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Vulnerability Comparison between Karst and Non-Karst Nature Reserves—With a Special Reference to Guizhou Province, China

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Abstract: Studying vulnerability has become one of the hot issues of ecological research under global change and sustainable development scenarios. However, there are few studies focusing on the vulnerability of karst areas, especially on the comparison between karst and non-karst areas. This study integrated climate factors, soil and vegetation factors, and social factors within a vulnerability evaluation framework that combined the analytical hierarchy process (AHP) technique to evaluate and compare the ecological environments of 10 karst nature reserves and five non-karst nature reserves in Guizhou Province, China. The evaluation results were divided into five categories: potential, light, moderate, severe, and extremely severe vulnerability. The results indicated that the general vulnerability of national nature reserves in Guizhou Province showed moderate vulnerability. The vulnerability index of karst nature reserves was significantly higher than that of non-karst nature reserves. The general vulnerability of karst nature reserves showed moderate vulnerability, while that of non-karst nature reserves showed light vulnerability. Average soil thickness, arable area, and the length of roads may be the factors contributing to the significant difference in the vulnerability between karst and non-karst nature reserves. Overall, this study is conducive to a comprehensive understanding of the ecological environment status of national nature reserves in Guizhou Province, and is of great significance to maintaining ecological security and sustainable development in karst areas.

Keywords: karst; nature reserves; vulnerability; vulnerability evaluation; AHP

1. Introduction

Due to the impact of global climate change, economic development, and anthropogenic activities, global and regional ecosystems are undergoing unprecedented pressure and deterioration such as vegetation reduction, soil erosion, and biodiversity loss [1–3]. Identifying and evaluating vulnerable zones is an essential step for ecological conservation and environmental management [4,5]. In recent years, the study of vulnerability has become one of the hot issues of ecological research under global change and sustainable development scenarios [6–9].

Vulnerability is generally defined as the instability of an ecosystem in comparison with its original steady-state after being affected by both natural environments and human activities at a specific spatial-temporal scale [10,11]. Vulnerability evaluation is a useful tool to help decision-makers understand the various impacts of natural and factitious elements on the ecosystem, and it has been widely used in marine and coastal ecosystems [12,13], freshwater ecosystems [14], forest ecosystems [15], grassland ecosystems [16], desert ecosystems [17], and agricultural ecosystems [18]. However, most studies focused on typical ecologically vulnerable regions with poor natural conditions or severe human interference, and research on the evaluation of vulnerability at a provincial scale is still rare [8,19]. Furthermore, although vulnerability evaluation has been widely applied in various vulnerable

zones, there are few studies focusing on the vulnerability of karst areas, especially on the comparison of vulnerability between karst and non-karst areas. Guo et al. (2020) studied the spatial-temporal change pattern and driving mechanism of ecological vulnerability in the southwest karst mountain region of China [20], which was useful for planning the conservation strategies or assessments of the conservation priorities in karst areas, but unfortunately, they did not distinguish karst and non-karst areas.

Karst is a type of landscape that is widely distributed around the world, accounting for approximately 15% of the global land area [21]. The karst landscape is formed from interactions between acidic water and minerals (e.g., limestone and gypsum) that generate spectacular yet vulnerable environments over time [22]. Compared with non-karst areas, the vulnerability of karst areas can be reflected in the following four aspects: (1) carbonate rocks are characterized by high resistance to wind erosion, showing a slow soil formation rate [23,24]; (2) the land surface in karst areas is very rugged and fragmented [20]; (3) the karst dual hydrogeological structures could make the surface habitat prone to drought and water shortage due to the downward leakage of water [25]; (4) the plant community in karst areas is characterized by simple structure, slow positive succession rate, and weak self-regulation ability [26]. Despite the above understanding of the driving mechanism of vulnerability in karst areas, to our knowledge, there are no studies that quantitatively compare the vulnerability between karst and non-karst areas.

This study aims to integrate climate factors, soil and vegetation factors, and social factors within a vulnerability evaluation framework that combines the analytical hierarchy process (AHP) technique to compare the ecological environments between 10 karst nature reserves and five non-karst nature reserves in Guizhou Province. The constructed vulnerability evaluation framework will be expected to answer the following two questions: (1) how is the general vulnerability of national nature reserves in Guizhou Province?; and (2) is the vulnerability of karst nature reserves higher than that of non-karst nature reserves? If so, which parameters account for this difference?

2. Materials and Methods

2.1. Study Area

Guizhou Province (24°37′–29°13′ N, 103°36′–109°35′ E) is located in southwest China, under the jurisdiction of six prefecture-level cities and three autonomous prefectures, with a land area of 176,167 km^2, a total population of 36,229,500, and a total GDP of CNY 1,676,934 million at the end of 2019, which is about half of the average provincial GDP of CNY 3,178,495 in China. Guizhou Province experiences a subtropical monsoon climate with a mean annual precipitation of 1292 mm and a mean annual temperature of 16.1 °C. The karst landscape in Guizhou Province is very typical, with an exposed karst area of 109,084 km^2, accounting for 61.9% of the total land area of the province, which is the largest karst area in China (Figure 1). The sharp contradiction between humans and land (large population, long-term disordered development of resources) leads to increasingly serious soil erosion and vegetation damage, resulting in serious rocky desertification and its continuous deterioration. In order to protect biodiversity and support the ecosystem's sustainable development, by the end of 2019, Guizhou Province had established 106 nature reserves, including 15 national nature reserves, seven provincial nature reserves, 12 municipal nature reserves, and 72 county-level nature reserves (Figure 1A). The total area of nature reserves accounts for 5.07% of the province's land area. Ten karst nature reserves (Baimianshui, Kuankuoshui, Dashahe, Maolan, Fodingshan, Siyetun, Yangxi, Mayanghe, Bailidujuan, and Gongtong) and five non-karst nature reserves (Suoluo, Xishui, Fanjingshan, Gedong, and Leigongshan) selected in this study are all terrestrial natural ecosystems. For further details on the peculiarities of each nature reserve, refer to the description in the Supplementary Information.
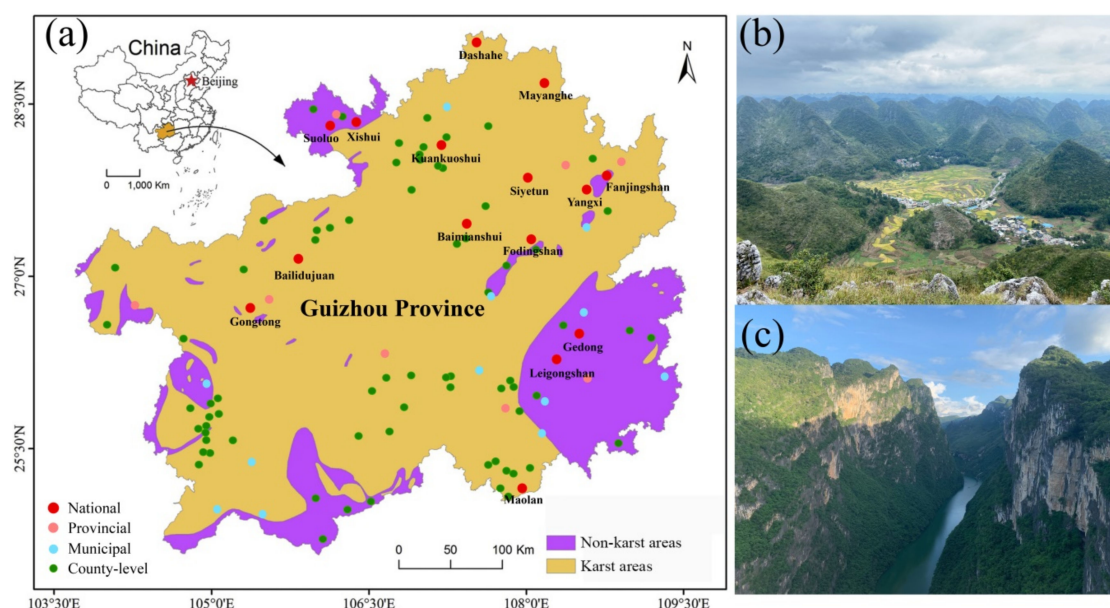
Figure 1. Distribution of nature reserves in Guizhou Province (**a**), the landscape of karst peak-cluster depression (**b**) and karst gorge (**c**).

2.2. Parameter Selection and Description

Vulnerability evaluation is a complicated process. For now, there is no internationally recognized standard or rule to stipulate how many and what parameters should be selected to capture vulnerability [27]. Various parameters influencing the vulnerability of nature reserves in Guizhou Province are considered. However, it should be noted that this selection of parameters is not exhaustive, and only those salient parameters for which information is of great significance are selected. Therefore, 17 representative parameters reflecting natural and anthropogenic elements are selected and divided into three groups: climate factors, soil and vegetation factors, and social factors (Table 1 and Figure 2).

As a basic climatic indicator, temperature and precipitation are the driving force of all natural factors and the energy basis of ecosystems [5]. The frost period directly affects agriculture production, ecological environments, the inhabitants, and the development of the social economy [5]. Runoff depth, closely related to precipitation, can objectively reflect the abundance of water resources per unit area. Therefore, average annual temperature, average annual precipitation, annual frost-free period, and runoff depth were selected as climate factors.

As an important indicator in vulnerability evaluation, vegetation condition directly influences and even determines the function of an ecosystem [28,29]. For example, high forest cover can effectively contain water and prevent soil erosion and disasters such as landslides and debris flows [30,31]. The number of plant species is the indicator of plant diversity, which plays an important role in ecosystem functions and services [32]. Besides, invasive species can accelerate the extinction of native species and disrupt the balance of the ecosystem [33], thus generating the vulnerability of the ecosystem. Plant growth is supported by the soil, which indirectly influences the vulnerability of an ecosystem through its effects on vegetation. Thus, average soil thickness, organic matter, total nitrogen, total phosphorus, forest coverage rate, the number of wild plant species, and the number of invasive species were chosen as soil and vegetation factors.

Road development and agricultural activities directly generate vulnerability for an ecosystem [34]. Population density is related to the intensity of human activity in an ecosystem. The land discarded by factories and mines could result in environmental pollution, and geological disasters such as landslides, debris flows, and surface collapses due to human activities or harsh environments could disrupt ecosystem balance. The construction of reservoirs has a direct impact on the vulnerability of an ecosystem. Therefore, the length

of roads, arable area, population density, the number of lands discarded by factories and mines, the number of geological disaster sites, and the number of reservoirs were selected as social factors.

Furthermore, the number of wild plant species, the number of invasive species, the length of roads, arable area, and the number of lands discarded by factories and mines were relativized by the area of nature reserves to avoid penalizing large nature reserves.

Table 1. Weights of groups and attribute parameters.

Object	Groups (G_i)	Global Weight (W_i)	Parameters (E_i)	Local Weight (W_i)	Data Sources
Vulnerability	G1: climate factors	0.2019	E1: average annual temperature	0.0777	Guizhou Meteorological Bureau
			E2: average annual precipitation	0.0411	
			E3: annual frost-free period	0.0357	
	G2: soil and vegetation factors	0.5062	E4: runoff depth	0.0474	GIS spatial overlay analysis
			E5: average soil thickness	0.1035	2019 Guizhou Nature Reserve Survey and Evaluation Project Team
			E6: organic matter	0.0730	
			E7: total nitrogen	0.0387	
			E8: total phosphorus	0.0472	
			E9: forest coverage rate	0.0993	
			E10: the number of wild plant species	0.0687	Management agency of nature reserve
			E11: the number of invasive species	0.0758	
	G3: social factors	0.2919	E12: the length of roads	0.0440	Overall planning of nature reserve
			E13: arable area	0.0478	
			E14: population density	0.0344	
			E15: the number of lands discarded by factories and mines	0.0728	GIS spatial overlay analysis
			E16: the number of geological disaster sites	0.0402	
			E17: the number of reservoirs	0.0527	
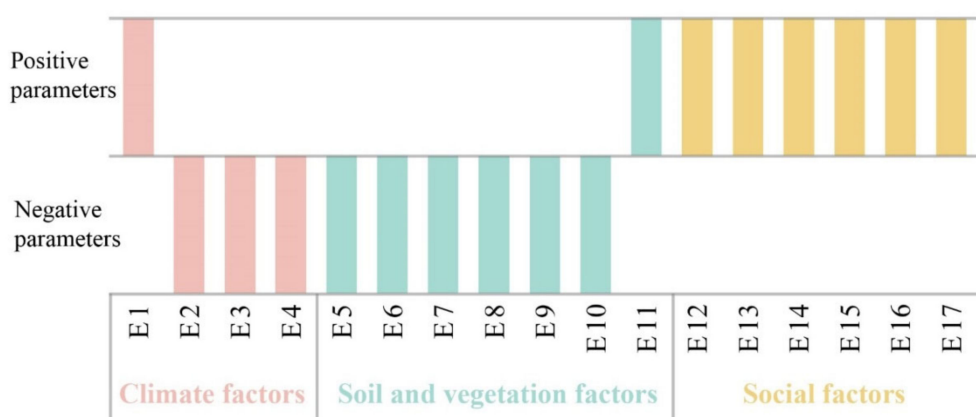
Figure 2. Schematic diagram of vulnerability evaluation framework.

2.3. Standardization of Evaluation Parameters

Since the data types and scales of the evaluation parameters were different and cannot be evaluated directly, the data need to be standardized to eliminate the influence of the scales before evaluation. The effect of evaluation parameters on vulnerability can

be divided into positive and negative impacts. Therefore, evaluation parameters were divided into positive and negative parameters (Figure 2). A positive parameter indicates that the higher the value of the parameter, the higher the degree of vulnerability, while a negative parameter suggests that the higher the value of the parameter, the lower the degree of vulnerability. By using the range standardization method, the original values were standardized with a range of 0–10 [35,36].

The positive parameter was standardized according to the formula shown below:

$$Z = \frac{Z_i - Z_{min}}{Z_{max} - Z_{min}} \times 10 \tag{1}$$

The negative parameter was standardized according to the formula shown below:

$$Z = \frac{Z_{max} - Z_i}{Z_{max} - Z_{min}} \times 10 \tag{2}$$

In Formulas (1) and (2), Z_i is the original value of i. Z_{max} and Z_{min} are the maximum and the minimum value of i. Z is the standardized value of i, with a range of 0–10.

2.4. Weight Determination

The analytical hierarchy process (AHP) is a systematic analyzing evaluation method to make the complex and multi-index system quantitatively, which could decompose the complex problem to some layers and some factors, and could compare and calculate as a result of weight [36]. Due to its ability to assign proper weights to various factors of complex systems, the AHP technique is applied to determine weights of the selected parameters in our vulnerability evaluation and other studies [27,29,36–39]. The main steps of the AHP technique are as follows [27]:

(1) Deconstruct the decision-making problem into a hierarchical structure. The object is "vulnerability", which is then deconstructed into the second layer, consisting of climate factors, soil and vegetation factors, and social factors. Finally, the second layer is further deconstructed into the third layer with corresponding parameters.

(2) Make decision tables for the hierarchical decomposition in each layer with pair-wise comparisons. A preference scaling approach is executed in the pair-wise comparisons with 17 scales: 9, 8, ... 2, 1, 1/2, ... 1/8, 1/9, where 9 means that one parameter is the most important for the object relative to another parameter, and 1 means that the contributions of two parameters are equal to the object, and so on down to 1/9, the least important.

(3) Make judgment matrices for the object layer and second layer with the scale numbers from step 2, respectively. In the judgment matrices, 1 is the value of diagonal. If the ith row is more important than the jth column, the value of (i,j) is more than 1, otherwise the jth column is more important than the ith row.

(4) Determine weight for each parameter by the largest eigenvalue of the judgment matrix, as shown in the following formula:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} i \left[\sum_{j=1}^{n} \left(a_{ij} w_j / w_i \right) \right]}{n} \tag{3}$$

(5) Estimate the consistency of the judgment matrix by consistency ratio (CR). The CR is related to consistency index (CI) and random index (RI) by the following formula:

$$CR = \frac{CI}{RI} \tag{4}$$

where the CI is calculated according to the formula:

$$CI = (\lambda_{max} - n)(n - 1) \tag{5}$$

and the RI is a random matrix defined as the average value of the resulting consistency index depending on the order of the matrix.

(6) Aggregate the local weight of each parameter to achieve the general weight of the corresponding group.

2.5. Vulnerability Index (VI)

The vulnerability index (VI) is an important index used to reflect and characterize the degree of vulnerability in the study area. The higher the VI value, the more vulnerable the ecological environment is. The parameters evaluated were combined by applying a weight of each parameter, followed by a summation of the results to yield a VI value. Thus, the VI can be calculated by the following formula [36,40]:

$$VI = \sum_{i=1}^{n} Z_i \times W_i \qquad (6)$$

where VI is the vulnerability index, Z_i is the standardized value of parameter i, and W_i is the weight of parameter i.

Furthermore, the non-parametric "Mann–Whitney U" test was used to compare the vulnerability between karst and non-karst nature reserves (SPSS 22.0, Chicago, IL, USA).

2.6. Classification of Vulnerability Index

Based on the actual ecological conditions of national nature reserves and the results of previous studies [27,41], the vulnerability index of national nature reserves in Guizhou Province was classified into five categories: potential, light, moderate, severe, and extremely severe (Table 2).

**Table 2.** Classification standards of vulnerability.

Vulnerability Classes	Description	Normalized Score Interval
1	Potential vulnerability	0.0–2.0
2	Light vulnerability	2.0–4.0
3	Moderate vulnerability	4.0–6.0
4	Severe vulnerability	6.0–8.0
5	Extremely severe vulnerability	8.0–10.0

3. Results

According to the classification standard of vulnerability (Table 2), the vulnerability evaluation results are shown in Table 3 and Figure 3. It can be seen that all the evaluation results of the 15 national nature reserves in Guizhou Province ranged from the level of light vulnerability to severe vulnerability (2–8), but none showed potential (0–2) or extremely severe vulnerability (8–10). One, eight, and one nature reserves among 10 karst nature reserves were classified into light, moderate, and severe vulnerability, respectively, while three and two nature reserves among five non-karst nature reserves were classified into light and moderate vulnerability. Generally, the vulnerability degree of karst nature reserves was higher than that of non-karst nature reserves.

Table 3. Vulnerability index between karst and non-karst nature reserves in Guizhou Province.

Name	Vulnerability Index	Vulnerability Degree	Name	Vulnerability Index	Vulnerability Degree
Karst nature reserves			Non-karst nature reserves		
Maolan	3.43	Light	Fanjingshan	2.74	Light
Kuankuoshui	4.15	Moderate	Leigongshan	3.58	Light
Fodingshan	4.43	Moderate	Suoluo	3.83	Light
Gongtong	4.62	Moderate	Gedong	4.12	Moderate
Dashahe	4.76	Moderate	Xishui	4.57	Moderate
Yangxi	5.34	Moderate			
Mayanghe	5.44	Moderate			
Bailidujuan	5.69	Moderate			
Baimianshui	5.76	Moderate			
Siyetun	6.51	Severe			
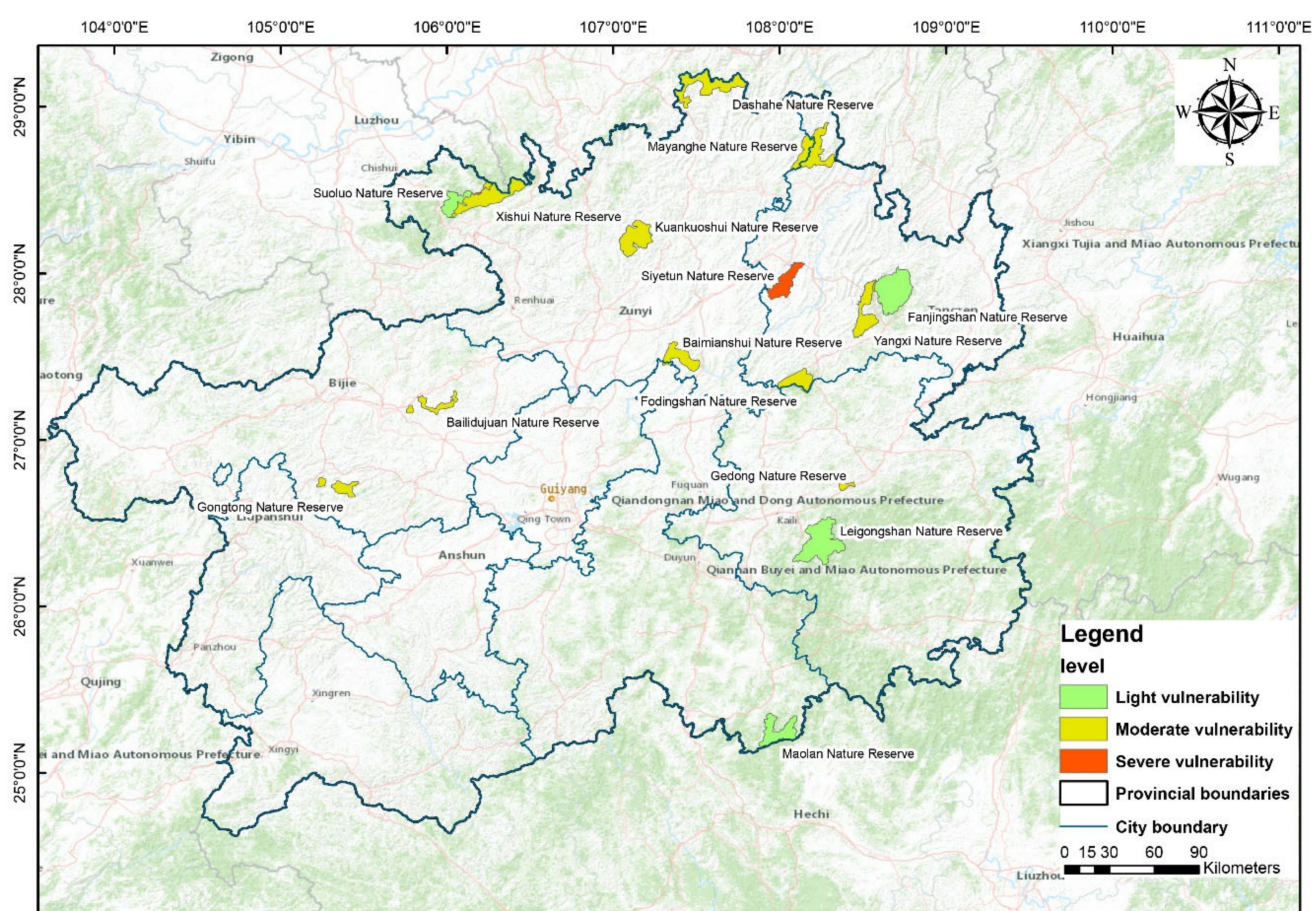
Figure 3. Distribution of vulnerability degree of nature reserves in Guizhou Province.

The general vulnerability of national nature reserves in Guizhou Province, obtained from the average vulnerability index of 15 national nature reserves, was 4.60, showing moderate vulnerability (4–6). Meanwhile, the general vulnerability of karst nature reserves and non-karst nature reserves, obtained from the average vulnerability index of 10 karst nature reserves and five non-karst nature reserves, was 5.01 and 3.77, showing moderate vulnerability (4–6) and light vulnerability (2–4), respectively (Table 3 and Figure 3). The non-parametric test also confirmed that the vulnerability index of karst nature reserves was significantly higher than that of non-karst nature reserves ($p < 0.05$).

In order to find which parameters account for the significant difference in the vulnerability index between karst nature reserves and non-karst nature reserves, we also conducted a non-parametric test to compare each parameter between karst and non-karst nature reserves (SPSS 22.0, Chicago, IL, USA). The results showed that the contributions of average soil thickness, road length, and arable area to vulnerability in karst nature reserves were significantly higher than those in non-karst nature reserves ($p < 0.05$, Figure 4e,l,m).
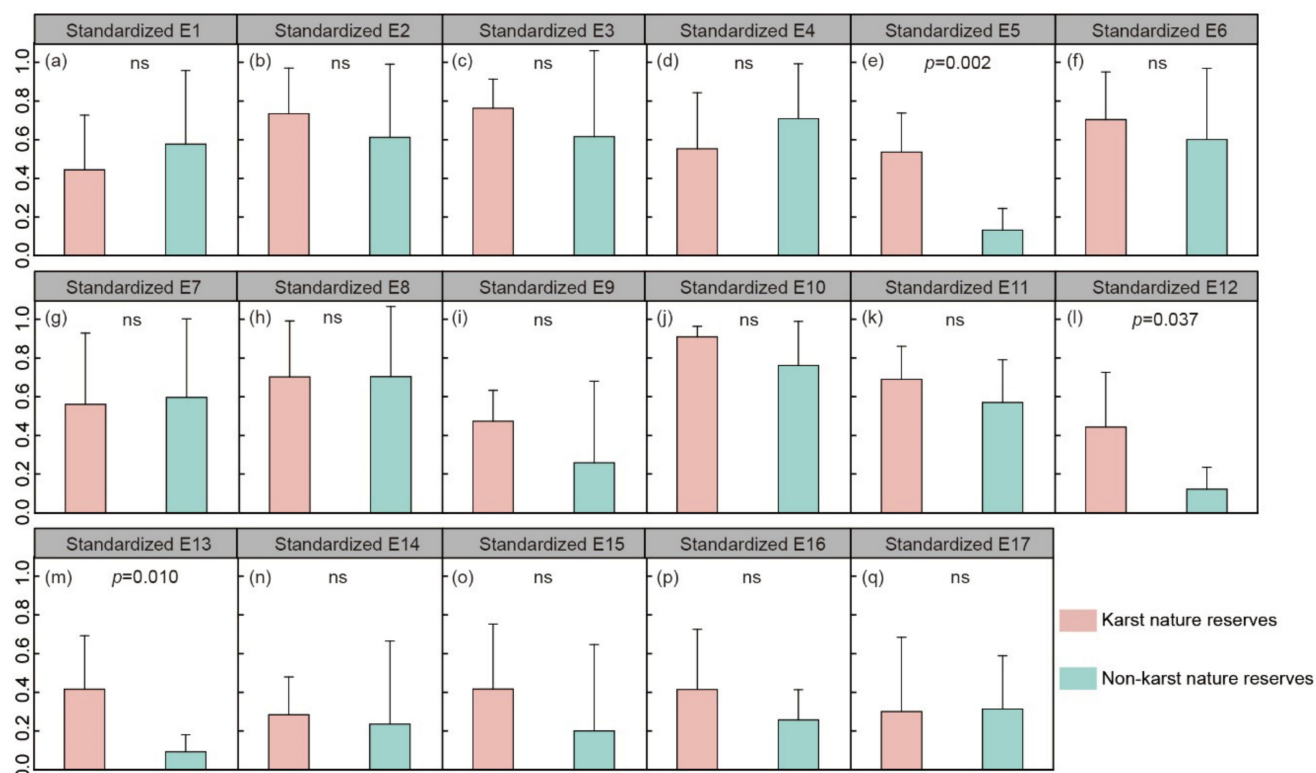

Figure 4. Comparison of the 17 parameters between karst and non-karst nature reserves. E1–E17 represent average annual temperature, average annual precipitation, annual frost-free period, runoff depth, average soil thickness, organic matter, total nitrogen, total phosphorus, forest coverage rate, the number of wild plant species, the number of invasive species, the length of roads, arable area, population density, the number of lands discarded by factories and mines, the number of geological disaster sites, and the number of reservoirs, respectively. $p < 0.05$ is considered as a statistical difference (Mann–Whitney U test); ns: not significant.

4. Discussion

Our results indicated that the general vulnerability of national nature reserves in Guizhou Province was 4.60, showing moderate vulnerability (Table 3). This may be related to the ecological environments and socio-economic conditions of Guizhou Province. On the one hand, the exposed carbonate rock area in Guizhou Province is 109,084 km², accounting for 61.9% of the total land area of the province. The large area of carbonate rocks combined with the warm-humid monsoon climate is conducive to the karst process and the formation of karst dual hydrogeological structures, which lay the foundation for the vulnerability of Guizhou Province [42,43]. Moreover, Guizhou Province is dominated by mountains and plateaus and is with rugged and broken land surfaces [44]. Under high-intensity rainfall during the rainy season, broken surfaces are prone to geological disasters such as landslides and debris flows, potentially increasing the vulnerability of Guizhou Province. On the other hand, anthropogenic activities such as mining, quarrying, and road development are directly correlated with the vulnerability of an ecosystem [45,46]. Due to the need for economic development, irrational and intensive anthropogenic activities against the background of vulnerable karst environments could trigger serious ecosystem

degradation such as severe soil erosion, the extensive exposure of bedrock, drastic decline in soil productivity, and the appearance of a desert-like landscape (Figure 5) [47]. Overall, the vulnerability of national nature reserves in Guizhou Province may result from the combined effects of anthropogenic activities and the fragile karst environments. Harsh natural environments make the ecosystem potentially vulnerable, while anthropogenic disturbances transform the potential vulnerability into actual vulnerability [8].
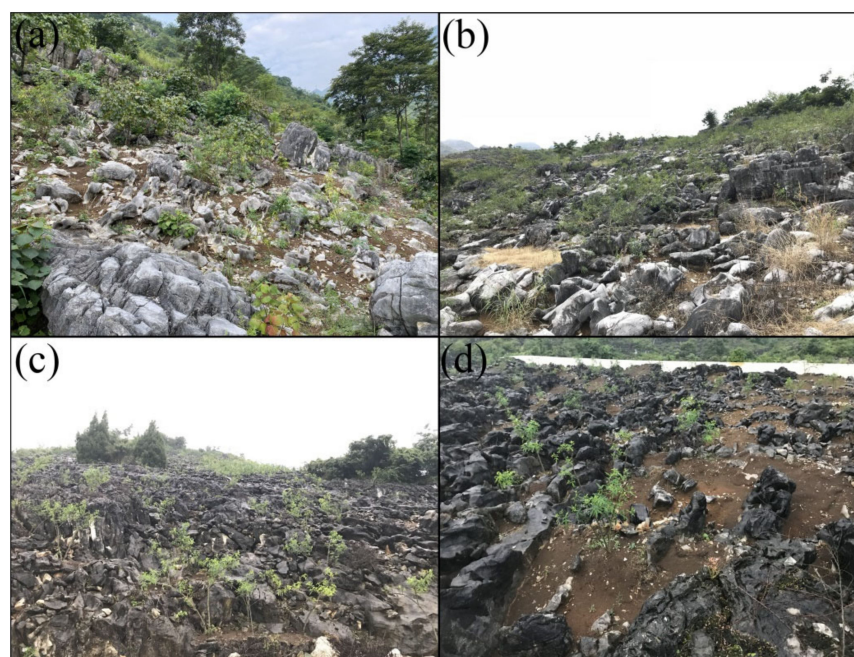
Figure 5. Landscapes of karst rocky desertification. Subfigures (**a**–**d**) show the karst ecosystem degradation in the form of severe soil erosion, the extensive exposure of bedrock, drastic decline in soil productivity, and the appearance of a desert-like landscape.

We also found that the vulnerability index of karst nature reserves was significantly higher than that of non-karst nature reserves (Table 3). Furthermore, the general vulnerability of karst nature reserves showed moderate vulnerability, while that of non-karst nature reserves showed light vulnerability. The difference in soil thickness may result in a significant difference in the vulnerability between karst and non-karst nature reserves (Figure 2). Furthermore, the weight of soil thickness was highest among 17 parameters in the vulnerability evaluation framework (Table 1), which indicated the great impact of soil thickness on vulnerability. Carbonate rocks are characterized by high resistance to wind erosion, showing a slow soil formation rate [24,25]. The previous study has shown that the weathering rate of limestone was 23.7–110.7 mm/ka, and only 2.47 mm of weathered soil layer would be formed in 1000 years, which was 10–80 times slower than non-karst areas [48]. Considering the coexistence of surface soil erosion and special underground leakage in karst areas [49,50], the slow soil formation rate and the thin soil layer could lead to higher vulnerability of karst areas than that of non-karst areas. In addition to the difference in natural factors between karst and non-karst areas, differences in the intensity of anthropogenic activities may also trigger the higher vulnerability in karst areas. The vulnerability of an ecosystem is closely associated with anthropogenic activities such as cultivation and road development [45,46]. Thus, the greater arable area and the longer length of roads could increase the vulnerability in karst nature reserves.

Although the constructed vulnerability evaluation framework in this study helps us to compare the vulnerability between karst areas and non-karst areas, it is advisable to include more karst-specific variables such as caves and underground water to capture the attributes resulting in the difference in vulnerability between karst and non-karst areas. Therefore, evaluating the vulnerability of karst ecosystems by a karst-specific evaluation framework

is our next step. In addition, despite the fact that studying the temporal heterogeneity of vulnerability is not the goal of the present study, evaluating vulnerability over time may be beneficial to deeply compare the vulnerability of karst and non-karst areas.

5. Conclusions

The vulnerability evaluation of ecosystems provides important information for ecological conservation and environmental management. In this study, we integrated climate factors, soil and vegetation factors, and social factors within a vulnerability evaluation framework that combined the analytical hierarchy process (AHP) technique to evaluate and compare the ecological environments of karst nature reserves and non-karst nature reserves in Guizhou Province, China. In general, the vulnerability of national nature reserves in Guizhou Province was 4.60, showing moderate vulnerability. Moreover, the vulnerability index of karst nature reserves was significantly higher than that of non-karst nature reserves ($p < 0.05$). Average soil thickness, arable area, and the length of roads may be the factors driving the significant difference in the vulnerability between karst and non-karst nature reserves. This study is of great significance for the ecological and environmental protection of the karst ecosystems in southwest China.

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