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Village ecosystem vulnerability in karst desertification control: evidence from South China Karst

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Against the background of global environmental changes and the intensification of human activity, the village ecosystem faces enormous challenges. In particular, the rural areas in South China Karst face serious problems, such as karst desertification and human–land conflicts. In recent decades, the Chinese government and scientific researchers have committed to controlling karst desertification. However, village ecosystems in the context of karst desertification control (KDC) remain fragile. To promote the sustainable development of villages in KDC, this study considered village ecosystems in different karst desertification areas as study cases. Based on the model of susceptibility-exposure-lack of resilience, we constructed an index system of vulnerability research, used the entropy method to determine the weight, and introduced a contribution model to clarify the vulnerability level and vulnerability driving factors to recommend related governance strategies. We found that (1) the village ecosystem vulnerability levels under KDC were different. Village ecosystems were mildly vulnerable in none-potential KDC areas, moderately vulnerable in potential-mild areas, and moderately and highly vulnerable in moderate–severe KDC areas. (2) The combined effects of the natural environment and human activity have led to the vulnerability of village ecosystems in KDC in South China Karst. Among them, topography, climate, forest coverage, landscape pattern, soil erosion, karst desertification, economic development level, and production and living activity are the main factors affecting the village ecosystem vulnerability of KDC in South China Karst, and the differences in these factors lead to differences in vulnerability levels of different village ecosystems. (3) We designed adaptive governance strategies for village ecosystems based on the factors influencing the characteristics and vulnerability of different karst desertification areas, with the primary goal of sustainable development. They provide a decision-making basis for promoting sustainable development of the village ecosystems in KDC.

KEYWORDS

karst desertification, ecological governance, village ecosystem, vulnerability, influencing factors, sustainability

1. Introduction

Global environmental changes, social and economic development, a decrease in species diversity, an increase in desertification, extreme weather events, and other issues of ecosystem degradation seriously threaten the sustainability of society, the economy and the survival of human beings (Easterling et al., 2000; Guo et al., 2020; Li et al., 2021). Concurrently, the rapid

urbanization, environmental pollution and waste of resources places ecosystems under tremendous pressure, which further exacerbates the degradation of ecosystems (Meng et al., 2018). The increase in human activity and global climate change have led to tremendous pressure on the ecosystem (Li and Song, 2021; Wang et al., 2023), aggravating the expression of ecosystem vulnerability and destroying the supply capacity of ecosystem services. It is estimated that 60% of ecosystem services worldwide are degraded because of human activity (Zhang et al., 2018), resulting in ecological problems such as the degradation of water, loss of biodiversity (Vitousek et al., 1997; Foley et al., 2005), and land degradation. The contradiction and conflict between humankind's pursuit of social and economic prosperity and the ecological environment have become the main challenges facing current global sustainable development. Therefore, the environment, development, and sustainability have become major issues of concern worldwide (Nandy et al., 2015; Zhang et al., 2022).

Driven by globalization, industrialization, and urbanization, the countryside is undergoing a holistic reconstruction. In particular, rural areas in developing countries generally experience population reduction, economic non-agricultural transformation, and environmental pollution, which lead to rural decline and affects the sustainability of rural economic and social development (Li, 2020). Rural populations have declined, and village labor shortages, economic recession, and social degradation have caused rural decline to become global issues (Liu and Li, 2017). Villages are more at risk due to poor infrastructure, low human development, high dependence on agriculture, and lack of government attention, which places villages more at risk (Jamshed et al., 2020). In the past few decades, rural areas worldwide have faced tremendous pressure due to land-use changes that threaten ecosystem services and environmental sustainability (Yu, 2022). In the context of rapid urbanization, many villages are experiencing a sharp increase in the proportion of construction land, leading to a reduction in ecosystem services (Zhang et al., 2020), and the destruction of the ecological environment. Currently, the elements and functions of village systems have undergone transformation and restructuring, while simultaneously, the stability of the villages has been disrupted, which makes them vulnerable (Yang and Pan, 2021). The driving factors of village ecosystem vulnerability differ across geographical environments. For example, coastal villages are vulnerable because of the disturbance caused by hurricanes, storm surges, tsunamis, and the lack of adaptability of the villages themselves (Colburn et al., 2016; Karuppusamy et al., 2021). The impact of extreme weather events, earthquakes, and harsh natural environments has contributed to the vulnerability of Himalayan villages (Pandey et al., 2017; Dasgupta and Badola, 2020). Villages in river regions are adversely affected by repeated flooding and riverbank erosion, which destroy property, agricultural land, and habitat, and cause social and economic crises and food security problems, leading to the vulnerability of villages (Ahmad and Afzal, 2021). Drought-type villages are affected by the high variability of seasonal water and long-term, frequent droughts, which intensify the exposure and sensitivity of the ecosystem (Tessema et al., 2021). In areas with frequent geological disasters, the higher the altitude, the more fragile is the village ecosystem (Liu et al., 2020). However, approximately half of the world's population lives in rural regions (Bavinck et al., 2017). The livelihoods of rural populations directly dependent on ecosystem services are particularly at risk (Malmborg et al., 2018). Village ecosystems provide ecosystem services, such as water filtration,

carbon absorption, and wildlife habitat, as well as food, freshwater, and energy that sustain both rural and urban residents (Miller Hesel et al., 2020). Concurrently, rural areas also provide the functions of supporting the population, maintaining culture, sightseeing tourism, and providing for the older urban residents (Huang, 2019). As an indispensable part of the global ecosystem, village ecosystems are of great significance for the sustainability of global development. Therefore, it is necessary to study the vulnerability of villages to provide scientific guidance for improving the service capacity of village ecosystems and promoting their sustainable development.

Therefore, it is of great scientific significance to construct a scientific and adequate vulnerability research index system, analyze the vulnerability level of village ecosystems, and reveal the driving factors of vulnerability. However, previous studies on the vulnerability of karst areas have neglected the analysis of the vulnerability of the human-land coupling system and its driving factors in karst desertification control villages. Therefore, they provide weak guidance to the consolidation of poverty alleviation achievements and the implementation of rural revitalization in karst desertification areas. To study the vulnerability of KDC villages, enhance their ecosystem service capacity, and promote the coordinated and sustainable development of their socio-economic and natural environment to consolidate the achievements of poverty alleviation and help rural revitalization, this paper provides a scientific and technological reference. As research cases, we selected villages in three different levels of KDC in the karst plateau mountainous areas, representing the overall structure of the karst desertification ecological environment type in South China Karst. The aim was to explore the level and influencing factors of village ecosystem vulnerability in the context of KDC and propose an adaptive management strategy for the KDC village ecosystem to provide a scientific and technological reference for the overall coordination and sustainable development of the KDC village ecosystem.

2. Literature review

Environmental changes are one of the biggest threats to global ecosystems in the coming decades, and currently scholars believe that vulnerability research should be incorporated into protection and planning to deal with the threat of environmental change to the sustainability of ecosystems (Lee et al., 2018). As one of the research themes in regional sustainable development, vulnerability assessment originates from the study of natural disasters. Since then, it has been widely used in geography, ecology, management, and other disciplines (Tai et al., 2020). Broadening of research on human factors in ecosystems led to the evolution of the concept of vulnerability from natural vulnerability to multi-dimensional vulnerability, which includes nature, the environment, society, the economy, and other factors (Wang et al., 2019). Research on the vulnerability of the social-ecological system, which considers the human-earth system to be the core, has become the focus of regional sustainable development research (Tian et al., 2013). Current research on the vulnerability of socio-ecological systems has focused on mountainous area (Brunner and Grêt-Regamey, 2016; Li et al., 2022), arid and semiarid areas (Liu et al., 2016; Chen et al., 2018), coastal areas (Hagenlocher et al., 2018; Silva et al., 2019; Koehn et al., 2022), and tourist areas (Jia et al., 2021; Li et al., 2022).

Studying the driving mechanisms of regional ecosystem vulnerability will be helpful in formulating ecological environment governance guidelines (Kang et al., 2018). Many international scientific programs (International Geosphere–Biosphere Program, Man and the Biosphere Program, and International Biological Program) have also included vulnerability as a topic of sustainability research in the context of global environmental changes (Hong et al., 2016). The current frameworks of vulnerability research mainly include the “pressure-state-response” (P-S-R; Hu et al., 2021), “exposure-sensitivity-adaptability” (V-S-D; Polsky et al., 2007), “sensitivity-resilience-pressure” (S-R-P; Li et al., 2015; Chen X. et al., 2021), driving force-pressure-state-impact-response (DPSIR; Malekmohammadi and Jahanishakib, 2017) and exposure-susceptibility-lack of resilience (E-S-LoR; Birkmann et al., 2013) models. Research methods used include principal component analysis (Xenarios et al., 2016), fuzzy evaluation method (Liu H. et al., 2014), analytic hierarchy process (Chen et al., 2022), comprehensive evaluation method (Guo and Huang, 2016), grey relational analysis (Luo and Zhang, 2018) and entropy method (Tai et al., 2020). Because the research purposes, regional characteristics, and foci may be very different, there is no unified indicator system (Li et al., 2021). However, sustainable governance strategies based on large-scale regions are not applicable to the village ecosystems. Scholars in all disciplines have conducted studies on village ecosystems in different types of ecological environments. Ghosh and Ghosal (2021) proposed improving the adaptability of residents through education, migration, increase in income, crop diversification, infrastructure and disaster early warning system construction aimed at the vulnerability factors of rural households in the Himalayan foothills. Farmers’ resistance to drought in arid rural areas can be enhanced by increasing income and crop diversification, promoting non-agricultural employment, and other strategies (Keshavarz and Moqadas, 2021). Villages in geological disaster risk areas should establish disaster warning systems, publicise and educate farmers about disaster reduction, and strengthen professional personnel and infrastructure construction at the grassroots level (Xu et al., 2020). Villages in coastal areas that are susceptible to meteorological disasters should adjust their industrial structure, choose more favorable places to live and produce, cultivate a variety of skills, and develop diversified livelihoods to enhance farmers’ adaptability to climate change (Touza et al., 2021). Poor villages in rocky desertification areas should establish a regional economic system, abandon extensive and predatory development at the expense of the environment and resources, and promote the transformation of rural development from a backward model to high-quality and sustainable development (Zuo et al., 2022). Thus far, research on rural sustainability has mainly analyzed rural adaptability to poverty, sustainable livelihood of farmers, and resilience of rural families to cope with disasters. Studies on the sustainability of village ecosystems from the perspective of human–environment coupling systems are lacking. However, the sustainability of villages in the KDC areas is mainly influenced by human activity and the natural environment, and the sensitive basic environment is fragile under the pressure of unsustainable human activity. Therefore, to promote sustainable development of the village ecosystem in the KDC, we must study its vulnerability characteristics.

Studying ecosystem vulnerability can effectively assist in monitoring environmental changes and mastering the motivation for environmental evolution to guide the rational protection and

governance of the environment (Kang et al., 2018). At present, research on the vulnerability of karst areas includes the vulnerability of water resources (Marín et al., 2015; Zhu et al., 2019), nature reserve vulnerability (Chen Y. et al., 2021), vulnerability of mountain ecosystem (Guo et al., 2020), ecological environment vulnerability (Liu C. et al., 2014), livelihood vulnerability (Ren et al., 2020; Wang C. et al., 2022), vulnerability of land system (Lu et al., 2019), grassland ecosystem vulnerability (Guo et al., 2014), and vulnerability of the agricultural ecological environment vulnerability (Shu et al., 2020). However, current research on the vulnerability of karst areas cannot provide scientific guidance for sustainable development of village ecosystems in the KDC region. A large numbers of people live in karst mountain villages with poor soil and steep terrain, poor transportation infrastructure, and underdeveloped production technologies (Zhao and Hou, 2019), and the entire system is fragile. Karst landforms are formed by the development of soluble rocks such as limestone, dolomite, and gypsum. Karsts occur in over 10–15% of continental areas and are inhabited by approximately 17% of the world’s population (Ford and Williams, 2013; Zhang et al., 2018). Because of special natural conditions and dense human activity, the karst ecosystem has degraded, which is mainly reflected in karst desertification, the most obvious outcome in South China Karst (Xiong and Chen, 2010). Karst desertification has resulted in fragile soil, vegetation, hydrology, and human environment in karst areas (Xiong and Chi, 2015). This seriously restricts the sustainability of the development of karst areas. Therefore, local governments and scientific researchers have actively promoted the control of karst desertification and achieved considerable results. However, the existing governance strategies designed for large-scale ecosystems are not applicable to village ecosystems. Therefore, it is necessary to study the vulnerability of village ecosystems and provide a scientific basis for the design of management strategies in for KDC.

3. Materials and methods

3.1. Study area

The South China Karst region, centered on the Guizhou Plateau, is the largest and most concentrated karst ecological vulnerable zone in the world and is facing serious karst desertification (Cheng et al., 2017; Chen Q. et al., 2021). This case study was conducted in the karst mountainous area of the Guizhou Plateau. Karst landforms are typical in Guizhou Province; there are karst distribution areas in 95% of the counties of the province, and 91.7% of the cultivated land, 88.3% of the rural population, 94% of the grain output, and 95.7% of the gross national product come from counties with karst distribution. The industry, agriculture, transportation, urban construction, tourism, ecology, and other aspects of the province are directly or indirectly affected by karst (Su and Zhu, 2000). Excessive human activities, such as deforestation and rapid population growth, have contributed to the degradation of the ecosystem quality in the region (Han et al., 2020). We selected village ecosystems at different levels of KDC as research cases (two villages selected in each KDC area) to investigate vulnerability levels and influencing factors. The none-potential KDC area is located in the east of Guizhou Province, it is typical dolomite karst, and it belongs to the subtropical humid monsoon climate. The potential-mild KDC area is located in the northwest Guizhou

Province. The landform type is mainly plateau mountain, and the rock type is mainly carbonate limestone. The moderate–severe KDC area is located on both sides of the Beipan River Canyon at the junction north of Zhenfeng County and south of Guanling County, Guizhou Province (Figure 1). The landform type is mainly a plateau canyon, the terrain fluctuates significantly, and the rock is mainly carbonate limestone.

3.2. Research framework and indicator system construction

The combination of human society and the environment has resulted in ecosystem vulnerability, and the factors influencing different ecosystem vulnerabilities vary (Kang et al., 2018). South China Karst has broken terrain, steep slopes, high vegetation sensitivity, low environmental carrying capacity, and poor land quality (Yang, 1990). Strongly developed underground cave systems lead to a lack of surface runoff, groundwater utilization is difficult, and engineering drought may occur (Liu C. et al., 2014; Qiu et al., 2021). According to the sensitive basic environmental characteristics, there is high system exposure and low resilience of village ecosystems in KDC. Therefore, we referred to relevant literature and selected the framework of E–S–LoR (Birkmann et al., 2013), and constructed an evaluation index system for the village ecosystem vulnerability of KDC with three dimensions of “exposure, susceptibility, and lack of resilience” and 26 indicators (Table 1). The details of the dimensions were as follows: (1) Susceptibility is the degree to which a system changes easily when disturbed, which reflects the stability of the

underlying environment. Therefore, we chose the annual average temperature, annual precipitation, annual sunshine hours, altitude, average slope, terrain undulation, proportion of karst desertification area, soil erodibility K, landscape fragmentation, landscape diversity, and forest coverage as the indicators to measure susceptibility. (2) Lack of resilience is the system’s self-adaptive capacity to deal with risk stress, including pre-event risk reduction for prevention, and post-event adaptive strategies. Herefore, we chose the length of roads open to traffic, livelihood strategies, net income per inhabitant, proportion of the population with high school education or above, number of pools, food production per unit of arable land area, area of returning farmland to forest, and annual control rate of karst desertification to reflect resilience. (3) Exposure reflects the extent to which an ecosystem is exposed to human activity and the external environment. The most direct manifestation is the pressure on production and population activity in the environment. We chose population density, population dependency ratio, proportion of building area, amount of fertilizer used on farmland, amount of pesticide used on farmland, proportion of labor outflow, and *per capita* cultivated land area to measure exposure.

3.3. Data sources

Basic natural and socio-economic data were used in this study. Basic natural data included meteorological, topographic, land-use type, and soil texture data. Socioeconomic data included demographic, economic income, production and population, and ecological governance-related data. Meteorological data were obtained from The

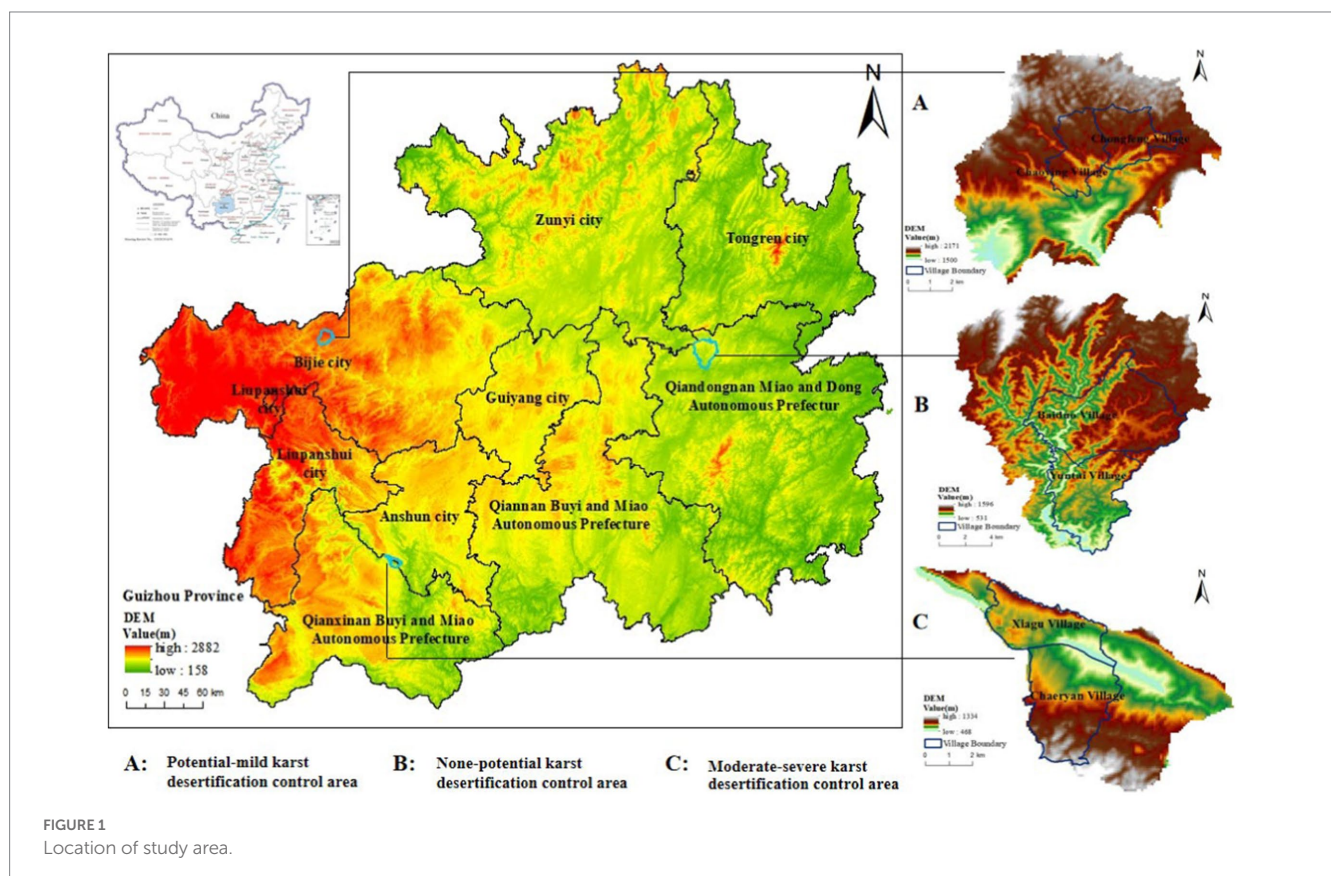


TABLE 1 Village ecosystem vulnerability indicator weights.

Dimension layer	Indicator	Indicator attributes and numbers	Weights	Description of indicator
Susceptibility	Annual average temperature	X1 (–)	0.069	Indicates impact on villages of climate, light, temperature and precipitation factors affecting the quality of the ecosystem
	Annual precipitation	X2 (–)	0.044	
	Annual sunshine hours	X3 (–)	0.021	
	Altitude	X4 (+)	0.077	Indicates impact of terrain on ecosystem. The slope and terrain undulation will affect the stability of slope materials, and the altitude will affect the temperature and precipitation
	Average slope	X5 (+)	0.031	
	Terrain undulation	X6 (+)	0.042	
	Proportion of karst desertification area	X7 (+)	0.045	Indicates the degree of karst desertification of the village
	Soil erodibility-K	X8 (–)	0.029	Indicates the sensitivity to soil erosion
	Landscape fragmentation	X9 (+)	0.038	Reflects the degree of human disturbance on the landscape
	Landscape diversity	X10 (–)	0.046	Represents the richness and complexity of landscape types and reflects the diversity of ecosystem structure
	Forest coverage	X11 (+)	0.053	Reflects the vegetation and ecological environment under the KDC environment
Lack of resilience	Length of road open to traffic	X12 (–)	0.02	Reflects the interference intensity of human activity on the ecological environment. Data based on the statistics of village committees
	Livelihood strategies	X13 (–)	0.046	Indicates the degree of diversification of farmers' livelihood sources. Data based on interviews with farmers
	Net income per inhabitant	X14 (–)	0.043	Reflects the risk response ability of farmers. Data based on interviews with farmers
	Proportion of population with high school education or above	X15 (–)	0.02	Represents the education level of residents. Data based on the statistics of village committees
	Number of pools	X16 (–)	0.019	Reflects degree of residential water safety. Data based on the statistics of village committees
	Food production per unit of arable land area	X17 (–)	0.018	Indicates village land production capacity. Data based on the statistics of village committees
	Area of returning farmland to forest	X18 (–)	0.026	Reflects efforts of ecosystem governance. Data based on the statistics of village committees
	Annual control rate of karst desertification	X19 (–)	0.031	Reflects effect of karst desertification control. Data based on remote sensing image interpretation
Exposure	Density of population	X20 (+)	0.029	Reflects pressure of population on village ecological environment and resources. Data based on the statistics of village committees
	Dependency ratio of population	X21 (+)	0.028	Reflects the pressure of residents' life. Data based on the statistics of village committees
	Proportion of building area	X22 (–)	0.079	Represents the interference of human activities to the ecological environment. Data based on remote sensing image interpretation
	Amount of fertilizer used on farmland	X23 (+)	0.031	Use of chemical fertilizers and pesticides pollute the soil and water, thus damaging the ecosystem. Data based on interviews with farmers
	Amount of pesticide used on farmland	X24 (+)	0.051	
	Proportion of labor outflow	X25 (+)	0.041	Represents the loss of village labor force. Data based on the statistics of village committees
	<i>Per capita</i> cultivated land area	X26 (+)	0.023	Reflects the pressure of population on cultivated land resources. Data based on the statistics of village committees

“+” indicates that the indicator is positively correlated with vulnerability; “–” indicates that the indicator is negatively correlated with vulnerability.

China Meteorological Data Service Center.¹ We downloaded the 30 m resolution digital elevation model from the geospatial data cloud² and then used ArcGIS10.2 to extract the elevation, slope, and topographic relief. The land-use type data were interpreted using 30 m resolution remote sensing image data downloaded from the geospatial data cloud. Based on land-use data, we calculated landscape diversity and landscape fragmentation using Fragstats 4.2. We referred to the classification standard of karst desertification (Xiong et al., 2002) to extract karst desertification data in the study area. Soil type data were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences.³ Demographic, economic income, production, and ecological governance-related data were obtained through village group statistics and interviews with farmers. All the data were obtained in December 2020.

3.4. Methods

3.4.1. Data standardization

Because each indicator has different attributes and dimensions, it is necessary to standardize the original data before assessment. There are two types of relationships between an indicator and vulnerability: positive and negative (Zhao et al., 2018). Therefore, this study referred to relevant research and selected the following formula to normalize the indicators (Kan et al., 2018).

Positive indicators: (1).

$$X_{ij} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

Negative indicators: (2).

$$X_{ij} = \frac{X_{\max} - X}{X_{\max} - X_{\min}} \quad (2)$$

where X_{ij} is the standardized indicator value, X is the original value of the indicator, X_{\min} is the minimum value of the original indicator, and X_{\max} is the maximum value of the original indicator.

3.4.2. Weight calculation

The methods used to determine the weight of the indicator include the expert scoring method, analytic hierarchy process, entropy method, and principal component analysis (PCA). However, the entropy method is more objective and accurate. Therefore, this study used the entropy method to determine the weight coefficients of the indicators.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}} \quad (3)$$

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^m P_{ij} \ln P_{ij} \quad (4)$$

$$W_j = \frac{1 - E_j}{\sum_{i=1}^n (1 - E_j)} \quad (5)$$

where P_{ij} is the proportion of each indicator; E_j is the information entropy value of the indicator; W_j is the indicator weight; m is the sample size; and n is the number of indicators.

3.4.3. Vulnerability calculation

Based on the above weight calculation, we used Equation (6) to calculate the ecosystem vulnerability value of the village ecosystem of the KDC.

$$V = \sum_j^n W_j \cdot X_{ij} \quad (6)$$

where V is the vulnerability value: the higher the value of V , the higher the vulnerability level, W_j is the weight of the j th indicator, and X_{ij} is the standardized value of the j th indicator of the i th village.

3.4.4. Contribution calculation

In addition to analyzing its vulnerability level and spatial distribution, research on vulnerability should also analyze the causes of ecosystem vulnerability. To clarify the driving factors of the village ecosystem vulnerability of the KDC, we referred to the relevant literature to introduce a factor contribution model (Wang L. et al., 2022). Based on the results of the study, we selected the indicators with a contribution of more than 5% as the main contributing factors.

$$C_j = \frac{W_j \cdot I_j}{\sum_{j=1}^m W_j \cdot I_j} \times 100\% \quad (7)$$

$$U_r = \sum_{j=i}^m C_j \quad (8)$$

where C_j represents the contribution of the j th indicator to vulnerability, U_r represents the contribution of the r th element layer to vulnerability, I_j is the standardized value of the j th indicator, and W_j is the weight of the j th indicator.

4. Results

4.1. Village ecosystem vulnerability characteristics in KDC

The vulnerability values of the three KDC areas (six villages) are listed in Table 2. The average village ecosystem vulnerability values was 0.468, with a minimum value of 0.29, and the maximum value was 0.646. We referred to the relevant research (Zhang et al., 2017), and divided the vulnerability into five levels according to the vulnerability values: slight (0–0.2), mild (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and extreme vulnerability (0.8–1). The vulnerability values of the Baiduo and Yuntai Villages in the none-potential KDC area were 0.318 and 0.29, respectively, indicating mild vulnerability. The vulnerability values of Chaoying and Chongfeng Villages in the potential-mild

1 <http://data.cma.cn>

2 <http://www.gscloud.cn>

3 <http://www.resdc.cn>

KDC area were 0.494 and 0.532, respectively, indicating moderate vulnerability. The vulnerability values of Chaeryan and Xiagu Villages in the moderate–severe KDC area were 0.527 and 0.646, respectively, indicating moderate and high vulnerability. Overall, the village ecosystem vulnerability of the KDC area was mild, moderate, and high.

4.2. Susceptibility value and contribution analysis

Based on statistical results (Figure 2A), the susceptibility values of Baiduo and Yuntai Villages in the none-potential KDC area were 0.167 and 0.105, respectively, whereas those of Chaoying and Chongfeng Villages in the potential-mild KDC area were 0.266 and 0.314, respectively. The susceptibility values of Chaeryan and Xiagu Villages in the moderate–severe KDC area were 0.204 and 0.289, respectively. We found that the susceptibility of the village ecosystem in the

none-potential KDC area was the smallest, whereas that of the mild-potential KDC area was the highest. The village ecosystem susceptibility contributions in the none-potential karst desertification areas were 52.5 and 36.3%, and in the potential-mild karst desertification areas were 53.9 and 58.9%, respectively. The contributions in the moderate–severe karst desertification areas were 38.7 and 44.8%, respectively (Figure 2B).

4.3. Lack of resilience value and contribution analysis

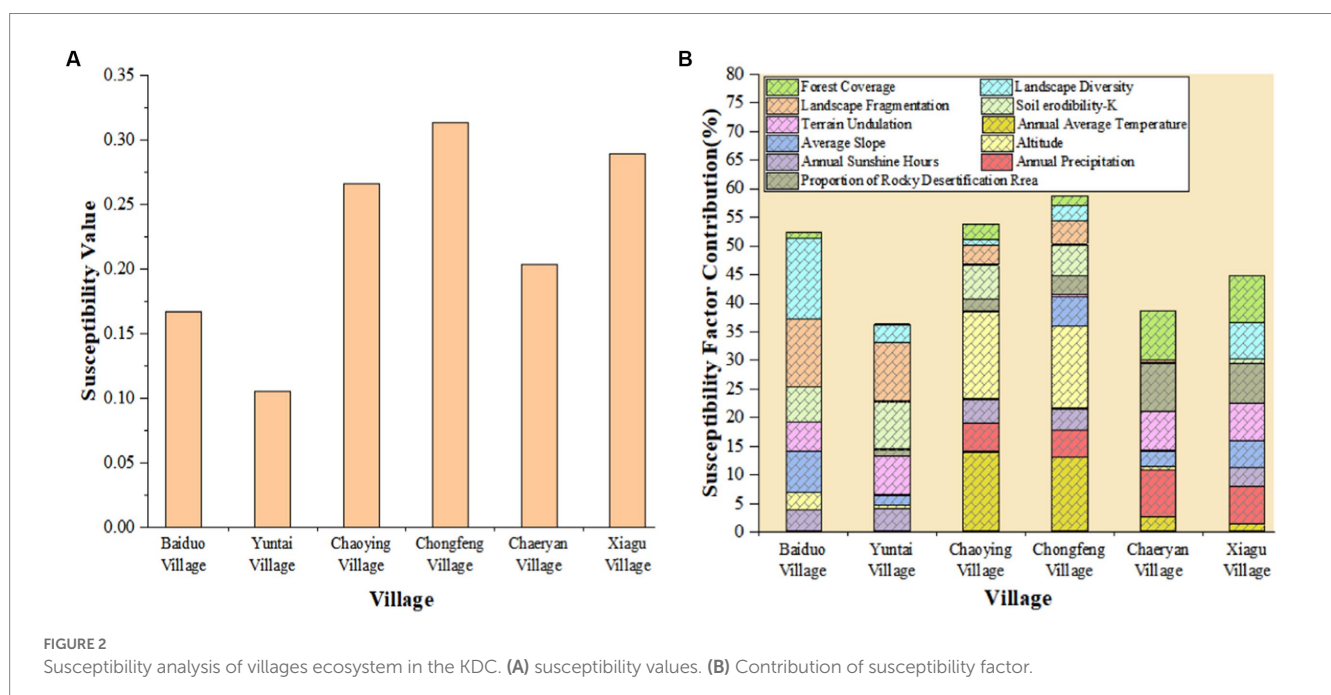
The lack of resilience values for village ecosystems in the different KDC areas differed (Figure 3A). The lack of resilience values were smallest for Baiduo and Yuntai Villages in the none-potential KDC area at 0.072 and 0.078, respectively. The lack of resilience values were largest in Chaoying and Chongfeng Villages in the potential-mild KDC area, at 0.154 and 0.171, respectively. The lack of resilience values of Chaeryan and Xiagu Villages in the moderate–severe KDC area were 0.121 and 0.145, respectively, which fall between the other two grades of karst desertification areas. The contributions of the lack of resilience of the village ecosystems of the none-potential KDC areas were 22.7 and 27%, respectively, in the potential-mild KDC area were 31.1 and 32.1%, respectively, and 23 and 22.4% in the moderate–severe KDC area, respectively (Figure 3B).

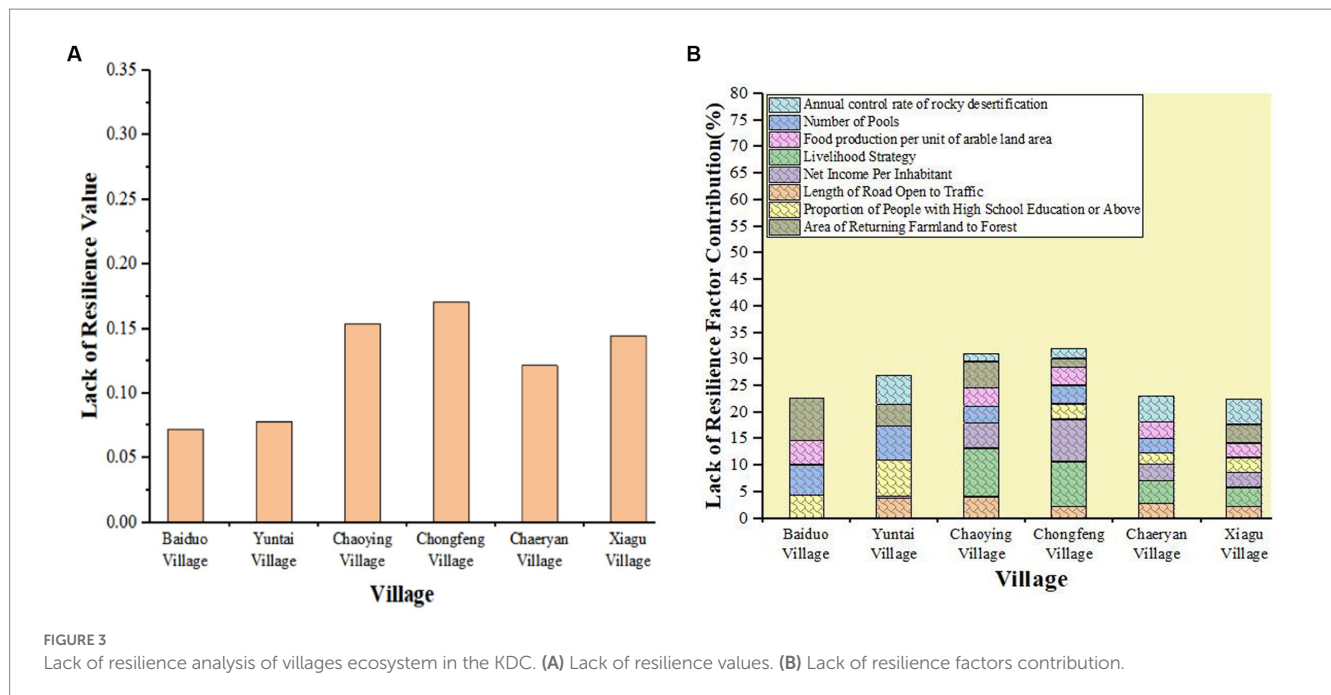
4.4. Exposure value and contribution analysis

Through the analysis of the exposure of the study area (Figure 4A), we found that the exposure values between the village ecosystems of the KDC displayed large differences, with a minimum exposure value of 0.048 and a maximum value of 0.211. The exposure values of the

TABLE 2 Village ecosystem vulnerability level.

The study area		Vulnerability value	Vulnerability level
None-potential KDC area	Baiduo Village	0.318	Mild vulnerability
	Yuntai Village	0.29	Mild vulnerability
Potential-mild KDC area	Chaoying Village	0.494	Moderate vulnerability
	Chongfeng Village	0.532	Moderate vulnerability
Moderate-severe KDC area	Chaeryan Village	0.527	Moderate vulnerability
	Xiagu Village	0.646	High vulnerability





Baiduo and Yuntai Villages in the none-potential KDC area were 0.079 and 0.106, respectively. The exposure values of the village ecosystems in the potential-mild karst desertification area were the lowest, and the exposure values of the Chaoying and Chongfeng Villages were 0.074 and 0.048, respectively. The exposure values of the village ecosystem in the moderate–severe KDC area were the largest, and the exposure values of the Chaeryan and Xiagu Villages were 0.202 and 0.211, respectively. In general, there was little difference in the exposure values of village ecosystems in the same KDC area. The exposure values of village ecosystems in different KDC areas were in the order of moderate–severe KDC areas > none-potential KDC areas > potential-mild KDC areas. The contribution of exposure differs from that of vulnerability. The exposure contribution of the village ecosystems in the none-potential KDC area was 24.8 and 36.7%, respectively, in the potential-mild KDC area, it was 15 and 9%, respectively, and in the moderate–severe KDC areas, it was 38.3 and 32.7%, respectively (Figure 4B).

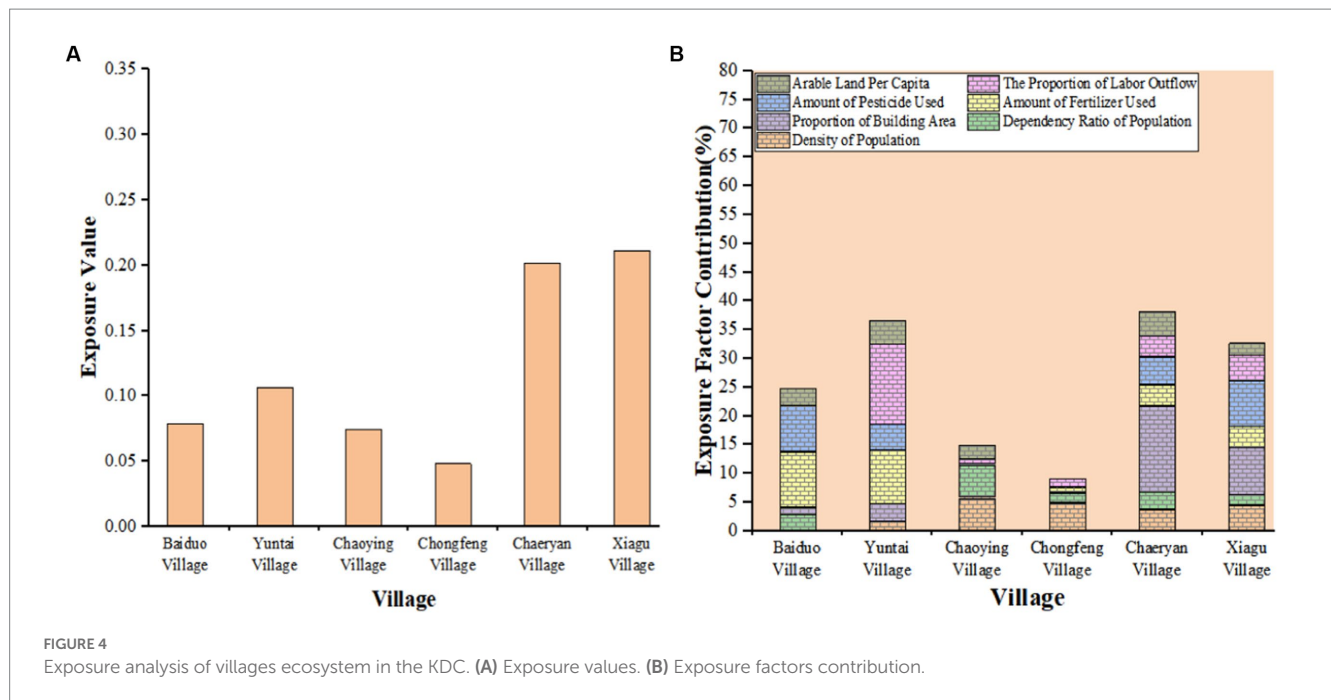
5. Discussion

5.1. Causes of village ecosystem vulnerability

It is very important to reveal the level and influencing factors of village ecosystem vulnerability in KDC to further restore vulnerable karst ecosystems. The differences in the natural and socio-economic conditions of village ecosystems in different KDC areas lead to significant spatial differences in vulnerability. According to our research, the vulnerability level of the village ecosystems of KDC in South China Karst showed mild and moderate vulnerability. The unique geology and lithology are the basis of ecosystem vulnerability, and the unreasonable human social and economic activities are the external pressure factors of ecosystem vulnerability in the South China Karst (Li et al., 2002).

We calculated the contribution rate of each indicator to the vulnerability of the village ecosystem and screened factors with a large contribution rate. In the none-potential KDC area, the maximum contribution rates of landscape diversity, landscape crushing, soil corrosive factor, slope (Figure 2B), and labor loss factors were 14.3, 11.8, 8.4, 7.1, and 14.1%, respectively. The maximum contribution rates of pesticide and fertilizer use were 8 and 9.7%, respectively (Figure 4B). In the potential-mild KDC area, the maximum contribution rates of the annual average temperature, altitude factor, maximum soil corrosive factor (Figure 2B), livelihood strategies, *per capita* net income (Figure 3B), and population density were 14.1, 15.2, 5.9, 9.2, 8, and 5.8%, respectively (Figure 4B). In the moderate–severe KDC area, the maximum contribution rates of precipitation, topography, karst desertification, landscape diversity, forest coverage (Figure 2B), construction land, and pesticides were 8.3, 6.9, 8.3, 6.3, 8.7, 15, and 7.9%, respectively (Figure 4B). The terrain significantly affects the stability of the slope material and conditions for agricultural farming. Rainfall and temperature have an important impact on ecosystem stability. The landscape pattern index, degree of karst desertification, and forest coverage were the main factors that causing ecosystem sensitivity. Soil erodibility is an important factor affecting soil and water loss. The use of chemical fertilizers and pesticides affects the quality of cultivated land. Livelihood strategies, population density, and labor loss have caused pressure on local residents, increasing their exposure. A low *per capita* income leads to a lower adaptability of farmers.

In none-potential KDC areas, local residents have a low level of education. To increase agricultural output, farmers use more pesticides and fertilizers during cultivation. There are few employment opportunities in the countryside; many young people choose to go away for work, leaving behind many older adults and children who are exposed to uncertain risks. The potential-mild KDC area is high in altitude, the average annual temperature is low, and the annual precipitation is insufficient. Serious soil erosion, low labor efficiency, and low economic income mainly rely on labor exports and



small-scale farming, and the incidence of poverty is extremely high (Ji et al., 2020; Ren et al., 2020). Our survey found that most local farmers' livelihoods came from labor output acquisition income, and small-scale planting and breeding industries, while the population pressure was high. The moderate-severe KDC area surface is crushed, the terrain of the area is steep, the surface soil and soil reservation capacity is insufficient (Mu et al., 2021), and annual precipitation is low. Karst in the region has a strong role; the soil formation rate is low, and a large amount of unreasonable reclamation in the early days has led to poor soil and discontinuous soil cover (Ren et al., 2020). This results in poor landscape diversity and forest cover. This shows serious karst desertification, which is difficult to control. To facilitate water access and agricultural cultivation, many people are concentrated in the valley area, accompanied by many construction facilities. Farmers use many pesticides to increase the output of Chinese red pepper and dragon fruit. According to the analysis of the difference in indicator vulnerability values (Figure 5), we found that topography, climate, forest coverage, landscape pattern, karst desertification degree, soil erodibility, KDC rate, production and construction activity, livelihood, and *per capita* net income were the key factors leading to the differences in village ecosystem vulnerability in the three different levels of KDC areas.

5.2. Comparison with previous studies

In recent years, scholars have conducted relevant research on karst ecological vulnerability. These studies included vulnerability and impact-factor analyses. Chen (2007) pointed out that owing to the deep soil layer and continuous soil cover in the karst trough area, there is a slight vulnerability. This is consistent with the results of our study of the karst plateau trough area (none-potential KDC area). Wang et al. (2021) studied the ecological vulnerability of karst areas in Yunnan Province, China, and revealed high vulnerability and extreme vulnerability in moderate-to-severe karst desertification areas. However, our results

show that the moderate-to-severe karst desertification areas are moderately vulnerable and highly vulnerable. This may be due to the differences in KDC measures, leading to different ecological restoration effects and different degrees of vulnerability. Guo et al. (2017) analyzed the vulnerability level and influencing factors were analyzed of mountain ecosystem in Southwest China Karst using the remote sensing method, and found that the vulnerability of regions with strong karst development, low vegetation coverage, and high bedrock exposure rate was higher than that of regions with high vegetation coverage, low karst desertification and better ecological environment in karst mountain areas in southwest China. The results of this study are consistent with the actual vulnerability of the village ecosystems in the three KDC areas. Many studies demonstrated that vegetation cover factors, precipitation, topography, soil erosion factors, and the degree of karst desertification on the impact of karst ecosystem vulnerability is more significant (Wang and Yu, 2005; Chen, 2007; Wang et al., 2021). However, the KDC village ecosystem was characterized by karst ecosystem vulnerability. Owing to the differences in spatial scale, data accuracy, and measurement indicators, large-scale studies cannot reflect the characteristics of small-scale ecosystem vulnerability. For example, the influence mechanism of farmers' production activities, living activities, and socio-economic development on the vulnerability of karst ecosystems is a problem that has not been investigated in current large-scale research. The study of vulnerability at the village ecosystem scale can accurately reveal the factors influencing vulnerability. This has important significance for providing guidance to the government in formulating planning policies, which is also the significance and necessity of small-scale research.

5.3. Adaptive governance measures

Various ecosystem problems caused by karst desertification seriously affect the lives of local residents and hinder the coordinated development of the local socioeconomic and ecological environments

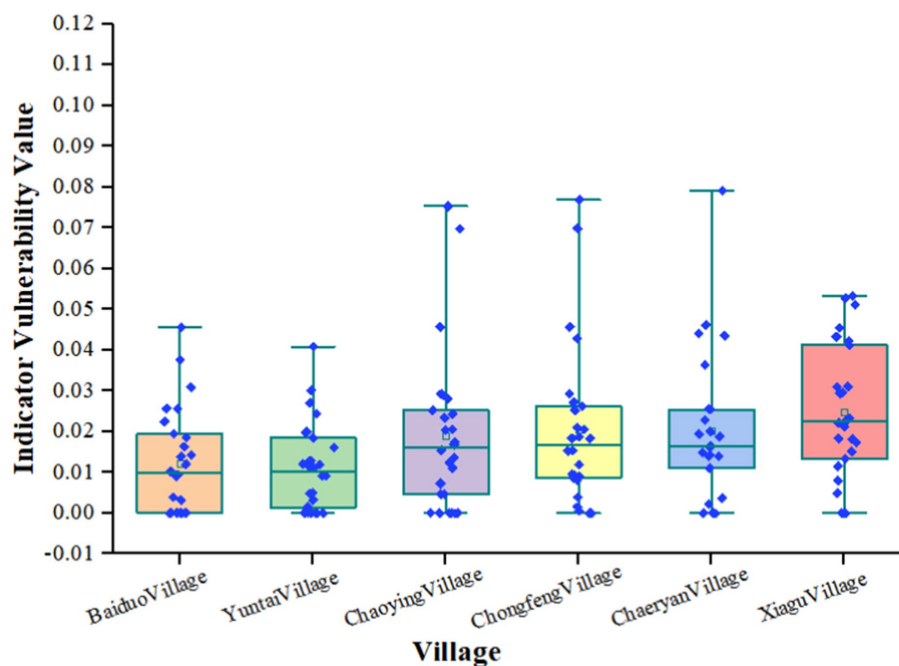


FIGURE 5
Indicator vulnerability value difference.

(Xiong and Chi, 2015). Over time, humans have attempted to control the deterioration of karst desertification in karst areas. For example, the Italian government restricts the cutting of firewood and prohibits goat breeding (Ford and Williams, 2013). KDC mainly adopts the measures of water storage, land management, returning farmland to forest and grassland, afforestation, three-dimensional ecological agriculture, and agricultural and forestry management development in the South China Karst (Xiong et al., 2006; Jiang et al., 2009). However, different levels of vulnerability still exist in rural areas of the KDC environment. Therefore, in view of the current situation of the village ecosystems of KDC, we should concentrate on both ecological management and socio-economic development, focusing on the sustainability of village development and proposing feasible adaptive management measures. In none-potential KDC areas, existing vegetation coverage should be maintained, the population scale should be controlled, population quality should be improved, and the rural labor force should be retained. Organic fertilizers and non-residual pesticides should be popularized and the use of stereoscopic agriculture in mountains should be developed. Forestry should be developed on mountain tops, the middle area of the mountain should be used for fruit industry development, and crop cultivation and livestock and poultry breeding should be carried out at the foot of the mountain and in low flat areas. The development of eco-tourism and the promotion of the sale of ecological products could promote economic development of the eco-industry. In mild-potential and moderate-severe KDC areas, the population size should be controlled, population quality should be improved, and population skills training should be strengthened along with the implementation of ecological and water storage irrigation engineering measures. The selection of an economic fruit forest with drought tolerance, calcium preference, and developed root systems for planting, implementing mountain closures for afforestation, and returning farmland to forests to increase

vegetation coverage and reduce water and soil loss are recommended while popularizing the use of organic fertilizers and non-residual pesticides and developing stereoscopic agriculture on mountains. Projects for transforming slopes into terraces and building of water-saving, intensive agricultural production systems should be implemented. In addition, unreasonable human activities, such as grazing and felling of trees, should be prohibited in stone and semi-stone mountainous areas. Local scientific research departments should increase their investments in scientific and technological research and investigate new processed agricultural products to increase their added value. Local governments should take advantage of local natural conditions to build research and tourism bases with karst characteristics and promote local employment while simultaneously promoting the coordinated development of socio-economic and ecological factors.

In general, it is necessary to change the current development mode and concurrently improve the ecological and socio-economic benefits to promote high-quality and sustainable development of rural areas in karst desertification areas. Talents, technology, capital, and superior management modes are necessary to achieve high-quality and sustainable development, enhancing the management ability of grassroots leaders, strengthening the training of farmers' knowledge and skills, and comprehensively enhancing the production skills and environmental awareness of residents. Based on the advantages of rural resource endowment, we should optimize the allocation of resources, build a sustainable production system, integrate various industries, strengthen the construction of rural industrial chains, and promote the transformation and upgrading of the industrial structure and technological innovation. A reciprocal mechanism between rural industry development and farmers' interests should be established to promote the integration and development of the rural industry. We should vigorously develop the ecological industry and promote the

specialization and integration of production, processing, storage, transportation, and sales of ecological products. Furthermore, amendments to the quality requirements of ecological products should focus on improvements in product quality and economic benefits. We should rationally plan land-use patterns and optimize the spatial structure of rural production, life, and ecology. The quality of the ecological environment and the service function of the system should be improved. We should abandon the development model of destroying the environment for economic benefit, build a virtuous rural system, and form a local sustainable and high-quality development model.

5.4. Future research

Current vulnerability research has been applied to ecological, natural, and societal subsystems, and coupled socio-ecological systems (Gallopín, 2006). Research on the vulnerability of coupled socio-ecological systems has not yet resulted in the formulation of a perfect theoretical system, and is not unified in terms of concept connotation, research framework, and evaluation methods. Analysis of the process and mechanism of human–environment coupling is still an unresolved issue in research on ecosystem vulnerability (Tian and Chang, 2012). Currently, empirical research is mostly quantitative, the research methods are immature, existing models are used to build the index system, and there is a lack of innovation and lack of pertinence (Tang et al., 2022). Moreover, there is a lack of analysis on the formation process and internal mechanisms of ecosystem vulnerability. The research mainly focuses on a particular spatial and temporal scale and lacks a dynamic comparative analysis of vulnerability at different spatial and temporal scales (Huang et al., 2014). In future research, it is necessary to improve the indicator system, research models, and innovative research methods. We should pay attention to the process of the comprehensive action of human and natural factors and analyze the impact of the human–environment coupling mechanism on the formation mechanism of ecosystem vulnerability. We need to extend the spatial and temporal scales of research and use the 3S technology to reveal the spatial and temporal dynamic change processes of ecosystem vulnerability to realize dynamic monitoring and prediction. We should analyze the interaction mechanisms of material flow, energy flow, information flow, and ecological processes in the social-ecological system, and the relationship between stakeholders and ecological processes, to reveal the coupling mode of social economic factors and ecological environment factors. We should explore the breakthrough point of the social-ecological system from one steady state to another to reveal the threshold of vulnerability of the social-ecological system. The mutual feedback mechanism of the relationship between social activities and ecological environment degradation or restoration should be studied to explore the mode of balance and coordination between human production, living activities, and ecological restoration to combine theoretical research and practical applications and provide a decision-making basis for promoting sustainable governance of fragile ecosystems.

6. Conclusion

In this study, we analyzed the vulnerability level and driving factors of village ecosystems in different KDC based on the

framework of “exposure–susceptibility–lack of resilience.” Finally, we propose sustainable governance strategies for the village ecosystems of KDC areas. The results showed that topography, climate, and land cover were the main natural factors affecting the vulnerability of villages to KDC. Social and economic activities are external stress factors for of village ecosystem vulnerability in KDC. Due to differences in geographical factors, the level and influencing factors of village ecosystem vulnerability in different KDC may vary. Villages in the none-potential KDC have a mild vulnerability level, villages in the potential-mild KDC are moderately vulnerable, and villages in moderate–severe KDC have moderate and high vulnerability levels. Landscape diversity, fragmentation, soil erodibility, labor loss rate, slope, and the use of pesticides and fertilizers are the main reasons for the vulnerability of village ecosystems in the none-potential KDC. The average annual temperature, altitude, soil erodibility, livelihood strategies, *per capita* income, and population density were the main factors affecting village ecosystem vulnerability in the potential-mild KDC. Annual precipitation, topographic relief, karst desertification degree, landscape diversity, forest coverage, construction land proportion, and pesticide usage are the main factors affecting village ecosystem vulnerability in moderate–severe KDC. We found that terrain, climate, forest coverage, landscape pattern, karst desertification degree, soil erodibility, KDC effect, production and construction activity, livelihood strategies, and *per capita* net income were the key factors influencing the differences in village ecosystem vulnerability in KDC. Finally, our suggestions for the sustainable development of village ecosystems in KDC are to govern the ecological environment, control population size, improve population quality, retain more labor, develop local characteristic industries, increase employment opportunities, increase residents’ economic income, promote the development of the ecological industry to drive economic increase, and promote sustainable development of village ecosystems in KDC.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

KX conceived the framework, secured funding, and oversaw the entire project. JT, QWa, YC, and QWu collected data. JT analyzed the data and wrote the manuscript. KX provided comments. KX and JT reviewed the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2023.1126659/full#supplementary-material>

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