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Vulnerability and Impact Mechanisms of Social-Ecological Systems in Karst Desertification Control: An Analysis Based on Farm Household Survey Data

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Abstract

Vulnerability and its assessment framework provide a new perspective for the study of social-ecological systems in Karst regions. Drawing on theories related to social-ecological systems and vulnerability, this paper explores the measurement and interpretation of human-land relationships in Karst mountainous areas under the context of rocky desertification governance. From the perspective of sensitivity and adaptive capacity, an evaluation index system is constructed. Through participatory household surveys and field research, the vulnerability of local social-ecological systems based on households is measured, and the vulnerability of different types of households and regions is analyzed. Taking regional sensitivity and household adaptability as entry points, practical countermeasures and suggestions are proposed to provide a basis for decision-making by relevant departments. The study shows that: (1) There is a severe lack of natural capital, and the social and financial capital of pure agricultural and agriculture-dominant households urgently need improvement. (2) The lack of natural capital and the differentiation of adaptive capacity are key factors affecting vulnerability. The construction of cognitive and social capital can enhance system adaptability and reduce system vulnerability. (3) The lack of natural capital and the differentiation of adaptive capacity increase system vulnerability, while household cognition and social capital construction help improve the system's ability to cope with risks, mitigating or reducing system vulnerability.

Keywords: karst desertification control, social-ecological system, vulnerability, household livelihoods

1. Introduction

Karst desertification refers to the process under the fragile ecological environment of karst areas where unreasonable socio-economic activities by humans exacerbate human-land conflicts, leading to vegetation destruction, soil erosion, gradual rock exposure, and land productivity decline or loss, causing the landscape to visually resemble a desert-like environment (Xiong et al., 2002). The feedback effects between the vulnerable natural environment and the human environment in karst regions have resulted in Guizhou forming a typical yet fragile karst plateau canyon geographical structure environment(Yang, 1990). With the advancement of desertification control projects, significant phased achievements have been made. However, studies on karst regional vulnerability predominantly focus on single ecological environments or regional scales, with fewer analyses examining the evolution of human-land relationships under desertification governance from the perspective of human-environment interactions. This research gap neglects the critical influence of institutional, policy, and cognitive socioeconomic factors on the sustainable development of regional human-land systems.

With the emergence and development of social-ecosystem theory, integrating this framework with vulnerability analysis provides a comprehensive approach to studying human-land relationships in karst geographical systems, facilitating an exploration of the complex and evolving coupled human-natural relationships. From the perspective of international research, the concept of "social-ecological systems" was proposed earlier and has developed a relatively mature theoretical system, representing a significant trend in global sustainability research in recent years. Holling (1973) introduced the concept of social-ecological systems (SESs)(Holling, 1973), defining them as complex adaptive systems where humans and nature are closely interconnected, exhibiting characteristics such as unpredictability, self-organization, multiple stable states, threshold effects, and historical dependence due to internal and external disturbances and drivers(Gunderson & Holling, 2003; Walker et al., 2006), Vulnerability, adaptability, and resilience constitute the three core attributes of social-ecological systems. In the study of social-ecological systems, these three critical attributes can be evaluated to focus on the dynamics and sustainability of social-ecological system changes. In 1981, Timmerman first introduced the concept of vulnerability in the field of geology and defined it as a degree, specifically the extent to which a system produces adverse responses during a disaster event(Timmerman, 1981). Scholars such as Adger developed a vulnerability conceptual framework based on exposure, sensitivity, and adaptive capacity(Adger, 2006). The RH model(Turner et al., 2003) and VSD model(Polsky et al., 2007) proposed by scholars like B.L. Turner II and Polsky have been widely applied.

Scholars have successively conducted research on the vulnerability of urban social-ecological systems (Chang et al., 2021), agricultural ecosystem vulnerability (Groot et al., 2016), tourist destination social-ecological systems (Tu et al., 2021), and lake watershed social-ecological systems (Janssens de Bisthoven et al., 2020). The research scale is predominantly at the county or village level, with some studies combining regional and farm household scales (Chen et al., 2015; Wen et al., 2016). Vulnerability studies in karst regions mainly focus on single natural ecosystems (Fang et al., 2022; Liu et al., 2021; Tang et al., 2023), while livelihood vulnerability research examines rural cooperative models and relocation-based poverty alleviation programs to explore sustainable development strategies for household livelihoods (Ren et al., 2020; Wang et al., 2022). However, integrated studies on social-ecological systems and vulnerability in karst regions remain relatively scarce, as do analyses addressing the development issues of karst mountain social-ecological systems under human-environment interactions from the perspective of household livelihood behaviors.

Therefore, this paper selects typical plateau mountainous areas with potential-mild rocky desertification and plateau canyon areas with moderate-severe rocky desertification. From the perspective of the interactive relationship between household livelihoods and local community development, the social-ecological system theory and vulnerability analysis framework are integrated into the study of karst regional development. By employing quantitative evaluation methods for vulnerability, this study analyzes the differences in vulnerability among different types of households and local social-ecological systems, providing practical references for the sustainable development of social-ecological systems and rural areas in the region.

2. Method

2.1 Study Area

With long-term scientific investment and policy support, rocky desertification governance in the study area has achieved significant results. Based on the typicality and representativeness of rocky desertification governance, two study areas with typical Karst landforms were selected, representing Karst plateau mountains and Karst plateau canyons. Differences in rocky desertification levels and natural environments have led to varying socio-economic development and lifestyles, resulting in different levels of vulnerability.

Salaxi study area is located in the upper reaches of the Wujiang River in northwestern Guizhou (27°11′09″N-27°17′28″N, 105°1′12″E-105°8′38″E), characterized by complex terrain, fragmented surface, and numerous karst depressions, representing typical Karst plateau mountain landforms with potential-mild rocky desertification. Huajiang study area is located in southwestern Guizhou, along the Huajiang River valley in the Beipan River (25°38′19″-25°41′32″N, 105°38′31-106°40′51″E), representing typical Karst plateau canyon landforms with moderate-severe rocky desertification. Rocky desertification governance involves a series of engineering measures such as returning farmland to forests and closing hillsides for afforestation, leading to changes in household livelihoods and increased instability in rural social structures, resulting in higher potential vulnerability risks.

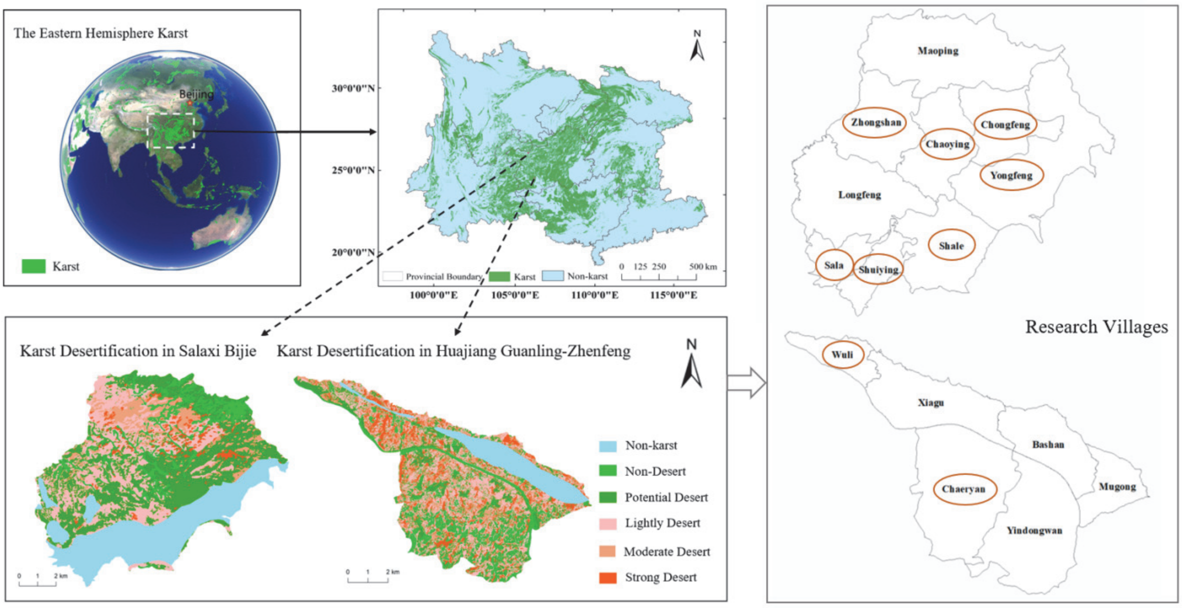

Figure 1. The location of the study areas

2.2 Data and Methods

2.2.1 Data Sources and Collection

(1) Land use data: The land use data were obtained from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, with a resolution of 30 meters) and reclassified into six categories: arable land, forest land, grassland, water bodies, construction land, and unused land. The DEM data were derived from the Geospatial Data Cloud (https://www.gscloud.cn/, with a resolution of 30 meters), extracted from the digital elevation maps of the ASTER satellite to obtain digital elevation model data.

(2) Household data: On the one hand, members of the research team obtained complete demographic data by consulting with town governments and village committees within the study area; on the other hand, participatory appraisal surveys were conducted among typical farm households in the study area to acquire questionnaire data. In December 2023, the author, as a member of the research team, participated in the investigation of typical farm households in Salaxi and Huajiang study area. A focused survey was carried out in nine villages, including Chongfeng, Chaoying, Sala, and Chaeryan Village. Among these, 94 questionnaires were collected from the Salaxi study area and 66 questionnaires from the Huajiang study area.

2.2.2 Index System Construction

Vulnerability is an attribute of a system's sensitivity to internal and external perturbations and its lack of coping capacity, which can lead to changes in the system's structure and function. Sensitivity and adaptive capacity are key components of system composition. The vulnerability of social-ecological systems in karst desertification areas results from the combined effects of natural and human factors, with the fragility of the livelihood system being a critical factor contributing to the vulnerability of the social-ecological system. Therefore, based on the sustainable livelihood analysis framework, this paper deconstructs the vulnerability of the social-ecological system in karst desertification areas into two parts: "sensitivity" and "adaptive capacity." Drawing on relevant studies (Chen et al., 2015; Li et al., 2013), we construct an evaluation index system for assessing the vulnerability of social-ecological systems in karst regions based on household survey data. Here, the system vulnerability indicators are defined as comprising two aspects: sensitivity to external disturbances at the regional level and adaptive capacity to respond to risks at the household level. System sensitivity includes three subsystems: ecological, social, and economic, while system adaptive capacity encompasses six types of capital, totaling 28 indicator factors (Table 1).

Table 1. Index system for social-ecological system vulnerability

Criterion Layer 1	Criterion Laye2	Indicator Layer	Attribute Layer	Indicator Weight
System Sensitivity	Ecological Subsystem (E)	(V1) Land Use Intensity	+	0.0842
		(V2) Landscape Pattern Index	+	0.0861
		V3 Area of Cultivated Land with Slopes Greater than 25°	+	0.0859
	Social Subsystem (S)	V4 Livestock Carrying Capacity per Unit Area	+	0.1012
		V5 Population Density	+	0.0900
		V6 Dependency Ratio	+	0.0865
	Economic Subsystem (E)	V7 Total Output Value of Agriculture, Forestry, Animal Husbandry, and Fishery	-	0.0839
		V8 Per Capita Grain Yield	-	0.0840
		V9 Per Capita Net Income	-	0.0843
System Adaptability	Human Capital (H)	X1 Labor Capacity	-	0.0050
		X2 Highest Level of Education in Household	-	0.0074
		X3 Employment Proportion in Secondary and Tertiary Industries	-	0.0088
	Material Capital (M)	X4 Type of Farmer's Housing	-	0.0264
		X5 Housing Area	-	0.0021
		X6 Number Of Household Material Asset Categories	-	0.0045
		X7 Rural Livestock Quantity	-	0.0021
	Financial Capital (F)	X8 Per Capita Household Income	-	0.0017
		X9 Borrowing Opportunities	-	0.0704
		X10 Cash Assistance	-	0.0020
	Social Capital (S)	X11 Social Connectivity	-	0.0047
		X12 Social Support	-	0.0050
		X13 Mutual Assistance During Farming Season	-	0.0213
	Cognitive Capital (C)	X14 Perception of Regional Development Prospects	-	0.0041
		X15 Local Identity	-	0.0272
		X16 Awareness of Policies	-	0.0143
		X17 Environmental Protection Awareness	-	0.0029
	Natural Capital (N)	X18 Per Capita Arable Land Area	-	0.0020
		X19 Per Capita Forest Land Area	-	0.0021

Note. + represents a positive correlation with vulnerability and - represents a negative correlation with vulnerability.

2.2.3 Data Processing and Analytical Methods

(1) Data standardization: This paper uses the range standardization method. The standardization formulas are as follows:

Positive indicator standardization: $Z_i = (X_i - X_{min})/(X_{max} - X_{min})$

Negative indicator standardization: $Z_i = (X_{max} - X_i)/(X_{max} - X_{min})$

Where Z_i represents the standardized value of the ith indicator, X_i represents the actual value of the ith indicator, X_{max} and X_{min} represent the maximum and minimum value of the ith indicator respectively. Z_i is between (0,1), the larger Z_i is, the greater the social-ecological vulnerability of the region is, and it is more susceptible to the external interference and damage.

(2) Weight determination: This study uses the entropy method to assign weights to vulnerability indicators. The calculation steps and formulas are as follows:

First, calculate the weight of the jth indicator value of the ith survey object: $P_{ij} = X'_{ij}/\sum_{i=1}^{m} X'_{ij}$

Secondly, calculate the information entropy of the indicator: $e_j = -k\sum_{i=1}^{m} P_{ij} \ln P_{ij}$, make k=1/ln m, there are $0 \le e_j \le 1$; the difference coefficient is $d_j = 1 - e_j$;

Finally, calculate the weight of the index: $\frac{d_j}{w_j} = \sum_{j=1}^{n} d_j,\ w_j = -(1-e_j)/\sum_{j=1}^{m}(1-e_j)$;

Where X_{ij} represents the value of the jth evaluation index of the ith survey object, $\min(X_j)$ and $\max(X_j)$ are the minimum and maximum values of the jth evaluation index respectively, where m is the number of survey objects and n is the number of indexes. When the coefficient of variation d_j is larger, the smaller e_j is, the more important the indicator is.

(3) Analysis methods

①Comprehensive index method: This method is widely used in academic research for vulnerability assessment. The calculation formula is as follows:

$$V = \sum_{j=1}^{n} w_j \times x'_{ij}$$

where: V represents the vulnerability index, w represents the weight of the jth indicator, and X' represents the standardized value of the jth indicator for the ith household.

②Contribution Degree Model: To explore the main contributing factors to SES vulnerability, this paper introduces a contribution degree model:

$$C_j = \frac{W_j \times I_j}{\sum_{j=1}^{m} W_j \times I_j} \times 100\%$$

$$U_r = \sum_{j=1}^{m} C_j$$

Where C_j represents the contribution degree of the jth indicator to vulnerability, Ur represents the contribution degree of the rth factor layer to vulnerability, I_j is the standardized value of the jth indicator, and W_j is the weight of the jth indicator

3. Results

3.1 Sample Classification and Characteristics

To analyze the needs of different household groups, households are classified into four types based on family size, composition, labor allocation, age, and education level: non-agricultural type, pure agriculture type, agriculture-dominant type, non-agriculture-dominant type(Guo et al., 2017; Ren et al., 2020). Pure agricultural households typically have larger family sizes, lower labor force participation, especially among women, and rely heavily on natural capital. Non-agricultural households have moderate family sizes, younger age structures, higher education levels, and rely mainly on secondary and tertiary industries. The non-agriculture-dominant type and agriculture-dominant type are further refined based on the non-agricultural income obtained by farm households. Households where non-agricultural income accounts for greater than or equal to 50% and less than or equal to 90% of total household income are classified as the non-agriculture-dominant type, whereas those with a proportion less than 50% are categorized as the agriculture-dominant type. The statistical characteristics of household samples in the study area are shown in Table 2.

Table 2. Statistical characteristics of sample households with different livelihood types

Feature Indicator	Pure Agriculture Type (PA)	Non-agricultural Type (NA)	Non-Agriculture-Dominant Type (NAD)	Agriculture-Dominant type (AD)
Proportion of Samples (%)	26.25	44.37	19.38	10
Average Age	51.74	35.20	35.84	35.67
Level of Education	1.67	2.35	2.68	2.25
Proportion of Non-agricultural Income (%)	0	97.98	73.52	24.74
Per Capita Net Income (ten thousand Yuan)	1.12	2.71	1.92	1.62
Awareness of Policies	0.31	0.37	0.48	0.44
Environmental Protection Awareness	2.69	2.70	2.90	3
Per Capita Arable Land (mu)	2.79	2.17	2.74	1.79
Housing Area (square meters)	134.33	162.10	168.68	146.87

Note. The levels of educational attainment and environmental protection awareness are scored using a five-point scale, while policy awareness is scored as 1 or 0. Other data represent the mean values obtained from the original survey dataset.

3.2 Analysis of Household SES Adaptability

Through the calculations, the adaptability conditions of social-ecosystem for farmers of different livelihood types are obtained (Table 3). The adaptability index of farmers in the plateau mountainous areas with potential-mild rocky desertification is generally higher than that in the plateau canyon areas with moderate-severe rocky desertification. The higher the index, the weaker the adaptability. Therefore, it can be concluded that the adaptability of farmers in the Salaxi study area is lower than that of farmers in the Huajiang study area.

Table 3. Adaptive index of SESs for households with different livelihood types

Study Area	Pure Agriculture Type (PA)	Non-agricultural Type (NA)	Non-Agriculture-Dominant Type (NAD)	Agriculture-Dominant type (AD)
Salaxi	0.1012	0.1003	0.0918	0.0902
Huajiang	0.0883	0.0845	0.0823	0.0956

Note. Adaptive capacity is treated as a negative indicator during data standardization, thus a lower index indicates stronger adaptability; the vulnerability index is calculated by weighting and summing using the composite index method.

The adaptive index of households in the Salaxi research area, from smallest to largest, is as follows: AD, NAD, NA, PA. The livelihood type with the strongest adaptive capacity is AD, while the weakest is NA. Overall, households in the Salaxi research area generally face issues such as a lack of natural capital, insufficient human capital, material capital, and social capital. There is a significant amount of abandoned land in the Salaxi research area, indicating low efficiency in the utilization of natural capital by households. The differences in human capital values are relatively small, suggesting a relatively balanced household structure and educational attainment among members. The human capital values for NAD and NA are slightly higher than those for PA and AD, indicating that households primarily dependent on migrant labor tend to have higher overall qualities. With the advancement of regional development and desertification control projects, conditions such as hydropower and transportation in the study area have continuously improved; however, due to natural constraints, the accumulated material capital among households remains quite limited. Among the four types of households, NA households have accumulated the highest level of material capital, suggesting that engaging in secondary and tertiary industries is a beneficial pathway to improving living standards. The financial capital measurement is highest for NA, indicating that households primarily reliant on labor migration achieve higher per capita net incomes. Social capital levels do not vary significantly across the Salaxi research area but remain relatively insufficient overall. Social connectivity, social support, and cash assistance determine the measurement of social capital among households. Analysis reveals that NA and NAD households score higher on social connectivity and cash assistance indicators compared to PA and AD households. In terms of cognitive capital, AD households exhibit relatively lower cognition. AD households mainly engage in the primary industry with secondary and tertiary industries as supplementary, currently undergoing a transformation in livelihood types. During the process of engaging in the primary industry, bottlenecks have been encountered, leading to a generally pessimistic attitude towards regional development prospects. In the Sala Creek Research Area, AD households previously engaged in Sichuan pepper cultivation; however, due to limitations imposed by natural conditions, the economic returns from Sichuan peppers were not promising. This has resulted in insufficient awareness among farmers regarding regional development prospects. The government should guide farmers to scientifically recognize the opportunities and risks associated with participating in regional economic development activities, encouraging them to seize development opportunities proactively while reducing or avoiding risks. Therefore, to promote diversification of livelihood types in the region, it is necessary to enhance the efficiency of natural capital utilization and develop distinctive ecological industries; increase the proportion of physical capital ownership and strengthen infrastructure construction; enhance communication between communities, village committees, and households, and mobilize the initiative, enthusiasm, and creativity of farmers for social integration.

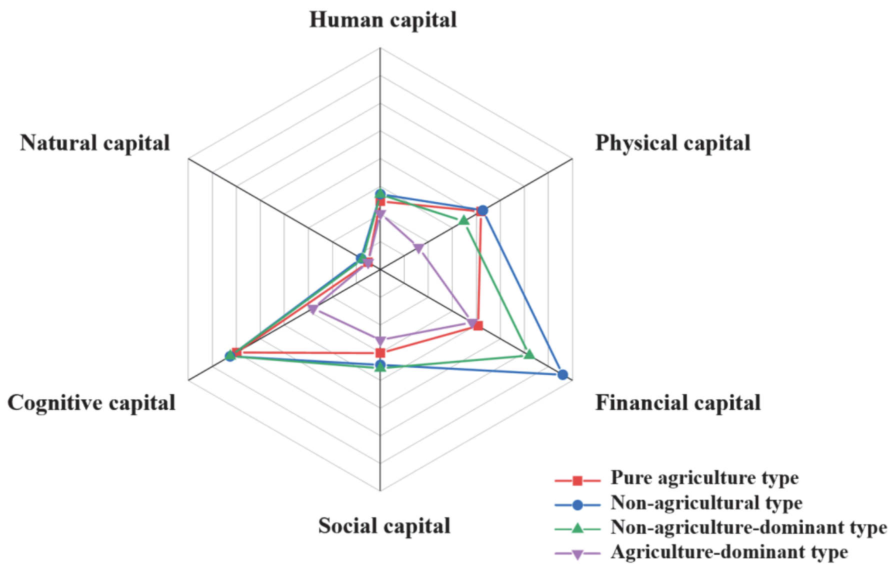

Figure 2. Differences in adaptive capital of SESs among different types of households in Salaxi

The adaptive index of farm households in the Huajiang research area, in ascending order, is as follows: NAD, NA, PA, AD. The strongest adaptive capacity lies with the NAD livelihood type, whereas the weakest is the AD livelihood type. Through analyzing the differences in adaptive capital among different types of farm households' SESs (Figure 3), it can be generally observed that farm households in the Huajiang research area commonly face severe deficiencies in natural capital. The Huajiang research area is a typical region characterized by moderate to intense rocky desertification in highland gorges, with a dry-hot river valley climate, which partly causes issues such as regional drought, water scarcity, and reduced grain production. Human capital for NAD and NA is higher than that of PA and AD, indicating that NAD and NA farm households have larger labor force scales and higher education levels compared to farm households primarily engaged in the primary industry. The material capital for the four types of farm households in the Huajiang research area is relatively high, with non-agricultural households whose income sources are from the secondary and tertiary industries having the highest material capital. Moreover, the material capital in the Huajiang research area surpasses that of the Salaxi research area, implying better living standards, living environments, and infrastructure conditions for farm households in the study area compared to those in Salaxi. Financial capital for NA and AD households is higher than for PA and AD households, suggesting that households where wage labor is the main source of income have higher per capita net incomes and more borrowing opportunities. Regarding cognitive capital, PA households exceed the other three livelihood types, indicating that farm households purely engaged in the primary industry in the Huajiang research area have a deeper local identity. The socio-economic conditions in the Huajiang research area are superior to those in the Salaxi research area, offering farm households more livelihood options, with promising prospects for the development of industries such as pitaya and Sichuan pepper within the region. However, there is a notable lack of natural capital in the Huajiang research area. The ratio of social capital and financial capital for PA and AD farming households urgently needs to be improved. Therefore, it is necessary to promote the diversification of livelihood types in the region, enhance land use efficiency, and formulate scientific land resource utilization plans; increase the amount of financial capital held by farming households, improve the quality of financial capital, provide skill training for PA and AD farming households, and broaden income channels; communities and village committees need to strengthen communication with farming households, promptly understand and address issues faced by farming households, and stimulate their enthusiasm for production.

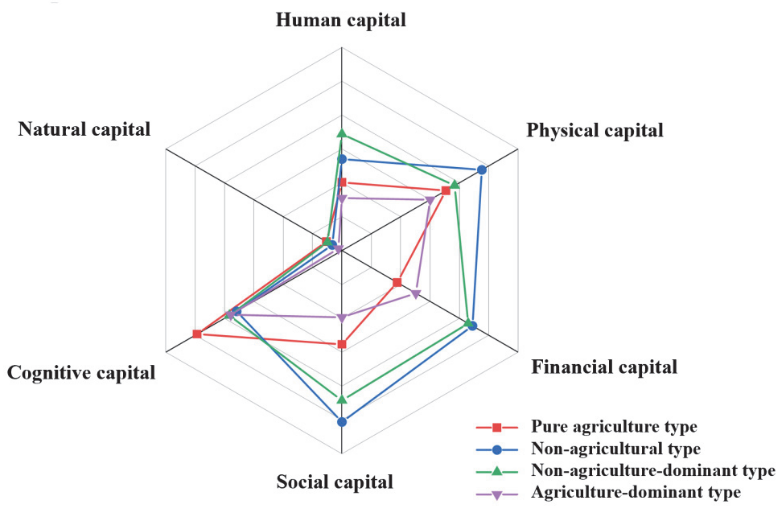

Figure 3. Differences in adaptive capital of SESs among different types of households in Huajiang

3.3 Analysis of the Vulnerability of Regional Social-Ecological Systems

This paper draws on relevant research findings (Li et al., 2008; Su et al., 2013), dividing the vulnerability index into three levels: low ($0 < DI \leq 0.4$), medium ($0.4 < DI \leq 0.7$), and high ($0.7 < DI \leq 1$). As shown in Table 4, the overall vulnerability level of the nine surveyed administrative villages is generally at a medium level. Among them, the vulnerability indices of Yongfeng and Chaeryan are below 0.4, while those of the other administrative villages mostly range between 0.4 and 0.6. The low vulnerability levels in Yongfeng and Chaeryan Villages are due to strong system adaptability and low system sensitivity, indicating that high adaptive capital (e.g., human, financial, social capital) combined with low sensitivity environments can form a good SES.

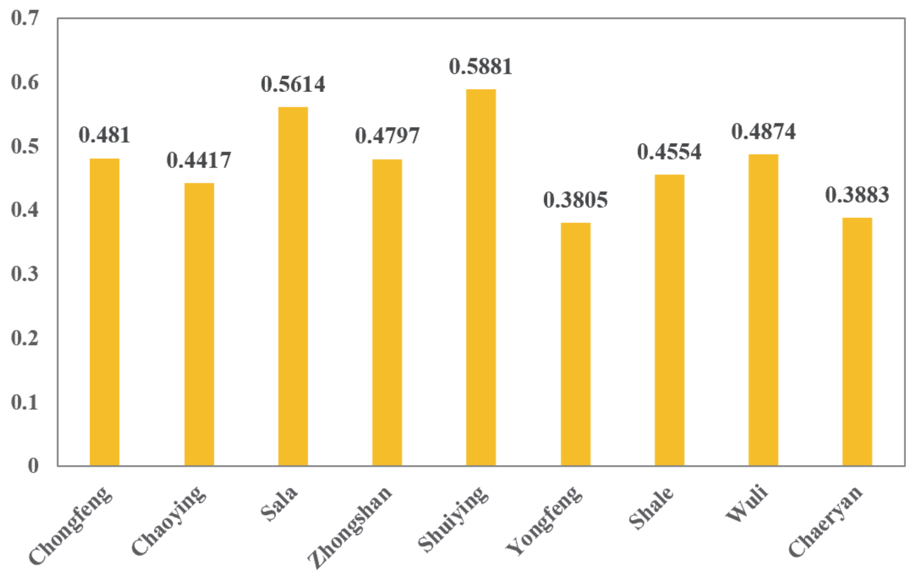

Figure 4. Vulnerability index of SESs in karst mountain areas of different villages

3.4 Mechanism of Vulnerability Impact

The vulnerability of SESs is influenced by numerous factors but is generally driven by key variables. In the seven surveyed villages of the Salaxi study area, the indicators with higher contribution to sensitivity were ranked as follows: V9 (per capita net income), V1 (land use intensity), V2 (landscape structure index), V7 (total output value of agriculture, forestry, animal husbandry, and fisheries), and V8 (per capita grain output). First, the indicator factors such as per capita net income, total output value of agriculture, forestry, animal husbandry, and fisheries, and per capita grain output belong to the economic layer indicators of the socio-ecological system. This suggests that a critical factor influencing the vulnerability of Salaxi's SES is regional economic development status, where household per capita income is a key factor affecting regional development. Thus, it is necessary to enhance both material and financial capital for households in the study area to improve their adaptive capacity in addressing regional vulnerability risks. Second, land use intensity and landscape structure index are also important factors influencing regional vulnerability, indicating the need to further strengthen ecological environment construction in the region. Additionally, combined with previous analyses on household adaptive capacity, it was found that natural capital for households is severely lacking. Therefore, the ecological compensation system should be implemented to promote improvements in livelihood strategies and increase livelihood capital for households, thereby diversifying their livelihood options and steering the socio-ecological environment toward sustainable development.

In the two surveyed villages of the Huajiang study area, the primary sensitive indicators were: V8 (per capita grain output), V2 (landscape structure index), V3 (proportion of cultivated land on slopes greater than 25°), V5 (population density), and V6 (dependency ratio). First, the key factor influencing the socio-ecological system of the region lies within the economic layer, specifically per capita grain output. The low per capita grain output leads to the fragility of the economic subsystem. This is the key to the vulnerability risk of socio-ecological systems. Therefore, it is necessary to increase regional per capita food production. In combination with the resilience of farming households, it is required to enhance human capital and cognitive capital of farming households. Secondly, indicators of the regional social subsystem also have a certain impact on the socio-ecological system. The population density in the Huajiang study area is relatively high, which exerts a certain pressure on the regional ecological environment. The relatively high population dependency ratio also poses corresponding risks to the social subsystem. In conjunction with the resilience of farming households, there should be an emphasis on optimizing human capital in the study area, improving the knowledge and skills, cultural and technical levels of farming households, and establishing and improving social security measures.

4. Conclusions and Discussion

4.1 Conclusions and Implications

4.1.1 Household Adaptability Analysis

The adaptive capacity index of farming households in Salaxi, from low to high, is sequentially AD, NAD, NA, and PA. Financial capital is relatively concentrated among the households, whereas natural capital, physical capital, and social capital are relatively insufficient. For Huajiang, the adaptive capacity index of farming households, from low to high, is NAD, NA, PA, and AD. In this region, natural capital is severely deficient, and there is an urgent need to enhance the social and financial capital of PA and AD households. Overall, the adaptive capacity of farming households in Salaxi is lower than that in Huajiang. There is a clear differentiation in the adaptive capacity of farming populations between the two study areas, with NA and NAD households generally exhibiting higher adaptive capacities compared to PA and AD households.

4.1.2 Regional Vulnerability Analysis

The vulnerability levels of the 9 surveyed villages are generally medium, with Yongfeng Village and Chaeryan Village having vulnerability indices below 0.4, and other villages ranging between 0.4-0.6. Low vulnerability levels are mainly formed by high adaptive capital (e.g., human, financial, social capital) combined with low sensitivity environments, indicating that reducing regional environmental sensitivity and improving household adaptability are key to building a good SES in Karst mountainous areas.

4.1.3 Vulnerability Impact Mechanisms

The lack of natural capital and the differentiation of adaptive capacity are key factors affecting vulnerability. The construction of cognitive and social capital can enhance system adaptability and reduce system vulnerability.

4.1.4 Practical Countermeasures

Households should transform traditional development concepts, improve skills, actively participate in agricultural technical training, and increase agricultural output and income. Diversifying livelihoods and broadening income channels can increase financial capital accumulation, enhancing livelihood resilience. Governments should provide diversified development platforms and policy guarantees, stimulating household development enthusiasm. Strengthening basic education and labor skill training can enhance overall labor quality. Providing non-agricultural employment and entrepreneurship opportunities, along with comprehensive agricultural support policies and ecological compensation mechanisms, can build a sound financial system, offering a favorable financing environment for households.

4.2 Discussion

By integrating SES theory with the vulnerability analysis framework, this study explores the relationship between household livelihoods and local SES vulnerability in Karst regions, revealing the main influencing factors and formation mechanisms of vulnerability. The results show that households, as the most micro-level economic actors in SES, profoundly influence the development and direction of SES. The vulnerability evaluation method combining regional sensitivity and household adaptability provides a new perspective for sustainable development research on regional human-land relationships.

However, this study has some limitations. First, the study area is limited to two typical Karst regions in Guizhou. Future research could expand to other Karst regions to verify the generalizability of the findings. Second, this study is mainly based on household survey data. Future research could incorporate more quantitative data (e.g., remote sensing data, socio-economic statistics) for multi-source data fusion analysis to improve accuracy and comprehensiveness. Additionally, the vulnerability evaluation index system could be further optimized, especially by refining indicators to build a more targeted evaluation system for different Karst landforms.

Future research could further explore the resilience and adaptive management strategies of SES in Karst regions, especially under the dual pressures of climate change and human activities, to enhance system risk resistance and sustainable development capacity through policy interventions and community participation. Combining more case studies, in-depth analysis of the impact of different livelihood strategies on system vulnerability could provide more specific practical guidance for SES management in Karst regions.

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