Research Article

Exploring the Variations of Redbed Badlands and Their Driving Forces in the Nanxiong Basin, Southern China: A Geographically Weighted Regression with Gridded Data

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At present, most of the international research cases on badlands are based on semiarid regions, while there are few studies on badlands in humid regions. Therefore, the research on badlands in humid regions has strong theoretical and practical significance. By taking the Nanxiong Basin, which is located in the humid regions of southern China as the research object, this paper analyzes the scale and spatial distribution variation characteristics of redbed badlands and builds a set of factors that influence redbed badlands to explore the driving forces influencing the variation of redbed badlands based on remote sensing images of the American KH-4A satellite from 1969 and a Landsat 8 image from 2017. The result shows that the scale of redbed badlands in the Nanxiong Basin had generally decreased from 1969 to 2017. The area of redbed badlands decreased from 1693.97 hm² in 1969 to 127.4 hm² in 2017, with a decrease of 92.48%. The spatial distribution of redbed badlands had gradually changed from the contiguous planar distribution form in 1969 to the dispersed island distribution form in 2017, forming four agglomerations. The influence degree of the driving forces for the scale variation of redbed badlands is in the order of lithology > road > aspect > residential locations > slope > water system > vegetation > garden plots. Among these driving forces, except vegetation and garden plots, which have a negative correlation with the variation of redbed badlands, other factors have a positive correlation. Lithology is positively correlated with the variation of redbed badlands and has the strongest influence on the redbed badlands of all the influencing factors. The road factor is second to the lithological factor; the more accessible an area is, the stronger the human influence will be and the more serious the damage to vegetation will be, which easily cause surface vegetation damage, induce land degradation, and form redbed badlands.

1. Introduction

Badlands represent a type of surface landscape cut by strong running water, and they are barren areas that feature dense ravines without vegetation coverage [1, 2]. The problems of badlands make them research hotspots domestically and internationally. The research direction mainly involves the material basis of badlands [3, 4], development and influencing factors [5–8], influence of human activities [9, 10], badland erosion [11, 12], badland ecology [13, 14], and other aspects. At present, most of the international research cases

on badlands are based on semiarid regions, while there are few studies on badlands in humid regions [15]. Therefore, research on badlands in humid regions has strong theoretical and practical significance.

A redbed badland is a geomorphologic shape developed based on the characteristics of the parent rocks of redbeds, which has typical characteristics such as the loss of the topsoil layer, the direct exposure of contiguous redbed bedrock or thin weathered crust of redbed, and the dense distribution of chicken feet-shaped erosion ditches [16]. The redbed badland may occur in any climatic region, and it is especially

FIGURE 1: Typical redbed badlands in the Nanxiong Basin.

worthy of people's attention when it occurs in humid regions [16]. At present, scholars have conducted an in-depth study on the development process of redbed badlands and their influencing factors. Among them, Zhu and Cui [17], Cui [18], and Tian et al. [19] mainly focused on soil and water loss in redbed zones from the perspectives of the water erosion desertification and red desertification in humid areas. Peng et al. [16, 20] believed that the redbed was the extreme form of redbed land degradation and a special type of desertification. Yan [21] analyzed the characteristics of "badland-style redbed desertification" from the perspectives of landscape, geomorphic, soil, and ecological features. In addition, Deng believed that the causes of the redbed degradation in humid regions include both natural and human aspects. Natural causes include climate, soil geology, vegetation, and other factors, while human causes include excessive deforestation, overloading of the land carrying capacity, and blind scale reclamation [22]. Lu believed that lithology is the internal factor for redbed badland formation, but the slope, aspect, and cultivation methods also have a strong influence [23]. Peng et al. believed that the degradation of redbeds is a result of comprehensive action of multifactors. They believed that the initial cause of redbed degradation is the destruction of vegetation and erosion of the soil shell. After

the vegetation is destroyed, the protection function of the vegetation to the soil shell decreases continuously, and the splash erosion ability of raindrops leads to the dispersion of soil particles [24–27], thus forming favorable conditions for the dispersion and erosion of soil particles. However, the research can be further extended to the aspects of the variations in the redbed badland degradation process and the quantitative identification and systematic research of their driving forces.

Redbeds in China's humid regions are mainly distributed in the intermountain small and medium basins in central China and southern China [28, 29], such as Hengyang Basin, Ganzhou Basin, and Nanxiong Basin. Among them, the Nanxiong Basin is located in the humid region of southern China, and the redbed region in Guangdong, Hunan, and Jiangxi is one of the hardest hit areas of soil erosion in China, which is the representative of redbed badland regions in China [21] (Figure 1). Therefore, based on the satellite image data from 1969 and 2017, this research uses RS and GIS spatial analysis methods to analyze the landscape pattern variation characteristics of redbed badlands in the Nanxiong Basin and adopts the geographically weighted regression method to quantitatively analyze the influencing factors of redbed badlands, so as to explore the variation characteristics

FIGURE 2: Location of the Nanxiong Basin. Note: the map of China in this figure is based on the standard map with the drawing approval number GS (2020) No. 4619 downloaded from the website of the Standard Map Service of the Ministry of Natural Resources, and the base map has not been modified.

and mechanism of redbed badlands in representative regions of China and provide a basis for scientific prevention and control.

2. Overview of the Research Area

The Nanxiong Basin is located in the northeast part of Shaoguan, Guangdong Province, at the border of Guangdong, Jiangxi, and Hunan Provinces. The latitude and longitude range from $113^{\circ}50' - 114^{\circ}44'E$ to $24^{\circ}35' - 25^{\circ}24'N$. The basin has a total area of 4500 km^2 , and the redbeds are distributed over an area of 1800 km^2 (Figure 2), accounting for 40%. The geomorphic form of the basin features in low mountains and hills has high terrain in the northeast and low terrain in the southwest, whose altitude ranges from 72 to 621 m. This region has a subtropical wet monsoon climate, with an average annual rainfall of 1535.6 mm, average annual temperature of 19.7°C , and good hydrothermal conditions [21]. The Nanxiong Basin is a typical redbed soft-rock basin, and its redbed belongs to the continental sedimentary rock series formed at the Cretaceous-Paleogene transition between the Meso-Cenozoic and Cenozoic in a dry and hot climate with short intervals of humid and hot climates. The redbed rocks

in the Nanxiong Basin are low in maturity; rich in calcite and feldspar; low in weathering resistance; soft in lithology, generally containing calcareous nodules, purple-red and brown-red in color; poor in diagenesis, and weak in weathering erosion resistance [30]. This city is a key control area of soil erosion in Guangdong Province. The regional GDP of this city achieved 11.384 billion yuan in 2019, with a resident population of 333,300 people.

3. Methodology and Data

3.1. Methodology

3.1.1. Geographically Weighted Regression Model. The factors influencing the development of redbed badlands have spatial characteristics, and the relationship between them changes with the change of geographical location. The general global regression model cannot consider the spatial heterogeneity of regression parameters of spatial data, so it cannot accurately describe the relationship between variables. The geographically weighted regression (GWR) model integrates the spatial attributes of data into the regression model to estimate local parameters, which has been widely used in revealing the

relationship between variables changing with spatial location. Based on this, this paper selects the GWR model to analyze the influencing factors of the development and change of redbed badlands, and the specific formula is [31]

$$y_i = \beta_0(u_i, v_i) + \sum_k a_k(u_i, v_i)x_{ik} + \varepsilon_i. \quad (1)$$

In this formula, y_i is the dependent variable at point i , β_0 is the intercept, x_{ik} is the value of the k th independent variable at point i , k is the independent variable count, i is the sample point count, ε_i is the residual error, (u_i, v_i) is the spatial coordinate of the i th sample point, and $a_k(u_i, v_i)$ is the local regression coefficient at point i .

3.1.2. Selection of Driving Force Indicators. Based on the grid scale, this paper discusses the driving force of changes of redbed badlands. The research area was divided into $1 \text{ km} \times 1 \text{ km}$ unit grids, and the area variation of each grid from 1969 to 2017 was considered to be the dependent variable in the regression model. The redbed badlands are explained as being caused by the joint action of natural factors and human factors. Among the natural factors, lithology, rainfall, slope, and aspect have a strong influence, while the human factors are mainly various human disturbances caused by construction and cultivation. Lithology, slope, and aspect can be directly quantified [21]. Rainfall is a homogeneous index over a small area, so it cannot be used directly and is replaced by the water system. The construction behavior in Nanxiong is mainly reflected by the residential locations and roads. The cultivation behavior mainly takes place in and garden locations. The farmlands in the Nanxiong Basin are paddy fields with no redbed badlands. Therefore, garden locations were used as a symbol of cultivation behavior. To sum up, lithology, slope, aspect, water system, vegetation, residential locations, garden plots, and roads are selected for use as indexes in this paper, and their substitute indexes are lithology, average slope, average aspect, average distance of the water system, average of the garden area, average density of residential locations, average density of garden plots, and average road distance (Table 1).

3.2. Data Sources and Processing

3.2.1. Information Extraction of Redbed Badlands. The basic data sources used in the research are images from the keyhole satellite KH-4B image (focal length: 61 cm; image coverage area per frame: $13.8 \times 188 \text{ km}$) from 1969 with spatial resolution of $1.8 \text{ m} \times 1.8 \text{ m}$ and the Landsat 8 remote sensing image from 2017. ENVI software was used to merge the Landsat 8 multispectral images with Google Earth orthographic images, and the spatial resolution after the fusion reached $0.61 \text{ m} \times 0.61 \text{ m}$.

An early image processing step was to select a specific band sequence in ArcGIS 10.8 for RGB synthesizer rendering and stretching processing and to obtain images with obvious hues, clear hierarchies, and significant color differences among ground objects. Combining the features of color, morphology, texture, and other auxiliary materials, corre-

sponding interpretation marks were established between the remote sensing image features and corresponding Google Earth image features, and visual interpretation and artificial vectorization were carried out in the redbed-poor areas. Some inferior patches with unclear boundaries were verified in the field in October 2017 and June 2018, and the redbed badland distribution map of the Nanxiong Basin was finally generated. In the images from 1969 and 2017, 707 and 331 patches of the red substratum were acquired, respectively (Figure 3).

3.2.2. Other Relevant Data Acquisition. The DEM for the Nanxiong Basin was downloaded through BIGEMAP, and the projection grid and resampling processing were carried out in ArcGIS. The resolution was 30 m, and the slope and aspect information was obtained by using ArcGIS. The current land use status used the land survey data from 2014, from which the river system and residential location elements were obtained. The road network data were obtained from the OpenStreetMap official website. The projection coordinate system (WGS_1984_UTM_Zone_49N) was used for conversion, correction, and spatial matching of the above data.

4. Results

4.1. Spatial-Temporal Variation Features of Redbed Badlands

4.1.1. Scale Variation Characteristics. From 1969 to 2017, the scale of redbed badlands in the Nanxiong Basin generally showed a decreasing trend. Specifically, the patch number of redbed badlands in the Nanxiong Basin decreased from 707 in 1969 to 331 in 2017, with a decrease of 53.18%. The area of redbed badlands decreased from 1693.97 hm^2 in 1969 to 127.4 hm^2 in 2017, with a decrease of 92.48%. The monomer scale of redbed badlands also decreased greatly (Figure 4). The average monomer area in 1969 and 2017 was 2.4 hm^2 and 0.38 hm^2 , respectively, with a decrease of 84.17%. In terms of the largest area of redbed badlands, it was 12.69 hm^2 in 1969 and 2.05 hm^2 in 2017, with a decrease of 83.85%. Among the redbed badlands in 1969, there were 252 areas that were larger than the largest area in 2017 (2.05 hm^2), which accounted for 35.64% of the total quantity of redbed badlands in that year. In 2017, 93.05% of the redbed badlands were smaller than 1 hm^2 and showed a fragmented distribution pattern.

4.1.2. Spatial Distribution and Its Change. In 1969, the redbed badlands showing a continuous plane distribution trend were mainly distributed in the northeast part of the Nanxiong Basin. In the Nanxiong Basin, Huangkeng Town boasts the largest number of redbed badlands accounting for 27.58% of the total number. Hukou Town has the largest redbed badland area accounting for 20.34% of the total area. The redbeds show a decentralized island distribution and form four distinct agglomerations (Figure 5). (1) The Youshan agglomeration is located in the northeastern part of the basin and includes Shangjiang Village, Aijing Village, and Gaosu Village in Youshan Town. In 1969 and 2017, this region belonged to agglomerations, with little change in the agglomeration scope. In 2017, 127 redbed badlands were distributed

TABLE 1: Independent variables and their substitute indexes.

Type of independent variables	Indicators	Index definition	Calculation method	Index definition
Natural factors	Lithology	Influence of different geological group types on the spatial pattern of redbed badlands	$y = \frac{S_i}{S} \times 100$	s_i is the area of the lithologic group type in the unit grid, and S is the area of the unit grid
	Average slope	Influence of slope on the spatial pattern of redbed badlands	$y = \tan \left(\sqrt{\left(\frac{d_z}{dx}\right)^2 + \left(\frac{d_z}{dy}\right)^2} \right) * 57.29578$	d_z/dx is the horizontal change rate of the central pixel, and d_z/dy is the vertical change rate of the central pixel
	Average aspect	Influence of aspect on the spatial pattern of redbed badlands	$y = 57.29578 * \arctan \left(\left[\frac{dz}{dx} \right], \left[\frac{dz}{dy} \right] \right)$	d_z/dx is the change rate of the unit pixel in the x direction, and d_z/dy is the change rate of the unit pixel in the y direction
	Average distance of the water system	Influence of the water system on the spatial pattern of redbed badlands	$d = \frac{\sum_{i=1}^n d_i}{n}, d_i = \sqrt{(x_0 - \chi_i)^2 + (y_0 - y_i)^2}$	x_0 and y_0 are vertical coordinates of badland and the nearest river, χ_i and y_i are centroid coordinates of the nearest badland, d_i is the distance from any badland to the nearest river in the unit grid, n is the number of badlands in the unit grid, and d is the average water system distance in the unit grid
	Average forestland area	Influence of forestland on the spatial pattern of redbed badlands	$y = \frac{\sum_{i=1}^n S_i}{n} \times 100\%$	s_i is the area of vegetation in the unit grid, and S is the area of the unit grid
Human factors	Average density of residential locations		$D = \frac{3(1 - \text{scale}^2)}{\pi r^2}$	scale is the area unit scale factor of residential locations in each grid, r is the neighborhood radius, and D is the average density of residential locations in the unit grid
	Average density of garden plots	Influence of human activities on the spatial pattern of redbed badlands	$D = \frac{3(1 - \text{scale}^2)}{\pi r^2}$	scale is the area unit scale factor of residential locations in each grid, r is the neighborhood radius, and D is the average density of residential locations in the unit grid
	Average road distance		$d = \frac{\sum_{i=1}^n d_i}{n}, d_i = \sqrt{(x_0 - \chi_i)^2 + (y_0 - y_i)^2}$	x_0 and y_0 are vertical coordinates of badland and the nearest river, χ_i and y_i are centroid coordinates of the nearest badland, d_i is the distance from any badland to the nearest river in the unit grid, n is the number of badlands in the unit grid, and d is the average water system distance in the unit grid

FIGURE 3: Distribution of redbed badlands in the Nanxiong Basin in different years.

FIGURE 4: Comparison of the monomer scale of redbed badlands.

FIGURE 5: Density distribution of redbed badlands in the Nanxiong Basin.

in the area, which accounted for 38.37% of the total quantity of redbed badlands and 45.56% of the total area. (2) The Hukou agglomeration is located in the northeastern part of the basin and includes Hukou Village, Xinjing Village, and Xiahu Village in Hukou Town. In 2017, 108 redbed badlands were distributed in the area, which accounted for 33.83% of the total quantity of redbed badlands and 28.59% of the total area. (3)

The Dungang agglomeration is located in the southwest part of the basin and includes Dutang Village and Yuanjing Village. In 1969, the agglomeration degree of this area was not high. In 2017, 60 redbed badlands were distributed in this area, which accounted for 18.13% of the total quantity of redbed badlands and 20.26% of the total area. (4) The Zhutian agglomeration is located in the southwestern part of the basin and includes

FIGURE 6: Types of redbed badlands in the Nanxiong Basin.

Wuzhou Village and Shing Mun Village in Zhutian Town. Different from the Donghang agglomeration area, the agglomeration degree of this area was not high in 1969, and in 2017, it had become an agglomeration area; however, its scale was small. In 2017, 32 redbed badlands were distributed in the area, which accounted for 9.67% of the total quantity of redbed badlands and 5.59% of the total area.

According to the spatial variation characteristics of redbed badlands from 1969 to 2017, the redbed badlands in the Nanxiong Basin can be divided into four types (Figure 6). (1) Type of increased: redbed badlands only existed in 1969. There were 389 redbed badlands with an area of 782.89 hm^2 . (2) Type of reduce: redbed badlands existed in both 1969 and 2017, but the area of the redbed badlands decreased significantly. There were 67 redbed badlands with an area of 463.89 hm^2 . (3) Type of intersect: redbed badlands in 2017 partly overlap with the redbed badlands in 1969, but the redbed badlands in 2017 were not completed within the redbed badlands in 1969. There were 236 badlands in total, and the area was 33.78 hm^2 . (4) Type of disappear: redbed badlands only existed in 2017. There were 19 new redbed badlands with an area of 58.66 hm^2 .

4.2. Influencing Factors and Spatial Heterogeneity of Redbed Badland Changes

4.2.1. Analysis of Influencing Factors Based on the OLS Model. Before taking the GWR model as the method of analysis, the

global regression OLS model must be used to test the relationship between the change scale of redbeds and the explanatory variables determined above. The operation results of the OLS model are shown in Table 2. The adjusted determination coefficient of the model is 0.576, which indicates that the global OLS model can account for 57.6% of the change of redbed badlands. Specifically, except that the garden density and the proportion of forestland are negatively correlated with the change of the redbed badland area, other explanatory variables are positively correlated with the change of the redbed badland area. The positive correlation coefficients of lithology, road, and slope are large, and the robust probability statistics are significant, which indicates that these three types of variables are the main factors affecting the research on changes of redbed badlands. The VIF values of all eight explanatory variables are less than 7.5, and there are no redundant explanatory variables. Meanwhile, the Koenker test shows that the global regression OLS model is unstable in the study area; that is, the relationship between the change of the redbed badland area and explanatory variables in the study area is spatially heterogeneous, which requires an analysis conducted by using the GWR model.

4.2.2. Influencing Factors and Spatial Heterogeneity Based on the GWR Model. The GWR model is analyzed by ArcGIS 10.2, in which the core type adopts the “fixed core” method, and the common Akaike information criterion (AICc) method is adopted to determine the model bandwidth. The

TABLE 2: OLS regression model results.

Explanatory variables	Estimation coefficient	Standard deviation	T statistical value	Robust probability	VIF
Intercept	-0.297470	0.250484	-1.187578	0.235955	—
Lithology	0.643417	0.035579	18.084160	0.000000*	1.069833
Average density of residential locations	0.214968	0.108997	1.972239	0.049511*	1.526899
Average density of garden plots	-0.105391	0.067333	-1.565223	0.118615	1.388346
Average aspect	0.218043	0.212271	1.196011	0.305163	1.175888
Average slope	0.122078	0.115866	1.053615	0.292913	2.472239
Average distance of water system	0.072180	0.041420	1.742632	0.082447	1.436574
Average road distance	0.293969	0.041704	7.048899	0.000000*	1.425976
Proportion of the forestland area	-0.008057	0.002583	-3.119311	0.002002*	2.186504
R^2	0.587				
Adjusted R^2	0.576				
AICc	443.340				
Koenker (BP) statistics	20.517				

TABLE 3: Descriptive statistical analysis of the regression coefficients of the GWR model.

Independent variable	Minimum	25% quantile	Median	75% quantile	Maximum
Constant term	-0.370	0.304	0.572	0.828	4.689
Lithology	0.643301	0.643388	0.64341	0.643435	0.643474
Average density of residential locations	0.214747	0.214941	0.215	0.215043	0.215113
Average density of garden plots	-0.105454	-0.105435	-0.105417	-0.1054	-0.105337
Average aspect	0.217806	0.217859	0.21791	0.21796	0.21814
Average slope	0.121726	0.121846	0.121931	0.122023	0.122358
Average distance of water system	0.071938	0.072142	0.072196	0.072249	0.07232
Average road distance	0.2940	0.294014	0.294024	0.294034	0.29407
Proportion of the forestland area	-0.00806	-0.008056	-0.008055	-0.008055	-0.008055
R^2	0.587				
Adjusted R^2	0.576				
Local R^2	0.587				
AICc	443.348				
Bandwidth	569385.634				

calculation results are shown in Table 3. The determination coefficient and adjusted determination coefficient of the model are 0.587 and 0.576, which are equal to the corresponding values of the global regression OLS model. The AICc value is slightly higher than that of the OLS model, with a difference of 0.008. Within the allowable error range, it can be considered that the performance of the two models is the same, but the local goodness of fit (local R^2) of the GWR model is 0.587, higher than the adjusted determination coefficient (0.576) of the OLS model, indicating that the GWR model is more explanatory in the heterogeneity of the local fit space, the number of conditions of the GWR model is less than 30, and there is no local multicollinearity in the model. Based on the regression coefficient of the GWR model to the influencing factors of each grid, Table 3 makes statistics on the mean value, minimum value, maximum value, upper and lower quartile value of each factor, etc. The median order

of the regression coefficients for each factor is lithology > road > residential locations > aspect > water system > slope > garden plots. From Table 3, it can be seen that from 1969 to 2017, the lithology, aspect, and water system among the natural factors and residential locations and roads among the human factors have a stable positive influence on the variations in the redbed badlands in the Nanxiong Basin. Among them, the median value of the regression coefficient of the lithological factor is approximately 0.643, which is much higher than that for the six other independent variables, followed by roads, residential locations, and slope. The regression coefficients of these three factors are close, ranging from 0.21 to 0.29. The influence of the water system factor is smaller, at only approximately 0.07. The slope and garden plot factors have a negative influence on the variations in the redbed badlands, with regression coefficients between -0.105 and 0.008.

(1) *The Lithological Factor (Figure 7(a))*. Lithology is positively correlated with the variation of redbed badlands and has the strongest influence on the redbed badlands of all the influencing factors. The regression coefficient showed an increasing trend from southwest to northeast in the area from Dungang Town to Youshan Town, indicating that lithology promoted the formation of redbed badlands, which was most significant in the northeast area around Youshan Town. Lithology is the material basis for redbed badland formation. The redbeds in the Nanxiong Basin mainly formed in the Cretaceous and Paleogene, and a total of nine groups are divided into two groups. The area of redbed badlands in the Zhutian, Zhenshui, and Shanghu Formations is as high as 87.98%, while the other redbed badlands are relatively less developed, which results from the main compositions of the redbeds in the Zhutian, Zhenshui, and Shanghu Formations which are argillaceous siltstone, silty mudstone, and silty mudstone, whose components are muddy cementation. The clay mineral content is as high as 28.4–50.3%. Clay minerals are mainly illite and illite-montmorillonite mixed layer, with weak cementation, high clay mineral content, and low degree of compaction. The redbeds are more prone to differential disintegration than other lithologies [30].

(2) *The Aspect Factor (Figure 7(b))*. Aspect is positively correlated with the variations of the redbed badlands; the regression coefficient indicated an increasing trend to the southwest from Youshan Town to Dungang Town, indicating that the influence of aspect on redbed badlands was most significant in the southwest area of Dungang Town. The Nanxiong Basin is located at $24^{\circ}35' - 25^{\circ}24'N$, the southeast direction, which is the aspect that receives the most solar radiation. According to the research of Li et al., increases in temperature accelerate the disintegration of redbed rocks, and the higher the average temperature is, the higher the erosion rate of redbed badlands will be and vice versa [32]. The fractured rock is exposed to the bedrock under rain wash, which is conducive to badland formation. Compared to the eastern slope, the northern slope receives less light, and the possibility of producing badlands decreases.

(3) *The Slope Factor (Figure 7(c))*. Slope is positively correlated with the changes in redbed badlands. The regression coefficient showed an increasing trend to the southwest from Youshan Town to Dungang Town. Badland formation is the extreme result of soil erosion, and the intensity of soil erosion is closely related to the slope. According to the statistics, the slopes in the Nanxiong Basin are between 0 and 51.73° . In 2017, 251 redbed badlands in the Nanxiong Basin were distributed on slopes of $0-5^{\circ}$, accounting for 75.83% of the total quantity. There were 71 badlands on slopes of $5-8^{\circ}$, which accounted for 21.45% of the total quantity. There were 9 badlands on slopes of $8-15^{\circ}$, which accounted for 2.72% of the total land quantity. From large to small, the distribution of badlands was as follows: $0-5^{\circ} > 5-8^{\circ} > 8-15^{\circ}$. No badlands developed on other slopes. The reason is that the rocks comprising the redbeds in the Nanxiong Basin mainly consists of soft rocks, such as siltstones and mudstones. These soft rocks

are characterized by low strength, high porosity, and poor cementation and are significantly affected by structural surface cutting and weathering. The presence of loose, soft, and weak rocks causes the slopes in redbed areas to be relatively slow. However, due to the existence of slope, the gravity will be beneficial to the erosion and movement of weathered soft rock and the formation of redbeds.

(4) *The Water System Factor (Figure 7(d))*. The water system is positively correlated with changes in redbed badlands but has the least influence of all the influencing factors. The regression coefficient showed an increasing trend to the northeast from Dungang Town to Youshan Town. The material foundation of redbeds is soft rock, which is prone to disintegration under a water system and can be completely disintegrated after half an hour of immersion [33]. Due to the existence of soft rocks, such as siltstone and argillaceous rock, when rainfall gathers on the surface, rainfall rarely penetrates into the ground and rapidly gathers and forms small streams of water to erode the surface. With continuous erosion, the parent rock outcrops and, finally, promotes the formation and development of badlands. However, the existence of water is also conducive to soil formation from the weathered debris of soft rock. Under a favorable set of hydrothermal conditions, vegetation recovery is faster, which makes it easy for redbed badlands to naturally recover vegetation or be governed.

(5) *The Residential Location Factor (Figure 7(e))*. The residential location is positively correlated with the changes in redbed badlands and has a strong impact on redbed badlands. The regression coefficient showed an increasing trend to the northeast from Dungang Town to Youshan Town and thus indicated that residential locations have a promoting effect on redbed badlands in all towns, and this effect is most significant in the northeast area around Youshan Town. It is estimated that the average distance between residential areas in the grid and redbed badlands is 405.29 m. In the grid of the redbed badland distribution, the average proportion of construction land is 0.57% and the maximum proportion is 27.54%, which shows that the denser the residential areas are, the more frequent the production and living activities of human beings are and the more serious the damage to vegetation may be. Once the surface vegetation is destroyed, an irreversible degradation process may occur, which becomes an important factor for redbed badland formation.

(6) *The Garden Plot Factor (Figure 7(f))*. The median value of the regression coefficient of garden plots was approximately -0.105, which was negatively correlated with the land changes of redbed badlands and was the same as the forestland factor. The regression coefficient showed an increasing trend to the southwest from Youshan Town to Dungang Town. The reason for this trend is that garden land is mainly a sentry land for redbed badlands. In the same area, if the land can be well utilized, then the possibility of redbed badland development will be decreased, leading to a negative correlation between the two.

FIGURE 7: Continued.

FIGURE 7: GWR model analysis.

(7) *The Road Factor (Figure 7(g))*. The road factor is second to the lithological factor but is also close to the strength of the aspect and residential location factors, indicating that the road factor is positively correlated with the changes in redbed badlands and has a strong influence on redbed badlands. The regression coefficient showed an increasing trend to the southwest from Youshan Town to Dungang Town, indicating that roads promoted redbed badlands in all towns, and it was most significant in the southwest area of Dungang Town. It is calculated that the average distance between roads in the grid and redbed badlands is 342.68 m. In the grid of the redbed badland distribution, the average proportion of road land is 0.56% and the maximum proportion is 5.14%, which is much higher than the grid without redbed badlands, which indicates that the more accessible an area is, the stronger the human influence will be and the more serious the damage to vegetation will be, which easily cause surface vegetation damage, induce land degradation, and form redbed badlands.

(8) *The Forestland Factor (Figure 7(h))*. The same as the garden factor, the forestland factor is one of the two negatively related to the change of redbed badlands, but its negative influence is smaller than that of the garden factor. From 1969 to 2017, the Nanxiong Basin continued to carry out governances for redbed badlands, in which afforestation was an important task. By 2018, the number of the forestland area had reached 445,800 hectares. The restoration of vegetation plays a good role in resisting erosion and conserving water for the degradation of redbeds and effectively inhibits the increase in redbed badlands. There is a trade-off between the two.

The analysis above indicates that the change of redbed badland is a multifactor comprehensive process based on lithology, induced by human activities, a joint action of natural factors such as rainfall, slope, and aspect and human factors such as residential areas and roads.

5. Discussion

A redbed badland is a geomorphologic shape developed based on the characteristics of the parent rocks of redbeds,

which has typical characteristics such as the loss of the topsoil layer, the direct exposure of contiguous redbed bedrock or thin weathered crust of redbed, and the dense distribution of chicken feet-shaped erosion ditches. The research should be further extended to the aspects of the variations in the redbed badland degradation process and the quantitative identification and systematic research of their driving forces.

In this paper, based on the remote sensing images data of American KH-4A from 1969 and Landsat 8 from 2017, the scale and spatial distribution characteristics of redbed badlands are analyzed, and the driving factors of redbed badlands are analyzed by the geographically weighted regression. We found that the landscape index of the redbed badlands generally showed a trend of reduction from 1969 to 2017. The influence degree of the driving factors of the scale change of the redbed badlands is lithology > road > residential locations > aspect > water system > slope > garden plots.

In previous studies, Deng believed that the causes of the redbed degradation in humid regions include both natural and human aspects. Natural causes include climate, soil geology, vegetation, and other factors, while human causes include excessive deforestation, overloading of the land carrying capacity, and blind scale reclamation [22]. Lu believed that lithology is the internal factor for redbed badland formation, but the slope, aspect, and cultivation methods also have a strong influence [23]. Peng et al. believed that the degradation of redbeds is a result of comprehensive action of multifactors. They believed that the initial cause of redbed degradation is the destruction of vegetation and erosion of the soil shell. After the vegetation is destroyed, the protection function of the vegetation to the soil shell decreases continuously, and the splash erosion ability of raindrops leads to the dispersion of soil particles [24–27], thus forming favorable conditions for the dispersion and erosion of soil particles. The conclusion of this paper is consistent with these studies. Furthermore, the research has been extended to the aspects of the variations in the redbed badland degradation process and the quantitative identification and systematic research of their driving forces. At the same time, the importance of the index is further studied.

It should be said that the selection of driving factors is not systematic enough, the analysis is relatively simple, and the quantitative analysis needs to be further strengthened. In addition, not only the plane variations of redbed badlands but also the variations of their height and shape deserve our attention. Based on a comprehensive consideration of the three-dimensional morphology of redbed badlands, future studies need to continuously improve the set of influencing factors and conduct a more in-depth modeling analysis of the factors that influence the development and evolution of redbed badland to clarify its influencing mechanism.

6. Conclusion

At present, most of the international research cases on badlands are in the semiarid areas, while the research on badlands in wet areas are less, so it is of great theoretical and practical significance to carry out the research on badlands in wet areas. Taking redbeds in the Nanxiong Basin located in the humid area of South China as the research target, this paper uses remote sensing images of the American KH-4A satellite from 1969 and Landsat 8 images from 2017 to analyze the scale and spatial distribution characteristics of redbeds, builds a set of factors that influence redbed badlands, and discusses the driving factors of changes of redbed badlands. The results show the following:

- (1) From 1969 to 2017, the landscape index of the redbed badlands generally showed a trend of reduction. In particular, the number of the patches of redbed badlands in the Nanxiong Basin had decreased from 707 in 1969 to 331 in 2017, with a decrease of 53.18%. The area of redbed badlands had decreased from 1693.97 hm² in 1969 to 127.4 hm² in 2017, with a decrease of 92.48%. In terms of spatial distribution, the spatial distribution of redbeds has gradually changed from the planar distribution pattern in 1969 to the island distribution pattern in 2017, forming 4 distinct agglomerations
- (2) The influence degree of the driving factors of the scale change of the redbed badlands is lithology > road > residential locations > aspect > water system > slope > garden plots. Except that the factors of forestlands and gardens are negatively correlated with changes of redbed badlands, other factors are positively correlated with each other
- (3) Lithology is positively correlated with the variation of redbed badlands and has the strongest influence on the redbed badlands of all the influencing factors. Redbeds are mainly composed of argillaceous siltstone, silty mudstone, and silty mudstone, whose components are muddy cementation. The clay mineral content is as high as 28.4–50.3%. Clay minerals are mainly illite and illite-montmorillonite mixed layer, with weak cementation, high clay mineral content, and low degree of compaction. The redbeds are more prone to differential disintegration than other lithologies

- (4) The road factor is positively correlated with the changes in redbed badlands, whose influence on redbed badlands is second to the lithological factor. The more accessible an area is, the stronger the human influence will be and the more serious the damage to vegetation will be, which easily cause surface vegetation damage, induce land degradation, and form redbed badlands

Data Availability

The datasets used in the experiments and discussed in the paper will be available if requested.

Conflicts of Interest

The authors declare no conflict of interest.

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