/</a>	National database that contains information on biodiversity of Yunnan

Due to the continuous emergence of new biodiversity data, these databases do not cover all the progress in the area of biodiversity information.

**Table 6**  
Conservation status of plants in Yunnan and China.

Category	Moss and Liverwort	Fern	Gymnosperm	Angiosperm	Higher Plants in Yunnan, 2017	Higher Plants in China, 2013
Extinct (EX)	1	0	0	4	5	27
Extinct in the Wild (EW)	0	0	0	2	2	10
Regional Extinct (RE)	0	0	0	2	2	15
Critically Endangered (CR)	38	13	10	224	285	583
Endangered (EN)	18	39	16	627	700	1297
Vulnerable (VU)	34	107	13	915	1069	1887
Near Threatened (NT)	29	131	7	1770	1937	2723
Data Deficient (DD)	140	405	9	988	<b>1542</b>	<b>3612</b>
Least Concern (LC)	1647	594	45	10577	12863	24296

of 10,018 species, 80,105 copies, belonging to 228 families and 2,005 genera (Li, 2018).

#### (4) *Near situ* conservation and PSESPs in Yunnan

*Near situ* conservation aims to protect small populations of wild plants, such as Plant Species with Extremely Small Populations (PSESPs) (Sun and Han, 2015). Ten *near situ* conservation gardens have been established in Yunnan and more PSESP work is ongoing, including the protection of 60 PSESPs *in situ* and 80 PSESPs *ex situ* (Sun and Han, 2015; Sun et al., 2019; Wang et al., 2020b; Yang et al., 2020).

A total of 120 PSESPs (Appendix 1) in southern China (Zhang et al., 2018) and 62 PSESPs (Appendix 2) in Yunnan require urgent protection. We found that SE Yunnan is a PSESP hotspot (Fig. 2F). Specifically, PSESP hotspots are located in Hekou (15 sp.), Pingbian (13 sp.), Jinping (13 sp.), Xichou (11 sp.), Malipo (11 sp.) and Maguan (10 sp.) counties. In addition, we identified six counties that have at least one PSESP but no nature reserves: Luxi, Fumin, Shilin, Songming, Yanshan and Ancient Town District (Lijiang) (Fig. 6).

## 4. Conclusion: current problems and recommendations

### 4.1. Survey data lack detailed GPS information

Although millions of specimens have been collected and are available, very few records of these specimens include detailed GPS information. Based on our roughly random sampling, 8.3% and 73.8% specimens collected from 1990 to 1995 and 2015 to 2019 have accurate GPS information, respectively. Because climatic niche

inference is sensitive to distribution data sampling, the county-level distribution data may introduce elevational bias into climate niche estimates (Pender et al., 2019).

### 4.2. The accuracy of specimen identification needs to be improved

Previous research showed that an estimated 50% of the world's collected tropical specimens may be incorrectly identified (Goodwin et al., 2015). We have roughly calculated (together with data from experts) that 35% of specimens in herbaria are inaccurately identified. Accurate identification is the basis of all other work and inaccurate identification greatly impacts research. Today, systematists pay more attention to gathering and analyzing molecular data than to doing traditional taxonomic work (i.e., field work and identification). Consequently, the new generation of systematists relies on the accurate identification of herbarium specimens. If these researchers fail to accurately identify material collected from the wild, future research will be of limited value (Yu et al., 2018).

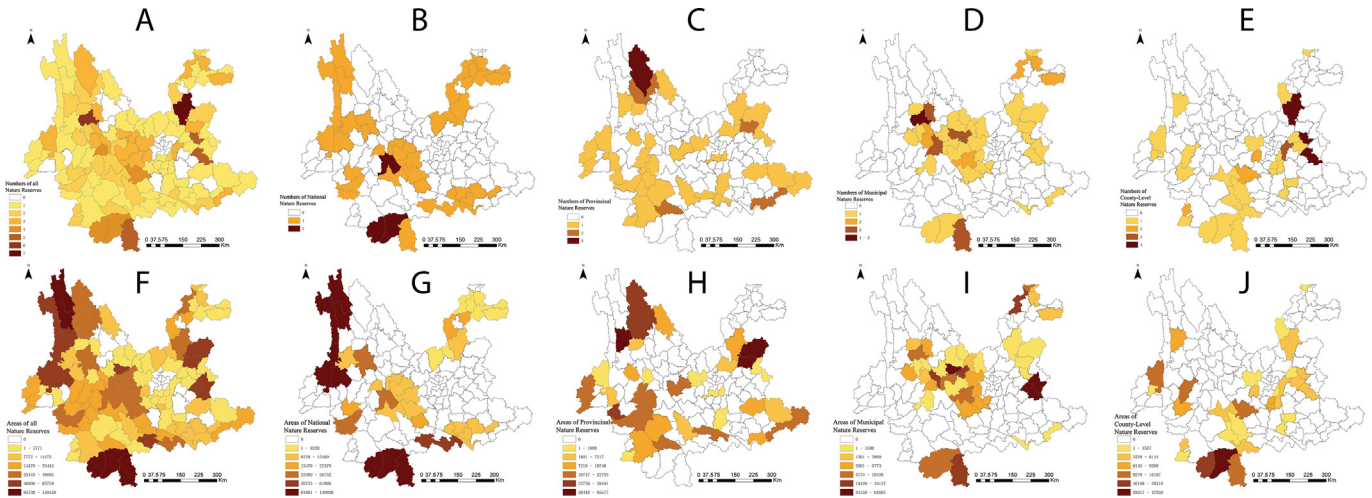
### 4.3. Species information in databases needs to be improved

The digitization of biodiversity data may provide many opportunities for biodiversity researchers (Wang et al., 2017, 2020a), but it also brings challenges: (1) these data resources are distributed over different platforms and articles, which are difficult to retrieve, update and collect; (2) because of the complexity of biodiversity itself, it is difficult to have a comprehensive understanding of a database over a short time, and some researchers may misuse the database, for example, by analyzing data directly without standardization or without checking null values; (3) there is a lot of data overlap, regional bias and incompleteness, including geographical





**Fig. 4.** Type specimens and recent photographs of re-discovered ‘type-only’ species. (A) *Hemiphysa serpens* (published in 1915). (B) *Ranunculus melanogynus* (published in 1960). (C) *Carex polymascula* (published in 1983). (D) *Delphinium oxycentrum* (published in 1937).



**Fig. 5.** Current status of nature reserves in Yunnan. (A–E) Number and county location of nature reserves. (F–G) Area (km<sup>2</sup>) of nature reserves in county level distribution. (A and F) All nature reserves. (B and G) National nature reserves. (C and H) Provincial nature reserves. (D and I) Municipal nature reserves. (E and J) County nature reserves.

coordinate errors and synonym problems, which may affect our understanding of biodiversity patterns (Meyer et al., 2016; Qian et al., 2018; Wang et al., 2017).

#### 4.4. Future perspectives

Protecting the plant diversity of Yunnan will require much future work. We recommend that specimens in all areas of Yunnan

be cleaned-up, poorly-collected areas (e.g., C, NE and E Yunnan) be investigated, and the locations of Data Deficient and ‘type-only’ species be re-investigated. Furthermore, specimen documentation should include GPS information and photos, and efforts should be made to build a framework for an integrated big data database that strengthens research on all taxa (including unpublished flora volumes of cryptogams). Protecting plant diversity in Yunnan will also require compiling district and/or county-level flora and more

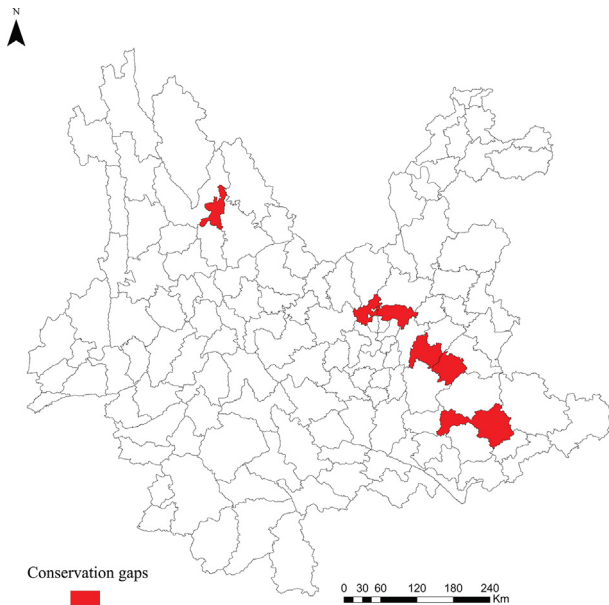


Fig. 6. Conservation gaps in Yunnan.

creative monographs (Liu and Peng, 2016; Lu et al., 2012; Yu et al., 2018; Zhang et al., 2012). We should also establish a more functional and integrated protection system, strengthen the protection of genetic diversity and pay more attention to popularizing science and environmental education (Chen and Sun, 2018; Lv et al., 2015; Sun and Han, 2015).

#### Author contributions

H.S., T.D. and J.H.C. planned and designed the research; J.H.C. collected and provided the data; L.S.Q. analyzed data; L.S.Q. wrote the manuscript.

#### Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.pld.2020.07.006>.

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