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Threatened Plants in China's Sanjiang Plain: Hotspot Distributions and Gap Analysis

Baojia Du [1,2], Yanyan Zheng [3], Jiping Liu [1,*] and Dehua Mao [2,*]

1 Institute of Ecology and Environment, Jilin Normal University, Siping 136000, China; dubaojiajl@163.com
2 Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China
3 No. 1 Senior Middle School of Siping, Siping 136000, China; jlsdzyy@126.com
* Correspondence: liujpjl@163.com (J.L.); maodehua@iga.ac.cn (D.M.); Tel.: +86-434-329-6107 (J.L.); +86-431-884-2254 (D.M.)

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Abstract: Global biodiversity is markedly decreasing in response to climate change and human disturbance. Sanjiang Plain is recognized as a biodiversity hotspot in China due to its high forest and wetland coverage, but species are being lost at an unprecedented rate, induced by anthropogenic activities. Identifying hotspot distributions and conservation gaps of threatened species is of particular significance for enhancing the conservation of biodiversity. Specifically, we integrated the principles and methods of spatial hotspot inspection, geographic information system (GIS) technology and spatial autocorrelation analysis along with fieldwork to determine the spatial distribution patterns and unprotected hotspots of vulnerable and endangered plants in Sanjiang Plain. A gap analysis of the conservation status of vulnerable and endangered plants was conducted. Our results indicate that six nationally-protected plants were not observed in nature reserves or were without any protection, while the protection rates were <10% for 10 other nationally-protected plants. Protected areas (PAs) cover <5% of the distribution areas for 31 threatened plant species, while only five species are covered by national nature reserves (NNRs) within >50% of the distribution areas. We found 30 hotspots with vulnerable and endangered plants in the study area, but the area covered by NNRs is very limited. Most of the hotspots were located in areas with a high-high aggregation of plant species. Therefore, it is necessary to expand the area of existing nature reserves, establish miniature protection plots and create new PAs and ecological corridors to link the existing PAs. Our findings can contribute to the design of a PA network for botanical conservation.

Keywords: hotspots; gap analysis; Sanjiang Plain of China; vulnerable and endangered plants

1. Introduction

Biodiversity plays an important role in determining ecosystem structure and function, as species composition and richness impact and respond to ecosystem properties [1]. Different species can alter abiotic conditions, which affect the energy and material fluxes that help to define an ecosystem [2]. The loss of even one species can impact multiple ecosystem functions and lead to ecosystem destabilization [3]. Due to habitat loss caused by human activities and climate change, the rate of species extinction has been rapidly increasing [4]. The unprecedented rates of biodiversity loss have been directly linked to human alteration of the environment, including changes in land cover and the destructive exploitation of natural resources [5]. A recent study suggested that current global extinction rates are 1000-times higher than the natural background extinction rates and may increase in the future [6]. Therefore, protecting biodiversity is a matter of great urgency. Additionally, the question of how to effectively reduce the rate of species extinction has become a major challenge for conservation biologists and policymakers [7,8].

One of the most effective ways to protect biodiversity is to establish protected areas (PAs). The importance of PAs has been generally recognized, and numerous international laws consider PAs as a key tool for environmental protection [9]. However, numerous studies about nature conservation networks have demonstrated that PAs cannot adequately protect all the biodiversity of a region or country [10,11]. Many nature reserve systems do not represent regional biodiversity, and many are unable to fulfill their conservation goals [12]. China harbors more threatened species than other regions in the world [13]. In China, the PA network has many gaps in terms of biodiversity representation at both the ecoregion and species level [14]. Much research concerning the geographic distribution of bird and vertebrate diversity in Southern China has already been carried out, but few studies have comprehensively investigated the distribution of threatened plant species diversity in Northeast China [15]. Therefore, there is an urgent need to detect and analyze the distribution of threatened plants in order to enhance the overall conservation efficiency of nature reserves [16].

Gap analysis is an effective approach to test the effectiveness of PAs in representing local biodiversity [17,18]. Gap analysis of threatened plant species in nature reserves could provide valuable information to improve management efficiency. It has been widely used in many European countries [4,18–21]. Sanjiang Plain in Northeast China is the largest freshwater marsh area in the country and has been identified as a key area for wetland biodiversity due to its high species richness and number of endemic species [17]. Using gap analysis, Liu et al. (2008) evaluated bird diversity in Sanjiang Plain, but studies of vulnerable and endangered plant species in Northeast China are rare [22–25]. Sanjiang Plain has many important vulnerable and endangered plant species and associated habitats. These habitats act as crucial areas for many globally-endangered plants. Gap analysis of threatened plant species is critical to improve the conservation efficiency of nature reserve systems in Sanjiang Plain.

Before the middle of the 20th century, natural wetlands were widely distributed in Sanjiang Plain. In the 1940s, there were >50,000 km^2 of wetlands in the region [18]. From the 1950s to the 2000s, areas of cropland expanded by 250%, mainly converted from natural wetlands [19]. The loss and fragmentation of wetlands damaged the habitats of endangered plants, significantly impacting the landscape and the biodiversity of this area. Protecting the wetlands in Sanjiang Plain not only benefits the ecological environment of Northeast Asia, but also contributes to mitigating the sharp loss of biodiversity [20]. Due to the importance of wetlands and valuable biodiversity, Sanjiang Plain has become a target of numerous research projects, including those aimed at detecting changes in habitats and biodiversity, analyzing the underlying anthropogenic drivers and formulating conservation strategies [26–29]. However, previous studies mainly focused on particular hotspots such as nature reserves at a local scale. Thus, conservation strategies have been generated based on local and site-based protection, which cannot be used as adequate guidelines for broad-scale freshwater wetland conservation initiatives across Sanjiang Plain. Therefore, using hotspot analysis and gap analysis, this study aimed to: (1) assess whether the PAs in Sanjiang Plain provide representative and biologically-sustainable coverage of the region's biodiversity; (2) evaluate the conservation status of 60 threatened plant species by comparing their distribution with the spatial database of the national nature reserves (NNRs) and therefore calculate the proportion of each species covered by the PAs; and (3) propose broad recommendations to improve the representativeness of the PA system. The results are expected to provide useful information for future botanical conservation and maintaining the habitats of endangered species in situ in Sanjiang Plain.

2. Data and Methods

2.1. Study Area

Sanjiang Plain is located in the northeastern region of Heilongjiang Province, ranging in latitude from 43°49′55″–48°27′40″ and in longitude from 129°11′20″–135°05′26″, covering a total area of 108,900 km^2. The altitude is lower than 200 m in most of the region. This area includes the alluvial plain of Heilongjiang, Songhua and the Ussuri River in the north of the Wanda Mountains, the Ussuri tributaries and Xingkai Lake to the south of the Wanda Mountains. It has a humid and semi-humid temperate continental climate, with a mean annual precipitation of 500–650 mm and a mean annual temperature of 1.4–4.3 °C [30]. There are eight major soil types: dark brown soil, meadow soil, white slurry soil, black soil, swamp soil, paddy soil, peat and sand soil. There are eight national nature reserves: Zhenbaodao National Nature Reserve (ZNNR), Dongfanghong National Nature Reserve (DNNR), Bachadao National Nature Reserve (BNNR), Sanjiang National Nature Reserve (SNNR), Naolihe National Nature Reserve (NNNR), Xingkaihu National Nature Reserve (XNNR), Qixinghe National Nature Reserve (QNNR) and Honghe National Nature Reserve (HNNR) (Figure 1).

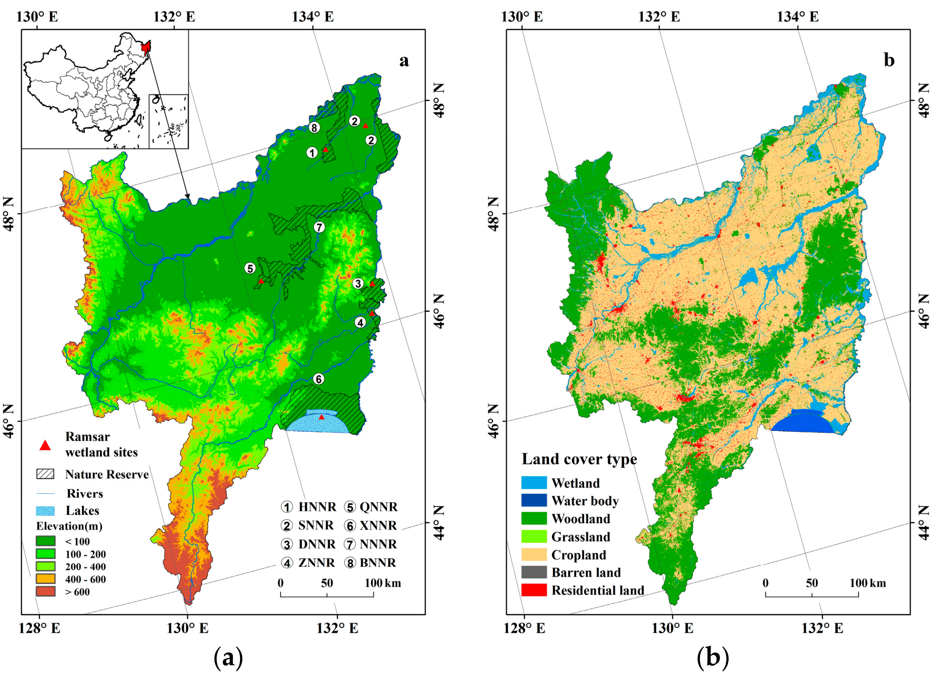


Figure 1. (**a**) Location and (**b**) land cover map of Sanjiang Plain. Zhenbaodao National Nature Reserve (ZNNR), Dongfanghong National Nature Reserve (DNNR), Bachadao National Nature Reserve (BNNR), Sanjiang National Nature Reserve (SNNR), Naolihe National Nature Reserve (NNNR), Xingkaihu National Nature Reserve (XNNR), Qixinghe National Nature Reserve (QNNR) and Honghe National Nature Reserve (HNNR)

2.2. Inventory of Vulnerable and Endangered Plant Species

In our study, we collected 60 plant species (40 vulnerable and 20 endangered), all of which were categorized as protected species at different levels. National threatened plant species in the study area are found on the China Species Red List, a list of rare and endangered plants in China (Ministry of Environment Protection of the People's Republic of China, 2013), the List of National Key Protected Wild Plants (National Forestry Administration and Department of Agriculture, 1999) and the List of Provincial Key Protected Wild Plants in Heilongjiang (government of Heilongjang Province, 2007). Provincial and regional threatened plant species are recorded in comprehensive investigation reports of nature reserves in Sanjiang Plain.

Distribution information on the 60 threatened plant species was obtained from four sources: (1) specimen collection records (including vegetation type and elevation range), (2) specimen records from the Chinese Virtual Herbarium (http://www.cvh.ac.cn/), (3) Flora of China, and (4) local Floras. All the collected information was reviewed, discussed and integrated. Finally, we established a distribution database of 60 threatened species, which includes their scientific names, habitats, vertical upper and lower distribution limits and present locations.

2.3. Other Geographic Datasets

To obtain information on topography, a digital elevation model (DEM) of Sanjiang Plain was extracted from the Shuttle Radar Topographic Mission 90-m Digital Elevation Database Version 4.0 (http://www.gscloud.cn/). The elevation coverage was produced by using the "Reclassify" option in ArcGIS10.0 to classify the DEM into five categories: <100 m, 100–200 m, 200–400 m, 400–600 m and >600 m. Land cover data from 2012 were derived from Wang et al. [30]. The overall classification accuracy for the land cover map in 2012 was 92.5% (assessed by 2436 field samples). The geomorphologic map, soil type map and vegetation type map were digitized from the existing corresponding maps. These electronic maps were obtained from the website of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences (http://www.osgeo.cn/map/). National nature reserve distribution maps came from the planning chart of the natural preservation areas administration.

2.4. Mapping Geographic Distributions of Species Richness

The geographic distributions of 60 threatened plant species were mapped using ArcGIS 10.0 software. The distribution of threatened plant species is influenced by five environmental factors: elevation, land cover types, geomorphologic conditions, soil types and vegetation types [31]. Based on species-habitat relationships and the available environmental layers [32], we predicted the distribution of threatened species through overlap analysis of those five layers. We generated a grid with a 3-km resolution to obtain the richness of threatened species in the study area. There were 12,578 grid cells in total covering the whole study area [33]. We summed and sorted the species richness of each grid, and the threatened species richness was divided into five levels: low (<5 species), low-mid (6–10 species), mid (11–15 species), mid-high (16–20 species) and high (>20 species).

2.5. Gap Analysis

Gap analysis is the process of finding the species and vegetation types that are not represented or not fully represented in PAs. Gap analysis emphasizes that every species in a region should occur at least once in the PA. A vegetation type or "hotspot" that does not appear is considered a gap [22]. Identifying conservation gaps of threatened plants within NNRs is done by overlapping and comparing the distributions of hotspots of threatened species with the distributions of protected areas [19,20,24,34,35]. We aimed to find ideal areas to expand protection; such planning makes it possible to improve the efficiency of conservation optimally while minimizing the cost of land area. We evaluated the conservation gaps of 60 threatened plant species by calculating the percentage of threatened plant species covered by nature reserves.

All threatened plant species distribution maps are assessed for their accuracy. As with the land cover maps, this is done by comparing the predicted distributions with independent reference data [17]. In this study, we compared the numbers of threatened plant species between field samples and predicted results. As shown in Table 1, the field survey found that the average prediction accuracy was >89%. The average prediction accuracy was 91.74% in Sanjiang Plain. The field sample surveys proved that the distribution map of threatened species was sufficiently accurate to meet the needs of this study. The actual numbers of threatened plant species of the field survey came from the Comprehensive Scientific Investigation Reports on ZNNR, on SNNR on DNNR and on BNNR.

Table 1. Accuracy of the predicted plant species in Sanjiang Plain.

Area	Actual Numbers of Plant Species	Predicted Numbers of Plant Species	Prediction Accuracy (%)
ZNNR	36	33	91.67
SNNR	37	33	89.19
DNNR	33	32	96.97
BNNR	46	41	89.13
Average	–	–	91.74

2.6. Spatial Autocorrelation Analysis and Hotspot Detection

An understanding of threatened plant species distribution is central to biodiversity conservation. The distributions of many organisms are spatially autocorrelated. Usually, if spatial autocorrelation exists, it will be exhibited by similarities between contiguous regions, although negative patterns of dependence are also possible [36]. Spatial autocorrelation analysis includes global spatial autocorrelation and local spatial autocorrelation. Global spatial autocorrelation detects the spatial pattern of the whole study area. In contrast, local spatial autocorrelation calculates the value of each unit relative to each neighboring unit. Local spatial autocorrelation analysis helps us more accurately master space element aggregation and heterogeneity characteristics. Using local spatial autocorrelation analysis, we can obtain the spatial position and range of the place of aggregation and measure the degree of local spatial correlation between each spatial unit and adjacent units [37].

In this study, we used Geoda software (Center for Spatially Integrated Social Science (CSISS), Chicago, IN, USA) for the spatial autocorrelation analysis of vulnerable and endangered plants [38]. Spatial autocorrelation analysis was used to test whether the values for richness of threatened species within a location were markedly related to those of neighboring areas [39,40]. A spatial autocorrelation analysis of the spatial distribution of threatened plant richness in Sanjiang Plain was conducted, then a cluster map of local indicators of spatial associations of threatened plants and the statistical results of local spatial autocorrelation were obtained.

Spatial aggregation of the vulnerable and endangered plant species was divided into four patterns: high-high aggregation (areas and their surroundings with high species richness), low-low aggregation (areas and their surroundings with low species richness), low-high aggregation (areas with low species richness that had surrounding areas with high species richness) and high-low aggregation (areas with high species richness that had surrounding areas with low species richness; that is, high value existed in the form of isolated wetlands or islands). Spatial autocorrelation analysis showed that the global autocorrelation coefficient was 0.5023, and the significance level was a = 0.01, which indicates that threatened species richness has significant spatial autocorrelation. Using ArcGIS10.0 software (Esri, Redlands, CA, USA), the results of the local spatial autocorrelation analysis were connected with the distribution maps of the NNRs, then exported to the attribute table, and Microsoft Excel was used to calculate the area ratio of the autocorrelation type region of each reserve (Table 2).

A hotspot is defined as a condition indicating some form of clustering in a spatial distribution that can separate clusters of high value from clusters of low value [41]. Hotspot detection is one of the methods for testing global aggregation, which not only can measure the degree of local correlation and analyze the characteristics of spatial distribution, but also can identify the clustering characteristics of high- or low-value species richness [42,43]. CrimeStat is spatial statistics software for the analysis of incident locations that can interface with most desktop geographic information system programs [44]. First, the data setup section required that we define the "Primary" file, which is a shape file of threatened plant species distribution incidence with X and Y coordinates and attribute fields. Second, we defined the reference grids and measurement parameters (which identify the type of distance measurement to be used and specify parameters for the area of the study region and the length of the spatial units) for various routines, such as the X, Y coordinates in the data setting module and running hotspot analysis tools, then obtaining the hotspot distribution map. The detailed operation steps of the software are available at http://www.icpsr.umich.edu/CrimeStat.

Table 2. Proportion statistics of spatial autocorrelation type of vulnerable and endangered plant species.

Area	Uncorrelated (%)	High-High Aggregation (%)	Low-Low Aggregation (%)	High-Low Aggregation (%)	Low-High Aggregation (%)
ZNNR	39.24	22.78	24.05	6.33	7.59
DNNR	63.08	21.54	3.08	12.31	0.00
XNNR	36.95	56.19	0.00	6.86	0.00
QNNR	10.71	50.00	0.00	39.29	0.00
SNNR	28.86	57.32	0.00	0.00	13.82
HNNR	27.78	50.00	0.00	0.00	22.22
NNNR	10.18	3.62	83.03	0.00	3.17
BNNR	65.22	19.57	0.00	0.00	15.22
Sanjiang Plain	26.75	21.28	41.37	4.08	6.54

3. Results

3.1. Geographical Distribution of Threatened Plant's Richness

As shown in Figure 2, threatened plants were distributed widely across Sanjiang Plain, and their geographic distribution was uneven. Regions with mid-high species richness were distributed mainly in the southeast part of Xiaoxinganling, Laoyeling Mountains, Taipingling and Wanda Mountains. Among these, the Xiaoxinganling area had the highest number of threatened species (27). The distribution of threatened species was relatively concentrated, and the distribution area was the largest. The pattern indicates that the species richness of mountainous areas is mid-high compared to the species richness of plains. By overlapping the threatened species richness map with the distribution of NNRs, we found that some areas with mid-high species richness in the eastern part of the study area have been protected. For example, HNNR, SNNR, DNNR and BNNR covered some areas of mid-high species richness. A large percentage of threatened plants in the central, northwest and southwest Sanjiang Plain were not covered by NNRs and had no protection.

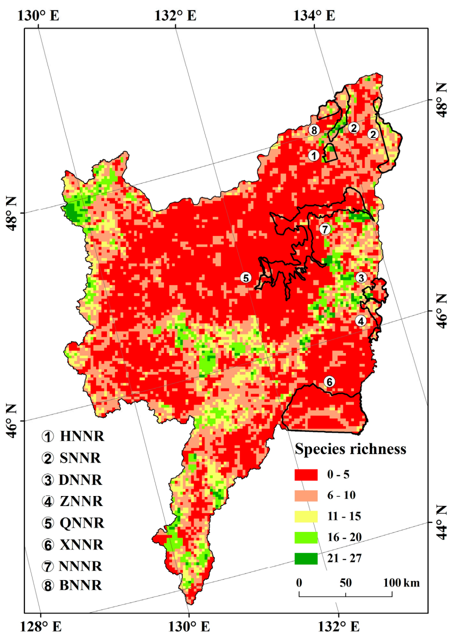


Figure 2. Species richness pattern of threatened plants in Sanjiang Plain.

3.2. Spatial Autocorrelation of Threatened Plant Distribution

Using local spatial autocorrelation analysis, we calculated the area percentage for each spatial aggregation type distribution within the PAs and generated a map of vulnerable and endangered plants by spatial aggregation. According to Figure 3 and Table 2, an area of uncorrelated types occupied the largest proportion in the DNNR and the BNNR, at 63.08% and 65.22%, respectively. An area of low-low aggregation type occupied the largest proportion in the NNNR, with a value of 83.03%. It was concluded that the spatial correlation of threatened plants was relatively low in the DNNR, BNNR, and NNNR. An area of high-high aggregation type occupied the largest proportion in the XNNR, QNNR, SNNR and HNNR, with values of 56.19%, 50%, 57.32% and 50%, respectively. The spatial correlation of threatened plants was relatively high. An area of high-low aggregation type occupied the largest proportion in the QNNR, with a value of 39.29%.

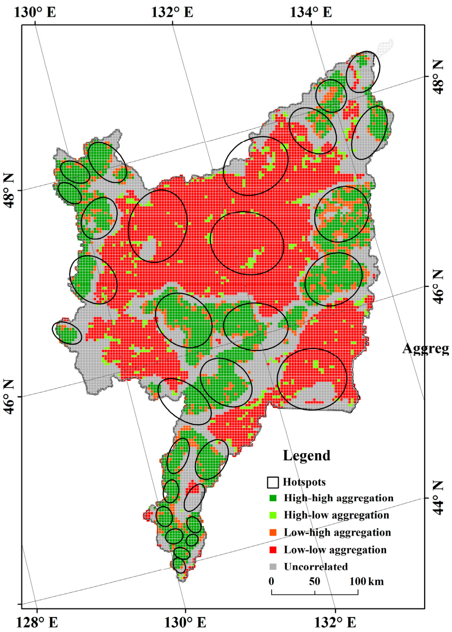


Figure 3. Spatial distribution pattern of aggregation type and hotspots of threatened plant species.

An area of high-high aggregation type accounted for about 21.28% of the total area in Sanjiang Plain. Areas of high-low aggregation type accounted for about 4.08% of the total area in Sanjiang Plain; that is, an area with mid-high species richness accounted for about a quarter of the total area. To protect the diversity of threatened plants in Sanjiang Plain, it is necessary to find the hotspots with high species richness.

3.3. Distribution of Threatened Plant Species Hotspots

Following the principles and methods of spatial hotspot inspection, we obtained a hotspot distribution map of 60 threatened plant species; 30 hotspots were identified in Sanjiang Plain. As shown in Figure 3, in the spatial position, the seven hotspots in the eastern Sanjiang Plain corresponded to the existing NNRs (Figure 1a). These hotspot areas were only partly covered by reserves. Among them, the four hotspots in the northeast corresponded to SNNR, BNNR and HNNR; two hotspots in the east corresponded to NNNR, DNNR and ZNNR. The one hotspot in the southeast corresponded to XNNR. There were 17 hotspots in the western and southern Sanjiang Plain, located outside the existing reserves. The three hotspots in the northern Sanjiang Plain were located in cropland, low floodplain, high floodplain, and river terrace. The 14 hotspots in the central and southern regions were mainly distributed in the Laoyeling Mountains and Taipingling. The six hotspots in the western Sanjiang Plain were located in southeastern Xiaoxinganling. Most hotspots were of the high-high aggregation type in spatial autocorrelation.

3.4. Conservation Gaps of Threatened Plants

To estimate the protective efficacy of PAs on threatened species, by overlapping the species richness distribution map and the NNR distribution map, we found that only 10.6% of the grid area (1331 of 12,578 cells) was covered by existing NNRs; 0.27% of the grid area (34 of 12,578 cells) with high species richness was not covered by existing NNRs and 1.66% of the grid area (207 of 12,578 cells) with mid-high species richness was not covered by existing NNRs (complete conservation gaps). We calculated the percentage for 60 threatened plants covered by PAs. As shown in Figure 4, 31 threatened plants were protected in NNRs, but only within <5% of their distribution areas. Only five threatened plants were protected in NNRs covering >50% of their distribution areas. As shown in Table 3, six of the 20 nationally-protected species (*Gymnadenia conopsea*, *Juglans mandshurica Maxim*, *Malaxis monophyllos*, *Dioscorea nipponica*, *Chosenia arbutifolia* and *Actinidia argute*) were identified in national conservation gaps, which indicates no protection. Ten species were found in NNRs with <10% of their distribution areas. Only four of the 20 nationally-protected species (*Astragalus membranaceus*, *Glycine soja*, *Myriophyllum propinquum* and *Nelumbo nucifera*) were protected by NNRs with >40% of their distribution areas. Three of the 10 provincially protected species (*Syringa reticulata*, *Spiranthes sinensis*, and *Rosa koreana Kom*) were identified in provincial conservation gaps, which indicates no protection, while seven species were protected in NNRs with <10% of their distribution areas.

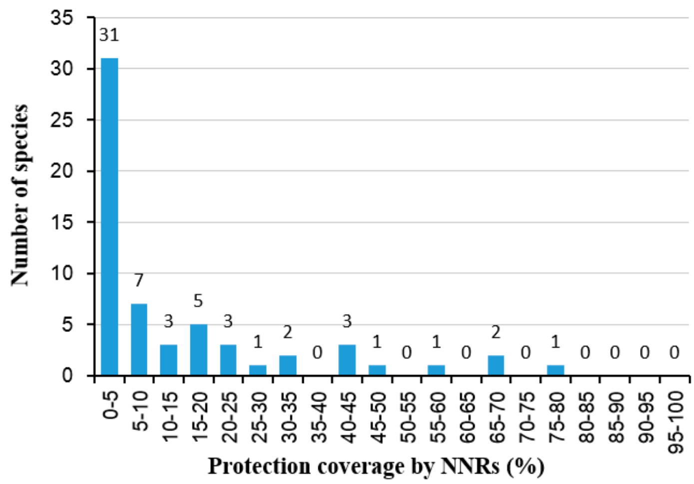


Figure 4. Numbers of threatened species in different percentages of areas covered by existing NNRs.

Table 3. Percentage of threatened plants being protected on Sanjiang Plain.

Plant Species	Protection Level	EN/VU	Unprotected Area (km^2)	Protected Area (km^2)	Total Area (km^2)	Protected Area/Total Area (%)
Utricularia intermedia	regional	EN	35.73	0	35.73	0
Gymnadenia conopsea	national II	EN	531.76	0	531.76	0
Syringa reticulata	provincial	EN	101.66	0	101.66	0
Juglans mandshurica Maxim	national III	EN	714.88	0	714.88	0
Malaxis monophyllos	national II	EN	39.91	0	39.91	0
Dioscorea nipponica	national II	EN	26.66	0	26.66	0
Spiranthes sinensis	provincial	EN	365.61	0	365.61	0
Chosenia arbutifolia	national II	EN	7.40	0	7.40	0
Commelina communis	regional	VU	48.04	0	48.04	0
Rosa koreana Kom	provincial	EN	478.51	0	478.51	0
Actinidia arguta	national II	EN	1636	0	1636	0
Lilium callosum	regional	VU	717.18	0.66	717.84	0.09
Polemonium liniflorum	regional	VU	439.13	0.74	439.87	0.17

Table 3. *Cont.*

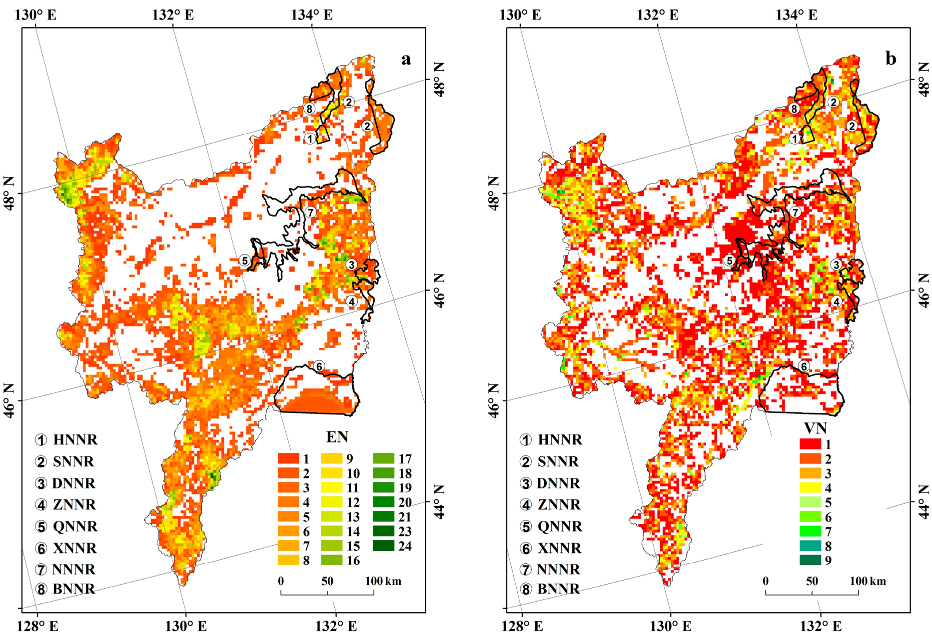
Plant Species	Protection Level	EN/VU	Unprotected Area (km^2)	Protected Area (km^2)	Total Area (km^2)	Protected Area/Total Area (%)
Platycodon grandiflorus	provincial	EN	2630.32	11.63	2641.95	0.44
Maackia amurensis	provincial	EN	1563.29	9.04	1572.33	0.57
Platanthera hologlottis	national II	EN	413.54	2.62	416.15	0.63
Lobelia sessilifolia	regional	VU	409.35	2.62	411.96	0.64
Actinidia polygamae	national II	EN	3611.04	33.79	3644.83	0.93
Schisandra chinensis	national II	EN	148.78	1.63	150.41	1.08
Rubus saxatilis	provincial	EN	2187.05	27.23	2214.28	1.23
Tilia amurensis	national II	EN	1100.28	18.18	1118.46	1.63
Paris verticillata	national II	EN	1044.97	18.18	1063.15	1.71
Ribes mandshuricum	national II	EN	950.78	18.17	968.95	1.88
Berberis amurensis	provincial	EN	974.19	19.28	993.47	1.94
Gentiana manshurica	provincial	EN	139.21	3.72	142.93	2.60
Acer mono Maxim	provincial	EN	1663.63	52.06	1715.69	3.03
Acanthopanax senticosus Harms	national III	EN	1547.04	52.06	1599.11	3.26
Phellodendron amurense	national II	EN	1408.19	52.06	1460.26	3.57
Aralia elata	provincial	EN	1560.39	67.10	1627.49	4.12
Ottelia alismoides	regional	VU	347.71	16.26	363.97	4.47
Valeriana amurensis	regional	VU	1585.90	75.30	1661.20	4.53
Hypericum ascyron	regional	VU	543.96	30.99	574.95	5.39
Fraxinus mandschurica	national II	EN	674.99	40.11	715.10	5.61
Anemone silvestris	regional	VU	204.13	15.87	220.00	7.21
Sagittaria trifolia	regional	VU	473.03	44.33	517.36	8.57
Butomus umbellatus	regional	VU	169.33	16.36	185.69	8.81
Sagittaria natans	national II	EN	270.71	27.40	298.11	9.19
Habenaria sagittifera	regional	EN	146.43	15.11	161.54	9.35
Caltha natans	regional	VU	186.86	28.95	215.81	13.42
Trollius ledebouri	regional	EN	598.55	99.46	698.01	14.25
Gentiana triflora	regional	VU	726.47	125.10	851.57	14.69
Eriophorum polystachion	regional	VU	147.99	28.36	176.36	16.08
Hemerocallis minor	regional	EN	506.61	104.88	611.49	17.15
Sparganium minimum Wallr	regional	VU	3698.23	795.15	4493.38	17.70
Monochoria korsakowii	regional	VU	377.77	86.43	464.20	18.62
Pedicularis grandiflora	regional	EN	171.22	40.07	211.29	18.96
Euryale ferox	regional	VU	399.78	110.25	510.03	21.62
Monochoria vaginalis	regional	VU	612.15	170.18	782.33	21.75
Lythrum salicaria	regional	VU	91.93	26.99	118.92	22.70
Stachys baicalensis	regional	EN	806.85	311.24	1118.09	27.84
Actinostemma tenerum	regional	VU	9.00	3.96	12.96	30.53
Lilium dauri	regional	EN	67.68	30.86	98.56	31.33
Nymphaea tetragona	regional	VU	50.78	36.91	87.69	42.09
Hemerocallislilio-asphodelus	regional	EN	52.37	38.13	90.50	42.13
Utricularia minor	regional	EN	117.99	96.14	214.13	44.90
Glycine soja	national II	EN	208.85	185.75	394.60	47.07
Astragalus membranaceus	national II	EN	158.38	224.95	383.33	58.68
Utricularia vulgaris	regional	EN	645.32	1229.77	1875.09	65.58
Myriophyllum propinquum	national II	EN	72.00	155.34	227.34	68.33
Nelumbo nucifera	national II	EN	368.60	1201.15	1569.75	76.52

EN: endangered species, VU: vulnerable species. Unprotected area: area unprotected by a PA. Protected area: area protected by a PA. Total area: total distribution area of threatened plant species.

4. Discussion

4.1. Conservation of Threatened Plants in Sanjiang Plain

Our results show that vulnerable and endangered plant species are mainly located in the southern, western and eastern Sanjiang Plain (Figure 5), which is consistent with findings from Zhang et al. [45]. In this study, we found that species richness was higher in the western than the eastern Sanjiang Plain. For the entire study area, the distribution of NNRs is far from providing adequate coverage of threatened plants. The total PA coverage is low when compared with the commonly used target of 10% [46], with only 8.7% of the area having PA status. NNRs cover 11.09% of the area of endangered plants and 12.18% of the area of vulnerable plants. At least 88% of the area of threatened species is not covered by NNRs.



(**a**) (**b**)

Figure 5. Species richness pattern of endangered plants (**a**) and vulnerable plants (**b**) and distribution of NNRs in Sanjiang Plain.

In this study, we identified 30 hotspots of threatened plants, most located in mountainous areas, which is consistent with the results of Tang et al. [47]. As shown in Figure 3, we found that parts of the areas of the seven hotspots in eastern Sanjiang Plain are covered by NNRs, but the covered area is very limited. The rest of the hotspots, located in Xiaoxinganling, Laoyeling Mountains, and Taipingling, are not covered by any NNRs (Figures 3 and 5). Compared with other hotspots, we found that three hotspots in the northern part of Sanjiang Plain and one hotspot in XNNR are rather special. Although the species richness of these four hotspots was not high, they were identified as important hotspots. According to the spatial autocorrelation analysis, in terms of spatial autocorrelation types, these four hotspots are high-low aggregation type. Zhao et al. [48] reported that cropland expansion was widespread in Sanjiang Plain from 1990–2010, which largely led to habitat fragmentation of the endangered species in this region. Isolated wetland has become an important habitat for threatened species in the northern part of Sanjiang Plain. Thus, there are considerable conservation gaps among these hotspot areas. Habitat conservation should be a high priority to prevent many threatened plant species from going extinct. We suggest that new nature reserves be established to fill the conservation gaps in these hotspot areas for threatened plants.

4.2. Threatened Plant Biodiversity Conservation: Problems and Recommendations

The destruction or fragmentation of natural habitats can lead to the extinction of threatened plant species. During the past three decades, the area has experienced extensive reclamation that has resulted in the rapid vanishing of marsh area, as well as croplands being converted from forests and grasslands. The important changes have been a decline in wetland (−53.32%) and a slight decline in woodland (−1.87%). Meanwhile, there was an increase in farmland (+13.40%) [30,49]. Moreover, overexploitation of natural resources and environmental pollution have led to serious habitat degradation, potentially compromising species survival. Our results also confirm that the threatened species richness is higher in mountains than in low-altitude areas. Compared with the plain, the human disturbance factors are relatively weak in mountainous areas.

As shown in Figure 3, most of the spatial aggregation types of threatened species in mountainous areas are characterized as the high-high aggregation type. The number of threatened species is higher.

On the other hand, human disturbance in the plains is more significant. This result is consistent with the findings of Zhang et al. [50]. For example, cropland expansion around isolated wetlands has resulted in the fragmentation of habitats of endangered plants. Most of the spatial aggregation types of threatened species in these regions are high-low. Therefore, these hotspots of high-high and high-low spatial aggregation should receive special attention, as this is where threatened species are particularly concentrated.

A large number of nature reserves have been established in Sanjiang Plain, and animal and plant protection has also been strengthened [22]. Although biodiversity conservation in Sanjiang Plain has achieved some success, the efficiency of these reserves is not ideal. The existing nature reserves in Sanjiang Plain are not adequate to protect the biodiversity of the threatened plants [45]. Our analysis clearly indicates that 11 threatened plants (including 6 national-level species) are not covered by nature reserves. Some hotspots with high species richness have not been adequately protected. The main reason for this is that the nature reserve system was originally established to conserve endangered animals, resulting in many endangered plant species being outside of PAs. The design of nature reserves was not completely rational in the past, nor have criteria addressing biogeographical and ecosystem representativeness been followed [51]. Conserving threatened plant species is therefore more urgent than ever before. On the basis of existing PAs in the eastern Sanjiang Plain, we propose the establishment of ecological corridors to protect threatened plant diversity. We also suggest filling the conservation gaps between the hotspots and nature reserves by establishing new protected areas and enlarging isolated nature reserves in the western and southern Sanjiang Plain. By reducing the area without protection for endangered or vulnerable plant species, new nature reserves can increase the proportion of protected species.

4.3. Uncertainty of the Present Study

This study successfully identifies the hotspots and conservation gaps of threatened plant species. However, there are some limitations to this study. First, the datasets regarding elevation range and habitat preferences of threatened species were important for predicting the distribution of species [12,22,24,52–54]. We confirm that DEM data at a fine scale provides more accurate support for predicting potential distributions of species than DEM data at coarse scale. In this study, we predicted the distribution of threatened species using DEM data with 90-m resolution, which may overestimate the distribution ranges of threatened species. Distribution information on threatened plant species is mainly extracted from different sources, including survey records, Flora of China, and local Floras. As the temporal and spatial resolutions of the datasets could directly impact the results of our research, there is an urgent need for more systematic field inventory surveys to obtain precise data on the species locations and trends of their habitat changes. Second, the land cover data we used were not updated. Land cover changes may also affect the distribution of threatened species [15]. Land use and land cover have changed rapidly over recent decades in Northeast China [48], especially species associated with cropland habitats. With the fragmentation and loss of natural wetlands attributed to cropland development, the habitat structures of threatened species may change. As human population has increased rapidly in Northeast China in recent decades, the anthropogenic influence is expanding and many threatened plant species have been overexploited as traditional medicines and foods, all of which could contribute either directly or indirectly to changes in species survival [55]. Continue studies based on field investigations and updated land cover datasets are needed in order to design nature reserves specifically for threatened plants at a local scale. Since this study used coarse datasets that are readily available, its usefulness could be extended to other countries and/or regions to assess species richness, conservation gaps of species and protection status.

5. Conclusions

As the global climate continues to change and an increasing number of species become extinct, people are paying closer attention to the consequences of decreased biodiversity. In this research, the hotspot and gap analysis strategy using multisource data provided a more accurate and comprehensive approach for predicting the distribution of vulnerable and endangered plant species. We identified some unprotected areas with remarkably high conservation value in Sanjiang Plain. Through our analysis, we not only found gaps, but also recommend where they could be filled most efficiently.

The results of our research show that the existing network of PAs is inadequate for the conservation of vulnerable and endangered plant species. Thirty one threatened plants were protected in NNRs, but only within <5% of their distribution areas. Only five threatened plants were protected in NNRs covering >50% of their distribution areas. NNRs cover 11.09% of the area of endangered plants and 12.18% of the area of vulnerable plants. At the national level, the reserve network still lacks minimum coverage for some endangered species; six nationally-protected plants have not been observed in the nature reserves and have no protection, while the protection rate of 10 other species is <10%. Furthermore, the distribution of only four threatened species is protected by >40%. Therefore, the existing nature reserves provide a limited degree of protection. We recommend expanding the existing NNRs in the eastern Sanjiang Plain to fill the conservation gaps, establishing miniature protection plots and creating new PAs and ecological corridors to link the existing PAs. Additionally, we should establish new nature reserves in the areas of Xiaoxinganling, Taipingling and the Laoyeling Mountains to improve the protective efficiency of nature reserves. We need to protect the high-high aggregation hotspots, that is the higher elevation wetlands and the surroundings of nature reserves. Second, we should protect the high-low aggregation hotspots (high-altitude central areas with low-altitude surroundings), that is the isolated wetlands or toroidal wetlands formed by abandoned farmlands.

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