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Spatial Difference Studies and Driving Force Analysis of Rural Settlements in the Northwest Sichuan Plateau

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Abstract: The scattered, isolated, and closed nature of rural settlements in northwest Sichuan is a constraint on the high-quality development of rural areas. Determining the spatial differences and driving forces of rural settlements in this area is the essential prerequisite for promoting rural revitalization. In this paper, the methods of the nearest neighbor index, the Voronoi diagram, and the Geodetector are used to analyze the spatial distribution characteristics of rural settlements and explore the driving factors of their spatial differences. The key findings are as follows. (1) The rural settlements exhibit the feature of "an extensive dispersion with localized concentrations". The spatial distribution is in the shape of dots, strips, and branches along the river valley. (2) The number and land use scale of rural settlements decreases from east to west. The spatial differences in settlement morphology have a clear feature that the settlement morphology along the river and road is more complex, while the settlement morphology in the plateau area and the river valley is relatively regular. (3) Mountain disasters and arable land resources have the greatest impact on the spatial differences of the settlements. The location and form of the settlements are greatly affected by the altitude and accumulated temperature, and the settlement scale is significantly affected by the traffic conditions and the scenic spots. The mutually reinforcing role of the driving factors is remarkable, especially the reinforcing effects of the enhancement between the arable land resources and other factors. The research results provide data support for the reconstruction, improvement, and high-quality development of rural settlements in this region.

Keywords: rural settlements; spatial distribution; Geodetector; Northwest Sichuan Plateau

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1. Introduction

The plateaus in the highland regions represent a geographical unit with a humanistic and geographic environment. It is the birthplace of many rivers and a place for water conservation. It is also a collection of valuable biological gene banks and scenic spots with abundant biological, mineral, and tourism resources. Meanwhile, the plateaus in the highland regions have complex and dangerous terrains that present dispersed arable land, the inconvenient circulation of population, transportation, information, and other elements, and unbalanced and inadequate regional development. Consequently, a widening urban-rural divide has formed. The dispersion, marginality, and closure of rural settlements in the plateaus in the highland regions have become important factors hindering the high-quality development of rural areas. Therefore, clarifying the spatial distribution characteristics of the rural settlements in high mountain plateau areas and their driving mechanisms will not only help to optimize the spatial structure of settlements in high mountain plateau areas but also provide a theoretical basis for realizing the ecological livability of rural settlements in high mountain plateau areas.

The study of rural settlements originated in Germany [1–3]. Subsequently, scholars conducted systematic studies on the formation and layout of different types of settlements [4,5]. Currently, Chinese researchers focus on the Yangtze River Delta [6–9], Northeast China [10,11], and Northwest China [11,12] regions from a geographic perspective, based on remote sensing image data, using kernel density estimation, landscape pattern analysis, and the Voronoi diagram [6,10,11] to analyze the spatial distribution characteristics and driving factors, layout planning and the implementation of the Land Consolidation Program, rural land use and functional changes, new countryside construction and village renovation, etc. [13–16]. However, mountainous areas account for about 70% of the total land area of China and are home to about one-third of its population [17]. At the same time, the scattered layout, lack of planning, and serious "hollowing out" of mountain settlements have seriously hindered the development of local society and economy, but relatively few studies have been conducted on rural settlements in mountainous areas. Therefore, understanding the spatial differentiation characteristics and driving mechanisms of rural settlements is conducive to promoting the socio-economic development of mountainous areas and realizing the sustainable development of mountainous areas in terms of population, resources, and environment.

In terms of spatial difference studies and driving force analysis of rural settlements, early scholars mostly evaluated using one-way analysis [18]. Later, scholars found many deficiencies in one-way analysis, so multi-factor evaluation methods gradually became mainstream [19,20]. In recent years, with the development of remote sensing (RS), geographic information systems (GIS), and other technologies, scholars began to carry out interdisciplinary and multivariate studies to further analyze the influence of driving factors on the evolution of the rural spatial form. Based on buffer zone analysis, many studies quantitatively studied the impact of various influences on the distribution and evolution of rural residents [12,21], but could not reveal the influence of different factors. There are also quite a few studies using a logistic regression model to explore the driving forces of rural settlement distribution [11,22], but the model is unable to explain the interaction between the factors and the dominant area of rural settlement distribution. In addition, the collinearity issue between factors affects the accuracy of the research results. The Geodetector model can avoid the above issues. It can not only effectively test the influence size of different impact factors, but also verify the consistency and validity between the spatial pattern of each impact factor and the spatial distribution of rural residents through a significance test [23,24]. However, its results are greatly influenced by the data discrete scale, which will lead to the bias of the results caused by subjective judgment.

In order to explore the spatial distribution characteristics and driving forces of rural settlements in the plateaus in the highland regions, this paper takes the Northwest Sichuan Plateau as the study area, takes the rural settlements in this region as the research object, and comprehensively uses the nearest neighbor analysis, Voronoi diagram, and landscape indices to systematically analyze the features of spatial differences of the location, scale, and form of the rural settlements in this region. A Geodetector model based on optimal parameters is introduced to detect the spatial differences and driving forces of rural settlements. Intensive efforts are made to enrich the study of rural settlement patterns in different geographical units, provide basic data for the establishment and improvement of rural settlements in terms of development planning in the plateaus in the highland regions, and enhance ecological livability in rural areas.

2. Materials and Method

2.1. Study Area

The Northwest Sichuan Plateau is located on the southeast margin of the Qinghai-Tibet Plateau (Figure 1). Its landforms are mainly high-mountain valleys and highlands. On the whole, it presents the plateaus in the highland regions in the southeast, the central mountain plateau region, and the northwest plateau region, ranging between 27°57′–34°21′ N and 97°22′–104°27′ E [25]. The total area is about 24,000 square km, accounting for 48.82% of the total area of Sichuan Province. The elevation in the area ranges from 770 to 7556 m, with an average elevation of 3000 to 4000 m, and the relative elevation difference is close to 7000 m. The area has highly undulating terrain. Under the influence of the Eurasian plate and the Indian Ocean plate, there are three seismic zones, including Longmen Mountain, Xianshuihe, and Anning River. The area has high occurrence zones of seismic and geological disasters with high intensity. The average temperature is about 9.01 to 10.5 °C, the climate has obvious vertical variation characteristics, and there are abundant water resources and solar energy resources [26].

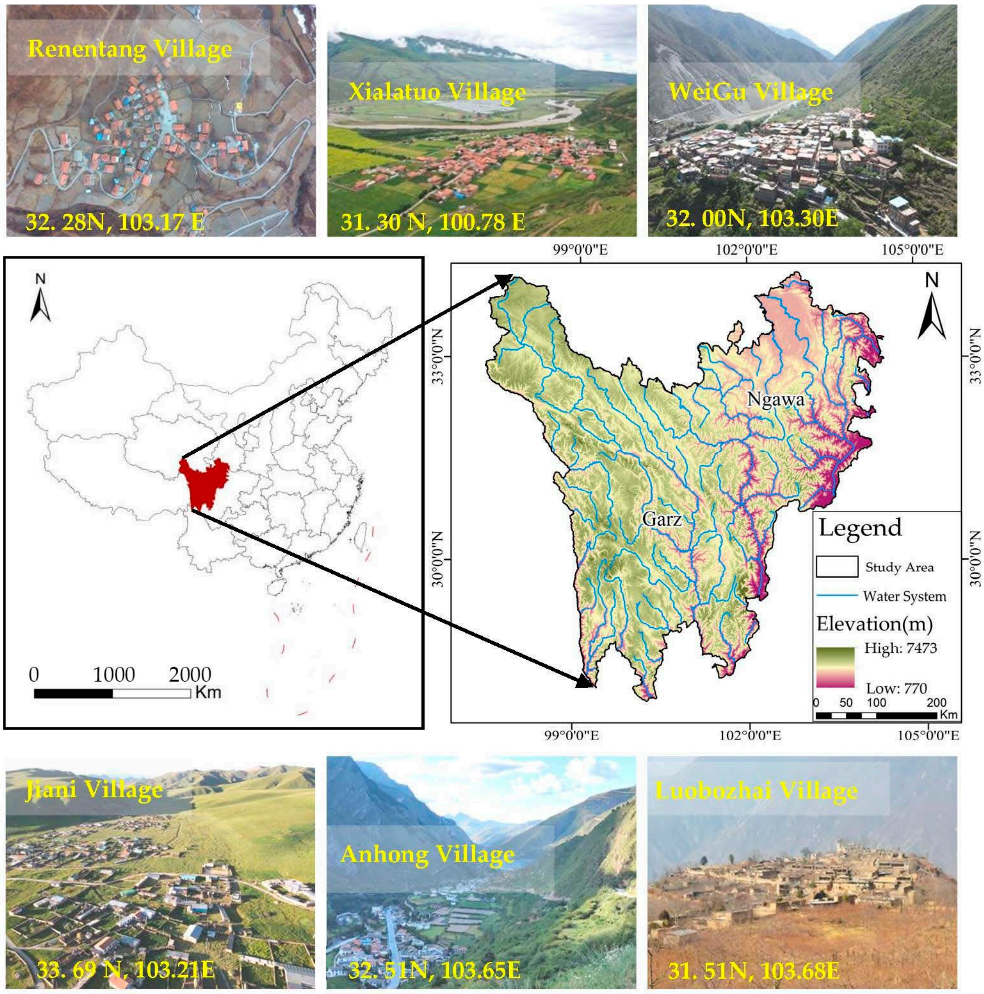


Figure 1. Location of the Study Area.

The northwest plateau of Sichuan with its variety of cultures is inhabited by Tibetan, Qiang people, Yi people, Hui people, and other ethnic minorities. Traditional settlement architecture uses local materials, which adapt to the regional climate and integrates into the multi-ethnic cultures. In terms of the settlement site selection, construction, function, and form, it is in harmony with the natural ecological environment and also bears the colorful culture and beliefs of various ethnic groups. By the end of 2021, the seventh census data showed that the population of the Northwest Sichuan plateau was 1.93 million, with an urbanization rate of only 35.48%. With a GDP of CNY 82.236 billion and a relatively under-developed industrial structure, it is a representative area of unbalanced and inadequate development in China.

2.2. Data Sources

The data used in this study included the following aspects: (1) The data on rural settlements and geological disasters were obtained from the Resource and Environmental Science and Data Center (http://www.resdc.cn, accessed on 23 August 2022). The rural settlement map patches were corrected using the survey data of land use change in the study area and Google images; (2) The spatial data of geographical elements: the data of administrative division boundary, transportation network, and river system of the study area were obtained from the National Geomatics Center of China. (3) The DEM data with a resolution of 30 m was gained from the official website of the United States Geological Survey (https://earthexplorer.usgs.gov, accessed on 7 March 2021). (4) Normalized Difference Vegetation Index (NDVI), 2020 GDP, and 2020 population raster data were obtained from the official website of the Geospatial Data Cloud (https://www.gscloud.cn/, accessed on 8 September 2022).

2.3. Methods

In this study, the study area was first divided into grids of different scales [27]; then, the spatial autocorrelation Moran's I value of the settlement patch areas was counted. It was found that the grid of 3 km × 3 km had the largest Moran's I value. Therefore, in this study, a 3 km × 3 km grid was used to divide the research area into 26,770 evaluation units. Firstly, the spatial attribute data of rural settlements were assigned to the corresponding grid, and the spatial distribution characteristics of rural settlements are explored by means of the average nearest neighbor index and Moran's I. Secondly, the Getis-Ord G_i* and landscape pattern index were used to analyze the spatial distribution characteristics of the rural settlement and its size and form. Finally, the Geodetector based on the optimal parameters was used to select the optimal spatial data discretization method and reveal the driving forces of the spatial distribution characteristics of the rural settlements. The main applied methods and research process (Figure 2) are as follows:

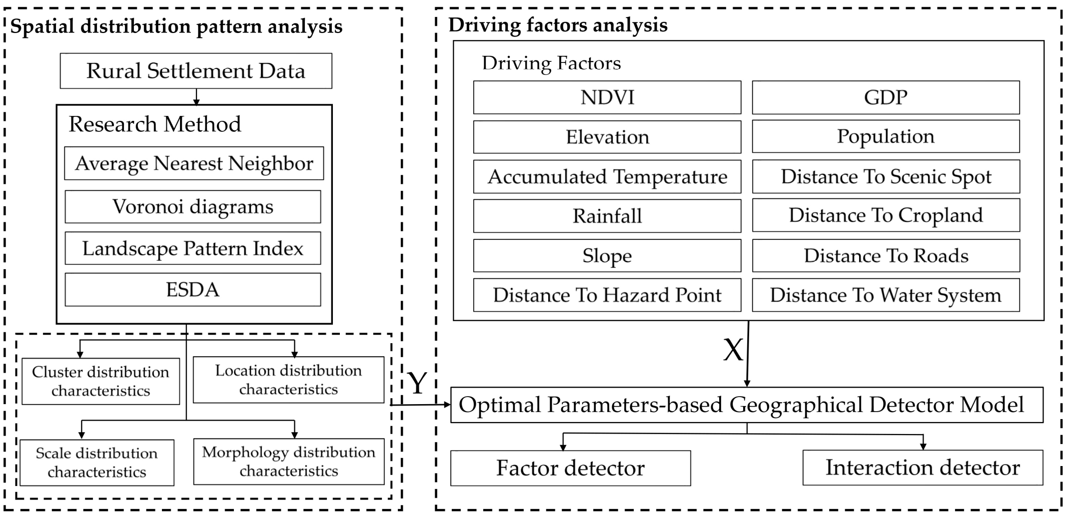


Figure 2. Research Path Diagram.

2.3.1. Research Methods of Spatial Distribution Characteristics

Average Nearest Neighbor

There are three distribution modes of rural settlements in concentrated, even, and random modes. The average nearest neighbor index judges the spatial distribution pattern of the rural settlements based on the ratio of the observed value and the expected value of the average distance of the nearest neighbor, which can accurately and objectively reflect the mutual proximity of rural settlement patches in geographical space [23,28]. The calculation formula is as follows:

$$ANN = \frac{\overline{D_o}}{\overline{D_e}} = \frac{\sum_{i=1}^{n} d_i/n}{\sqrt{A/(2n)}} \tag{1}$$

where D_o represents the average distance observed value. D_e is the expected value of the average distance. n represents the total number of plaques. d is the distance. A represents the size of the study area. When $ANN > 1$, it is randomly distributed. When $ANN < 1$, it is grouped. When $ANN = 1$, it is evenly distributed.

Voronoi Diagrams

A Voronoi diagram is a partition of the plane. In any convex Voronoi polygon, the distance between any interior point and the occurrence point of the convex polygon is less than the distance between the point and any other occurrence point. These occurrence points are also called the center of mass or generator of a Voronoi diagram. The density is defined as the distribution space occupied by a specific number of points that coincides with the Voronoi plot, so the reciprocal of the area of each Voronoi diagram unit is calculated as the density value corresponding to the number of settlements [29]. Meanwhile, the coefficient of variation (CV) is a powerful tool for proximity analysis to further verify the distribution pattern of the rural settlements. The formula is as follows:

$$CV = (Std/Ave) \times 100\% \tag{2}$$

Duyckaerts proposed three suggested values. When the point set was randomly distributed, the CV value was 57% (including values ranging from 33% to 64%) [30]. When the point set was distributed in clusters, the CV value was 92% (including values greater than 64%). When the point set is evenly distributed, the CV value is 29% (including values less than 33%).

Landscape Pattern Index

The landscape pattern index can well reflect the characteristics of a patch landscape structure and its spatial morphological distribution and has high applicability in studying the spatial distribution of rural settlements [21]. In this paper, four indexes, including the patch area, patch density, average patch shape index, and average patch fractal dimension, were selected to analyze the scale characteristics and morphological features of rural settlements in the study area. Both the patch shape index and the fractal dimension were estimated by the perimeter-area ratio. The larger the patch shape index is, the more complex its shape is. In addition, the larger the patch fractal dimension index is, the more irregular the patch structure is and the higher the degree of fragmentation is [31]. These four indicators were measured in Fragstats4.2, and the calculation formula is shown in the following Table 1:

Table 1. Pattern Index.

Category	Index	Formula
Settlement Scale	Patch Area	$\sum_{i=1}^{n} a_i$
	Patch Density	n/A
Settlement Morphology and Structure	Average Patch Shape Index	$\frac{\sum_{i=1}^{n} [(p_i/4)/\sqrt{a_i}]}{n}$
	Mean Patch Fractal Dimension	$\frac{\sum_{i=1}^{n} [\ln(p_i/4)/\ln(\sqrt{a_i})]}{n}$

a_i is the area of the ith patch in the grid. While p_i is the perimeter of the ith patch in the grid. n is the number of patches in the grid, and A is the area of the grid.

Exploratory Spatial Data Analysis

ESDA (Exploratory Spatial Data Analysis), as one of the important methods in the current rural settlement research, can effectively reveal the spatial agglomeration and heterogeneity of the scale characteristics of rural settlements. The ESDA module in ArcGIS software was used to explore the spatial distribution model and heterogeneity features of the rural settlements in the Northwest Sichuan Plateau [7]. The Moran's I index was selected to reflect the degree of global autocorrelation. We chose the Queen adjacency matrix for the calculation of Moran's I index; and the hot spot analysis (Getis-Ord G_i*) index was used to identify the distribution locations of high-value and low-value regions with significant spatial agglomeration characteristics [6].

2.3.2. Geodetector

Optimal Parameter-Based Geodetector Model

Geodetectors reveal the driving force behind the dependent variable by analyzing whether the independent variable and the dependent variable are similar in spatial distribution [32]. In addition, the classification method and classification level of the independent variable has a great impact on the q statistics of Geodetectors. Therefore, with the GD package [33] in R language, full energy was devoted to applying equal breaks, natural breaks, quantile breaks, geometric breaks, and standard deviation breaks to categorize the independent variable in five different ways. After a series of experiments, it was found that the maximum value of the q statistics was concentrated in the range of 10~15 classification series. Therefore, the classification grade number was set to 10~15 categories, from which the spatial scale with the largest q value was selected as the parameter for the geographical detector analysis.

On the basis of selecting the optimal parameters, the driving force of the spatial distribution characteristics of the rural settlements was revealed by using factor detection in the geographical detector. The interaction detector was used to determine the characteristics of the interaction between the two variables, and the q(Xi∩Xj) value of the detection results was used to identify whether the combined interaction between the driving factors increased or weakened the explanatory power of the analyzed variables [32]. The calculation formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} Nh\sigma_h^2}{Nh\sigma_h^2} = 1 - \frac{SSW}{SST} \tag{3}$$

where, q represents the explanatory power of the factor, whose range is [0, 1]. The closer it is to 1, the greater the explanatory power is. h is the explanatory variable or the strata of the explained variable. N_h and N are the numbers of units in layer h and the whole region, respectively. σ_h and σ^2 represent the variance of the h and Y values in the whole region, respectively. SSW and SST are the sum of the in-layer variances and the total variances of the whole area, respectively.

Driving Factors' Selection and Processing

The land scale and the spatial structure of the rural settlements are jointly influenced by natural geographical conditions and socio-economic development [33]. Taking the overall factors such as the natural condition, resource endowment, and socio-economic development of the Northwest Sichuan Plateau into account, efforts were made to set an index system for the influences of the spatial distribution characteristics of rural settlements by following the principles of theoretical judgment and data availability. In this process, three factors, including the physical environment, regional conditions, and socio-economic development are taken into consideration (Table 2). The physical environment included (1) Landform features: A bird's eye view of China would indicate that China's terrain descends in four steps from west to east. The Northwest Sichuan Plateau is located at the border of the first and second steps in China, with fiercely undulating terrain that affects the spatial distribution of the rural settlements. Hence, elevation (X_1) and slope

(X_2) are selected for study [23]. (2) Hydrothermal conditions: Due to the special landform features in the research area, many changes were observed in the vertical climate zone. The annual accumulated temperature (X_3) and rainfall (X_4) were selected to represent this [34]. (3) Vegetation cover: Vegetation is one of the important indicators of the ecological environment's change. In addition, high or low vegetation cover can objectively reflect the situation of the ecological environment of the region to a certain extent [35]. Thus, the location of settlement tends to choose areas with a good ecological environment, and the NDVI (Normalized Difference Vegetation Index) (X_5) was selected to reflect the vegetation cover; and (4) Natural disasters: Many severe seismic geological disasters occur frequently in the research area. The distribution of rural settlements often has the characteristic of "getting benefits and avoiding problems" [36], which may impact the distribution of the rural settlements. The distance to the hazard point (X_6) was selected to reflect the natural disaster situation of each grid. The location conditions included (1) Accessibility: Rural settlements often tend to be located in areas with convenient traffic and many advantages [24]. The selection of distance to the water system (X_7) and distance to roads (X_8) reflected the accessibility of each grid; and (2) Production resources: The spatial structure of the rural settlements should meet the production needs of the local residents. The ecological environment of the Northwest Sichuan Plateau is fragile [37], and the industrial structure is relatively poor. A considerable part of the production activities is mainly in the primary industry [38]. At the same time, the research area has extremely rich natural tourism resources [39] and is one of China's important tourist destinations. Therefore, the distance to the cropland (X_9) and the distance to the scenic spot (X_{10}) were selected to reflect the production resource status of each grid. In terms of socio-economic development, regions with higher economic growth and more concentrated populations often have a larger scale of rural settlements [21]. Hence, GDP (X_{11}) and population (X_{12}) were selected to represent the situation of socioeconomic development of the study area.

Table 2. Calculation method of driving factors for spatial distribution characteristics of rural settlements in the Northwest Sichuan Plateau.

Indicators	Driving Factors	Calculating Methods
Landform features	Elevation (X_1) Slope (X_2)	The Zonal Statistics as Table tool in ArcGIS is used to obtain DEM data.
Hydrothermal conditions	Accumulated Temperature (X_3) Rainfall (X_4)	The Zonal Statistics as Table tool in ArcGIS is used to get data sets.
Vegetation cover	NDVI (X_5)	The Zonal Statistics as Table tool in ArcGIS is used to get data sets.
Natural disasters	Distance To Hazard Point (X_6)	Euclidean Distance can be calculated in ArcGIS.
The living standards and amenities of local communities	Distance To Water System (X_7) Distance To Roads (X_8)	Euclidean Distance can be calculated in ArcGIS.
Production resources	Distance To Cropland (X_9) Distance To Scenic Spot (X_{10})	Euclidean Distance can be calculated in ArcGIS.
Social economy development	GDP (X_{11}) Population (X_{12})	The Zonal Statistics as Table tool in ArcGIS is used to get data sets.

3. Results and Analysis

3.1. Spatial Distribution Pattern

3.1.1. Cluster Distribution Characteristics

A combination of the ANN, Voronoi diagram analysis, and NP's Moran's I determined the spatial distribution pattern of the rural settlements (Table 3). It can be seen that the ANN of the rural settlements in the study area was 0.16; the *CV* in the Voronoi diagram is 1950.26%; and Moran's I of NP was 0.52. The corresponding *p*-value was far less than 0.01, indicating that the probability of the random occurrence of the spatial distribution pattern of the rural settlements in the Northwest Sichuan Plateau was far less than 1%. The spatial distribution of the rural settlements was relatively concentrated. The land terrain of the study area is dominated by mountain valleys with rugged geographical terrain. While most rural settlements are located in flat terrain. Hence, the rural settlements are distributed concentratedly.

Table 3. Indicators of the Spatial Distribution Pattern of Rural Settlements.

Indicators	Value	Zscore
ANN	0.16	−477.03
CV	1950.26%	-
Moran's I	0.52	119.44

3.1.2. Scale Distribution Characteristics

The integrated use of the Voronoi diagram analysis, patch density (PD), patch area (PA), and patch area hot spot analysis (Getis-Ord G_i*) was selected to analyze the scale distribution characteristics of the rural settlements. As can be seen from Figure 3, there were significant spatial differences in the scale of land use (Figure 3a,b) and the number of rural settlements (Figure 3c,d) in the study area. However, the overall spatial trend decreased from east to west. In the east, the upper reaches of the Minjiang River and Dadu River basin were the most intensive areas dominated by rural settlements. The reason is that the area is relatively low in elevation and habitable for humanity. At the same time, the area benefits from arable land resources, water resources, better transportation conditions, and so on, which are suitable for working and living. In its central region, including the Xianshui River basin, which flows through Ganzi County, Luhuo County, and Daofu County, rural settlements, rural settlements were distributed along the strip. This area, located in the Xianshui River Valley area, with a low elevation and better transportation conditions, is conducive to settlement development. The western rural settlements were relatively sparse and dispersed, and most of the rural settlements were distributed in the valley area of the Jinsha River Basin. The reason for this is that this area is dominated by a V-shaped valley landform, resulting in small-scale and scattered settlements.

3.1.3. Morphological Distribution Characteristics

The mean shape index (MSI) and mean patch fractal dimension (FRAC_AM) were used to reflect the plane morphology of the rural settlements in the study area. As shown in Figure 4a,b, the spatial characteristics of the mean shape index and the mean patch fractal dimension based on the rural settlements' grid varied greatly. The distribution correlation was significant at the level of 0.01 (two-tail). Pearson correlation coefficient is 0.666, while the positive correlation is evident. The mean shape index ranged from 0.893 to 5.404, with a large change. Most of them ranged from 1 to 1.2, indicating that the plane morphology complexity of the rural settlements varied greatly. The mean patch fractal dimension distribution was generally consistent with the mean shape index. In addition, the mean patch fractal dimension value was close to 1 in most of the grids, but there were still a few areas where the mean patch fractal dimension value was large. Meanwhile, human activities in these areas are significantly restricted by the natural environment.

The shape index and fractal dimension of the rural settlements in the upper reaches of the Minjiang River, the northeast of Jiuzhaigou, and the middle of Dege County and Aba County were higher, indicating that rural settlements in these areas are complex and irregular in shape, and their distribution is relatively dispersed. This is because the traffic conditions in the upper reaches of the Minjiang River and Jiuzhaigou Valley are relatively good. The rural settlements mostly were constructed along roads and were distributed in strips. The central parts of Dege County and Aba County are located in the valley regions. Influenced by terrain, the rural settlements were distributed along the river course, resulting in a large shape index and fractal dimension. The shape index and fractal dimension of the rural settlements in Ruoergai and the southern parts of Kangding City and Jinchuan County were relatively low. The main reason is that the terrain is relatively flat, and the shape of rural settlements was simple and regular. Therefore, the distribution was very well organized and concentrated. The rural settlements in the south of Jinchuan County were mostly located in the high mountains and the mountainside areas, with dispersed distribution and small scale. Their forms were less affected by rivers and roads and were relatively regular.

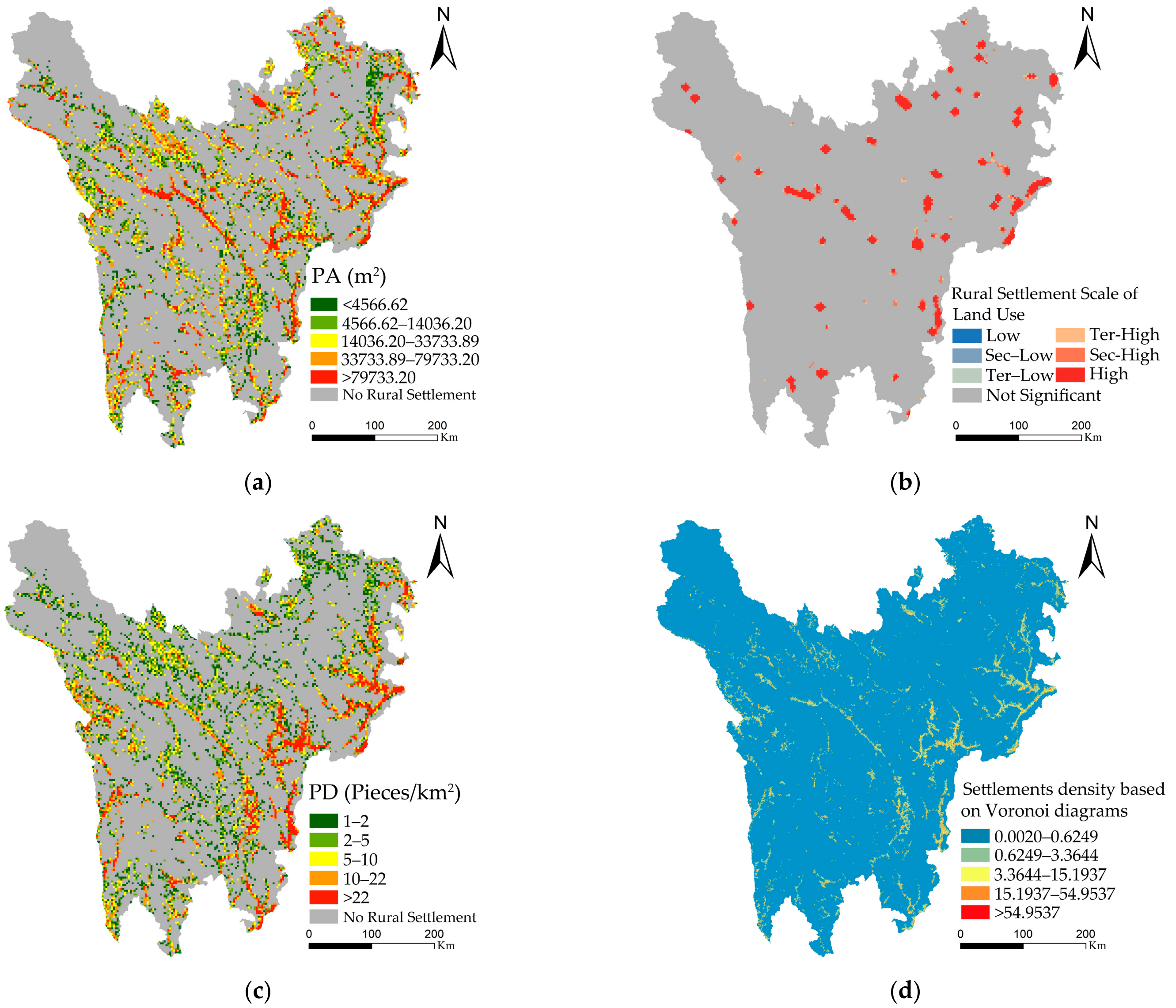
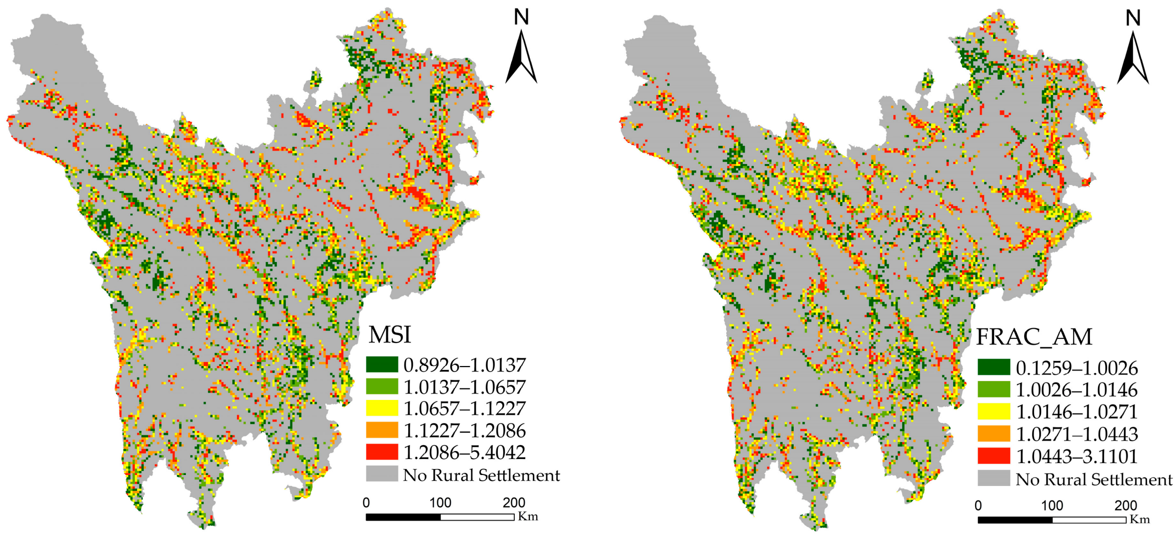


Figure 3. Spatial Differentiation of the Scale of the Rural Settlements. (**a**) Grid-based spatial distribution map of PA; (**b**) Grid-based "hot spot" map of rural settlements in the Northwest Sichuan Plateau; (**c**) Grid-based spatial distribution map of PD; (**d**) Density distribution of rural settlements based on Voronoi diagrams.



(**a**) (**b**)

Figure 4. Spatial Differentiation of the Morphological Structure of Rural Settlements. (**a**) Grid-based spatial distribution map of MSI; (**b**) Grid-based spatial distribution map of FRAC_AM.

3.2. Driving Factors Analysis

3.2.1. Optimal Parameter Selection

In order to further reveal the driving forces of the spatial distribution characteristics of rural settlements, energy was devoted to selecting the patch density (PD) to reflect the features of the rural settlements' locations, to choosing a patch area (PA) to reflect the scale characteristics, and to choose a mean shape index (MSI) to reflect the morphological characteristics. Geodetectors were used to measure the impact of various driving forces on the spatial distribution of rural settlements. In the process of Geodetectors' use, different discrete spaces and various combination methods of interval numbers had obvious influences on the q value, for instance, the selection of the optimal scale of the spatial differences of the rural settlement scale (Figure 5). Taking X_2 as an example, the q value of the equal interval classification was significantly larger than that of the other values, and the q value reached its maximum when the number of intervals was 12. Therefore, X_2 should be the optimal parameter in the geographical detector with 12 quantiles. The discrete spaces varied with the driving factors, and the one with the maximum q value was taken as the optimal parameter of the geographical detector in this study.

3.2.2. Analysis of Driving Factors

Factor Detector. The optimal Geodetector model was used to detect the driving factors of the location, scale, and spatial distribution of the rural settlements in the study area (Table 4). The p-values of each factor all approached 0, passing the significance test of 0.01%. By analyzing the driving factors of the location, scale, and form of the rural settlements, X_9 (distance to cropland), X_1 (elevation), X_6 (distance to hazard point), and X_3 (accumulated temperature) were the main driving factors for the location choice of the rural settlements. This indicates that the settlements were more likely to be distributed in the low-altitude areas around cultivated land with better hydrothermal conditions. However, the settlements in the Northwest Sichuan Plateau rural areas are close to disaster points with hidden trouble. In addition, X_9 (distance to cropland), X_6 (distance to hazard point), X_8 (distance to roads), and X_{10} (distance to scenic spot) were the main driving factors for the size of rural settlements. The Northwest Sichuan Plateau is economically disadvantaged, and primary industry accounts for a relatively high proportion. Therefore, arable land resources had a greater influence on the scale distribution of rural settlements in the northwest plateau of Sichuan. The rapid development of the tourism industry in this region has a significant impact on the distribution of settlement size. X_9 (distance to cropland) and X_6 (distance to hazard point) were the main driving factors affecting the form of rural settlement. In addition, X_8 (distance to roads), X_3 (accumulated Temperature), and X_1 (elevation) also had obvious influences on its morphology. The arable land conditions and disasters not only had a significant influence on the location and scale of rural settlements but also had a profound impact on the morphology of settlements. The roads in the study area are mostly located in areas with low altitudes and good hydrothermal conditions, but the settlement forms along the side of roads were mostly complex, which had a strong influence.

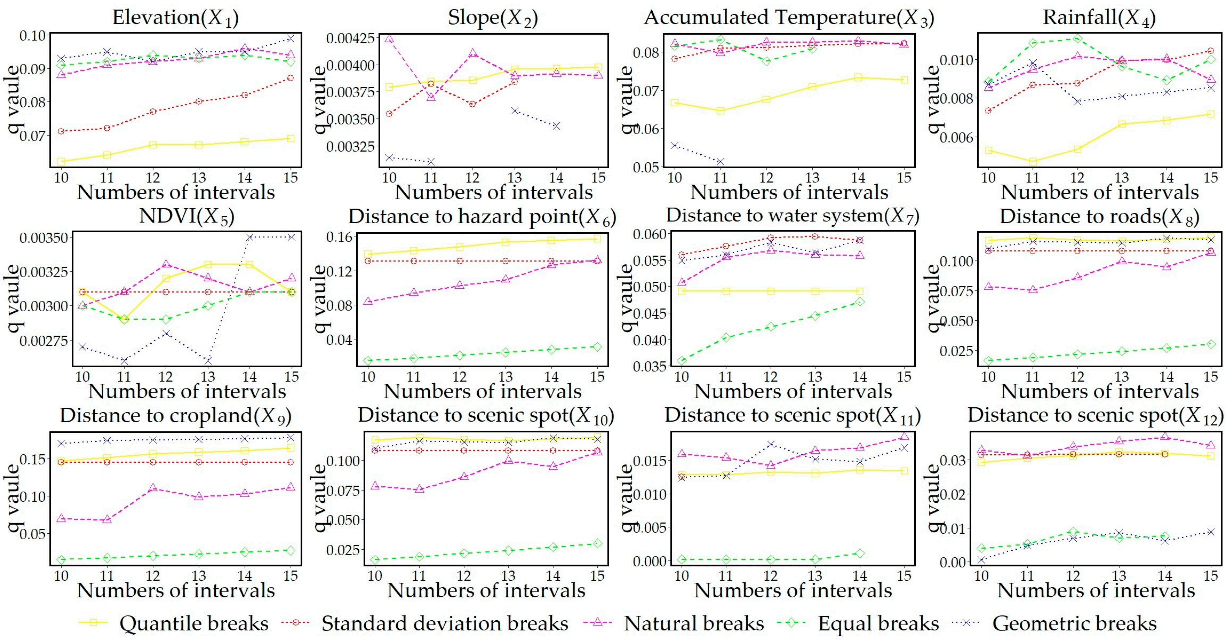


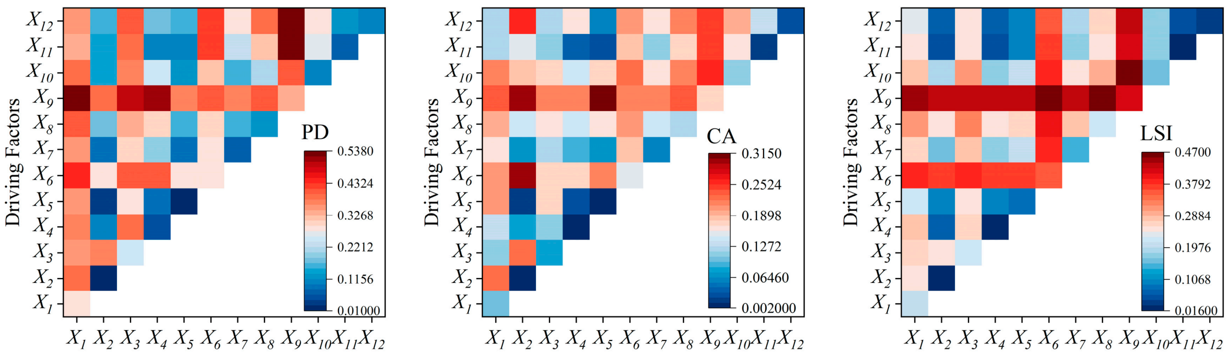
Figure 5. Statistical Chart of Different Classification Methods and q-values of the Number of Partitions in Terms of the Patch Area.

Table 4. Results of Driving Factors of Rural Settlements from the Perspectives of Location-Scale-Morphology.

Driving Factors	Patch Density (PD)-Location	Patch Area (PA)-Scale	Landscape Shape Index (MSI)-Morphology
X_1	0.2798	0.0986	0.2018
X_2	0.0135	0.0045	0.0232
X_3	0.2470	0.0766	0.2252
X_4	0.0571	0.0092	0.0178
X_5	0.0114	0.0029	0.0780
X_6	0.2766	0.1574	0.3503
X_7	0.0718	0.0614	0.1454
X_8	0.1297	0.1196	0.2263
X_9	0.3422	0.1781	0.4112
X_{10}	0.1143	0.1164	0.1541
X_{11}	0.0704	0.0159	0.0253
X_{12}	0.1037	0.0331	0.0351

Interaction Detector. The Reinforcing Effects of Factors. On the basis of studying 12 factors, their interplay was explored in the study (Figure 6). It was found that most of the effects of the different driving factors on the spatial pattern of the location-scale-form of the rural settlements in the Northwest Sichuan Plateau had a nonlinear effect or mutually reinforcing relationships. This shows that there was an interactive relationship between the spatial distribution characteristics of the rural settlements in the Northwest Sichuan

Plateau and each driving factor. $X_9 \cap X_{12}$, $X_1 \cap X_9$, $X_9 \cap X_{11}$, and $X_4 \cap X_9$ had the strongest influence on the spatial distribution of the rural settlements' location (Figure 6a) and their q values were relatively close, at 0.5364, 0.5339, 0.5322, and 0.5049, respectively. All of these were related to X_9. It was further indicated that arable land resources played an active role in the site selection of the rural settlements, while X_{11} and X_{12} had a weak effect on the location spatial distribution of the rural settlements. However, their interplay with X_9 had a significant effect on the location and spatial distribution of the rural settlements. That is to say, the social and economic conditions did not affect the location and spatial distribution of rural settlements alone. However, social and economic conditions and arable land resources together play a fundamental role in the construction and development of rural settlements. $X_5 \cap X_9$, $X_2 \cap X_9$, and $X_2 \cap X_6$ had the most significant impact on the spatial distribution of the rural settlements' scale (Figure 6b), with q values of 0.3145, 0.3028, and 0.2991 respectively. The most significant interplay didn't lie in the factor with the strongest driving effect in the single factor detection but in the interplay between the two factors with the weakest driving effects. In other words, the two factors with the strongest driving effect had the weakest interplay on the spatial distribution characteristics of rural settlements in the Northwest Sichuan Plateau, while the factors with the strongest driving ability and the weakest driving ability had a relatively strong mutual enhancement effect. All of them jointly promoted the development of the rural settlements in the Northwest Sichuan Plateau. Different from the previous situation, the interplay between factors with strong driving ability had the most significant impact on the spatial distribution of the rural settlements' morphology (Figure 6c). When the q value was greater than 0.35, $X_6 \cap X_9$ played the largest role in driving the shape, and the highest q value was 0.4695. It was further revealed that arable land conditions and disaster factors had impacts on the shape of the rural settlements.



(**a**) (**b**) (**c**)

Figure 6. Results of the Detection of the Reinforcing Effects of the Spatial Distribution Characteristics of Rural Settlements from the Perspectives of Location (**a**)-Scale (**b**)-Morphology (**c**).

4. Discussion

4.1. Characteristics of Rural Settlements Distributions

Owing to the long-term geographical isolation and environmental changes, the Northwest Sichuan Plateau has developed a unique ecological and geological environment, which has had a profound impact on the spatial pattern of the rural settlements in this region [40]. The study found that rural settlements in this region were concentrated in low-altitude valleys and mountainside areas, which was in keeping with the findings of Feng Wenlan [41] and Wang Qing [42]. As the valley of the river is very narrow, rural settlements were distributed along this region in strips, dots, and branches. Meanwhile, the differences in the location, scale, and morphological characteristics of rural settlements were also very significant. The eastern rural settlements were dense, while the western rural settlements were very sparse. Low-altitude areas such as the upper reaches of the

Minjiang River, the Xianshui River basin, and the Dajinchuan River had a relatively large scale of rural settlements. The shape of the settlements was significantly affected by the altitude, the settlement shape was more complex, and the degree of fragmentation was higher in the low-altitude valley area. In the high-altitude grassland and mountainside areas, the settlement form was less restricted by the terrain, the shape was relatively simple, and the degree of fragmentation was low. The spatial distribution characteristics of the rural settlements in the Western Sichuan Plateau fully prove that human activities were constrained by the special geographical environment in the study area [24,43], which makes it difficult to achieve the high-quality development of the rural settlements and comprehensive rural revitalization in this region.

4.2. Relationship between the Rural Settlements and Influences

The spatial differences of the rural settlements in the Northwest Sichuan Plateau were also affected by social and economic development, transportation conditions, and the cultural environment. Moreover, the driving forces varied from place to place. The research shows that arable land resources had a significant impact on the spatial differences of the rural settlements, which was closely related to the industrial structure and the ways of living and working in the study area. That is to say, residents remain highly dependent on arable land resources. In addition, roads also had a significant impact on the spatial distribution of the rural settlements in this region. Restricted by the complex terrain in the region, the construction cost of transportation is high, and the transportation network is underdeveloped [44]. Therefore, the rural settlements in this area always continue to move in a positive direction with traffic convenience, and the spatial layout of settlements had an obvious traffic orientation.

Natural disasters also played an important role in the process of rural settlements' formation and evolution [45]. The study region is one of the area's most earthquake-prone with the mass occurrence of geological disasters in China. Thus, there was even a certain spatial interplay between mountain disasters and rural settlements [46]. The q values of the disaster factors on the location, scale, and shape of the rural settlements were 0.2766, 0.1574, and 0.3503, respectively, which significantly affected the spatial differences of the rural settlements. The spatial distribution of rural settlements did not show the characteristics of "getting benefits and avoiding problems" but had close ties has the distribution of disasters. The reason is that the study area is in the highland regions with the geomorphic features of "high altitude and abyssal fault" [47]. The formation of this landscape was closely related to tectonic movements. When tectonic movements make the terrain higher than the base level of erosion and accumulation, the geomorphic features of "high altitude and abyssal fault" are formed under the erosion of rivers. This also leads to the development of rivers, sufficient water resources, and fertile land at the bottom of canyons, which are suitable for agricultural production [48]. The development of rural settlements is guaranteed by those resources.

In the single factor detection, the interaction of factors with larger q statistics was not more significant on the spatial differences of the rural settlements, and the synergistic enhancement effect between factors with larger q statistics and factors with smaller q statistics was often stronger. For example, the single factors of NDVI and slope had a small impact on the rural settlement scale, but the interaction of the NDVI, slope, and arable land factors had the most significant impact on the rural settlement scale. The reason is that the vegetation coverage of regions with large rural settlements tends to be low, while snow-capped mountains are widely distributed in the study area, such as Siguniang Mountain and Chola Mountain, and the vegetation coverage of these regions is also small; so, rural settlements and cropland are rarely distributed. The topography of the study area is undulating, and there are few regions with gentle slopes, so the development of rural settlements often needs to overcome the unfavorable factors introduced by the slope, while cropland is the key factor in the development of rural settlements in the Northwest Sichuan Plateau, and around cropland, local residents usually choose relatively gentle areas to develop rural settlements. The influence of rainfall on the location of rural settlements was very limited. However, when it interacted with arable land resources, the combined effect was very significant and was inseparable from the special geographical environment of the Northwest Sichuan Plateau. Here, the high mountain valleys block the warm air masses from the southeast Pacific monsoon and the southwest Indian Ocean monsoon flow, resulting in a "Foehn Effect" in the valleys, which also leads to more frequent rainfall in the eastern part of the study area than in the western part. Although many areas in the east receive sufficient rainfall, the altitude restriction makes it difficult for rural settlements to develop, while in the lower-altitude areas in the west of the study area, the relatively sufficient rainfall facilitates the development of agriculture and thus the development of rural settlements. Due to the special geographical environment of the study area, the impacts of the population and GDP on rural settlement differences alone were small, but the combined effect with arable land was particularly significant. The q statistics after the interaction of factors even exceeded the values of the interaction between arable land and the other factors with large q statistics. The reason may be that the productivity and industrial structure of the study area are relatively underdeveloped. In addition, the proportion of agriculture, animal husbandry, and tourism is relatively high. The development of rural settlements requires not only natural resources such as arable land, but also capital, policy support, and mass participation.

4.3. Policy Suggestions

The research results show that the spatial distribution of rural settlements in the Northwest Sichuan Plateau is significantly constrained by natural conditions. People have been living either in large or small communities separately. The spatial differentiation characteristics of rural settlements are mostly affected by the current development status of productivity, a relatively poor industrial structure, and the spatial differentiation of cultivated land resources. The research area is a disaster-prone area, and disasters also have a profound impact. In view of the developments outlined above, this article makes the following recommendations for action.

First and foremost, efforts should be made to improve the amenities of local communities and enhance the living standards of rural residents. Next, local decision-makers should take into consideration road planning and traffic control, realize the grading of rural roads, and connect various rural settlements to promote the flow of urban and rural socio-economic factors in the research area. At the same time, steps should be taken to strengthen the construction of basic infrastructure such as water supply and sewage systems, and communication facilities, enhance the living standards of rural residents and achieve rural revitalization in the Northwest Sichuan Plateau.

In addition, it is necessary to guide and promote the development of non-agricultural industries in rural areas, promoting industrial upgrading. Active steps should be taken to promote the industrial transfer of urban and rural regions, cultivate advantageous industries, develop high-quality products, explore local characteristic brands, and reduce reliance on cultivated land resources, thereby enhancing regional industrial competitiveness.

Finally, we should scale up the capacity for conducting disaster prevention and mitigation measures, establishing key disaster resistance projects, and conducting emergency maintenance of infrastructure. Meanwhile, further steps should be taken to release early warning information in a timely manner and take corresponding measures when necessary, and reduce the impact of natural and man-made disasters on rural settlements.

4.4. Advantages and Limitations

In this paper, the landscape pattern index was used to analyze the spatial differences of rural settlements in the Northwest Sichuan Plateau, and the Geodetector model based on the optimal parameters was introduced to detect the spatial differences of rural settlements in the study area. Previous studies have chosen small research scales, and the selected research areas tend to be too typical [6–9], ignoring the more common features of other regions. Taking the Northwest Sichuan Plateau as the research area, we not only explored the common characteristics of the rural settlement differences in the plateaus in the highland regions, but also provided a reference for high-quality rural settlement development, rural settlement optimization, and rural revitalization. In the analysis of driving factors, many scholars adopted the logistic regression model [11,12]. This method is easy to implement and is highly efficient in training, but it cannot solve nonlinear problems. Many researchers also established buffer zones for single factors and superimposed them with rural settlement patches to explore their influence on the location of rural settlements [20,21], but this method cannot compare the effects of different factors. The Geodetector model solved the above problems well [22,23], but its results are greatly affected by the data discretization scale. Therefore, the optimal Geodetector model was used in this study to reduce the biases in the results caused by subjective judgment and to reveal the influence mechanism of various geographical elements on the spatial pattern of rural settlements more scientifically.

In this paper, the landscape pattern index was tapped to analyze the spatial differences features of the rural settlements in the Northwest Sichuan Plateau, and the Geodetector model based on the optimal parameters were introduced to detect the spatial differentiation of rural settlements. Those efforts not only reduced the biases in the results caused by subjective judgment but also provided support for the research on the influence mechanism of various geographical factors on the spatial pattern of rural settlements. However, there were some limitations. In the selection of driving factors, the natural and socio-economic conditions of the study area were mainly concerned, but policies and regulations were not considered [49,50]. Cultural norms and other factors that have an important impact on rural settlement patterns are difficult to quantify. The discretization in the R language GD package is relatively traditional, thus many new discretization options are not included, such as the k-means model and the case-based reasoning method [51]. Different data discretization methods impact the results of Geodetector. In order to obtain more accurate results, it is necessary to compare different discretization methods, which need attention in the follow-up study.

5. Conclusions

In this paper, the nearest neighbor index, the Voronoi map, and the landscape pattern index based on a geographic grid were comprehensively used to study the spatial differentiation characteristics of the location, scale, and morphology of rural settlements in alpine canyons, and the driving factors of detection based on optimal parameters were introduced by Geodetector. The main results were as follows:

(1) The rural settlements in the Northwest Sichuan Plateau exhibit the feature of “an extensive dispersion with localized concentrations”. The average nearest neighbor index was 0.16. The coefficient of variation CV was 1950.26%, and Moran’s I of the number of patches (NP) was 0.52, indicating a clear aggregating trai. However, due to geographic bounds the spatial distribution of settlements is extremely dispersed. Instead of forming an obvious distribution area of “core density area—a circular—core expansion group zone”, the spatial distribution is in the shape of dots, strips, and branches along the river valley.

(2) The number and land use scale of rural settlements in the study area decreased from east to west. The rural settlements in the upper reaches of the Minjiang River and Dadu River basin were the most concentrated, and the Xianshuihe River basin also had banded gathering areas, while the rural settlements in the west were sparse and dispersed. Although the morphology of most rural settlements is relatively simple, the spatial difference is also obvious. Most rural settlements build along rivers and roads, which makes the shape of rural settlements more complex. While the morphology of rural settlements is more regular in plateaus and valley areas.

(3) Restricted by the development status of the productivity and industrial structure of the study area, arable land resources have the most significant impact on the spatial difference characteristics of rural settlements. The geohazards affect the safety of the

settlement site and the spatial difference between rural settlements. The location and morphology of settlements are greatly affected by natural conditions such as altitude and accumulated temperature, while the scale of settlements is significantly compromised by the distance from highways and scenic spots. The mutually reinforcing role of driving factors is remarkable. In particular, the reinforcing effects of the arable land resources and factors with smaller population and q statistics are often stronger, which further proves the influence of arable land resources on the spatial differences in rural settlements in the study area.

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