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Spatiotemporal Variations and Driving Factors of Ecological Sensitivity in the West Qinling Mountains, China, Under the Optimal Scale

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Abstract: This study selected the five indicators of soil erosion, climate environment, geological hazards, biodiversity, and human disturbances and uses the entropy weight method to calculate the ecological sensitivity of the West Qinling Mountains from 2000 to 2020. The analysis produced a spatiotemporal distribution of ecological sensitivity over the 20-year period. An equal step size of 500 m was used to progressively increase the spatial scale from 500 m to 6 km. The optimal scale for the spatial differentiation of ecological sensitivity in the West Qinling Mountains was determined by analyzing the characteristics of changes at different scales, response mechanisms, and optimal parameters for geographical detector spatial scale identification. Based on this scale, the change in intensity and pattern and the influencing factors of ecological sensitivity were analyzed. The results show the following: (1) The 5.5 km spatial scale balances the requirements of accuracy, spatial heterogeneity, and data adequacy, making it the optimal scale for analyzing the spatiotemporal variation patterns of ecological sensitivity in the West Qinling Mountains. (2) From 2000 to 2020, the mean ecological sensitivity in the West Qinling Mountains exhibited a decreasing trend, indicating an improvement in the ecological environment. Spatially, the ecological sensitivity of the West Qinling Mountains showed a spatial distribution pattern of "low in the west and high in the east, low in the south and high in the north". During the study period, the ecological sensitivity in the West Qinling region remained generally stable, with no high-frequency changes observed. (3) Population density is the primary driving factor of spatial differentiation of ecological sensitivity in the West Qinling Mountains, while GDP serves as a secondary factor. Overall, socioeconomic factors have the most significant impact on ecological sensitivity. (4) Over 75% of the ecological sensitivity trends exhibit patterns of perennial unchanged and fluctuating unchanged trends, with areas of fluctuating increase smaller than areas of fluctuating decrease. Regions of perennial high sensitivity are primarily concentrated in the northeastern part of the West Qinling Mountains, while areas with increased fluctuation in ecological sensitivity are mainly located in the western and southern parts of the West Qinling Mountains. Future efforts should focus on these regions.

Keywords: driving factor; ecological sensitivity; spatiotemporal variation; spatial scale; West Qinling Mountains; China

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1. Introduction

The ecological environment is the foundation of human survival and development [1]. Ecological sensitivity is a key indicator for evaluating changes in the regional ecological environment, with its changes reflecting the extent to which natural and human disturbances impact the environment in the region [2,3]. It reveals the severity and likelihood

of potential ecological issues in the environment. Research on regional ecological sensitivity helps to clearly identify the ecosystem's ability to resist external disturbances under current conditions. This research aids in spatially identifying and prioritizing areas that require focused efforts for ecological protection and restoration, thereby curbing the trend of ecological degradation. This provides integrated support for environmental monitoring and risk management in the region, enhancing the effectiveness and sustainability of management [4]. Currently, a substantial body of research has been conducted on regional ecological sensitivity. Yu et al. [5] comprehensively evaluated the ecosystem sensitivity of Jinghong City, Xishuangbanna, from four aspects: biodiversity sensitivity, water resource sensitivity, geological hazard sensitivity, and soil erosion sensitivity. Liu et al. [6] evaluated the ecological sensitivity of the Fenhe River Basin in terms of landscape risk sensitivity, soil erosion sensitivity, and biodiversity sensitivity. Zhao et al. [7] conducted a comprehensive evaluation of the ecological sensitivity of the Tibetan Plateau, focusing on four aspects: land desertification, soil erosion, landslide disaster, and freeze–thaw erosion. They further explored the spatiotemporal evolution characteristics and proposed protection and management zoning. Fang et al. [8] selected the four aspects of geological hazards, soil quality, soil erosion, and surface water environmental quality to evaluate the ecological sensitivity of Wuhan. Large-scale ecological studies have shown that landscape patterns and ecosystem services exhibit significant scale dependency across spatial scales. The characteristics of ecological processes and their interaction patterns may vary significantly under different scales. Scale effects have an important impact on the accuracy of landscape analysis [9,10]. When grain size and amplitude are arbitrarily determined, the assessment results may fail to reflect the actual situation of ecological risk. Zuo et al. [11] quantitatively determined the optimal grain size of 50 m and the amplitude of 4 km in the mountainous area of Southwest Hubei Province by using landscape ecology indicators and geostatistical analysis. This accurately and effectively reflected the regional landscape ecological risks and the existing issues. Wen et al. [12] deeply analyzed the scale-deductive relationship of different landscape indices with the change in spatial amplitude, determining 900 m as the optimal scale for studying the landscape pattern evolution of the Shiyang River Basin. Zhou et al. [13] discovered that the landscape pattern of the Guangxi Gulf of Tonkin Economic Zone exhibits significant scale dependency, with some landscape indices sensitive to the change in grain size. Based on the results of an information entropy analysis, the optimal analysis grain size was determined to be 60 m. Yuan et al. [14] validated the scale effect of the landscape ecological condition index on the coastal zone of Jiangsu Province, China, across 10 spatial scales ranging from 100 m to 1000 m in intervals of 100 m. This analysis revealed that 300 m is the optimal spatial scale. Chen et al. [15] used exploratory spatial analysis and an optimal parameter-based geographical detector model to identify the scale effect of spatial differentiation. This study found that the township unit is the most optimal scale of differentiation for the ecosystem service supply–demand relationship in Guizhou Province. Zhang et al. [16] found that the spatial differentiation of ecosystem service supply–demand relationships in Shanghai exhibits significant scale dependency. The 1500 m grid scale and the township administrative scale serve as reference scales for the construction and optimization of the ecological security pattern. Therefore, a key scientific question is whether ecological sensitivity also exhibits scale dependency. Addressing this issue is not only concerned with the deepening of ecological theory but also has important implications for practical ecological management. For this reason, it is necessary to systematically evaluate the differentiation characteristics of ecological sensitivity at multiple spatial scales and further explore the existence and applicability of an optimal scale. Such research will help to reveal the dynamic change patterns of ecological sensitivity at different scales, thus providing a more scientific and precise basis for regional ecological protection and planning.

As the western extension of the Qinling Mountains, the West Qinling Mountains is an important geological unit in western China. It plays a significant role in shaping China's geographic structure and biodiversity patterns, as well as in ecological security [17].

Regarding the scientific study of the West Qinling Mountains, ecological studies have started relatively late, and the availability of information is limited. Du et al. [18] conducted a study on the landscape ecological risk of the West Qinling Mountains and found that the overall ecological condition is biased. Li et al. [19] evaluated the landscape pattern changes and ecosystem health of the West Qinling Mountains. This research revealed that over 60% of the area of the West Qinling Mountains is in a healthy state. Furthermore, from 2000 to 2018, the ecosystem health index of the West Qinling Mountains showed an increasing trend, indicating a gradual improvement of the ecosystem status. However, these studies have primarily focused on landscape pattern changes and ecosystem health, with no reports specifically addressing the ecological sensitivity of the West Qinling Mountains. Meanwhile, the existing ecological sensitivity studies mainly emphasize evaluation and spatial analysis but lack the optimal spatial scale study of ecological sensitivity differentiation in the study area.

To address the above deficiencies, this study selects five sensitivity indicators, which are soil erosion, climate environment, geologic hazards, biodiversity, and human disturbances, on the basis of the ecological sensitivity evaluation index system put forward by previous researchers [7,20,21]. The entropy weight method was applied to calculate the weight of individual indicators, aiming to reduce the uncertainty introduced by subjective weighting in the evaluation results, and to assess the ecological sensitivity of the West Qinling region from 2000 to 2020. Subsequently, the spatial scale of the evaluation unit in the study area was gradually increased from 500 m to 6 km in steps of 500 m. The optimal scale for the spatial differentiation of ecological sensitivity in the West Qinling Mountains was determined based on the spatial variation characteristics of ecological sensitivity at different scales, the response mechanism, and the optimal parameter geodetector spatial scale identification. Finally, based on this optimal scale, an analysis was conducted of the intensity of changes, patterns of change, and influencing factors of ecological sensitivity. This analysis provides a scientific basis for the formulation of environmental management policies and landscape optimization measures. It also offers a fundamental reference for the protection and sustainable development of the ecological environment in the West Qinling region.

2. Materials and Methods

2.1. Overview of the Study Area

The West Qinling Mountains are situated in west–central China. They commence in Maqu, Gansu Province, in the west and end in Liangdang, Gansu Province, in the east. In the north–south direction, they begin in Jiuzhaigou, Sichuan Province, in the south and end in Zhang County, Gansu Province, in the north (Figure 1). The terrain of the West Qinling region lies within the folded system of the Qinling–Kunlun Trough and is mainly composed of plateaus and mountains. Its terrain is highly undulating, with altitudes ranging from 448 to 5528 m. The West Qinling region is a mountainous area that divides the Yellow River and the Yangtze River. In the north, it is the watershed of the Taohe River and the Weihe River, and in the west, it is the watershed of the Taohe River and the Bailong River. Climatically, the West Qinling region is a transition zone between warm temperate and northern subtropical climates, including northern subtropical, mesothermal, and alpine climates. The West Qinling region is also a transitional zone between the Tibetan Plateau, Loess Plateau, and Qinba Mountains. The ecosystems of the West Qinling region are diverse and complex. The vertical zonation of vegetation is highly conspicuous. Temperate deciduous broad-leaved forests dominate in the north, while subtropical evergreen broad-leaved forests dominate in the south. Such vegetation diversity provides a rich habitat for organisms and further enhances the ecological value of the West Qinling Mountains.

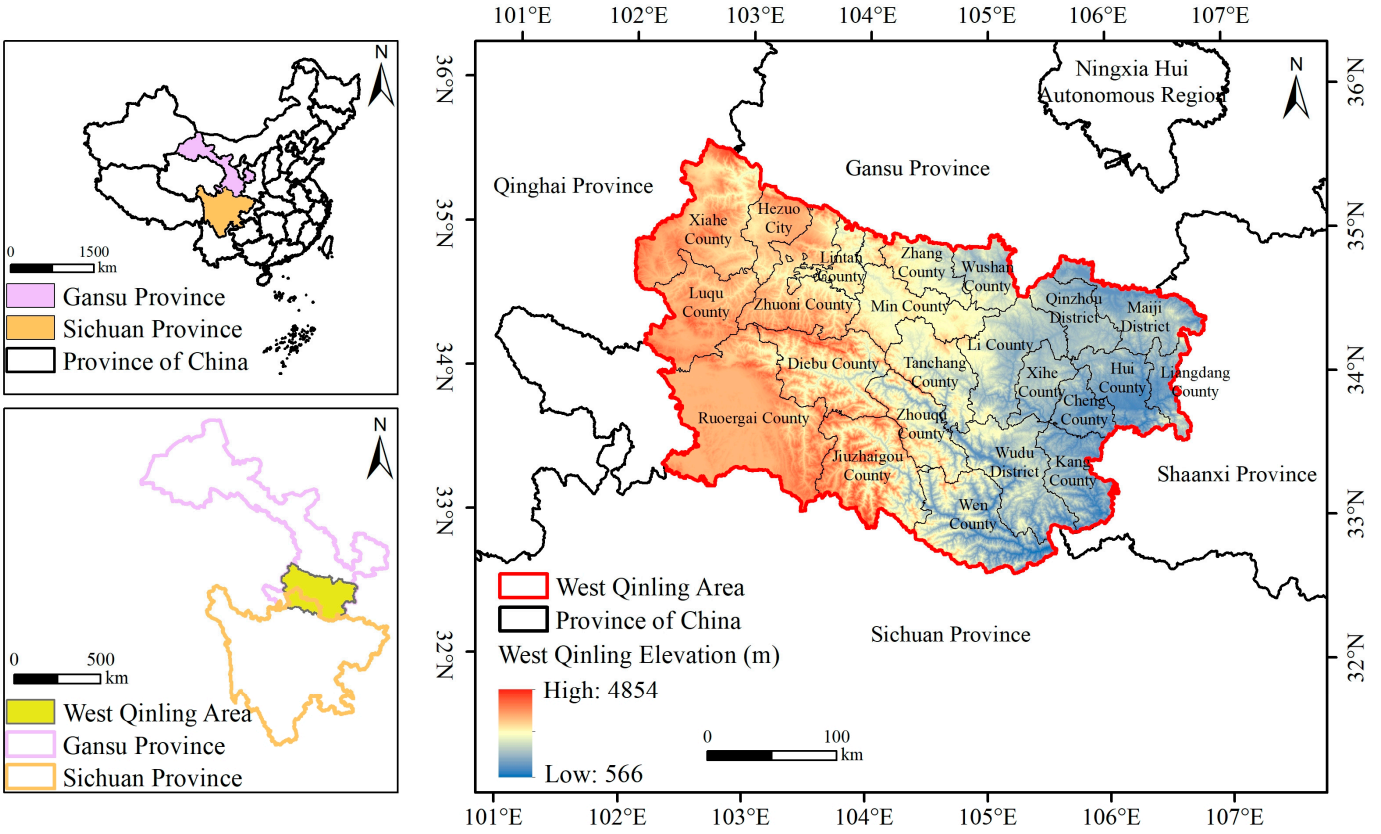


Figure 1. Location of the West Qinling Mountains in China.

2.2. Data Sources

To examine the spatial and temporal variations, determine the optimal spatial scales, and identify the influencing factors of ecological sensitivity in the West Qinling region, the following data sources were utilized: (1) DEM data and water body data obtained from the Geospatial Data Cloud (http://www.gscloud.cn (accessed on 5 June 2023)); (2) mean temperature, precipitation, and mean wind speed datasets from the China Meteorological Data Network (https://data.cma.cn (accessed on 20 June 2023)); (3) soil data obtained from the World Soil Database (https://www.fao.org/ (accessed on 1 July 2023)); (4) the normalized differential vegetation index (NDVI) and land use data from the Resource and Environmental Science Data and Center of the Chinese Academy of Sciences (https://www.resdc.cn (accessed on 2 August 2023)); (5) geologic hazard point data obtained from the Geographic Remote Sensing Ecology Network (https://www.gisrs.cn/ (accessed on 6 August 2023)); and (6) population density and GDP data obtained from the Gansu government website (https://tjj.gansu.gov.cn/ (accessed on 7 August 2023)) and Sichuan Provincial Bureau of Statistics website (https://tjj.sc.gov.cn/ (accessed on 9 August 2023)). For the consistency of resolution, the above data were resampled to a 30 m × 30 m raster and uniformly converted to WGS_1984_UTM_48N.

2.3. Construction of the Indicator System

The selection of ecological sensitivity evaluation factors must be grounded in the core of the research question and tailored in line with the specific ecological conditions of the study area [22]. This ensures that the chosen factors accurately reflect the ecological sensitivity characteristics of the study area, resulting in a more comprehensive understanding of the overall condition of the regional ecological environment and its changing trends. Due to the differences in anthropogenic factors and natural features across different regions, the study combines the unique characteristics of the West Qinling Mountains and draws on previous research results [23]. It was found that the region faces serious soil erosion,

significant climatic impacts, frequent geological hazards, rich biodiversity, and pressure on ecosystem stability from intensified human activities. Therefore, this study selected soil erosion, climate environment, geological hazards, and biodiversity indicators at the natural factor level, while human disturbance indicators were chosen at the anthropogenic factor level, thereby constructing a comprehensive evaluation index system for ecological sensitivity in the West Qinling Mountains. The specific ecological sensitivity indicators and their calculation are shown in Table 1.

Table 1. Indicators of ecological sensitivity and calculation formulas.

Target Layer	Primary Indicators	Secondary Indicators	Tertiary Indicators	Formula	Specific Parameters and Description
Sensitivity	Natural factors	Soil erosion [24–26]	Precipitation erosivity (+)	$SS_i = \sqrt[4]{R_i \times K_i \times LS_i \times C_i}$	SS_i is the soil erosion sensitivity; R_i is the precipitation erosivity; K_i is the soil erodibility; LS_i is the slope and slope length; C_i is the vegetation coverage.
			Soil erodibility (+)		
			Slope and slope length (+)		
			Vegetation coverage (−)		
		Climate environment [23]	Annual precipitation (−)	$CES = \sum_{i=1}^{n} w_i x_i$	CES is the climate environmental sensitivity index; w_i is the weight of the i-th indicator; x_i is the i-th indicator after standardization.
			Average annual temperature (−)		
		Geological hazards [27]	DEM (+)	$GHS = \sum_{i=1}^{n} w_i x_i$	GHS is the geological hazard sensitivity index; w_i is the weight of the i-th indicator; x_i is the i-th indicator after standardization.
			Slope (+)		
			Degree of topographic relief (+)		
			Vegetation coverage (−)		
			Annual precipitation (+)		
			Density of geologic hazard sites (+)		
			River distance (−)		
		Biodiversity [28–30]	Biological richness index (−)	$BAI = A_{bio} \times (0.35 \times$ Forest + 0.21 × Grassland + 0.28 × Water + 0.11 × Cropland + 0.04 × Built + 0.01 × Unused)/Area	BAI is the biological abundance index; A_{bio} is the normalized coefficient of the biological abundance index; $A_{bio} = 100/A_{max}$, A_{max} is the maximum value of the biological abundance index before normalization.
	Human factors	Human disturbance [31]	Population density (+)	$RL = \sum_{i=1}^{n} w_i x_i$	RL is the human disturbance sensitivity index; w_i is the weight of the i-th indicator; x_i is the i-th indicator after standardization.
			GDP (+)		

2.4. Methodology

2.4.1. Indicator Standardization Method

Due to the varying dimensions of each evaluation factor, they cannot be directly involved in the sensitivity calculation. Consequently, this study standardizes the evaluation factors with varying dimensions (Table 1) to calculate the ecological sensitivity status of the West Qinling Mountains. The specific standardized calculation formula is as follows [32–34]:

Positive standardization:

$$Y_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Negative standardization:

$$Y_i = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (2)$$

where Y_i is the normalized value of the i-th factor; X_i is the original value of the i-th factor; and X_{max} and X_{min} are the maximum and minimum values of the original value.

2.4.2. Entropy Weight Method

To quantify the uncertainty of each evaluation indicator in the comprehensive ecological sensitivity results, the entropy weighting method is employed to determine the objective weights, ensuring the scientific nature of the evaluation process and the objectivity

of the results. According to the definition of information entropy in information theory, the entropy of the *j*-th information entropy is calculated as follows [35]:

$$H_j = -k\sum_{i=1}^{m} r_{ij} ln r_{ij} \quad (3)$$

where H_j denotes the information entropy of the *j*-th evaluation factor; $k = \frac{1}{ln(m)}$; $r_{ij} = \frac{Y_i}{\sum_{j=1}^{m} Y_i}$; Y_i is the normalized value of the *i*-th factor; *m* is the number of evaluation units; and $0 \leq H_j \leq 1$.

The formula for calculating the weight of the *j*-th evaluation factor using the entropy weight method is as follows [36,37]:

$$w_j = \frac{1 - H_j}{\sum_{j=1}^{n}(1 - H_j)} \quad (4)$$

where w_j denotes the weight of the *j*-th evaluation factor; H_j denotes the information entropy of the *j*-th evaluation factor; and *n* is the number of evaluation factors.

2.4.3. Calculation of Comprehensive Ecological Sensitivity

The weights of each indicator (Table 2), calculated using the entropy weight method, are combined with the raster data through a weighted overlay in a GIS environment [38], ultimately producing a spatial distribution map of comprehensive ecological sensitivity. To deeply compare and analyze the spatiotemporal evolution of comprehensive ecological sensitivity indicators in the West Qinling region in different periods, this study employs the natural break method to classify the obtained data. The sensitivity classification uses the 2000 baseline as the reference for grading indicators in different periods. The specific grading criteria are shown in the following table (Table 3).

Table 2. The weights of single sensitivity indicators from 2000 to 2020.

Indicator Layer	Weight				
	2000	2005	2010	2015	2020
Soil erosion sensitivity	0.470	0.454	0.461	0.486	0.480
Climate environmental sensitivity	0.031	0.041	0.027	0.027	0.037
Geological hazard sensitivity	0.129	0.132	0.110	0.110	0.100
Biodiversity sensitivity	0.068	0.068	0.070	0.069	0.074
Human disturbance sensitivity	0.301	0.304	0.332	0.309	0.309

Table 3. Sensitivity classification standards.

Sub-Indicator	Insensitive	Low Sensitivity	Moderate Sensitivity	High Sensitivity	Extremely Sensitive
Soil erosion sensitivity	<0.03	0.03–0.07	0.07–0.11	0.11–0.15	>0.15
Climate environmental sensitivity	<0.27	0.27–0.45	0.45–0.61	0.61–0.75	>0.75
Geological hazard sensitivity	<0.12	0.12–0.18	0.18–0.26	0.26–0.36	>0.36
Biodiversity sensitivity	<0.18	0.18–0.32	0.32–0.45	0.45–0.58	>0.58
Human disturbance sensitivity	<0.04	0.04–0.09	0.09–0.24	0.24–0.47	>0.47
Comprehensive ecological sensitivity	<0.11	0.11–0.18	0.18–0.27	0.27–0.39	>0.39
Assignment code	1	2	3	4	5

2.4.4. Spatial Data Exploration of Ecological Sensitivity

In this study, the global spatial autocorrelation Moran's *I* is used to measure the spatial heterogeneity of ecological sensitivity. When Moran's $I > 0$, a larger value indicates a stronger spatial correlation of ecological sensitivity in the region. When Moran's $I < 0$,

a smaller value indicates a higher degree of negative spatial correlation of ecological sensitivity. When Moran's $I = 0$, it indicates that ecological sensitivity presents a random distribution in space [39]. The formula is as follows [40]:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})^2} \quad (5)$$

where I represents Moran's I; x_i and x_j represent the mean value of the comprehensive ecological sensitivity index of grids i and j; $\overline{x}$ is the mean value of the comprehensive ecological sensitivity of all grids; and w_{ij} is the magnitude of the weight of the spatial neighborhood of ecological sensitivity.

2.4.5. Optimal Parameter Geographical Detector Model

In this study, the GD package in R is used to set the scale in steps of 500 m and increase from 500 m to 6 km to determine the optimal grid scale. The discretization methods include equal intervals, natural breaks, quartiles, geometric intervals, and standard deviation methods [41–43]. The number of partitions was set between 3 and 9, and the optimal spatial scale was identified as the one where the 90th percentile of the q-value reached its maximum [44]. The formula used is as follows [45]:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h {\sigma_h}^2}{N\sigma^2} \quad (6)$$

where q represents the explanatory power of the factor; L represents the stratification of factors; N_h represents the number of units corresponding to the ecological sensitivity and factors in the h-th layer; N represents the number of units corresponding to the ecological sensitivity and factors in the entire region; ${\sigma_h}^2$ represents the variance of ecological sensitivity in the h-th layer; and σ^2 represents the variance of ecological sensitivity in the entire region.

2.4.6. Frequency Change

Using ArcGIS software, the coding of the comprehensive ecological sensitivity of the West Qinling region in adjacent periods was subtracted. Areas without change were assigned a value of 0, while areas with change were assigned a value of 1 [46]. The subtracted values of the four periods were then summed to obtain a comprehensive ecological sensitivity change frequency map. The calculation is based on the following formula [47]:

$$C = |C_1| + |C_2| + |C_3| + |C_4| \quad (7)$$

C denotes the frequency of change in ecological sensitivity between 2000 and 2020, and C_1, C_2, C_3, and C_4 correspond to the coding changes in comprehensive ecological sensitivity for the periods 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively. A value of $C = 0$ indicates no change, while $C = 1$ indicates one instance of sensitivity change, and so on, which is referred to as sensitivity change intensity.

2.4.7. Geocoding Method

The geocoding method can effectively monitor long-term trends in comprehensive ecological sensitivity changes and visualize these changes spatially. By following the formula, the changes in comprehensive ecological sensitivity from 2000 to 2020 can be determined (Table 4). The calculation formula is as follows [31,48]:

$$\begin{aligned} Change = {} & 10,000 \times Code_{2000} + 1000 \times Code_{2005} + 100 \times Code_{2010} \\ & + 10 \times Code_{2015} + Code_{2020} \end{aligned} \quad (8)$$

where $Change$ represents the change in comprehensive ecological sensitivity from 2000 to 2020, and $Code_{2000}$, $Code_{2005}$, $Code_{2010}$, $Code_{2015}$, and $Code_{2020}$ correspond to the graded

results of comprehensive ecological sensitivity for the years 2000, 2005, 2010, 2015, and 2020, respectively.

Table 4. Classification of ecological sensitivity changes.

Overall Conversion Type	Conversion Coding	Classification Criteria
Perennial unchanged zones	11111, 22222, 33333, 44444, 55555	The ecological sensitivity grade values for the years 2000, 2005, 2010, 2015, and 2020 must remain consistent.
Fluctuating unchanged zones	11121, 11211, 12111, 12121, 12211, 12221, 21112, 21222, 22112, 22122, 22212, 22232, 23222, 23322, 23332, 32223, 32333, 33223, 33233, 33323, 33343, 33433, 33443, 34333, 34443, 44334, 44344, 44434, 44544, 45444, 55545	The ecological sensitivity grade values for 2000 and 2020 must be equal, and the ecological sensitivity grade values for 2005, 2010, and 2015 may either increase, decrease, or remain unchanged.
Fluctuating increase zones	11112, 11122, 11212, 11222, 12112, 12122, 12212, 12222, 12232, 22223, 22233, 22323, 22333, 23223, 23233, 23323, 23333, 33334, 33344, 33444, 34444	The ecological sensitivity grade value for 2020 must be higher than that for 2000, and the ecological sensitivity grade values for 2005, 2010, and 2015 may either increase, decrease, or remain unchanged.
Fluctuating decrease zones	21111, 21121, 22111, 22121, 22211, 22221, 32211, 32221, 32222, 33222, 33232, 33322, 33332, 43333, 44333, 44343, 44433, 44443, 55444, 55544, 55554	The ecological sensitivity grade value for 2020 must be lower than that of 2000, and the ecological sensitivity grade values for 2005, 2010, and 2015 may either increase, decrease, or remain unchanged.

3. Results and Analysis

3.1. Spatiotemporal Variation Patterns of Comprehensive Ecological Sensitivity

The comprehensive ecological sensitivity of the West Qinling Mountains in 2000, 2005, 2010, 2015, and 2020 was classified into five grades: insensitive, low sensitivity, moderate sensitivity, high sensitivity, and extremely sensitive (Figure 2). A statistical analysis of the area for each grade was conducted (Table 5). The results indicate that from 2000 to 2020, the ecological sensitivity of the West Qinling Mountains was dominated by the insensitive grade, accounting for 37.81%, 33.31%, 37.16%, 39.96%, and 34.90% of the total area of the study area in 2000, 2005, 2010, 2015, and 2020, respectively. In these 20 years, the mean ecological sensitivity of the West Qinling Mountains showed a downward trend (Figure 3), and the proportion of extremely sensitive areas decreased from 3.72% in 2000 to 2.26% in 2020. This trend suggests that the overall ecological environment of the West Qinling Mountains has remained stable and has gradually improved. With the implementation of ecological protection policies, particularly measures such as the Returning Farmland to Forests Program and the Natural Forest Protection Program, the ecosystems in the West Qinling region have been effectively restored and improved, leading to a continuous enhancement in the ecological environment's carrying capacity.

From 2000 to 2020, the ecological sensitivity levels in the West Qinling Mountains exhibited significant spatial variation, characterized by a distribution pattern of "low in the west and high in the east, low in the south and high in the north". This pattern is closely related to the natural and social environment of the region. The western part (Gannan Tibetan Autonomous Prefecture) and the southwestern part (Sichuan Province) of the West Qinling are predominantly insensitivity and low sensitivity, while the eastern and northeastern regions (including parts of Longnan City and Tianshui City) are predominantly characterized by high sensitivity and extreme sensitivity. This difference is primarily due to the high vegetation coverage and rich biodiversity in the western part of the West Qinling region, coupled with minimal human activity, which contributes to lower ecological sensitivity. In contrast, the high-sensitivity and extremely sensitive areas in the eastern region are mainly concentrated around densely populated urban areas and in the ecologically vulnerable mountainous and hilly regions. Anthropogenic actions such

as urban expansion, agricultural reclamation, and resource exploitation have increased environmental pressures, leading to a decrease in the carrying capacity of the ecosystem.

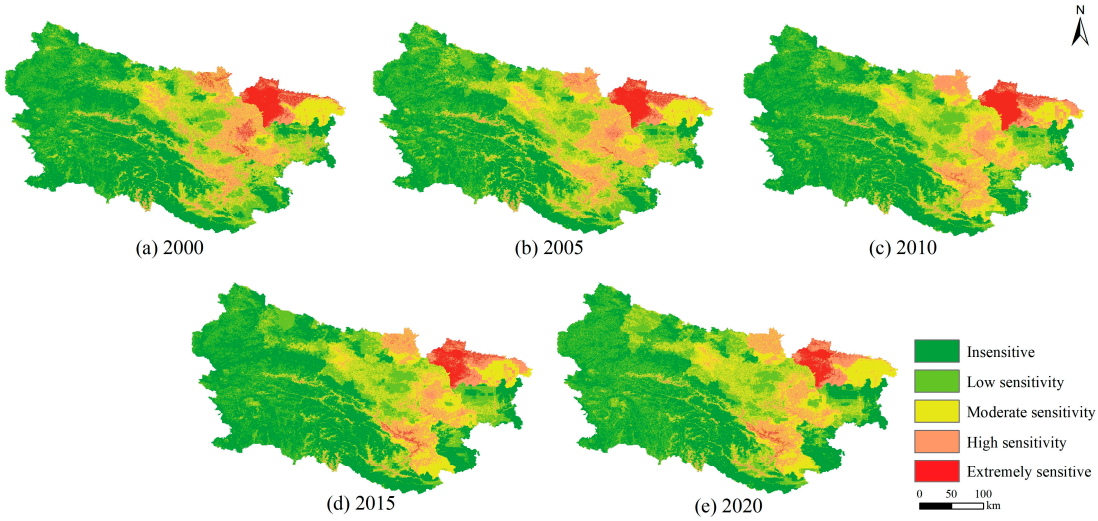


Figure 2. Comprehensive ecological sensitivity map of the West Qinling region from 2000 to 2020.

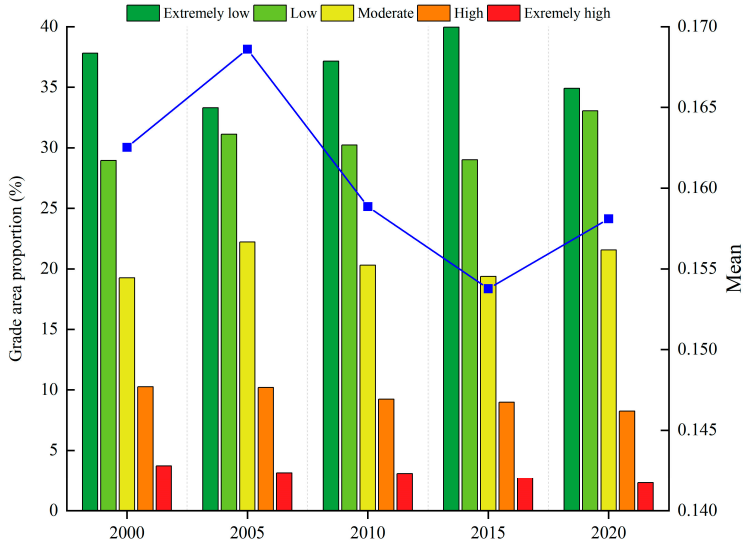


Figure 3. Area percentage of the comprehensive ecological sensitivity grade of the West Qinling region.

Table 5. Area statistics of comprehensive ecological sensitivity zones from 2000 to 2020.

Sensitivity Classification	2000		2005		2010		2015		2020	
	Area/ km^2	Ratio /%	Area /km^2	Ratio /%	Area /km^2	Ratio /%	Area /km^2	Ratio /%	Area /km^2	Ratio /%
Insensitive	31,794.29	37.81	28,010.68	33.31	31,248.14	37.16	33,596.36	39.96	29,345.72	34.90
Low sensitivity	24,339.83	28.95	26,164.96	31.12	25,406.94	30.22	24,381.98	29.00	27,784.06	33.04
Moderate sensitivity	16,197.42	19.26	18,684.61	22.22	17,067.97	20.3	16,298.34	19.38	18,123.58	21.55
High sensitivity	8624.06	10.26	8587.77	10.21	7763.58	9.23	7550.28	8.98	6933.38	8.25
Extremely sensitive	3128.48	3.72	2636.07	3.14	2597.46	3.09	2257.12	2.68	1897.33	2.26

3.2. Scale Response Characteristics of Comprehensive Ecological Sensitivity

3.2.1. Variation Characteristics of Ecological Sensitivity Based on Different Scales

Using 30 m as the base scale, the spatial distribution of comprehensive ecological sensitivity was obtained. To explore the range of scales where the influence of scale dependence weakens, this study selected 12 scales ranging from 500 m to 6 km with 500 m increments. Analyzing the spatial distribution characteristics at these scales helped identify the range where the influence of scale dependence decreases. The trend in ecological sensitivity in the West Qinling Mountains across 12 spatial scales from 2000 to 2020 is illustrated in Figure 4. The findings indicate that the spatial distribution of ecological sensitivity is significantly affected by changes in spatial scales. Specifically, at spatial scales of 500 m × 500 m and 1000 m × 1000 m, the scales are relatively fine, but there are considerable variations in spatial distribution. This may be attributed to the fact that at smaller scales, localized environmental factors have more pronounced effects on ecological sensitivity, leading to more complex and diverse distribution patterns. At scales ranging from 1.5 km × 1.5 km to 4 km × 4 km, the spatial distribution of ecological sensitivity presents different characteristics. This indicates that ecological sensitivity demonstrates a significant scale effect at different scales. The spatial distribution characteristics vary according to the scale, reflecting the spatial heterogeneity of regional ecosystems. As the scale increases from 4.5 km × 4.5 km to 6 km × 6 km, the spatial distribution of high-value and low-value areas remains relatively unchanged, displaying a general pattern of "low in the west and high in the east, low in the south and high in the north". This suggests that as the spatial scale increases, the factors driving changes in ecological sensitivity within each grid tend to stabilize, leading to a gradual reduction in the impact of spatial scale on the distribution of high-value and low-value zones. In addition, the spatial distribution within this scale range aligns with the overall spatial and temporal distribution characteristics of ecological sensitivity. This suggests that within the 4.5 km × 4.5 km to 6 km × 6 km scale range, the spatial distribution of ecological sensitivity tends to be stabilized, becoming less influenced by scale variations. The dependence on scale is weakened or may even disappear.

To further verify whether the range of diminished scale dependence is consistent with the range identified from the spatial distribution characteristics, this study used the natural break method to classify ecological sensitivity at different scales into five grades: insensitive, low sensitivity, moderate sensitivity, high sensitivity, and extremely sensitive. The area and proportion of each sensitivity level were then calculated (Figure 5). The results indicate that from 2000 to 2020, the West Qinling region was predominantly characterized by the insensitive and low-sensitivity levels of ecological sensitivity. This finding suggests that most areas of the West Qinling Mountains have relatively stable ecosystems with low sensitivity to external disturbances and strong self-regulation and recovery capacity. As spatial scale increases, the proportion of insensitive areas initially rises and then stabilizes, while the proportion of low-sensitivity areas first decreases and then reaches stability. These changes tend to stabilize beyond the 4.5 km scale, indicating that at larger scales, the overall characteristics of the ecosystem become more stable, and the spatial distribution of ecological sensitivity becomes significantly less dependent on scale variation. Since the proportions of the other sensitivity levels (moderate sensitivity, high sensitivity, and extremely sensitive) are relatively low compared to the proportions of insensitive and low-sensitivity areas, analyzing the area proportions of these two levels can further confirm that within the 4.5 km × 4.5 km to 6 km × 6 km scale range, the ecological sensitivity regions have reached a stable state. The influence of scale effects on the distribution of ecological sensitivity within this scale range gradually weakens and may even disappear.

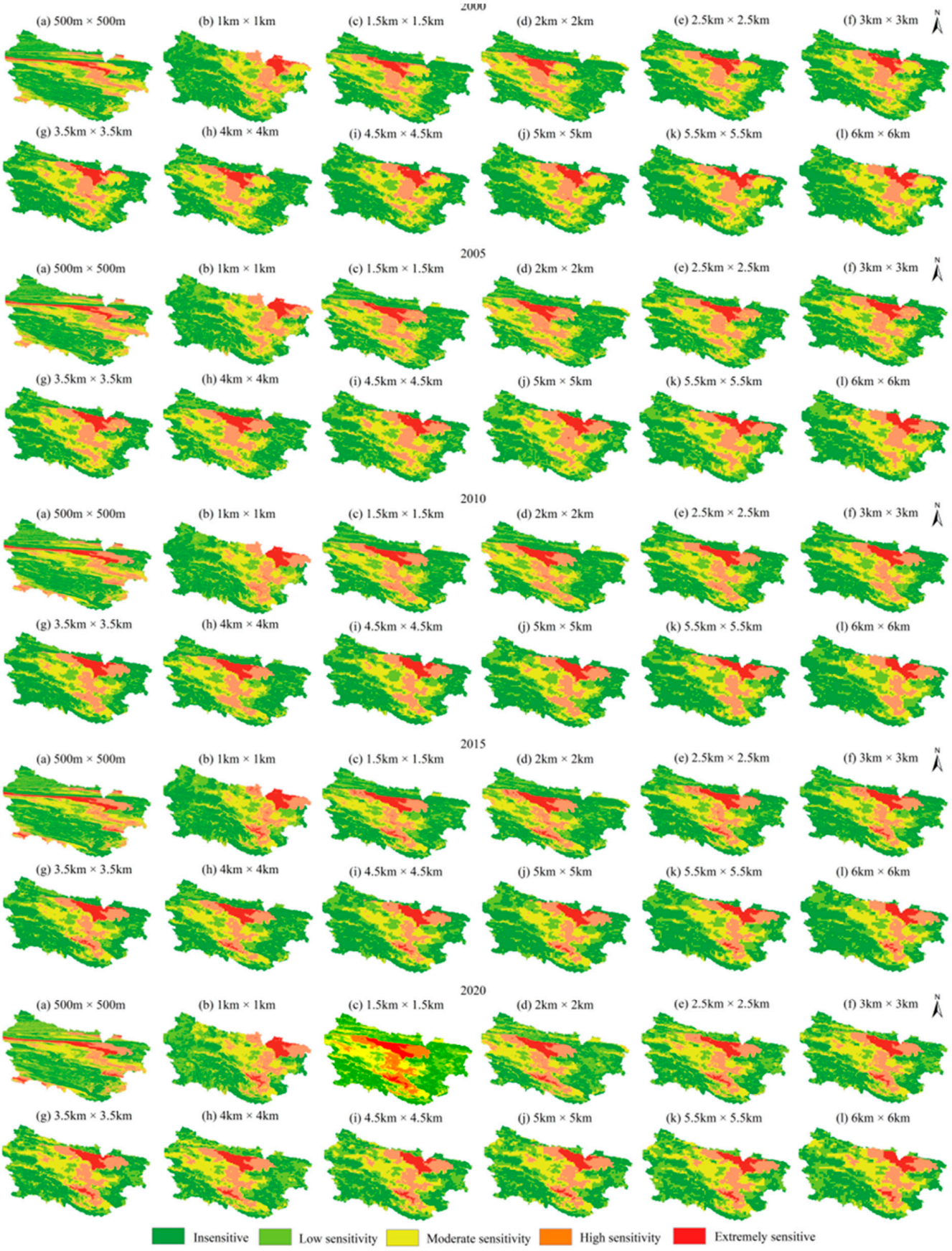


Figure 4. Response characteristics of the spatial distribution of ecological sensitivity to scale variations in the West Qinling region from 2000 to 2020.



Figure 5. The area proportion of ecological sensitivity levels at different scales in the West Qinling region from 2000 to 2020.

3.2.2. Response Mechanism of Ecological Sensitivity at Different Scales

To determine the most appropriate scale for analyzing the spatial differentiation of ecological sensitivity in the West Qinling region, this study calculated the coefficient of variation and Moran's *I* at 12 different spatial scales (Figure 6). The results show that from 2000 to 2020, the Moran's *I* values for ecological sensitivity were consistently greater than 0 across all spatial scales. This indicates that the ecological sensitivity of the West Qinling region has a significant positive spatial correlation during this period. In other words, areas of high sensitivity and areas of low sensitivity show a certain degree of spatial aggregation. As the spatial scale increases, the Moran's *I* initially decreases and then stabilizes, fluctuating between 0.88 and 0.96 with minimal variation. This indicates that at larger scales, the spatial pattern of ecological sensitivity tends to stabilize, and its dependence on scale variations significantly weakens. Additionally, we found that the change in the coefficient of variation leveled off during 2000–2020, especially after the spatial scale exceeded 4.5 km. This indicates that the scale dependence was significantly reduced at this time. Especially at the spatial scale of 5.5 km, the coefficients of variation for the years 2000, 2005, 2010, 2015, and 2020 reached minimum values of 0.5616, 0.5042,

0.5507, 0.5600, and 0.5064, respectively. This further suggests that the uniformity of spatial distribution of ecological sensitivities is the strongest at this scale. Therefore, this study preliminarily identifies 5.5 km as the most appropriate scale for analyzing the spatial variation of ecological sensitivity in the West Qinling Mountains.

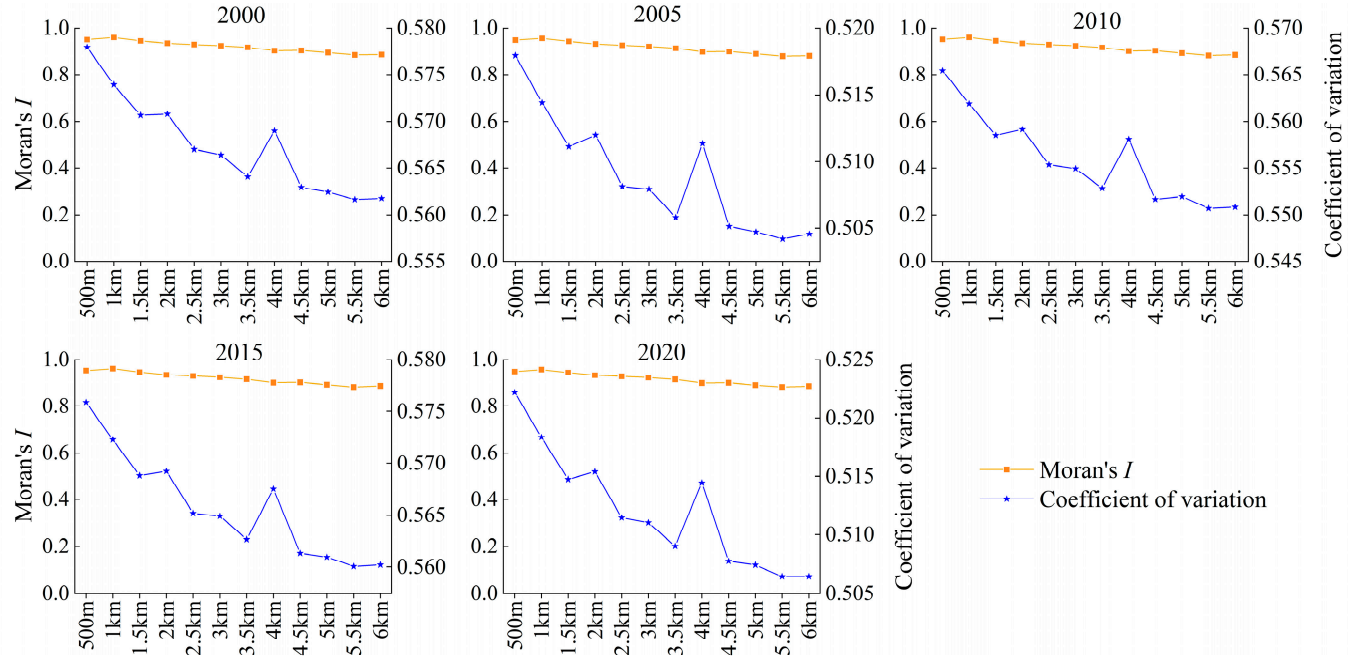


Figure 6. Descriptive statistical parameters of ecological sensitivity in the West Qinling Mountains at different scales from 2000 to 2020.

3.3. Analysis of Ecological Sensitivity Impact Factors Based on the Optimal Parameter Geographical Detector

3.3.1. Identification of the Optimal Spatial Scale

To verify whether 5.5 km is the optimal scale for ecological sensitivity in the West Qinling Mountains and to more precisely identify the specific factors influencing the differences in ecological sensitivity, tertiary indicators were further used as drivers to detect the influence of various ecological sensitivity factors under different scales. The selected factors include 14 key environmental and socioeconomic factors: elevation, slope, topographic relief, slope and slope length, annual precipitation, average annual temperature, vegetation coverage, precipitation erosivity, soil erodibility, density of geologic hazard sites, river distance, biological richness index, population density, and GDP (Figure 7). These factors can comprehensively reflect the complexity and sensitivity of the ecosystems in the West Qinling region. The study utilizes the latest data from 2020 and uses OPGD to investigate the driving mechanism of ecological sensitivity in 2020 to ensure the consistency of the cycle. Through a comprehensive analysis of the spatial distribution, area proportion of grade, Moran's *I*, and coefficient of variation of ecological sensitivity at different spatial scales, we found that the dependence of ecological sensitivity on scale variation gradually weakens in the range of 4.5 km to 6 km. The study ultimately selected scales of 4.5 km, 5 km, 5.5 km, and 6 km for analysis, revealing that the 90th percentile of the *q*-value initially increases and then decreases, reaching its maximum at the 5.5 km scale. This indicates that the factors have the greatest explanatory power for the spatial divergence of ecological sensitivity at this scale. This finding further confirms the rationality and scientific validity of 5.5 km as the optimal scale for the spatial differentiation of ecological sensitivity in the West Qinling region.

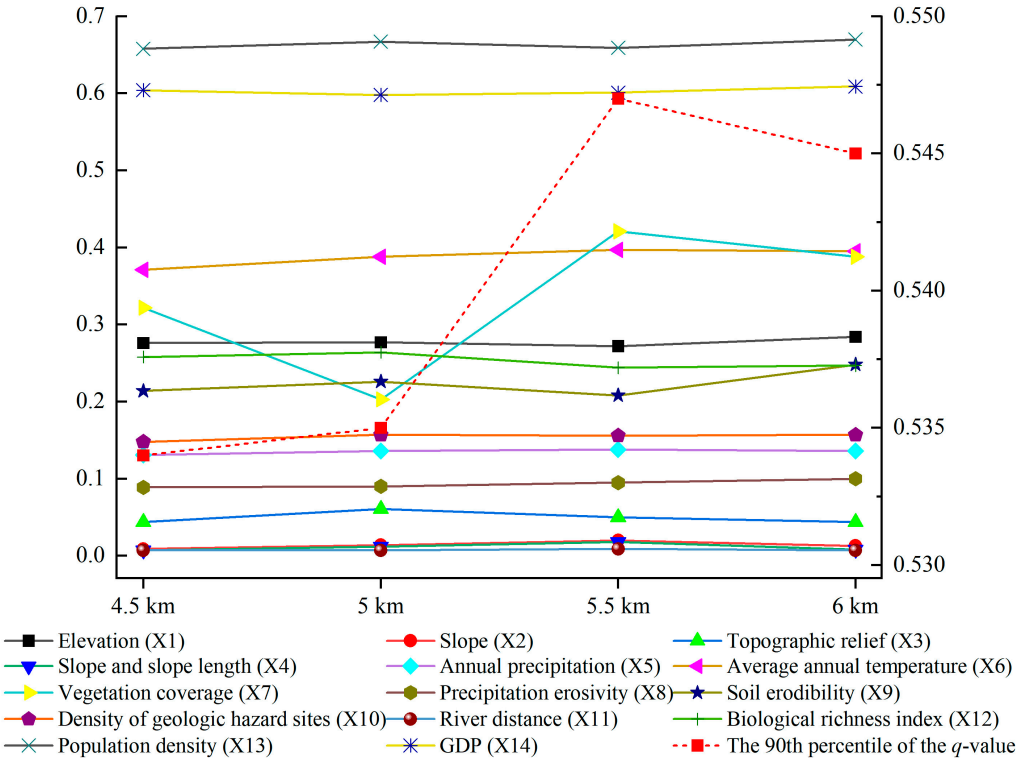


Figure 7. Optimal spatial scale selection of impact factors in the West Qinling Mountains.

3.3.2. Analysis of Driving Factors

The spatial heterogeneity of regional ecological sensitivity differences is influenced by natural, socioeconomic, and locational factors. In this study, all selected indicator factors have *p*-values less than 0.01, indicating that the driving factors sufficiently explain ecological sensitivity. Specifically, socioeconomic factors have more significant influence on ecological sensitivity (Table 6). Among these, population density, GDP, and vegetation coverage stand out in explaining spatial differences in ecological sensitivity, with *q*-values of 0.659, 0.601, and 0.421, respectively.

Table 6. Results of the driving factor detection.

Factor	*q*-Value	Ranking	Factor	*q*-Value	Ranking
Elevation (X1)	0.272	5	Precipitation erosivity (X8)	0.095	10
Slope (X2)	0.020	12	Soil erodibility (X9)	0.208	7
Topographic relief (X3)	0.050	11	Density of geologic hazard sites (X10)	0.156	8
Slope and slope length (X4)	0.018	13	River distance (X11)	0.009	14
Annual precipitation (X5)	0.138	9	Biological richness index (X12)	0.244	6
Average annual temperature (X6)	0.397	4	Population density (X13)	0.659	1
Vegetation coverage (X7)	0.421	3	GDP (X14)	0.601	2

Through the analysis of driving factors, it was found that parts of Tianshui City and Longnan City exhibit high ecological sensitivity, mainly due to the accelerated process of urbanization. Rapid urban expansion in these areas has failed to synchronize with ecological protection, resulting in an unbalanced development situation. Therefore, stricter ecological protection measures are recommended for these regions, while promoting sustainable development. This approach aims to alleviate ecological pressure and achieve a better balance between environmental conservation and regional development.

3.4. Characteristics of Ecological Sensitivity Change Intensity at the Optimal Scale

This study investigated the spatial differentiation characteristics of the ecological sensitivity of the West Qinling Mountains and identified a 5.5 km × 5.5 km grid as the optimal scale. At this scale, the data were processed using spatial analysis to effectively convert the raster attribute values into vector data for more in-depth result analysis. The results, as shown in Table 7, indicate that the ecological sensitivity of the West Qinling Mountains exhibited relative stability between 2000 and 2020. The unchanged area reached 51,070.44 km^2, which constitutes 60.74% of the total study area. This part of the area is large and evenly distributed, covering almost all the counties in the West Qinling region. This stability is likely attributed to the region's relatively stable natural environment, high vegetation coverage, and minimal human disturbance. This is followed by the weaker one-time change area, which covers an area of 169,22.57 km^2, accounting for 20.13% of the total area. Despite these areas experiencing a one-time change in ecological sensitivity, the overall magnitude of the change was small, and the ecological environment remained relatively stable. This change was likely associated with localized climate change or minor human activities, but it did not significantly affect the overall stability of the regional ecosystem. The areas that experienced two or three changes cover a total of 16,050.98 km^2, accounting for 19.09% of the total area. These regions are primarily clustered in the western part of the West Qinling region (Figure 8). This distribution is largely due to the fact that these areas belong to the Tibetan Plateau, which is closely associated with its unique geographical environment. The high altitude and complex topography of the Tibetan Plateau make the surrounding regions more sensitive to external environmental changes. These regions are particularly vulnerable to natural factors such as climate change and precipitation variability, resulting in more pronounced fluctuations in ecological sensitivity compared to other areas. The area that experienced four instances of change covers only 40.09 km^2, representing just 0.05% of the total study area. Regarding the general trend, the ecological sensitivity of the West Qinling Mountains exhibited significant fluctuations in a few areas, while the majority of the region remained relatively stable. Based on different levels of change, targeted management measures can be implemented. This is of great significance for predicting future ecological trends and identifying key areas for protection, thereby achieving a better balance between ecosystem conservation and regional sustainable development.

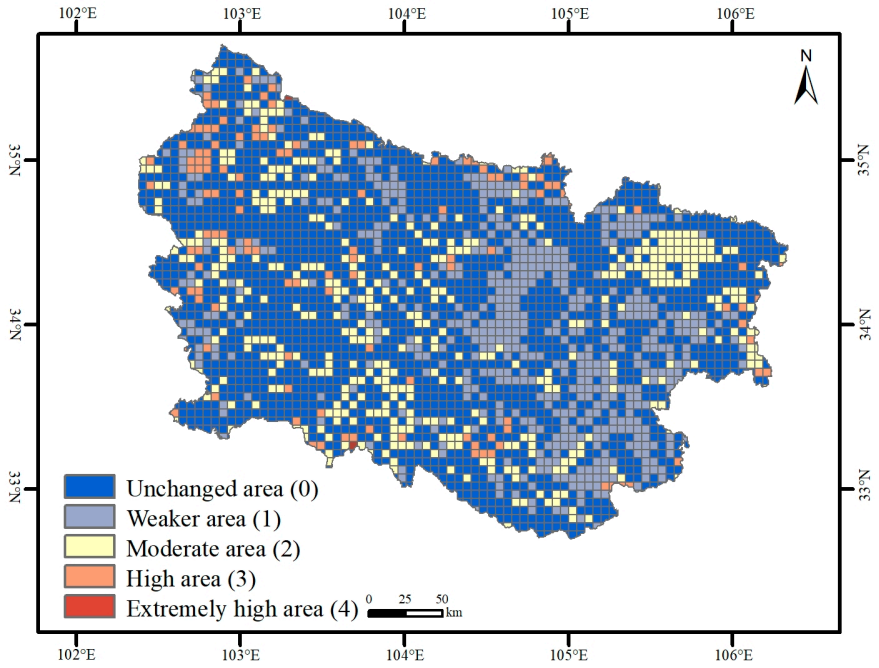


Figure 8. Frequency zoning of ecological sensitivity changes in the West Qinling Mountains.

Table 7. Area statistics for the frequency of changes in ecological sensitivity zones from 2000 to 2020.

Classification of Change Intensity	Frequency of Changes	Area/km^2	Proportion/%
Unchanged area	0	51,070.44	60.74
Weaker area	1	16,922.57	20.13
Moderate area	2	12,524.75	14.9
High area	3	3526.23	4.19
Extremely high area	4	40.09	0.05

3.5. Analysis of Ecological Sensitivity Change Patterns at the Optimal Scale

Based on the spatial distribution map of ecological sensitivity coding zones in the West Qinling Mountains (Figure 9) and the area statistics table (Table 8), the ecological sensitivity of the Western Qinling region was predominantly characterized by unchanged areas, which covered an area of 51,070.44 km^2, accounting for 60.74% of the total study area between 2000 and 2020. The unchanged zone is further divided into five categories: perennial insensitive, perennial low sensitivity, perennial moderate sensitivity, perennial high sensitivity, and perennial extremely sensitive. Among these zones, the perennial insensitive area is the largest, with an area of 24,755.10 km^2, accounting for 29.44% of the total area of all the zones. This region is primarily located in Ruoergai County, Jiuzhaigou County, and Luqu County. Conversely, the area of perennial extreme sensitivity is the smallest, encompassing only 1775.89 km^2, which constitutes 2.11% of the total zones. These areas are mainly distributed in Wushan County and Qinzhou District. Additionally, this study further subdivided the fluctuating zones into fluctuating increase zones, fluctuating decrease zones, and fluctuating unchanged zones (Table 9). The findings show that the area of fluctuating increase zones is smaller than that of fluctuating decrease zones, and the area of fluctuating increase zones accounts for 8.54% of the total study area. This suggests that although the overall ecological environment has improved and remained stable over a large area, the localized fluctuations in ecological sensitivity reflect the instability of the ecological environment that these areas are still facing.

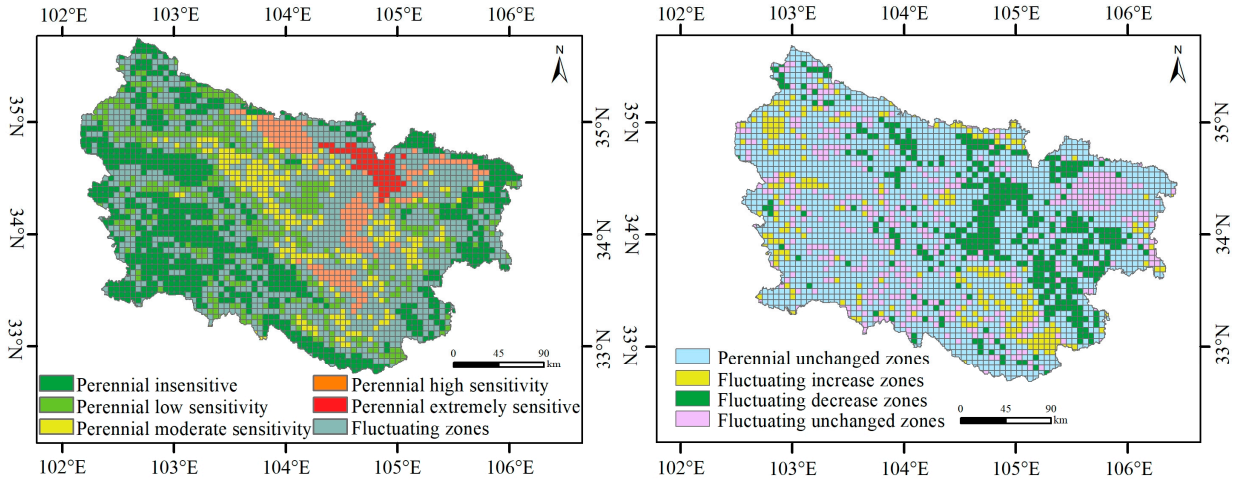


Figure 9. Spatial distribution of ecological sensitivity coding zones from 2000 to 2020.

Table 8. Area statistics of unchanged ecological sensitivity zones from 2000 to 2020.

Zoning	Area/km^2	Proportion/%
Perennial insensitive	24,755.10	29.44
Perennial low sensitivity	12,343.11	14.68
Perennial moderate sensitivity	7205.62	8.57
Perennial high sensitivity	4990.72	5.94
Perennial extremely sensitive	1775.89	2.11

Table 9. Area statistics of fluctuating ecological sensitivity zones from 2000 to 2020.

Zoning	Area/km^2	Proportion/%
Fluctuating increase zones	7181.21	8.54
Fluctuating decrease zones	13,358.35	15.89
Fluctuating unchanged zones	12,474.09	14.84

4. Discussions

4.1. Collinearity Diagnosis of Indicators

Given the complex and multifaceted nature of the evaluation indicators, there may be overlapping information among them that could affect the comprehensive assessment of ecological sensitivity. Therefore, tolerance (TOL) and variance inflation factor (VIF) in SPSS are employed to examine the severity of collinearity between indicators. A threshold of TOL < 0.1 and VIF > 10 is used to indicate the presence of multicollinearity [49]. This study validates the indicators for the West Qinling Mountains in 2020. According to the results in Table 10, all single indicator influence factors have tolerance (TOL) values greater than 0.1 and variance inflation factor (VIF) values less than 10. These findings indicate that there is no severe multicollinearity among the sensitivity indicators for soil erosion, climate environment, geological hazards, biodiversity, and human disturbance. The selection of these indicators is based on actual ecological environmental issues and the research objectives, and their rationality and scientific validity have been further verified through collinearity analysis. Consequently, the comprehensive ecological sensitivity model constructed has a solid theoretical basis and scientific foundation.

Table 10. Collinearity diagnosis results of ecological sensitivity indicators for 2020.

Indicator Layer	*p*	TOL	VIF
Soil erosion sensitivity	0.000	0.817	1.224
Climate environmental sensitivity	0.000	0.842	1.187
Geological hazard sensitivity	0.000	0.798	1.253
Biodiversity sensitivity	0.000	0.876	1.142
Human disturbance sensitivity	0.000	0.879	1.138

4.2. Causes of Ecological Sensitivity Changes

From the perspective of spatial distribution, the ecological sensitivity of the West Qinling Mountains from 2000 to 2020 generally shows a distribution pattern of "low in the west and high in the east, low in the south and high in the north", with obvious spatial differentiation. The moderate and highly sensitive areas are primarily located in the northeastern part of the West Qinling Mountains. The land use types in these areas are dominated by cultivated land and moderately low-cover grassland, with low vegetation cover and easily eroded soil [50]. In addition, construction activities in human agglomerations are frequent, and environmental disturbances are intensive, which further exacerbates ecological sensitivity [51]. Insensitive and low-sensitivity areas are mainly distributed in the western part of the West Qinling Mountains, where the vegetation cover is relatively high [52] and the biodiversity is rich [53]. Due to the relatively low population density and minimal human interference activities, the regional ecological environment is well protected, and ecological sensitivity is relatively low. From a temporal perspective, the ecological sensitivity of the West Qinling region showed a decreasing trend from 2000 to 2020, resulting in a gradual improvement in the ecological environment quality. This finding is consistent with the results of Li Feng's study and aligns with the region's actual geographical and ecological characteristics [19]. According to the time period, the ecological sensitivity of the West Qinling Mountains showed an upward trend from 2000 to 2005. This trend stems from a rapid development stage of economic growth and ecological conservation efforts. The traditional rough economic model led to regional environmental damage, soil erosion, grassland degradation, and other ecological and environmental problems [54,55], thus

increasing regional ecological sensitivity. From 2005 to 2015, the government paid more attention to environmental and ecological protection [56]. Comprehensive initiatives were implemented to systematically enhance the ecological environment of the West Qinling region. These initiatives included large-scale efforts for vegetation restoration, reforestation, soil erosion control, and biodiversity conservation, yielding substantial ecological benefits. From 2015 to 2020, driven by both economic development and policy implementation, the socioeconomic transformation underwent significant changes, leading to notable shifts in ecological environmental issues. Additionally, due to the involvement of multiple administrative regions within the West Qinling area, ecological issues often exhibit characteristics of cross-regional transmission, making comprehensive protection more challenging and contributing to an increase in ecological sensitivity. In addition, during this study period, the perennial high-sensitivity areas were in Wushan County, Li County, and Qinzhou District. In view of this, future ecological governance and protection efforts should prioritize these regions to implement effective measures aimed at improving the ecological environment and reducing ecological sensitivity.

4.3. Scale Differences in Ecological Sensitivity Variation and Driving Factors

The complexity of the ecological environment results in varying characteristics of ecological sensitivity at different scales and processes. Therefore, the scientific evaluation of ecological sensitivity requires the comprehensive consideration of multiple scale factors. In the choice of scale, small scales can only reflect the degree of local ecological sensitivity and are inadequate for accurately representing the overall ecological status. Conversely, overly large scales may overlook numerous microscopic details, leading to biased results [57]. Therefore, the choice of scale is particularly important in ecological research. This study identifies the spatial distribution patterns and response mechanisms of ecological sensitivity across different scales, as well as spatial scale recognition based on optimal parameter geographic detectors. The findings reveal that the spatial differentiation of ecological sensitivity exhibits significant scale-dependent characteristics. This is consistent with the findings of Zhang et al. [16], who discovered scale dependency in the supply-demand relationship of ecosystem services. In addition, beyond the 5.5 km scale, the spatial differentiation characteristics of ecological sensitivity became less pronounced, with a reduction in scale dependence. Meanwhile, the coefficient of variation is minimized at this scale. Therefore, the 5.5 km scale is determined to be the optimal scale for analyzing the spatial differentiation of ecological sensitivity in the West Qinling region. This scale not only provides abundant information on spatial variability but also maintains a moderate data volume, effectively balancing the overall ecological status. Furthermore, it significantly reduces the errors associated with scale selection. This finding provides a scientific basis for the formulation of subsequent ecological protection measures and emphasizes the importance of comprehensively considering different spatial scales in the evaluation of ecological sensitivity, thus ensuring the accuracy and reliability of the evaluation results. Based on this optimal scale, the factor detection results indicate that population density and GDP are the primary driving factors of the spatial differentiation of ecological sensitivity in the West Qinling region. This finding is consistent with the results of Guo et al. [58]. The population density and GDP of the West Qinling region generally show a spatial distribution pattern of "low in the west and high in the east, low in the south and high in the north", which is the same as the spatial pattern of the ecological sensitivity of the area. Areas with frequent human activities and a high level of economic development have a high degree of ecological sensitivity. Therefore, future ecological governance and protection efforts should prioritize these regions, implementing stringent environmental control measures and rational resource allocation to mitigate the negative impacts of population and economic factors on the ecological environment.

4.4. Limitations and Future Prospects

Building upon previous research, this study developed a comprehensive ecological sensitivity evaluation model for the West Qinling region, incorporating factors such as soil erosion, climatic environment, geological hazards, biodiversity, and human disturbance sensitivity. This model effectively revealed the spatial distribution and temporal variations in ecological sensitivity within the study area. However, due to the complexity of ecological sensitivity and the interactions between evaluation factors, the current evaluation system and method have not yet realized a comprehensive and precise evaluation, which requires further refinement in future research. Due to space constraints, this study does not provide a detailed presentation of the spatial distribution and temporal dynamics of individual indicators. In future research, we will conduct a more in-depth exploration of these indicators' spatiotemporal characteristics to better reveal their specific impacts on ecological sensitivity. Nonetheless, the identification of the 5.5 km scale as the optimal scale for ecological sensitivity differentiation in the West Qinling region establishes a crucial foundation for subsequent studies and holds significant potential for broader application.

5. Conclusions

The West Qinling Mountains represent one of the hotspots for ecological environmental protection in China. Assessing the ecological sensitivity of the region provides valuable insights for improving biodiversity management strategies and implementing targeted biodiversity conservation measures. The study revealed the following conclusions:

(1) From a spatial scale perspective, the dependence of ecological sensitivity on scale variation diminished at spatial scales ranging from 4.5 km to 6 km. Over the 20-year period, the coefficient of variation reached its minimum at 5.5 km, while the 90th percentile of the *q*-values of the influencing factors was the largest at this scale. Considering the descriptive statistics and data volume requirements of each scale, the 5.5 km spatial scale reaches a balance between precision, spatial heterogeneity, and data suitability, making it the optimal scale for analyzing the spatiotemporal variation patterns of ecological sensitivity in the West Qinling region.

(2) From a temporal perspective, the mean ecological sensitivity in the West Qinling region showed a decreasing trend, from 0.163 in 2000 to 0.160 in 2020, indicating an improvement in ecological conditions. Spatially, ecological sensitivity exhibited significant spatial differentiation, characterized by a pattern of "low in the west and high in the east, low in the south and high in the north". High and extremely high sensitivity were mainly concentrated in the northeastern part of the West Qinling region, while insensitivity and low sensitivity were mainly concentrated in the western and southwestern parts. Overall, the ecological sensitivity of the West Qinling exhibits a relatively stable state in space and time, with no significant high-frequency changes.

(3) According to the results of the geographical detector, the *q*-value for population density is 0.659, making it the primary driving factor of spatial differentiation in ecological sensitivity in the West Qinling region. The *q*-value for GDP is 0.601, highlighting it as a secondary driving factor. Overall, socioeconomic factors exert a greater influence on ecological sensitivity than natural environmental factors.

(4) From the pattern of change, the area of fluctuating increase zones is smaller than that of fluctuating decrease zones, the ecological sensitivity of the West Qinling region shows a downward trend. However, the fluctuating increase zones account for 8.54% of the total study area. This indicates that the ecological management and prevention of the West Qinling region is still challenging under the background of drastic changes in the global ecological environment.

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X.L. (Xuelu Liu); funding acquisition, X.L. (Xuelu Liu) All authors have read and agreed to the published version of the manuscript.

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