Vulnerability Assessment and Spatio-temporal Differentiation of Micro-scale Rural Human Settlement Systems in the Loess Plateau Semi-arid Region: A Case Study of Jia County, Shaanxi Province (Postprint)

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Abstract

From the perspective of human-environment system vulnerability, this study explores the spatiotemporal differentiation process of micro-scale rural human settlement systems in Jia County from 1980 to 2017, based on 65 sample points, 451 household survey questionnaires, and 65 village thematic questionnaires, employing methods such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The conclusions indicate that: (1) The mean vulnerability of the rural human settlement system has decreased from 0.66 to 0.45, while spatial disparity has expanded significantly from 3.99% to 15.31%, demonstrating a pattern of differentiation from a spatially severely vulnerable equilibrium state to one dominated by medium-low vulnerability, with 24.62% of villages still in a high-vulnerability state. (2) The vulnerability of residential, natural, and social subsystems has decreased significantly, with mean values declining to 0.38, 0.42, and 0.47, respectively; the residential subsystem has only 1.54% of villages remaining in high vulnerability. The mean vulnerability of support and human systems has remained at or risen to a high level above 0.54, with the proportion of high-vulnerability villages in both exceeding 2/3. (3) The residential, natural, and social subsystems have evolved from global coverage by high-vulnerability sample villages to widespread distribution among low-vulnerability sample villages, while the human system exhibits a spatiotemporal pattern of evolution from an interspersed distribution of low- and medium-vulnerability sample villages to global coverage by highly vulnerable sample villages. The spatial pattern of the support system is volatile, with low-vulnerability levels concentrated only in sample villages along transportation arteries and at administrative centers.

Full Text

Preamble

Measurement and Spatial-Temporal Differentiation of Microscale Rural Human Settlement System Vulnerability in the Semi-Arid Loess Plateau: A Case Study of Jiaxian County, Shaanxi Province

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Abstract: Low rainfall, fragile ecology, and economic poverty are typical characteristics of the Loess Plateau. Jiaxian County of Yulin City, Shaanxi Province, is a typical county in the semi-arid Loess Plateau, and is the main battlefield for ecological restoration and poverty alleviation in China. Following the theory of human-land system vulnerability, using TOPSIS model, this study measured the vulnerability value of microscale rural human settlement and natural, dwelling, human, support and social subsystems during the four historical periods from 1980 to 2017 (1980s, 2000, 2008, 2017) based on 65 sample villages, 451 household questionnaires, and 65 thematic questionnaires for key village figures. Additionally, the spatial and temporal differentiation characteristics of vulnerability of rural human settlements in the research area, based on GIS spatial analysis technology, were also discussed. The study results show the following. (1) The average vulnerability of rural human settlements in the 65 sample villages decreased from 0.66 to 0.45, and the vulnerabilities of dwellings, and natural and social subsystems were significantly reduced, with the mean vulnerability values for dwellings and natural and social subsystems in the 65 sample villages falling to 0.38, 0.42, and 0.47, respectively. However, the mean value of support and human system vulnerability in the 65 sample villages remained unchanged or rose above 0.54. (2) Based on the 65 sample villages, the spatial differences of vulnerability of the comprehensive system and the five subsystems of rural human settlements all showed expanding trends with different ranges. Among these, spatial differences of the integrated system and the dwelling subsystem increased by nearly 12 percentage points to 15.31% and 17.88%, respectively. The natural subsystem (30.77%) had the largest spatial difference, followed by the support subsystem (21.61%), both of which increased by a factor of two compared to the 1980s. The spatial differences in vulnerability of both human and social subsystems increased slightly, rising by only 3 percentage points since the 1980s. (3) The comprehensive system of rural human settlements has evolved from a uniform distribution of severely vulnerable sample villages to a main distribution of sample villages with medium and low vulnerability, and 24.62% of the highly vulnerable sample villages existed. Dwelling, natural, and social subsystems all presented similar evolution processes, shifting from a global coverage of high vulnerability sample villages to a widespread distribution of low vulnerability sample villages, with only 1.54% of the high vulnerability villages left in the dwelling subsystem. In contrast, the human subsystem evolved from a main distribution of medium and low vulnerability sample villages to a global coverage of high vulnerability sample villages. Additionally, the spatial pattern of the support system is unstable, with the low vulnerability level concentrated in sample villages located along major traffic lines or in the administrative centers of towns. At present, the proportion of high vulnerability sample villages of human and supporting subsystems have both been exceeded two-thirds. Based on the above findings, this study discusses the temporal and spatial process of rural human settlement vulnerability from the micro scale, which better reflects the development and unbalanced characteristics of rural human settlements. Therefore, this paper suggests that future work should not only focus on the vulnerability of the human and support subsystems, but also on spatial imbalances of the natural, support, and dwelling systems.

Keywords: rural human settlement; vulnerability; spatial and temporal pattern; TOPSIS model; Jiaxian county

Introduction

The science of human settlements, developed by Wu Liangyong and others under the inspiration of Doxiadis' ekistics theory, focuses on the study of human settlement systems. Since China' s reform and opening up, the Loess Plateau region has achieved certain progress in economic development and infrastructure construction, gradually becoming more open and accessible. However, due to limitations in terrain conditions, ecological environment, and resource endowments, the local economy remains weak and rural transformation has been slow. Simultaneously, the impact of urbanization on traditional villages has led to a continuous outflow of human capital and other factors, resulting in aging and weakening of the rural population, gradual withdrawal of commercial outlets, and increasingly prominent vulnerability of human settlements. The "Three-Year Action Plan for Rural Human Settlement Environment Improvement" points out that improving the rural human settlement environment and building beautiful and livable villages is an important task in implementing the rural revitalization strategy. Both domestic and international academic circles have paid considerable attention to rural human settlement systems, forming rich research achievements on the evaluation of their spatial-temporal states. Macro-scale studies have primarily focused on comprehensive quality and natural suitability levels, while a few scholars have discussed the evolution and mechanisms of human settlements in ecologically fragile and functionally important regions. Meso- and micro-scale research has either focused on quality of life and community satisfaction, or emphasized qualitative analysis of traditional villages and tourism destinations.

Currently, case studies based on the "indicator-evaluation" model mostly rely on macro socioeconomic statistical data, lacking spatiotemporal microdata that reflect ground-level realities and focus on "human experience." Microscale research tends to treat human settlement construction as an engineering project, focusing on hardware and specific forms, while studies on the spatiotemporal processes of rural human settlement systems based on panel microdata remain weak.

Vulnerability refers to the potential damage that a system may suffer when exposed to risks, disturbances, or pressures, and has gradually become a new research perspective and important analytical tool for global environmental change, sustainability science, and human-land systems. In the field of human-land system vulnerability, a series of achievements have emerged. First, several representative vulnerability analysis frameworks or assessment systems have been proposed, such as Turner et al.' s human-environment coupling system analysis framework. Second, the focus has shifted from natural disturbances to humanistic disturbances such as relocation and industrial transformation, with case studies conducted on the vulnerability states and influencing factors of typical human-land systems including social-ecological systems, urban systems, and human-environment coupling systems. Meanwhile, the vulnerability issues of urban and rural human settlement systems under multiple disturbances have begun to attract scholarly attention. However, domestic research on human-land system vulnerability started relatively late and has not yet formed a systematic knowledge system. Most existing research results are based on sustainable livelihood frameworks to study livelihood and social-ecological system vulnerability, with insufficient attention paid to specific types of human-land systems or rural sustainability under multiple disturbances.

Serving national major strategic needs is an important practice for the development of vulnerability theory. This article focuses on the semi-arid region of the Loess Plateau, which is characterized by ecological fragility and economic poverty, using Jiaxian County, Shaanxi Province as the study area. Based on 451 household survey questionnaires, 65 village thematic questionnaires, and 65 sample points, this study explores the spatiotemporal evolution of microscale rural human settlement system vulnerability under multiple disturbances from 1980 to 2017, providing theoretical support for "targeted treatment" of rural human settlements in the semi-arid Loess Plateau and the national rural revitalization strategy.

1.1 Study Area Overview

Jiaxian County is located in Yulin City, Shaanxi Province, with a total land area of 2029.8 km^2. In 2017, the county governed 12 towns, 1 subdistrict office, and 326 administrative villages, with a total population of 269,700. It has a continental dry semi-arid climate with precipitation concentrated in July-September, with an average annual precipitation of 386.6 mm. Natural disasters such as drought, flood, hail, and landslides occur frequently. The terrain is high in the northwest and low in the southeast, forming three distinct geomorphological regions: northern sandy area, southwestern hilly-gully area, and Yellow River 沿岸 rocky mountainous area. The jujube industry is an important pillar of the county' s commodity economy and the main source of farmers' livelihood. By 2017, jujube forest area accounted for 26.59% of the county' s total land area, with per capita jujube forest area of 0.2 hm^2.

This study adopted stratified random sampling for 65 sample villages (points), selecting 2-3 sample villages per town, using the location of the village committee as the sample point, and collecting latitude and longitude coordinates. The distribution is shown in [Figure 1: see original paper].

1.2 Historical Period Determination

From July 20-30, 2017, the research team conducted the first field interview in Jiaxian County. For the three geomorphological regions, 2 towns were selected from each region, 2 villages from each town, and 2-3 key informants (village leaders, rural elites, etc.) were interviewed for 30-40 minutes per person. A total of 39 valid interview recordings were collected. Through textual analysis of recordings focusing on "What changes have occurred in various fields of the village or residence since 1980?" and "What are the reasons for these changes? Have farmers or local governments promoted these changes?" , the analysis revealed that changes in Jiaxian' s rural human settlement state since 1980 are closely related to key events such as the implementation of the household contract responsibility system, the Grain for Green program, the Village-to-Village Connectivity Project, and the New Rural Cooperative Medical System.

In 1983, the household contract responsibility system was fully implemented, with land primarily used for cultivation, and the system state was relatively stable. In the 1980s, the rural human settlement system in the study area was in a stable stage. In 2000, the Grain for Green project effectively improved the local natural ecological environment, and the relocation project fundamentally transformed the living environment of relocated households (villages). In 2008, Shaanxi Province designated Jiaxian as a pilot county for the New Rural Cooperative Medical System, and since then, rural medical security, old-age security, and other welfare policies have experienced a process from non-existence to establishment.

Based on the above, this paper takes the years or decades of these key rural events as the research historical periods: 1980s, 2000, 2008, and 2017.

1.3 Data Acquisition

Quantitative measurement data for rural human settlement system vulnerability were primarily obtained through field household surveys and village thematic questionnaires conducted from July 20-30, 2017. For the 65 sample points, 7-8 households were sampled per point, yielding 451 questionnaires with 447 valid responses (99.1% validity). The age distribution of respondents was as follows:

45 aged 60 and above, 204 aged 40-59, 164 aged 20-39, and 34 under 20. Through key informant (village leaders, rural elites) discussions, each sample point generated a 40-question thematic questionnaire, resulting in 65 valid village thematic questionnaires.

To ensure clear and accurate recall by farmers and key informants, and to guarantee accuracy and comparability of indicator data across different households, historical period content was mostly designed as perception questions measurable by 5-point scales. The questionnaire also used recall cues or prompted respondents to recall their age at corresponding periods, with survey personnel entering data according to unified standards. Specifically, the 1980s period used recall cues such as "when the household contract responsibility system was just implemented" or "the 1980s." The 2000 period used cues like "the turn of the century" or "when the Grain for Green (Grass) pilot project began." The 2008 period used "2008 Beijing Olympics" or "NRCMS work" as recall cues. The 2017 period reflected actual conditions.

Survey content included: (1) basic household information and population structure and livelihood sources at different stages; (2) status of rural human settlement subsystems, including natural system (land use, natural disasters, ecological conditions, etc.), dwelling system (residential environment, housing renewal, housing structure and facilities, etc.), support system (infrastructure and public services, etc.), human system (village population status, individual behavior and psychological perception, etc.), and social system (social interaction, village development, wealth gap, government services, security environment, etc.). Each questionnaire lasted approximately 60 minutes.

Additionally, spatial vector data for county-level administrative areas, water systems, etc., were obtained from the 1:1,000,000 national basic geographic database of the National Geographic Information Resources Directory Service System (www.webmap.cn). Base maps for each year, township administrative boundaries, and transportation networks were sourced from historical maps and other materials.

2 Assessment Framework and Methods

2.1 Microscale Vulnerability Measurement Indicator System

The essence of rural human settlements is the regional manifestation of human-land relationships. Combining the concept and connotation of human-land system vulnerability, this article understands rural human settlement system vulnerability as the state in which the environment related to residents' living, life, and basic production activities in rural areas, due to its sensitive attributes and insufficient adaptive capacity, is susceptible to negative impacts or damage when exposed to internal and external natural and human disturbances. Among these, natural, human, and dwelling subsystems mostly exhibit sensitivity-exposure attributes, while support and social subsystems mostly exhibit adaptive capacity characteristics.

Using the county-scale rural human settlement vulnerability measurement indicator system as a base and referencing microscale human settlement quality assessment literature, this study conducted word frequency statistics on 39 valid interview recordings from the pre-survey to screen indicators highlighting microscale human settlement characteristics and focusing on factors related to farmers' behavior, psychology, and experience. Applicable quantifiable indicators with spatiotemporal comparability were selected for the factor layer, and indicator directions were determined. Finally, following scientific and targeted principles for indicator system establishment, a microscale spatiotemporal evaluation-oriented rural human settlement system vulnerability measurement indicator system was constructed ().

2.2 Data Processing

Non-categorical variables in sampling surveys may contain outliers. This study used box plots to revise the dataset, identifying upper and lower truncation points as variable maximum and minimum values, with outliers revised to these truncation point values. Indicator data were nondimensionalized using the extreme value standardization method, considering differences in indicator directionality for vulnerability calculation: positive indicators used formula (1), while negative indicators used formula (2).

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

Where: m represents evaluation samples, n represents evaluation indicators, x_{ij} is the value of sample i for indicator j, and x'_{ij} is the corresponding standardized value.

2.3 Vulnerability Assessment Model

2.3.1 Indicator Aggregation and Weight Determination Vulnerability composite index integration often employs weighted or unweighted mathematical operations. Using unweighted (equal-weight) variables for integration is a widely applied method in vulnerability assessment. Compared to weighted variables, equal-weight variables do not change the information conveyed by the composite index and are more easily interpreted. Therefore, the assessment model uses equal-weight processing for factor layer and subsystem layer aggregation.

2.3.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) TOPSIS is a commonly used method for multi-objective decision analysis, primarily evaluating relative superiority based on distances between research objects and optimal and worst solutions. This study uses TOPSIS to assess comprehensive and subsystem vulnerability of rural human settlements. The basic steps are:

1) Construct a nondimensional data matrix $(x'_{ij})_{m\times n}$, where m represents evaluation objects, n represents evaluation indicators, and x'_{ij} is the standardized indicator value.

2) Determine the optimal solution X^+ and worst solution X^-:

$$X^+ = \{x_1^+, x_2^+, \cdots, x_n^+\} = \{\max(x_{i1}), \max(x_{i2}), \cdots, \max(x_{in})\}$$

$$X^- = \{x_1^-, x_2^-, \cdots, x_n^-\} = \{\min(x_{i1}), \min(x_{i2}), \cdots, \min(x_{in})\}$$

3) Calculate distances between each evaluation sample and the optimal and worst values:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}(x'_{ij} - x_j^+)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}(x'_{ij} - x_j^-)^2}$$

4) Calculate the closeness coefficient V_i of each evaluation sample to the optimal value, i.e., the vulnerability value. Larger V_i indicates greater vulnerability:

$$V_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

2.3.3 Vulnerability Level Classification Based on TOPSIS-determined vulnerability values (V_i) for sample subsystems and comprehensive systems, where V_i ranges between [0,1], boundary points for vulnerability strength were established to define vulnerability levels. $V_i = 1$ indicates absolute system vulnerability, while $V_i = 0$ indicates zero vulnerability (completely robust state). The vulnerability level classification intervals are shown in .

2.4 Variation Coefficient Analysis

The variation coefficient is a commonly used method for studying spatial differences in geographic data. This study employs variation coefficient analysis to measure the spatial differentiation degree of rural human settlement systems and subsystems across the four periods. The calculation formula is:

$$CV = \frac{1}{V}\sqrt{\frac{\sum_{i=1}^{m}(V_i - V)^2}{m-1}} \times 100\%$$

Where: CV is the variation coefficient, V is the average vulnerability value of all sample points, V_i is the vulnerability value of sample point i, and m is the number of sample points. A smaller variation coefficient indicates a more balanced vulnerability pattern within the study area.

3 Results

3.1 Changes in Vulnerability Levels and Spatial Differences

As shown in , the comprehensive system and dwelling subsystem in the study area have both seen continuous reduction in high-vulnerability sample points since the 1980s, with decreases exceeding 70 percentage points. By 2017, only 24.62% of sample villages remained in a high-vulnerability state for the comprehensive system, and merely 1.54% for the dwelling system. High-vulnerability sample villages in natural and social systems have steadily decreased, with the reduction rate gradually increasing since 2000, reaching approximately 15% by 2017. On the other hand, support and human systems are currently the most concerning. High-vulnerability sample villages in the support system have continued to decrease slightly, but 66.15% remain in a high-vulnerability state. The human system shows a clear deterioration trend, with 75.38% of sample villages in a high-vulnerability state by 2017.

Additionally, spatial differences in the comprehensive system and five subsystems continue to expand at varying magnitudes. Natural and support system spatial differences have exceeded 20%, with the natural system increasing by 24.62 percentage points. Spatial differences in comprehensive and dwelling systems have gradually increased to around 15%. Human and social system spatial differences have increased slightly, rising by only 3 percentage points since the 1980s.

3.2 Spatial-Temporal Patterns of Vulnerability

3.2.1 Comprehensive System Vulnerability The comprehensive system evolved from uniformly severe vulnerability to predominantly low-moderate vulnerability, with the mean vulnerability decreasing from 0.66 to 0.45. Except for the traditional village of Mutouyu along the Yellow River, all other villages were at severe or extreme vulnerability levels in the 1980s. By 2000, vulnerability levels of villages along market towns, main roads, and the Yellow River coast decreased to high vulnerability. Thereafter, thanks to relocation, Grain for Green, and Village-to-Village Connectivity projects, vulnerability in most sample villages decreased, though some villages experienced increased vulnerability.

Two distinct zones formed by 2017: one is a triangular zone with vertices at Manengmao in Fangta Town, Hejiawa in Zhujiawa Town, and Zigeduping in Wu Town, where high-vulnerability villages cluster and agricultural production focuses on grain crops; the other is the area outside this triangle, where villages are basically at moderate or lower vulnerability levels, with villages near the county seat evolving to low vulnerability or robust levels.

3.2.2 Subsystem Vulnerability **Natural Subsystem:** Evolved from uniform high-severe vulnerability occupation to a new pattern where high and low vulnerability levels stand on opposite sides, with robust levels clustering in the southeast. Vulnerability significantly decreased, with the mean dropping from 0.71 to 0.42. The northern sandy area was completely occupied by severe and extreme vulnerability levels in the 1980s. Between 2000-2008, ecological protection and restoration projects led to large-scale vulnerability reduction. Thereafter, under climate change, autumn rains caused large-scale jujube forest yield reductions, and market cooling made jujube sales difficult. As jujube-based livelihoods became unsustainable, farmers widely abandoned cultivation and fertilization, allowing natural forest vegetation to recover and natural subsystem vulnerability to drop significantly to 0.42. By 2017, extreme vulnerability levels had disappeared, and the proportion of high and severe vulnerability sample villages shrank to 15.38%, with a large proportion of robust and low vulnerability levels emerging.

Dwelling Subsystem: Vulnerability gradually decreased toward robustness, with the mean dropping from 0.71 to 0.38. The pattern evolved from uniform extreme vulnerability to low vulnerability dominance. Between 2000-2008, vulnerability in most sample villages decreased and levels dropped, with severe and extreme vulnerability levels only scattered sporadically in the southwestern hilly-gully area. Today, the living environment has improved qualitatively, with low vulnerability levels forming a "厂"-shaped distribution belt and robust-level villages distributed along transportation arteries. Villages in the northern sandy area have almost all decreased to low vulnerability or robust levels.

Human Subsystem: Evolved from alternating low-moderate vulnerability distribution to comprehensive high-vulnerability coverage with sporadic moderate levels, with the mean vulnerability continuously rising from 0.42 to 0.56. In the 1980s, moderate vulnerability dominated with low vulnerability uniformly distributed. By 2000, the low vulnerability distribution range shrank to the southeastern Yellow River 沿岸 area, birth rates dropped sharply below 10‰, and the male-female ratio exceeded 115. The pattern shift occurred between 2000-2008, after which human subsystem vulnerability showed comprehensive deterioration. By 2017, villages along main roads or in market towns were at moderate or lower vulnerability levels, while some remote or town-boundary villages had deteriorated to severe or extreme vulnerability.

Support Subsystem: The mean vulnerability decreased from 0.55 to 0.54, with the spatial pattern evolving from uniform severe vulnerability distribution

(66.15%) to extreme differentiation. Benefiting from Village-to-Village Connectivity projects, vulnerability decreased comprehensively in 2000, with 7 sample villages in town (township) administrative centers decreasing to moderate-low vulnerability levels. By 2008, the mean rebounded to 0.58, with sample villages almost equally divided among extreme, severe, and high vulnerability levels at a 1:1:2 ratio. Thereafter, spatial differentiation increased, with robust to moderate vulnerability levels concentrated along provincial roads and the Yellow River highway, or in villages with town (township) administrative center or market town functions.

Social Subsystem: The mean vulnerability continuously decreased from 0.71 to 0.47, with most villages showing reduced social vulnerability but still hovering at moderate-high levels. The pattern evolved from alternating high-severe vulnerability distribution to a medium-vulnerability-dominated spatiotemporal pattern. In 2000, severe vulnerability distribution shrank to the southern part of the county, while high vulnerability remained widespread. By 2008, moderate vulnerability sample villages were widely distributed in central and northern areas, while high and moderate vulnerability dominated the south. After the southern section of the Yellow River highway was completed, social system vulnerability along the route decreased to moderate-low levels. Additionally, villages in the northern sandy area near Yulin city and Shenmu County always had lower social system vulnerability than other areas.

4 Discussion

This article approaches from the human-land system vulnerability perspective, constructing a microscale indicator system covering natural, human, dwelling, support, and social subsystems with 25 factors based on farmer participation. Using Jiaxian County as an example, it explores spatiotemporal patterns of rural human settlement system vulnerability across four periods. Macro-scale studies of Jiaxian County' s rural human settlement system evolution indicate that the system experienced three characteristic stages from 1980-2017, with dwelling and social system vulnerability comprehensively decreasing, support system vulnerability rebounding and intensifying, and human system vulnerability moving toward severe levels. The four typical periods selected in this microscale study align with these macro-scale characteristic stages, demonstrating that the historical period selection in microscale research is representative. Moreover, the evolution trends of natural, dwelling, human, social, and support system vulnerability are basically consistent with macro-scale findings.

Chen Jia and Lu Daming' s county-scale studies show that Jiaxian County' s social and ecosystem vulnerability significantly decreased during 1980-2017. Zeng Juxin et al. noted that the comprehensive quality of rural human settlements in Lichuan City, Wuling Mountain area, increased during 2000-2015, with microscale rural populations concentrating in basins and low mountainous areas, and per capita income vertical differences narrowing. These studies discussed macro human-land system vulnerability or rural human settlement quality evolution, showing results consistent with this study' s conclusion that comprehensive human settlement system and natural, dwelling, and social subsystem vulnerability have significantly decreased. Li Bohua et al. and Luo Zhanfu et al. used household questionnaires to evaluate satisfaction with human settlements in typical study areas, finding large differences in natural and dwelling environment satisfaction across different research areas but consistently high satisfaction with infrastructure construction. These meso- and micro-scale studies only discussed the human settlement state in the survey year without examining spatiotemporal differentiation processes. This study explores the spatiotemporal differentiation process of rural human settlement system vulnerability in the research area from 1980-2017 across four typical periods and 65 sample points. The results not only show that, except for increasing human subsystem vulnerability, the comprehensive system and other subsystems show varying degrees of vulnerability reduction, but also indicate expanding spatial differentiation in the research area, presenting an unstable spatial pattern of the support system where low vulnerability concentrates along transportation lines and in market towns, and a pattern where the human system has deteriorated from globally low vulnerability to predominantly high vulnerability, while other systems have evolved from globally high vulnerability to predominantly low vulnerability distribution.

5 Conclusions

1) The average microscale rural human settlement system vulnerability decreased from 0.66 to 0.45, with the proportion of high-vulnerability sample villages reducing by 75.38 percentage points. The average vulnerability of natural and social subsystems decreased to around 0.45, while the dwelling subsystem dropped significantly from 0.71 to 0.38, with only 1.54% of villages remaining at high vulnerability. The human subsystem vulnerability mean continuously rose to 0.56, while the support subsystem remained stable at a high level of 0.54, with both subsystems having over two-thirds of sample villages at high vulnerability.

2) Spatial differences in vulnerability of the comprehensive system and five subsystems expanded to varying degrees. The natural system spatial difference reached 30.77%, the support system reached 21.61% (both doubling compared to the 1980s), the human system spatial difference rose slightly to 13.01%, and the social system remained at 12.00%.

3) The comprehensive system and natural, dwelling, and social subsystems all evolved from high-vulnerability sample village dominance to low-vulnerability sample village dominance. The natural system in southeastern sample villages has evolved to robust levels, while social system vulnerability in the northern sandy area near Yulin city and Shenmu County has always been lower than in southern areas. Conversely, the human system evolved from alternating low-moderate vulnerability distribution to comprehensive high-vulnerability coverage with sporadic moderate levels. The support system evolved from uniform severe

vulnerability distribution to extreme differentiation, with moderate and lower vulnerability levels mostly belonging to villages along provincial roads, the Yellow River highway, or villages with town (township) administrative center or market town functions.

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