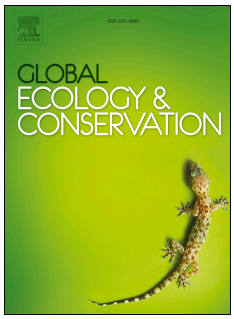

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Hotspots and Conservation Gaps: A Case Study of Key Higher Plant Species from Northwest Yunnan, China

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Abstract: Northwest Yunnan is rich in flora and is home to many key higher plant species with endemic and endangered attributes. However, there are still some species and biodiversity hotspots that are not included in the established reserve system. As such, the area is riddled with conservation gaps. Thus, we have adopted hotspot identification and gap analysis methodology in order to reasonably allocate resources for conservation of the key higher plant species in Northwest Yunnan. To begin, we comprehensively considered seven attributes to select 114 key species. Next, we obtained and superimposed the longitude and latitude coordinates of each species' location on a grid map with a 0.05° × 0.05° resolution. The ArcGIS10.2 software and R language were used to analyze species distribution; meanwhile hotspot identification and gap analysis were also performed in ArcGIS10.2. The results showed that: 1) there were 114 key higher plant species in Northwest Yunnan, which belong to 37 families and 68 genera; 2) the species distribution in Northwest Yunnan showed significant clustering and positive spatial correlation (Z = 2.90; P < 0.05), with the distribution relatively concentrated in Shangri-la and Gongshan counties; 3) approximately 60% of the hotspots were located in Gongshan, Deqin, and Shangri-la counties in the North; 4) the total priority conservation area was 5615 km^2, ~ 20.30% of which have been designated as nature reserves; and 5) a total of 13 conservation gaps were identified and put forward with targeted suggestions for expanding the conservation areas and building ecological corridors. The results of our study identified the priority conservation areas of key higher plant species in Northwest Yunnan, which aids in optimizing the existing conservation network system.

Keywords: Biodiversity conservation, Northwest Yunnan, Key higher plant species, Priority conservation areas, Hotspot analysis, Gap analysis, Spatial autocorrelation

1. Introduction

The Global Strategy for Plant Conservation (2011-2020) (GSPC, https://www.plants2020.net/) formulated by Botanic Gardens Conservation International (BGCI) and others emphasized the importance of recording plant diversity and its distribution for future plant diversity conservation. (Blasi et al., 2011; Wu et al., 2016a; Ren, 2017). A total of 16 goals were proposed by the GSPC, of which goal 5 was to implement at least 75% effective protection for areas that are identified as important for plant diversity conservation. Under this strategy, the most important plant diversity areas were identified based on a range of criteria, including endemism, species and habitat vulnerability, species richness, and habitat uniqueness. Focusing on biodiversity hotspots, or

species-rich centers, has been widely considered an effective global protection strategy (Myers, 2003). In addition to being one of the world's 36 biodiversity hotspots (Conservation International, https://www.conservation.org/priorities/biodiversity-hotspots), Northwest Yunnan is also a strategic area for plant diversity protection, and previous studies have identified it as a key area for plant diversity conservation (Xu and Wilkes, 2004; Ruth et al., 2007; Ruth et al., 2008; Haynes et al., 2013; Feng, 2019).

Key species usually attain these status by being endangered, unique and rare, which gives them higher ecological, scientific, and social value (Livi et al., 2011; Jiang, 2019; Shi et al., 2019). Northwest Yunnan has a high concentration of higher plant species (Ye et al, 2020). However, considering that it is difficult to know the habitat and distribution of all species. Therefore, we selected some key higher plant species (KPHs) from the catalogue of all higher plant species for research by further considering the species' endemism and threatened status, rare and endangered degree, regional representativeness, and especially the availability of distribution data. Conservation of these key species has far reaching significance. For example, *Sorolepidium glaciale* can be classified as an umbrella species, and protecting them can bring many species that coexist with them naturally into conservation status (Fleishman et al., 2000; Shi et al., 2019). In addition, Orchidaceae plants are usually sensitive to the environment, and their distribution is strongly correlated with environmental factors (Keppel, 2016). As such, they can be used as environmental indicators to reflect environmental changes (Wei, 2015). Therefore, protecting these species is a primary task from a plant diversity conservation perspective.

The establishment of nature reserves is the main form of natural resource and plant diversity protection under the existing conditions (Chape et al., 2005). However, due to a lack of unified planning and other issues during the early nature reserves' construction, in situ conservation is not sufficient, as there are still conservation gaps. Thus, identifying hotspots and conservation gaps (Myers et al., 2000; Xu et al., 2017) significantly impacts in situ conservation and macro planning of nature reserves; and has therefore become a central focus in biodiversity research (Rayn and Sutherland, 2011; Ma, 2016).

In order to improve the understanding of current effectiveness of nature reserve system on biodiversity conservation and enhance the efficiency of the nature reserve network in Northwest Yunnan, biodiversity hotspot assessments and conservation gap research at fine resolution are primary and urgently required (Zhang et al., 2016; Xu et al., 2017). In this study, a total of 114 KHPs were selected. To begin, a 0.05° × 0.05° grid map was used to analyze the distribution pattern and identify the hotspots of KHPs in Northwest Yunnan. Next, we analyzed the spatial distribution pattern, autocorrelation, and overall spatial distribution state of the KHPs. Following that, we evaluated the protection status of the priority conservation areas and identified the conservation gaps using superposition analysis of the priority conservation areas in conjunction with the spatial data of existing nature reserves.

2. Data and methods

2.1 Study Area

Northwest Yunnan is located in the Northwest Yunnan province, between 24°38'-29°15'N and 98°05'-101°16'E. The administrative capacity includes 18 counties (cities or districts) (Appendix I), which cover a total area of 79,800 km^2, and account for 20.2% and 0.8% of the total land area for the province and the whole country, respectively (Wu et al., 2016b). The elevation variation is nearly 6,100 m, a rarity in the world, and ranges from 6,740 m in the Meili Snow Mountain to 648 m in the Nujiang River Valley (Fig. 1). The terrain is complex, and the climate is prone to vary in response to vertical change. The average temperature in this region is 10 to 15 □, the ranges of highest and lowest temperatures are 30 to 37 □ and -4 to -12 □, respectively. The mean annual precipitation is between 1,185 and 1,439 mm (Li and Zhou, 2005). The area's vegetation is rich, varied, and relatively well preserved. There are 10,198 species of higher plants (including subspecies) that account for 55.7% of the total number in Yunnan province, among which > 50% are national endemic species and 910 are regional endemic species (Yunnan Provincial Government and Yunnan Provincial Department of Ecology and Environment, 2009). Northwest Yunnan is currently home to four national and nine provincial nature reserves.

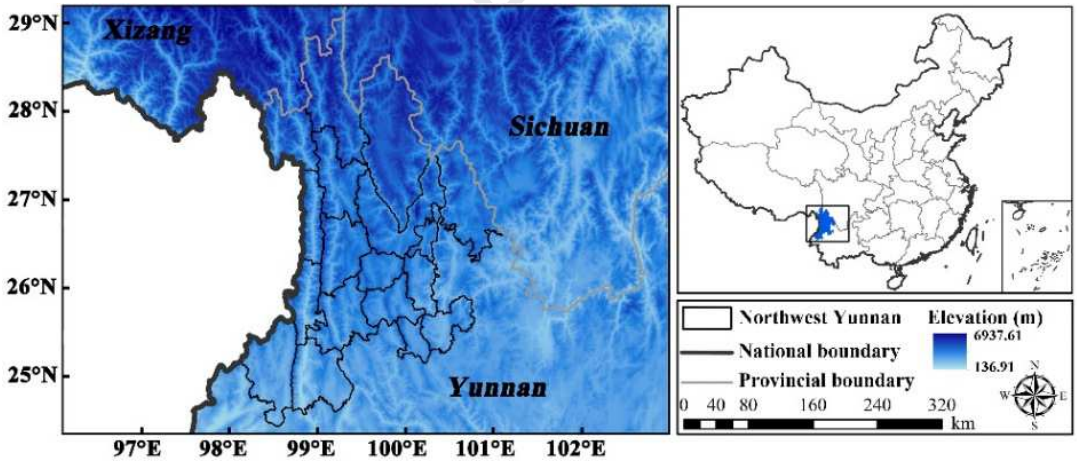

Fig. 1. Geographic location and topographic map of Northwest Yunnan.

2.2 Checklist of KHPs in Northwest Yunnan

In this study, we integrated seven attributes and used them as criteria for comprehensively selecting higher plant species that need to be focused on and protected in Northwest Yunnan. These attributes consisted of: the IUCN threatened grade, endemism, The National Key Protected Wild Plants List (the first), The National Key Protected Wild Plants List (the second), The List of Key Protected Wild Plants in Yunnan Province (the first), Plant Species with Extremely Small Populations (PSESP), and The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

The suggested checklist of KHPs in Northwest Yunnan was determined through literature and

relevant expert evaluation. Firstly, we chose 136 higher plant species, these species should: 1) belong to the national protected plant species and rare and endangered plant species; and 2) at least have one of another attributes mentioned above. After comparing the list with relevant literature and the status quo of species protection, widely distributed species were deleted as appropriate. Then, the checklist was reviewed and edited by relevant experts, after which the final checklist of KHPs in Northwest Yunnan was obtained. The final checklist consisted of 114 species, belonging to 37 families and 68 genera. Additional contributing sources consisted of: China Plant Red Data Book-Rare and Endangered Plants (Volume 1) (Fu, 1991), The National Key Protected Wild Plants List (the first) (The State Forestry Administration and The Ministry of Agriculture, 1999), The National Key Protected Wild Plants List (the second), China's Red List of Biodiversity-Higher Plants Volume (The Ministry of Environmental Protection and Chinese Academy of Sciences, 2013), Rare and Endangered Plants in Yunnan Province, China (I) (Gong et al., 2006), National Protected Wild Plants in Yunnan Province, China (Yunnan forestry department and Yunnan academy of forestry, 2005), and The CITES (2013 edition).

The information for establishing the species checklist was mainly derived from: 1) Chinese Field Herbarium (CFH) (http://www.cfh.ac.cn/); 2) Species 2000 China Node (http://www.sp2000.org.cn/); 3) Flora of China (Chinese version and English version); 4) Information System of Chinese Rare and Endangered Plants (ISCREP) (http://www.iplant.cn/rep/); and 5) Flora of Yunnan (Wu, 2006). All collected and collated information was checked by relevant experts from local universities and research institutes. The established checklist of KHPs in Northwest Yunnan included Taxonomy Levels, IUCN threat level, Endemism, National protection level, Provincial protection level, whether is PSESP, and classification by CITES appendix.

2.3 Collection of geographic coordinates of species

The longitude and latitude data of species distribution were primarily obtained from two sources: 1) the main digital herbarium in China, such as the Chinese Virtual Herbarium (http://www.cvh.ac.cn/) and Herbarium, Kunming Institute of Botany, CAS (http://www.kun.ac.cn/); and 2) field survey data for nearly a decade. Species distribution longitude and latitude coordinates that were provided in the obtained data were directly used. For plants where the only provided data was the name of a small species distribution site, the coordinates of longitude and latitude were determined using Google Maps (Li et al., 2019). The final data set consisted of 941 records that represent the distribution of KHPs in Northwest Yunnan. We superimposed the species distribution map on a grid with a 0.05° × 0.05° resolution (about 5.5 km × 5.5 km). In addition, all points of the same species that fall into a 0.05° × 0.05° grid cell were considered as one occurrence (Yu et al., 2017) (Fig. 2a). Data processing was performed using ArcGIS10.2 software, and we finally got 586 valid records for calculation (Appendix II). The recommended 0.05° × 0.05° resolution was roughly equivalent in spatial extent to the village level and the size of the smallest nature reserve established in Northwest Yunnan.

2.4 Collection of Geographic Datasets

The Yunnan province administrative zoning map and 1-km spatial resolution digital elevation

(DEM) data were obtained from the National Earth System Science Data Center Sharing Service Platform (http://www.geodata.cn/). The latest nature reserves data set (1:3600000), which covers through 2018, was obtained from Ministry of Ecology and Environment of the People's Republic of China (http://www.mee.gov.cn/). Northwest Yunnan consists of four national and nine provincial nature reserves, covering a total area of 9, 074.75 km^2, and accounting for 11.37% of the total area of Northwest Yunnan (Fig. 2b; Appendix III).

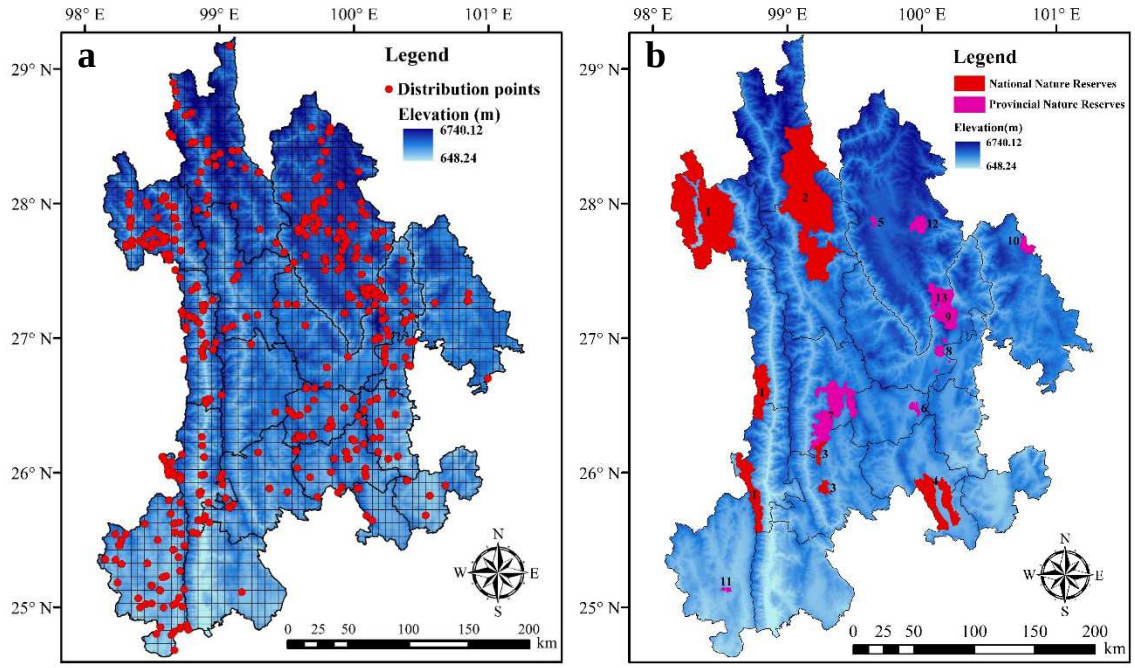

Fig. 2. a. Spatial distribution of key protected species. **b.** Distribution map of nature reserves. (At the national level 1: Gaoligong Mountains; 2: Baima Snow Mountain; 3: Yunlong Tianchi; 4: Erhai Lake; At the provincial level 5: Napa Lake; 6: The Sword Lake Wetland; 7: Yunling; 8: Lashihai Plateau Wetland; 9: Yulong Snow Mountain; 10: Ninglang Lugu Lake; 11: Beihai Wetland; 12: Bita Lake; 13: Haba Snow Mountain.)

2.5 Hotspots identification and priority conservation areas identification

Hotspots are defined as some form of clustering condition in a spatial distribution (Chaikaew et al., 2009). Thus, to begin, we superimposed the species distribution map onto a 0.05° × 0.05° resolution grid map. Next, we identified protection hotspots based on the total number of KHPs in each grid. In addition, protection of endemic, endangered and other key species was also an important consideration factor in the determination of conservation hotspots. As such, the sum of weighted score value of all attributes for all the species in each grid (Table 1) (Qu et al., 2012; Cañadas et al., 2014; Zhang et al., 2016) were used to further comprehensively judge the protection hotspots. ArcGIS10.2 software (ESRI, 2012) Hot Spot Analysis (Getis-Ord Gi*) was used to calculate the GiZScore of each grid, identify the spatial clustering of high values (hotspots) with statistical significance (Chen et al., 2017; Cao et al., 2019), and then identify the hotspot distribution of KHPs in Northwest Yunnan. When 1.65 < GiZScore < 1.96, 1.96 < GiZScore < 2.58, and GiZScore > 2.58, 90%, 95%, and 99% of the grid's confidence is hotspot, respectively (Chen et al., 2017). Using the layer overlay analysis tool, the hotspots calculation result, which

was based on the total number of KHPs in each grid and the weighted score value of all species in each grid, was superimposed to obtain the common hotspots grid. These locales were regarded as the priority conservation areas of KHPs in Northwest Yunnan.

Table 1

Weighted attributes and eigenvalues of conservation target for KHPs in Northwest Yunnan.

Species attributes	Weighted attributes and eigenvalues		
Whether is PSESP	Yes	No	
	1	0	
IUCN Threat Level	CR	EN	VU
	1	0.6	0.3
Endemism	Endemic to Yunnan	Endemic to China	Non-endemic
	1	0.6	0
Protection Level	National first level	National second level	Provincial level
	1	0.8	0.6
CITES	CITES appendix I	CITES appendix II	CITES appendix III
	1	0.6	0.3

2.6 Regional spatial autocorrelation analysis of KHPs

Spatial autocorrelation analysis can reflect whether the spatial distribution of a given subject has significant clustering, and can be divided into global autocorrelation and local autocorrelation. In this study, Moran's *I* coefficient was used as a global spatial autocorrelation tool to analyze the overall spatial distribution state (aggregation, dispersion, or randomness) of KHPs in Northwest Yunnan (Moran, 1950). The calculation formula is expressed as follows (Xiong et al., 2019):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i-\bar{y})(y_j-\bar{y})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(y_i-\bar{y})^2} \quad (1)$$

where I is the Moran index; n is the number of evaluation units; y represents the evaluation unit's attribute value; $\bar{y}$ is the mean value of the evaluation unit's attribute value; w_{ij} is the weight matrix that measures the relationship between an evaluation unit and its neighboring evaluation units, and w_{ij} is also an important quantity that affects the results of spatial autocorrelation analysis.

The value of Moran's *I* falls between ±1. A positive value indicates that the research object's attribute values are positively correlated in space (aggregation); a negative value implies negative correlation in space (dispersion); and a value of zero represents random distribution in space. The *I* value's statistical significance is generally tested by significance test formula *Z*, using the following formula (Wang, 2006):

$$Z = \frac{1-E(I)}{\sqrt{\mathrm{Var}(I)}} \quad (2)$$

where, *E*(*I*) and Var(*I*) are the expectation and variance of the *I* value, respectively. Based on the assumption of a normal distribution test, the significance test level was selected as 5% — i.e., the critical value equaled 1.96. Thus, an absolute value of Z >1.96 indicates that the variable has significant spatial autocorrelation.

The Spatial statistics toolbox of the Spatial Autocorrelation (Global Moran's *I*) tool in ArcGIS

10.2 was used to calculate the Moran's *I* coefficient, which was then combined with the R language for drawing. MASS and ggplot2 packages to analyze the spatial autocorrelation of the KHPs' distribution. Finally, we obtained the statistical results of the spatial distribution autocorrelation and the contour density heat map reflecting the agglomeration distribution area. Higher density values on the contour density heat map demonstrated denser species distribution points, and a higher probability of regional KHPs occurrence.

2.7 Identification of conservation gaps

Gap analysis is the process of identifying grids in which relevant species are not covered or not completely covered by nature reserves (Guo et al., 2013). To perform our gap analysis, we used the ArcGIS 10.2 software to digitize the distribution of 13 national and provincial nature reserves in Northwest Yunnan (Fig. 2). Next, we obtained the conservation gaps for KHPs in existing nature reserves by superimposing the priority conservation areas over the existing nature reserves boundary (Zhang et al., 2016; Liu et al., 2018).

3. Results

3.1 Checklist of KHPs in Northwest Yunnan

As mentioned above, the compiled Northwest Yunnan checklist of KHPs included 114 species (83 herbaceous plants and 31 woody plants) from 68 genera and 37 families. Among them, there are 12 families with more than two species (Table 2), while the remaining 25 families have only one genus and one species. In addition, the number of threatened species is the highest among all attributes (Table 3).

Table 2

The families with more than two KHPs in Northwest Yunnan.

Family (≥ 2 Species)	Number of genera	Number of species	Proportion of the total number of genera (%)	Proportion of the total number of species (%)
Orchidaceae	23	58	33.82	50.88
Liliaceae	3	6	4.41	5.26
Magnoliaceae	3	4	4.41	3.51
Taxaceae	2	4	2.94	3.51
Ericaceae	1	3	1.47	2.63
Leguminosae	2	2	2.94	1.75
Compositae	2	2	2.94	1.75
Nyssaceae	2	2	2.94	1.75
Berberidaceae	2	2	2.94	1.75
Actinidiaceae	1	2	1.47	1.75
Solanaceae	1	2	1.47	1.75

Cephalotaxaceae	1	2	1.47	1.75

Table 3

The number of KHPs of different attributes in Northwest Yunnan.

Attributes	Family	Genera	Species
Threatened Species (CR/EN/VU)	34	62	101
Endemic Species (Endemic to China and Yunnan)	30	46	66
National Protected Species (The First)	22	24	28
National Protected Species (The Second)	12	34	67
CITES Appendix Species	4	26	63
Provincial Protected Species (The First)	4	7	7
PSESP	3	5	6

3.2 The distribution pattern of KHPs in Northwest Yunnan

On the whole, the administrative units located in the north have more KHPs than the administrative units in the south (Fig. 3, Table 4). Among them, Shangri-la county is home to 33 KHPs, the largest number in Northwest Yunnan; in contrast, Dali city has the fewest KHPs, and has only three species (Table 4).

Table 4

The number of KHPs distributed in each counties (cities or districts) of Northwest Yunnan.

The number range of KHPs	Counties (Cities or Districts)	Number of species
3-9	Dali	3
	Ninglang	4
	Binchuan	5
	Lanping	6
	Longyang	6
	Heqing	9
	Eryuan	10
	Yunlong	10
10-16	Jianchuan	11
	Weixi	11
	Gucheng	13
	Yulong	13
17-23	Fugong	22
	Deqin	23
	Lushui	26
24-30	Tengchong	27
	Gongshan	29
>31	Shangri-La	33

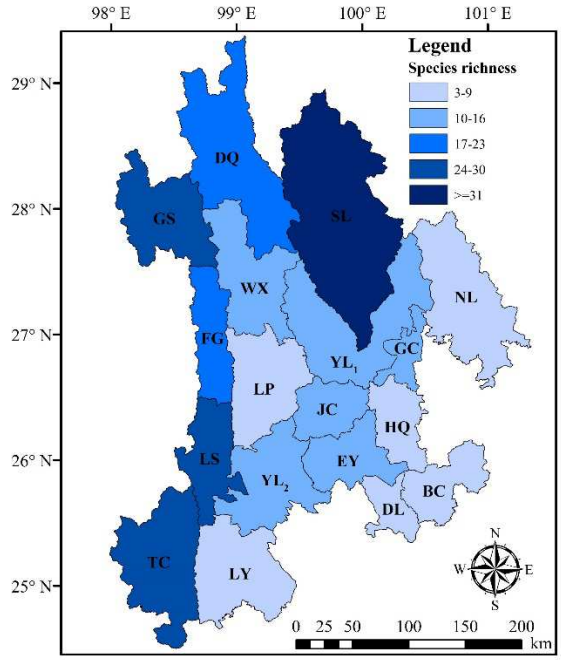

Fig. 3. Distribution pattern of KHPs in Northwest Yunnan at county level. (GS: Gongshan; DQ: Deqin; SL: Shangri-La; NL: Ninglang; FG: Fugong; WX: Weixi; YL_1: Yulong; GC: Gucheng; LP: Lanping; JC: Jianchuan; HQ: Heqing; LS: Lushui; YL_2: Yunlong; EY: Eryuan; DL: Dali; BC: Binchuan; TC: Tengchong; LY: Longyang.)

3.3 The spatial distribution of KHPs in Northwest Yunnan

Global spatial autocorrelation analysis results showed that the KHPs in Northwest Yunnan are remarkably clustered and positively correlated with space (Z = 2.90; P < 0.05) (Table 5). The distribution contour density heat map demonstrated that the distribution of KHPs in area A (located in Shangri-la county) and area B (located in Gongshan county) is relatively concentrated (Fig. 4). Note that area A is adjacent to Baima Snow Mountain National Nature Reserve, and area B is adjacent to Gaoligong Mountain National Nature Reserve.

Table 5

Results of global autocorrelation analysis of KHPs distribution in Northwest Yunnan.

Index	Abbreviations	Value
Moran's Index	Moran's *I*	0.018
Expected Index	E(*I*)	-0.002
Variance	Var(*I*)	0.000
Z-Score	*Z*	2.900
P-Value	*P*	0.004

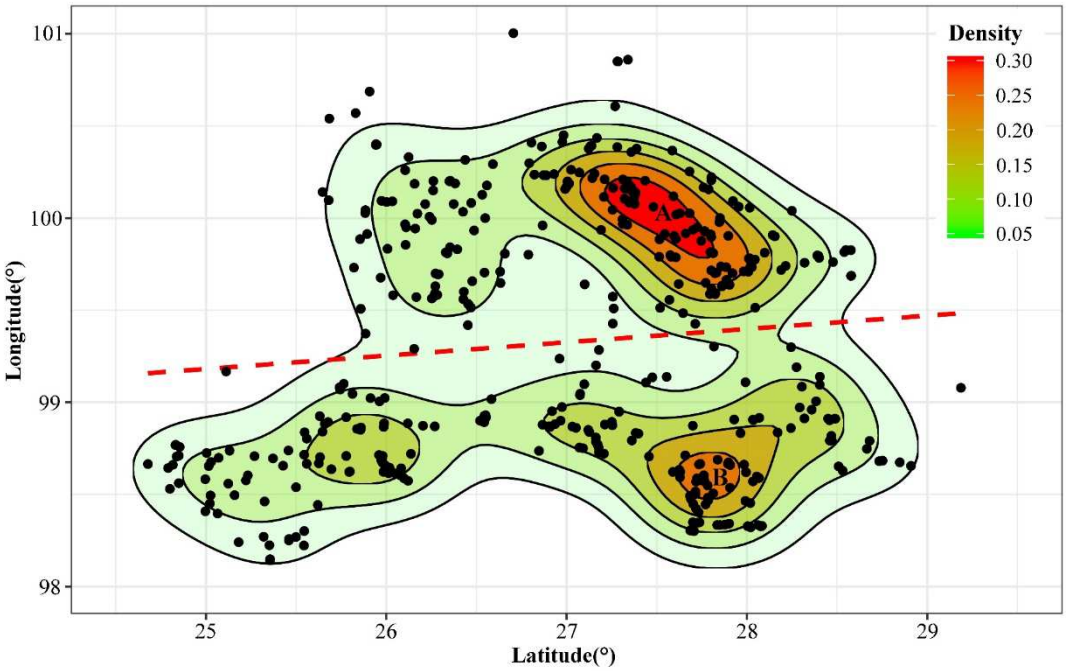

Fig. 4. Contour density heat map of KHPs distribution in Northwest Yunnan.

3.4 Hotspots distribution for KHPs in Northwest Yunnan

3.4.1 Hotspots calculated by species richness in the grid

With respect to the overall assessment, 90%, 95%, and 99% of the confidence grids accounted for 32.03%, 22.94%, and 45.03% of the total hotspot grids, respectively. 59.31% of the hotspots are located in the northern counties of Gongshan, Deqin, and Shangri-la, while the rest are scattered throughout the central and southern regions. In addition, 41.89% of the 90% confidence grids, 62.26% of the 95% confidence grids, and 69.23% of the 99% confidence grids are distributed throughout Gongshan, Deqin, and Shangri-la counties (Fig. 5a).

3.4.2 Hotspots calculated by weighted value

With respect to the overall assessment, 90%, 95% and 99% of the confidence grids accounted for 19.25%, 24.88%, and 55.87% of the total hotspot grids, respectively. 60.56% of the hotspots are located in Gongshan, Deqin and Shangri-la counties in the north, while the rest are scattered in the central or southern regions. In addition, 41.46% of the 90% confidence grids, 60.38% of the 95% confidence grids, and 66.39% of the 99% confidence grids are distributed throughout Gongshan, Deqin, and Shangri-la counties (Fig. 5b).

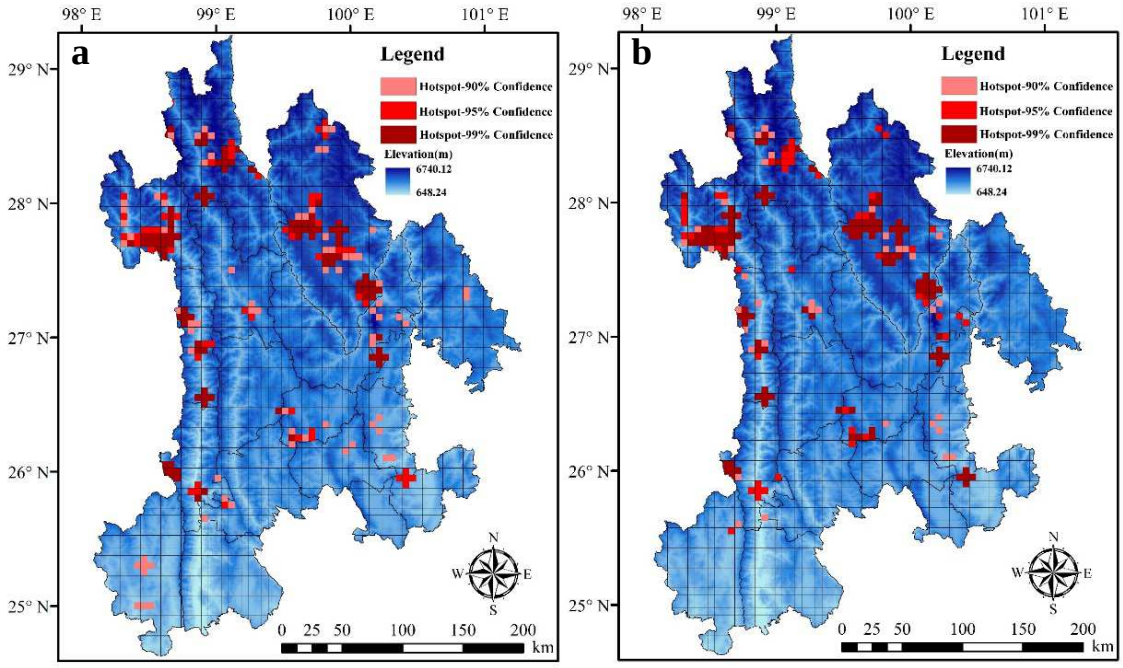

Fig. 5. a. Hotspot distribution - calculated by species richness in the grid; **b.** Hotspot distribution - calculated by the weighted value.

3.5 The priority conservation areas and conservation gaps of KHPs in Northwest Yunnan

Figure 6 depicts Fig. 5a overlaid on Fig 5b, with the hotspot grids common to both graphs selected as the priority conservation areas. Overall, the hotspot overlap rate between the two graphs is 81.22%. Specifically, the overlap rate of Hotspot-90% confidence (1.65 < GiZScore < 1.96) is 29.21%, Hotspot-95% confidence (1.96 < GiZScore < 2.58) is 26.19%, and Hotspot-99% confidence (GiZScore > 2.58) is 74.22%. In addition, 63.82% of the priority conservation areas are distributed in Gongshan, Deqin, and Shangri-la counties, and the remaining priority conservation areas are scattered in the central or southern regions.

By overlapping the distribution of priority conservation areas with existing nature reserves, it is determined that the total biodiversity priority conservation area is 5,615 km^2, which accounts for 7.04% of the total area of Northwest Yunnan. Currently, about 20.30% of priority conservation areas are covered by existing nature reserves, but that still leaves a large number of areas with high conservation value that are not covered. In total, we identified 13 conservation gaps within existing nature reserve network (Fig. 6). These conservation gaps were divided into two groups based on their locale: 1) six priority conservation areas were located outside the existing nature reserves — GAP1, GAP4, GAP6, GAP7, GAP10, and GAP13; and 2) seven priority conservation areas were partly covered by existing nature reserves — GAP2, GAP3, GAP5, GAP8, GAP9, GAP11, and GAP12.

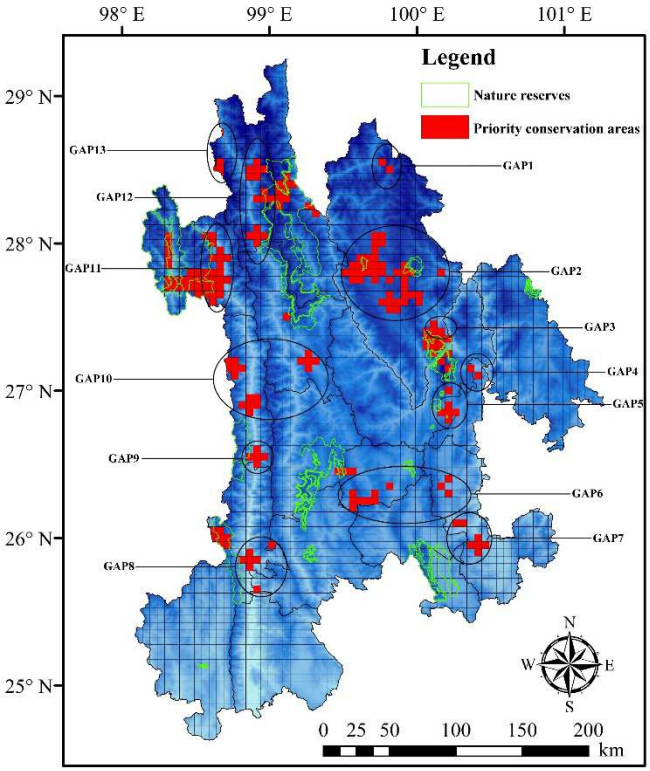

Fig. 6. The priority conservation areas and conservation gaps of KHPs in Northwest Yunnan.

4. Discussion

4.1 The spatial distribution of KHPs in Northwest Yunnan

This research focuses on the spatial distribution of KHPs, which plays an important role in their effective conservation. Overall, the administrative units located in the north have more KHPs than those in the south, this is consistent with the distribution pattern of higher plant species in Northwestern Yunnan (Ye et al., 2020). This may be due to the fact that the Gaoligong Mountain, the Baima, Haba, and Yulong Snow Mountains, and several other large mountains are located in the north. These mountains are associated with massive altitude variations, different climate features, and diverse habitats, enabling them to meet the varying needs of different species. These characteristics make the species diversity extremely rich, which is consistent with the hypothesis of habitat heterogeneity proposed by Shmida and Wilson (1985). In addition, the KHPs distribution in Northwest Yunnan is remarkably clustered and positively correlated with space (Z = 2.90; $P < 0.05$); and the distribution in Shangri-la and Gongshan county is relatively concentrated. This is highly consistent with the results reported by Yu et al. (2015), indicating that the Baima Snow Mountain and Gaoligong Mountain National Nature Reserves established in this region in 1983 have played an important role in the conservation of KHPs. Previously, many plant species were distributed outside nature reserves and were not effectively protected (Fig. 2), and plant diversity conservation faces blind collection driven by interests and other issues in Northwest Yunnan (Yunnan Provincial Governmen, 2008). The survival of many species is endangered or threatened. This study came up with expanding the conservation areas and building ecological

corridors to basically establish a biodiversity protection system and strengthened the ability of biodiversity conservation, and will help to improve the conservation of species having threat of extinction.

4.2 Hotspots distribution of KHPs in Northwest Yunnan

The distribution of hotspots throughout the grid shows consistent results using species richness and the species characteristics' weighted score. Both methods indicate there are more hotspots located northwest and northeast of the study area (Fig. 5). The Baima Snow Mountain and Gaoligong Mountain National Nature Reserves in the northwest cover more hotspots (Fig. 7) and play an important role in the conservation of the KHPs in this area. In addition, Baima Snow Mountain National Nature Reserve mainly protects alpine coniferous forests, and Gaoligong Mountains National Nature Reserve primarily protects forest vegetation vertical belt spectrum. Therefore, the unique and abundant forest vegetation types protect many habitats of KHPs. This result is consistent with the findings reported by Ma et al. (2007). However, the hotspot grids in the northeast are not fully covered by existing nature reserves (Fig. 7), mainly due to the small area of provincial nature reserves in the Napa and Bita Lake. In addition, the central and eastern hotspots are well covered by the Yulong and Haba Snow Mountain Provincial Nature Reserves (Fig. 7), which may be primarily due to the rich habitat types for KHPs in the two nature reserves, including temperate coniferous forest and subalpine meadow (Ma et al., 2007). The rest of the hotspot grids scattered in the southern and midwest regions are not adequately covered by the existing nature reserves (Fig. 7), mainly because the nature reserves were originally established to protect endangered animals, resulting in many of the KHPs being outside the reserves (Du et al., 2018).

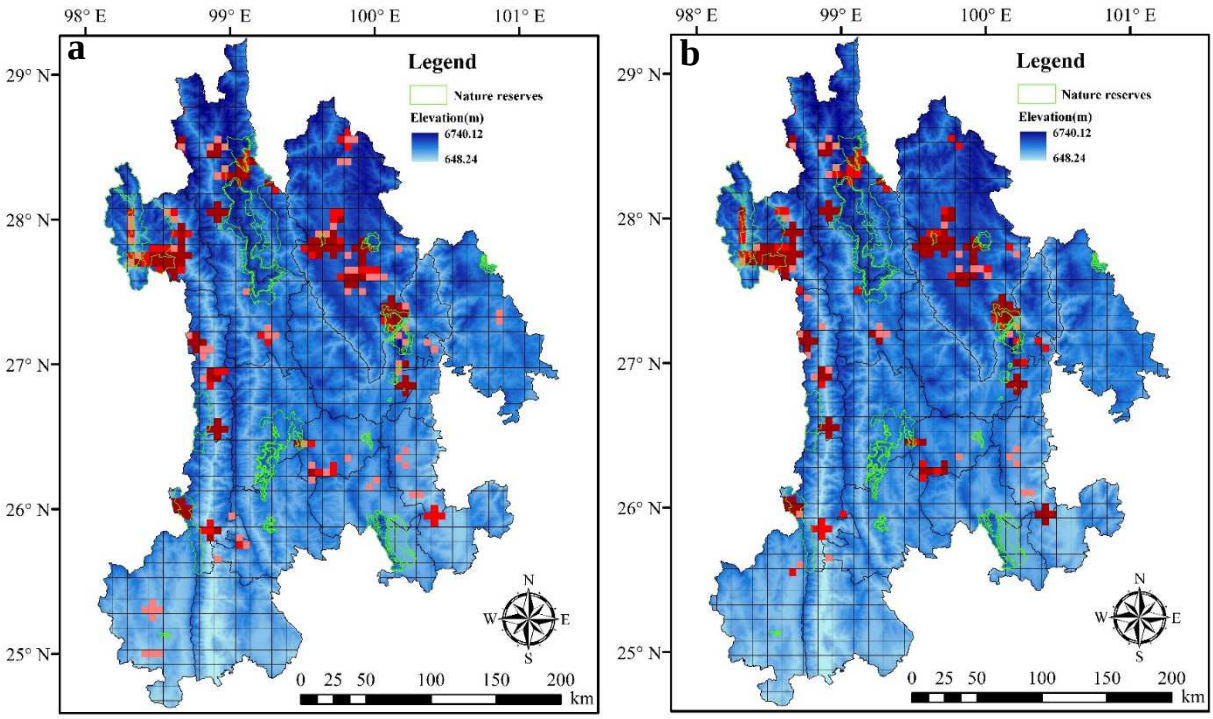

Fig. 7. Hotspots overlap with protected areas. **a.** Calculate hotspots according to coordinate points (number of species) in the grid. **b.** Calculate hotspots according to the weighted value

in the grid.

4.3 Priority conservation areas and conservation gaps

The results showed that the priority conservation area of the KHPs in Northwest Yunnan encompass 5,615 km^2. Many priority conservation areas are distributed on the boundary line of Northwest Yunnan or the boundary line between counties within the region, which parallels the results from a study on threatened plants in Shanxi Province conducted by Zhang et al. (2016). In addition, over 60% of the priority conservation areas for KHPs in Northwest Yunnan are concentrated in Gongshan, Deqin and Shangri-la counties, which is in good agreement with the research results reported by Ma et al. (2007). Although 13 national and provincial nature reserves have been established in Northwest Yunnan, their distribution is inadequate for providing sufficient coverage of the priority conservation areas for KHPs. Compared with the existing natural conservation network, more effective nature conservation networks have been established in the northwest and mideast parts of Northwest Yunnan, while many conservation gaps in the northeast, midwest and south parts of Northwest Yunnan manifest as a network of less efficient protected areas. At present, the existing nature reserves cover 20.30% of all priority conservation areas, but ~ 80% of priority conservation areas with high protection value are not covered by nature reserves (Fig. 6). Thus, there are many gaps in the conservation of KHPs.

Through the method of gap analysis, we identified 13 conservation gaps. Some of these gaps are completely outside nature reserves, while others are partially covered by nature reserves. Therefore, we put forward targeted suggestions to fill the conservation gaps according to the position and gap type. We propose: 1) to establish new nature reserves for GAP1, GAP10, and GAP13, in order to protect *Cypripedium elegans*, *Rhododendron protistum* var. g*iganteum*, *Diphylax contigua*, *Coptis teeta*, *Actinidia pilosula* and *Cypripedium guttatum*, etc. At the same time, establishing ecological corridors between the surrounding nature reserve should also be considered; 2) to expand the nature reserves in the Napa and Bita Lake and establish ecological corridors to address GAP2; 3) to expand the adjacent provincial nature reserves of Haba and Yulong Snow Mountains and Lashihai Plateau Wetland, as well as implement unified planning and supervision to mitigate GAP3, GAP4, and GAP5; 4) to expand the adjacent Erhai Lake National Nature Reserve and Yunling Provincial Nature Reserve to enclose GAP6 and GAP7, and consider establishing ecological corridors to simultaneously increase the degree of landscape connection between conservation and restoration of biodiversity (Zheng et al., 2019); 5) to expand Gaoligong Mountain National Nature Reserve to include GAP8 and GAP9; and 6) establish ecological corridors between Gaoligong Mountain and Baima Snow Mountain National Nature Reserves to address GAP11 and GAP12, and enhance the connection between the two nature reserves and give full attention to the overall conservation role of the priority areas. This research results identified the priority conservation areas of KHPs in Northwest Yunnan, which could help to further rationally allocate resources and optimize the existing conservation network system, thereby strengthening the protection of endangered or threatened species.

4.4 Limitations of the present study

In studies of biodiversity conservation, the completeness, accuracy, and reliability of data on

geographical distribution of species is crucial for identifying hotspots and conservation gaps (Zhang et al., 2016; Wu et al., 2016a). Although we have collected quite a lot of species distribution data through different methods and approaches, data on some species still consist of only few distribution records, it is difficult to represent the distribution of these species comprehensively. The main reasons are as follows: 1) insufficient investigation and recording of distributed data (Wu et al., 2016a); 2) the vast majority of data is scattered in the hands of many scientific researchers, etc (Dai and Zhao., 2016). Due to some of these objectivity issues in data collection, the resulting deviation may affect the assessment of species diversity and may influence reliable inference on the potential diversity drivers, as well as mislead the determination of conservation prioritization (Engemann et al., 2015). Furthermore, in this study, most of the hotspots are located in Gongshan, Deqin and Shangri-la counties in the north. Investigate its reason: on the one hand, because the biodiversity of these counties is richer than that of other regions, but on the other hand, it may also be due to more surveys and complete records in these counties. This also indicates that supplement data information such as the lacking species distribution information, especially in areas with fewer investigations, is one of the work priorities for identifying priority areas for biodiversity conservation in the future.

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Declaration of interests

☑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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: