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Study on the Coupling Relationship between Relocation for Poverty Alleviation and Spatiotemporal Evolution of Rocky Desertification in Karst Areas of Southwest China

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Abstract: The implementation of China's ex situ poverty alleviation and relocation project has alleviated the further deterioration of the ecological environment in the relocation area. It can create favorable conditions for the management of ecological problems such as the natural restoration of rocky desertification and soil erosion. Panzhou City, Guizhou Province, is one of the key areas for the implementation of ex situ poverty alleviation and relocation projects in the 13th Five-Year Plan for China's National Economic and Social Development. The typical ecological problem of karst rocky desertification is an important factor hindering the sustainable development of local society, economy, and ecology. Based on the five-phase remote sensing images and relocated population data, the dynamic change rate, transition matrix, and coupling coordination degree model are utilized to analyze the spatiotemporal changes in rocky desertification in Panzhou City. Meanwhile, the cellular automata (CA) Markov model is used to simulate its future scenarios of rocky desertification. The results show that (i) over the past 20 years, the vegetation coverage in Panzhou has generally increased. The implementation of the ex situ poverty alleviation and relocation project has significantly promoted the reduction of the area and degree of rocky desertification. After relocation (2015–2020), the positive improvement rate of rocky desertification accelerated. (ii) After relocation, the potential rocky desertification (PRD), light rocky desertification (LRD), medium rocky desertification (MRD), severe rocky desertification (SRD), and extreme severe rocky desertification (ESRD) showed a trend of transition to the no rocky desertification (NRD). The improvement effect of rocky desertification is remarkable, and the main contribution is from the PRD and LRD. (iii) The greater the relocation intensity is, the more obvious the improvement effect of the rocky desertification area is, and the higher the corresponding coupling coordination level is. The coupling coordination between LRD and relocation intensity is the highest. (iiii) The forecast results show that by 2025 and 2035, rocky desertification in Panzhou will continue to improve.

Keywords: relocation for poverty alleviation; rocky desertification; spatiotemporal evolution; coupled coordination model; CA Markov

1. Introduction

In the karst area of southwest China, due to the special geological environment and the dual pressures of population overload and socioeconomic backwardness, the ecological environment has been seriously degraded [1], and the problem of karst rocky desertification with a large area of exposed bedrock has occurred. Karst rocky desertification refers to a kind of desertification landscape formed against the background of a subtropical fragile karst environment, which is disturbed and damaged by unreasonable human social and economic activities, resulting in serious soil erosion and exposed bedrock [2]. Its existence not only increases the incidence of poverty, immigration, and other social problems [3] but endangers the survival of human beings. Therefore, karst rocky desertification has become the most serious ecological and geological environmental problem restricting the sustainable development of Southwest China [4]. Its influencing factors include geology, hydrology, and human activities [5]. Among them, ecological restoration projects are an important factor. Through timely management, degraded surface vegetation can be gradually restored and promote ecological restoration [6].

The relocation project for poverty alleviation is to relocate poor farmers living in areas with fragile ecological environments, such as deep mountains, rocky mountains, and areas with rocky desertification and a lack of basic development conditions. It is the best way to break the vicious circle of "pover⟶environmental degradatio⟶further poverty" [7,8]. Changes in human social behavior are regarded as important factors leading to changes in the relationship between economic development and the natural environment [9–11], and policy is a major driver of its change. Ecological migration is one of the main models of rocky desertification control [12]. It is beneficial to improve rocky desertification by making scientific resettlement plans [13]. Disturbed by human activities, the direction, and speed of rocky desertification caused by ex situ poverty alleviation and relocation projects may be different under different human activities. The research results of these differences are significant for promoting the prevention and improvement of rocky desertification in karst areas.

The content of rebuilding the livelihood space and capital of the poor through poverty alleviation and relocation includes economic, ecological, and social aspects [14]. Sarah Rogers [15] discussed the key differences between the different families in Ji County. Fan Minning [16] analyzed the impact of resettlement on the livelihood of herdsmen in western Inner Mongolia. Kevin Lo [17] presents unique suggestions for the government to formulate resettlement programs. In addition, many scholars have discussed the spatial distribution, law, and evolution trend of rocky desertification based on different scales [18–24], providing a scientific basis for making forward-looking and targeted ecological environment protection and restoration plans.

By 2020, Guizhou Province had completed the relocation of 1.92 million people and built a win-win Guizhou model of socioeconomic development and ecological protection [25]. From the existing studies, the research on ex situ poverty alleviation and relocation at present mainly focuses on socioeconomic development, and most evaluation indicators proposed are broad and fuzzy. In addition, there are few research results to simulate the future scenarios of rocky desertification in karst areas, which makes it difficult to provide effective data support for the current and future rocky desertification control. The coupling coordination degree model can quantitatively reveal the coupling coordination degree between different relocated population densities and rocky desertification variables caused by ex situ poverty alleviation and relocation. Meanwhile, the cellular automata (CA) Markov prediction model with a strong spatial dynamic evolution advantage will play an important role in predicting its development trend.

Panzhou City belongs to the rocky desertification area of Guizhou in China. It has a large surface cutting degree and high population pressure [26], which belongs to a region with strong ecological environment sensitivity [27]. Analyzing the improvement of rocky desertification on a city scale can reflect the quality of the regional ecological environment. In this paper, Panzhou City, which is located in an important area for ex situ poverty alleviation and relocation and ecological restoration projects during the "13th Five-Year Plan" period, is taken as the research area. The data from 2000, 2005, 2010, 2015, and 2020 are utilized to reveal the evolution law of rocky desertification in Panzhou City from the spatiotemporal perspective. Based on the relocated population and other data, combined with the coupling coordination degree model, the relationship between the spatiotemporal evolution of local rocky desertification and the support policy response driven by the ex situ poverty alleviation and relocation project was analyzed, which can put forward scientific and effective decision support and policy recommendations for the follow-up assistance measures and effective use of funds for the ex situ poverty alleviation and relocation project. The cellular automata (CA) Markov prediction model with a strong spatial dynamic evolution advantage is used to simulate the rocky desertification scenarios of Panzhou City in 2025 and 2035. It is expected to provide data support for exploring the evolution law and effective management of rocky desertification in subtropical karst areas and the long-term goal of fundamental improvement of the ecological environment in China from 2020 to 2035.

2. Materials and Methods

2.1. Study Area

Panzhou City is located at the junction of Yunnan, Guizhou, and Guangxi Provinces. It is the west gate of Guizhou Province, which is located in southwestern Liupanshui City, with a land area of 4056 km^2, situated in the birthplace of the northern and southern Panjiang River in the Pearl River Basin, the transitional slope position of the Yunnan Guizhou Plateau and the upstream slope of the southwest monsoon. Guizhou is a bridgehead open to Yunnan and Southeast Asia, a strategic energy base in southern China, and an important node of Yunnan Guizhou transportation, energy, commerce, logistics, and tourism. The terrain in the area is undulating and broken, and the types of karst landforms are complete. The local natural climate is pleasant; the annual average temperature is 15.2 °C, the average annual frost-free period is 271 d, the sunshine hours are 1593 h, the average annual precipitation is 1390 mm, and the rain and heat are basically the same every season. Under the unique karst landform background and the influence of unreasonable human production activities, the existing eco-environmental problems are mainly rocky desertification and soil erosion. The ecological environment is sensitive and fragile. It is one of the counties with a large karst area and rocky desertification area and the most serious rocky desertification degree in Guizhou. It is one of the counties with the largest karst area and the most serious rock desertification in Guizhou. To date, the city has completed the relocation of 29,490 people in 8183 households (including 25,456 poor people in 7135 households). In 386 administrative villages, 112 natural villages were relocated as a whole, and the relocation occupancy rate was 100% (Figure 1).

2.2. Data Source and Processing

The remote sensing data sources used in this study come from 91 bitmap (http://www.91weitu.com/, accessed on 2 January 2022), with a spatial resolution of 2.5 m, for accuracy verification) and Landsat images (http://www.gscloud.cn/, accessed on 2 January 2022, resolution 30 m, used to interpret rocky desertification). No resolution matching of different remote sensing data is involved. The remote sensing data are preprocessed by means of radiometric calibration, atmospheric correction, and masking. The relevant data on rocky desertification in five phases (imaging time is from March to May) in the study area from 2000, 2005, 2010, 2015, and 2020 were extracted. Support vector machine (SVM, SVM is a machine learning method based on statistical learning theory SVM can automatically find those support vectors that have a large discrimination ability for classification.) is used to interpret the image of the study area and extract water, building land and other ground features. There are many evaluation indicators to characterize the classification accuracy of remote sensing images, but the most commonly used indicators in the academic community to evaluate the classification accuracy of remote sensing images are the overall classification accuracy (equals the sum of correctly classified cells divided by the total number of cells. The number of correctly classified cells is distributed along the diagonal of the confusion matrix, and the total number of cells is equal to the total number of cells in all true reference sources.) and Kappa coefficient (Kappa coefficient is an indicator of consistency in statistics, with a value of [−1, 1], and often used to measure classification accuracy. It is calculated by multiplying the total number of pixels in all ground truth categories (N) by the sum of the diagonal lines of the confusion matrix (Xkk), and then subtracting the sum of the total number of ground truth pixels in a class and the total number of classified pixels in that class). Because the overall classification accuracy can well characterize the classification accuracy of remote sensing images, the Kappa coefficient can make a more comprehensive and objective analysis of the classification accuracy. We match the surface real region of interest generated by the field survey results with the final classification results. Combined with the confusion matrix, the accuracy of the classification results is verified. The overall classification accuracy is 92.30%, and the kappa coefficient is 0.84. Nonkarst data come from the 1:50,000 geological map of the karst Science Data Center (http://www.karstdata.cn/, accessed on 2 January 2022). The poverty alleviation and relocation population data in Panzhou City come from the Ecological Immigration Bureau of Guizhou Province.

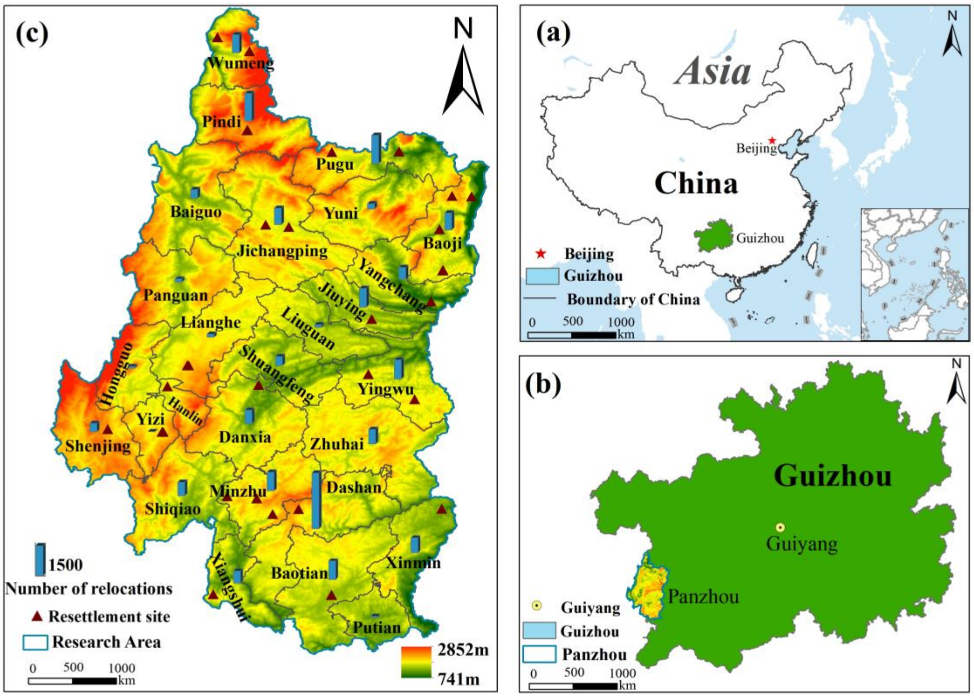

Figure 1. The location map of Panzhou in Guizhou City, China. Notes: (**a**) Guizhou City in China; (**b**) Panzhou District in Guizhou City; (**c**) Overview and relocation population density of Panzhou.

2.3. Rocky Desertification Index

The evaluation index of rocky desertification is generally selected by the landscape characteristics and main causes of these characteristics. The most direct sign of rocky desertification landscape is the large-area exposure of bedrock and the decline of vegetation coverage. At present, it has become the classification index with the highest selection rate for rocky desertification research [28–32]. In addition, slope is an important natural influence condition in the evolution of rocky desertification and is often used as its grading index. Combined with the principles of purpose, operability, and representativeness of the selection of rocky desertification monitoring indicators. At the same time, the dominant factors and geographical environment affecting the evolution of rocky desertification in the study area are considered. Finally, three indices, namely, fractional vegetation cover (FVC), rock exposure (RE), and slope, were selected as the evaluation indices for the evolution of the spatial pattern of rocky desertification in this study (Table 1).

Table 1. Classification of rocky desertification.

Strength Grade		Rock Exposure Rate (%)	Vegetation Coverage (%)	Slope (°)
NRD		<20	>70	<5°
PRD		20~30	60~70	5°–8°
Rocky desertification	LRD	30~50	50~60	8°–15°
	MRD	50~70	30~50	15°–25°
	SRD	70~90	10~30	25°–35°
	ESRD	>90	<10	>35°

2.4. Classification of Rocky Desertification

In view of the differences in index thresholds and the scope of the study area, the classification standards of rocky desertification are different. In some studies, rocky desertification is divided into four grades by using vegetation coverage and the bedrock exposure rate [33]. According to the differences in classification standards, the State Forestry Administration formulated the technical regulations on rocky desertification monitoring in karst areas (revised in 2011). Rocky desertification is divided into no rocky desertification (NRD), potential rocky desertification (PRD), light rocky desertification (LRD), medium rocky desertification (MRD), severe rocky desertification (SRD), and extreme severe rocky desertification (ESRD). In this study, the classification standards of rocky desertification were selected according to the classification standards of predecessors and combined with factors such as data availability and research purposes; refer to Table 1 [34].

2.5. Research Methods

2.5.1. Rate of Change

The evolution of rocky desertification is a dynamic and complex process. Choosing a scientific time scale is a key problem in calculating the evolution rate of rocky desertification. The expression formula is:

$$V = \frac{(S_j - S_i)}{T} \tag{1}$$

S_i and S_j are the initial and final areas of rocky desertification during the monitoring period, respectively. The area of rocky desertification improvement/deterioration is the area difference between them. When the value is greater than 0, rocky desertification is a positive evolution. In contrast, it is a reverse evolution [35]. V is the average annual change rate of rocky desertification. The higher its value is, the faster the improvement or deterioration rate of rocky desertification is. T is the monitoring time period.

2.5.2. Image Difference Analysis

Image difference analysis refers to the difference between the image data at the end and initial stage of the monitoring period, and its value can reflect the improvement or degradation of vegetation coverage/rock exposure rate in adjacent years [36].

2.5.3. Transfer Matrix

The evolution direction and scale of rocky desertification are complex over a certain period of time and often vary from place to place. Therefore, building a rocky desertification transfer matrix model aims to clarify the evolution direction and transformation trend of rocky desertification in the study area [37]. The expression formula is:

$$S_{ij} = \begin{bmatrix} s_{11} s_{12} \cdots s_{1n} \\ s_{21} s_{22} \cdots s_{2n} \\ \cdots\cdots\cdots\cdots \\ s_{n1} s_{n2} \cdots s_{nn} \end{bmatrix} \tag{2}$$

where S_{ij} is the rocky desertification transfer matrix. n is the number of rocky desertification types. i and j represent the rocky desertification grade serial number at the beginning and end of a cycle, respectively.

2.5.4. Coupling Coordination Model

Coupling coordination refers to the interaction between itself and the outside world. To better reflect the impact of relocation on rocky desertification in the study area. Establish the coupling degree and coupling coordination degree model between rocky desertification variables and relocated population density in the study area [38,39]. The coupling coordination degree model is suitable for analyzing the coordinated development level of things. This study was conducted using the SPSSAU online platform; based on the results of rocky desertification interpreted from remote sensing data, the variation was obtained and coupled with the relocation density of towns in Panzhou City. The townships participating in the coupled analysis do not include areas that are not involved in relocated populations and where rocky desertification has not occurred. The coupling degree C and coupling coordination degree D are utilized to describe the degree of their interaction and overall development level, respectively. The model expression is:

$$C = \sqrt{\frac{U_1 \times U_2}{[(U_1 + U_2)/2]^2}} \tag{3}$$

$$D = \sqrt{C \times T}; T = \alpha \times U_1 + \beta \times U_2 \tag{4}$$

where U_1 is the standardized data of the rocky desertification increment in the village. U_2 is the relocated population or the proportion of the relocated population in the village. C is the system coupling degree, T is the comprehensive evaluation index of U_1 and U_2. α, and β is the undetermined coefficient, taken as $\alpha = \beta = 0.5$. D refers to coupled co-scheduling, and the high/low value of D indicates that there is a high/low-level mutual promotion/restriction relationship between the two systems [40]. In view of the division standard of physics (Table 2), the coupling degree and coupling coordination degree are graded to illustrate the coupling relationship between rocky desertification variables and relocated population density [41].

Table 2. Coupling Stages division of rocky desertification area increment and scale of relocated population.

Coupling Level	Low Coupling	General Coupling	Highly Coupling	Extreme Coupling
Coupling coordination level	Low coupling coordination degree	General coupling coordination degree	Highly coupling coordination degree	Extreme coupling coordination level
Coupling degree C/Coupling coordination degree D	[0, 0.3)	[0.3, 0.5)	[0.5, 0.8)	[0.8, 1)

Note: Coupling degree C illustrates the relationship between rocky desertification variables at all levels and the relocated population. Coupling coordination degree D can explain the relationship between the systems and the overall development level of the system, indicating whether the systems are restricting or promoting.

2.5.5. CA-Markov Model

Cellular automata (CA) is a spatiotemporal dynamic model based on discontinuity. Its time, space, and state are discrete. The model expression is:

$$S_{(t+1)} = f[S_{(t)}, U] \tag{5}$$

$S_{(t+1)}$ and $S_{(t)}$ are finite and discrete state sets of cells at different times, and U is cell neighborhood. F is the transformation rule of local space cell state. The Markov model is a method formed based on the Markov stochastic process theory, which can be used to analyze the development law of events and predict its future trend [42]. The expression is:

$$S_{(t+1)} = S_t \times Z_{ij} \quad (6)$$

$S_{(t+1)}$ and $S_{(t)}$ are the states of different space-time systems. Z_{ij} is the state transition matrix. Cellular automata (CA) model has powerful spatial computing ability and can effectively simulate the spatial changes of the system [43–45]. CA-Markov model combines the spatial dynamic evolution advantages of CA model and the long-term prediction advantages of Markov model. It can effectively simulate the spatial change of rocky desertification patterns. The basic idea of the CA Model is to infer the trend of future scenarios based on the laws of past changes of events. Using the situation at a certain moment and the probability of development to predict the future state of the event, its predictability can reach a high level. It is generally believed that the state transition of a researched thing at a certain moment is only related to the state of the previous and has nothing to do with the state of other. The principle of CA-Model is to take the distribution pattern of rocky desertification as a simulation site and to simulate the grid in the image as a cell, and the attribute of each cell (the type of rocky desertification it belongs to) is the cell state. Existing studies have proved that the application of this model to simulate the development trend of rocky desertification is applicable and scientific [45,46]. This study is based on the interpretation results of remote sensing image data. On the basis of the rocky desertification data obtained by interpretation, the CA-Markov model is used to simulate the development scenario of rocky desertification in Panzhou City, and the results predicted by the model can basically reflect the development trend of rocky desertification.

3. Results

3.1. Spatiotemporal Evolution Analysis of Influencing Factors of Rocky Desertification

The changes in pixel vegetation coverage and the rock exposed rate are closely related to the evolution of rocky desertification. Using the interactive operation of ENVI5.3 and ArcGIS10.2, the distribution map of vegetation coverage and rock exposure rate from 2000 to 2020 was obtained (Figure 2). From 2000 to 2020, the vegetation coverage of Panzhou showed an overall increasing trend. In 2000, the vegetation coverage in the study area was higher in the northeast and south and lower in the middle and northwest. The vegetation coverage of towns and villages in central and northern China was low in 2010. In 2015, the vegetation coverage of Panzhou City increased, with the high-value areas mainly concentrated in the southeast and the low-value areas concentrated in the western part of the study area. The growth trend is the most obvious in 2020, with lower vegetation coverage of rivers and construction land and higher vegetation coverage in other areas. The closer to the construction and water area, the higher the rock exposure rate. The area of the rock exposed rate is the largest in 2010 and the smallest in 2020.

The grid calculator is used to subtract the vegetation coverage and rock exposure rate in different years to obtain the corresponding change map in different periods (Figure 3). Among them, a positive value indicates that the vegetation coverage/rock exposure rate grade of the corresponding area is increasing, and a negative value indicates that it is decreasing. The higher the absolute value, the more significant the trend of grade increase/decrease. From 2000 to 2005, the vegetation coverage in the northeast and southwest of the study area showed a decreasing trend, especially in Wumeng and Pingdi. The grade of rock exposure rate increased obviously, but the grade of vegetation coverage increased significantly from 2005 to 2010. From 2010 to 2015, the vegetation coverage in the East of the study area was mostly higher than that in 2005–2010. Compared with the other three periods, the improvement of vegetation coverage in 2015–2020 is the most obvious. The places with reduced vegetation coverage are mainly concentrated in rivers and densely built areas. The rock exposure rates in Pugu and Baoji township from 2005 to 2010, as well as in Wumeng and Pingdi Township from 2010 to 2015, were significantly improved.

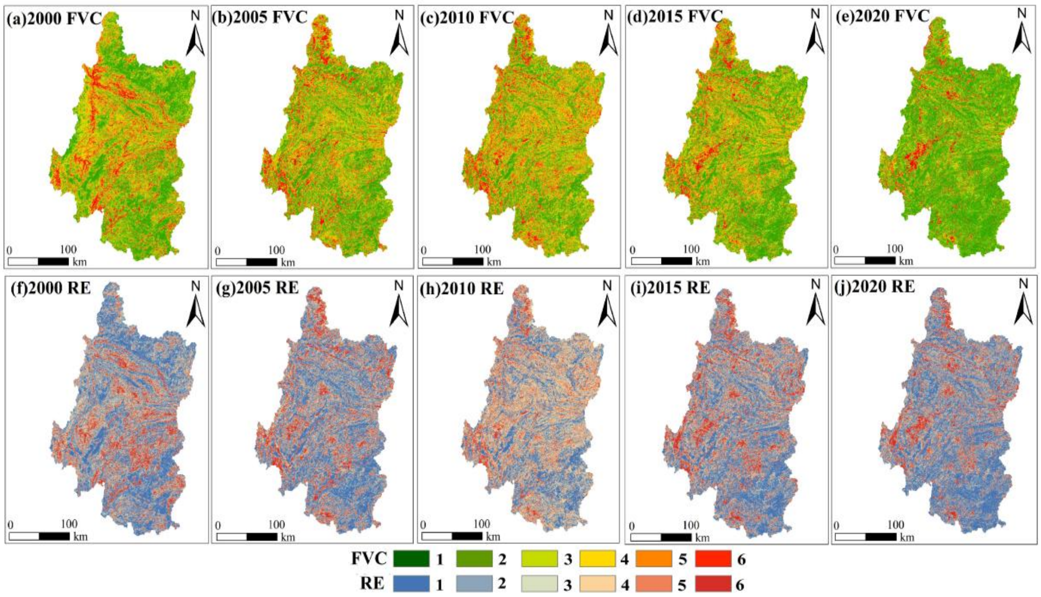

Figure 2. Distribution of fractional vegetation cover (FVC) and rock exposure (RE) rate (Numbers "1–6" indicate the classification of fractional vegetation cover and rock exposure. The higher the value, the lower the fractional vegetation cover and the higher the rock exposure.).

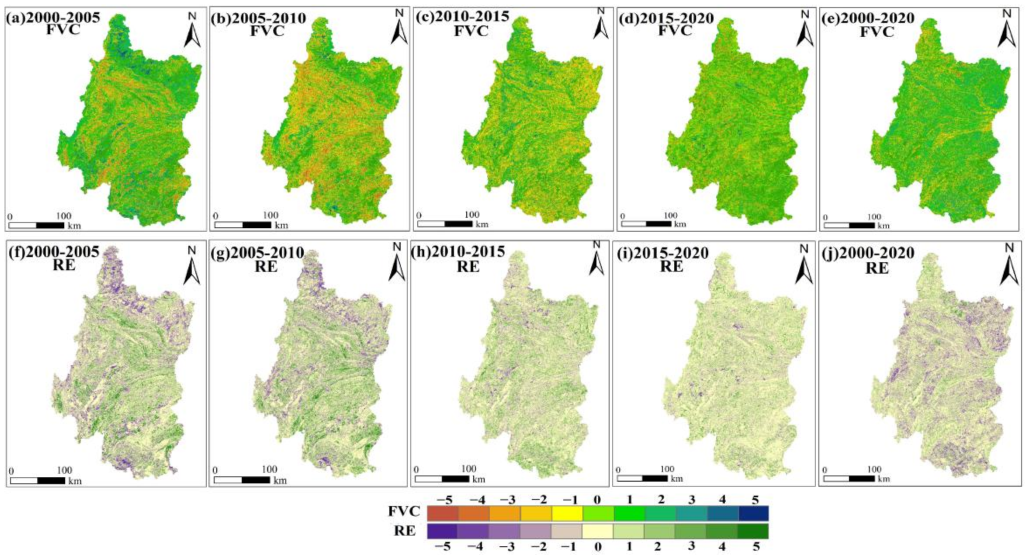

Figure 3. Fractional vegetation cover (FVC) and rock exposure (RE) changes in each period (Numbers "−5–5" indicate the change level of fractional vegetation cover and rock exposure, a positive value indicates an increase in the regional fractional vegetation cover/rock exposure, and a negative value indicates a decrease in the regional fractional vegetation cover/rock exposure.).

3.2. Spatial and Temporal Distribution Pattern of Rocky Desertification

3.2.1. Distribution of Rocky Desertification

The karst development in Panzhou City, Guizhou Province, is strong; the terrain is undulating and broken, and the rocky desertification types and the grades are complete. In 2000, the area of rocky desertification occurred was 1269.76 km^2, accounting for 48.17% of the karst area (Table 3). In 2005, the distribution region of rocky desertification decreased slightly with an area of 1264.70 km^2. The proportion of rocky desertification area ranks from large to small: NRD > MRD > LRD > SRD > PRD > ESRD, with an area of 718.86 km^2, 605.46 km^2, 299.54 km^2, 249.44 km^2, 224.79 km^2, 110.25 km^2 respectively (Table 3).

Table 3. Statistics of rocky desertification area in Panzhou City from 2000 to 2020 (Unit: km^2).

	2000		2005		2010		2015		2020	
	Area	**Ratio (%)**	**Area**	**Ratio (%)**	**Area**	**Ratio (%)**	**Area**	**Ratio (%)**	**Area**	**Ratio (%)**
NRD	670.34	31.87	682.86	32.46	502.52	23.89	665.14	31.62	934.23	44.41
PRD	235.25	11.18	186.09	8.85	173.81	8.26	222.78	10.59	266.38	12.66
LRD	307.43	14.61	269.54	12.81	244.12	11.60	298.68	14.20	300.18	14.27
MRD	607.35	28.87	605.46	28.78	684.71	32.55	595.57	28.31	416.76	19.81
SRD	198.33	9.43	249.44	11.86	364.56	17.33	221.43	10.53	105.89	5.03
ESRD	84.94	4.04	110.25	5.24	133.92	6.37	100.04	4.76	80.2	3.81

Note: "Ratio" in Table 3 represents the proportion of different rocky desertification grades in the total rocky desertification area of each grade.

In 2010, MRD, SRD, and ESRD were widely distributed in all villages and towns in the study area. The deteriorating area of rocky desertification is increasing, and there are still many NRD lands that are constantly eroded by rocky desertification. The area of rocky desertification above the LRD is expanding, and the area of SRD increases most significantly. The second is MRD, with an area of 109.99 km^2. Baoji Township, located in the northeast of the study area, is a typical representative area. The relatively pure middle massive limestone and dolomitic limestone in the local area provide the geological basis for the development of rocky desertification. Meanwhile, the karst area is mainly a carbonate distribution area; the surface water is easy to lose, the soil forming conditions are poor, and the lack of water and soil makes the vegetation recovery slow. Human activities destroy the surface vegetation and disturb the soil, which has become the direct inducement of rocky desertification. From 2010 to 2015, the area of MRD and SRD decreased by 105.88 km^2 and 123.39 km^2, respectively. Compared with 2010, the PRD increased significantly, and the MRD increased slightly. In 2020, the area of rocky desertification at all levels and types in the study area was decreasing, and only a few areas have serious rocky desertification. Among them, the areas of LRD, MRD, SRD, and ESRD decreased by 8.50 km^2, 142.80 km^2, 79.26 km^{2,} and 26.12 km^2, respectively. The proportion of NRD and PRD is relatively high, close to half of the regional karst area. The land and homestead left by nearly 30,000 people who have been relocated for poverty alleviation in Panzhou City have been reclaimed and greened or converted to ecological construction land. The local forest coverage has been greatly improved, and the population pressure in the relocated areas has been alleviated to a certain extent. After the implementation of the ex situ poverty alleviation and relocation project, a large number of small-scale water conservancy projects, such as "three small" water conservancy, matching of smoke and water, rainwater collection, and storage, have been implemented in Wumeng, Pingdi, Minzhu, Baoji and other towns where rocky desertification is serious (Figure 4). At the same time, a fair amount of projects such as enclosure management and returning farmland to forests and grasslands have been implemented one after another. The implementation of the policy of returning farmland to the enclosure by ecological immigrants has replaced the original annual, rotating, and low farmland crops with perennial and tall natural wild vegetation. Make the vegetation coverage increase greatly, and have a more favorable impact on the local climate conditions of the surrounding areas. This will help to effectively reduce rocky desertification, realize the restoration of vegetation as soon as possible, and curb man-made soil erosion leading to rocky desertification.

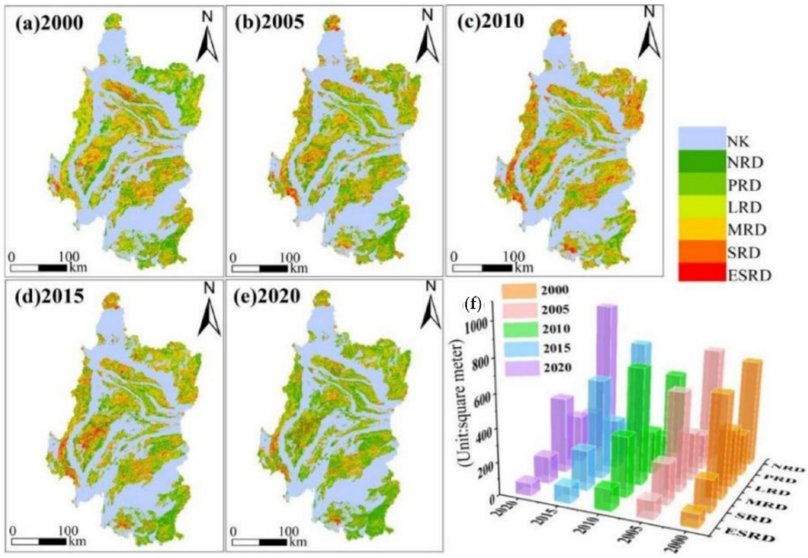

Figure 4. Rocky desertifification distribution data. (**a**–**e**) respectively show the distribution of rocky desertification in corresponding years. (**f**) shows the statistical area of rocky desertification.

3.2.2. Dynamic Change Rate of Rocky Desertification

The study takes 5 years and 10 years as time periods, respectively, and adopts long-term and short-term time scales for analysis. Calculate the annual average change rate of rocky desertification in different monitoring periods in order to find the long-term and short-term evolution law of rocky desertification in the study area (Figure 5, Tables 4 and 5). As can be seen from Figure 5, the annual average change rates of rocky desertification change areas at all levels are different in seven monitoring periods. In the short term, the period from 2000 to 2005 (the Tenth Five Year Plan) is actually the period when rocky desertification really begins to be controlled, and the evolution rate of rocky desertification is relatively slow. From 2005 to 2010 (the Eleventh Five Year Plan), the governance effect of the Tenth Five-Year Plan was characterized during this period, and The rate of evolution was accelerating, evolving at the rate of 9.52 km^2/a. From 2015 to 2020, the improvement rate of rocky desertification is the fastest, and MRD and ESRD have been effectively controlled. The area without NRD and PRD increased significantly, and the ecological environment continued to improve. It shows that the effect of rocky desertification control is not immediate but a long-term recovery process.

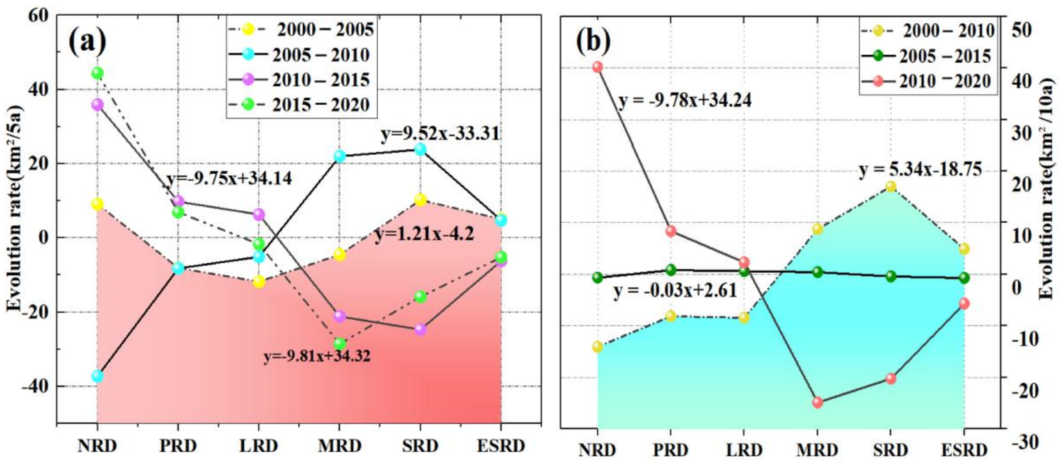

Figure 5. Evolution speed curve of rocky desertification type (The time step is 5 years for (**a**) and 10 years for (**b**)).

Table 4. Reversal area and evolution speed of short-term rocky desertification.

	2000–2005		2005–2010		2015–2010		2020–2015	
	ΔS	ΔV	ΔS	ΔV	ΔS	ΔV	ΔS	ΔV
NRD	45.52	9.10	−186.34	−37.27	179.62	35.92	222.08	44.42
PRD	−40.46	−8.09	−40.99	−8.20	48.97	9.79	34.59	6.92
LRD	−58.88	−11.78	−25.42	−5.08	31.56	6.31	−8.50	−1.70
MRD	−22.63	−4.53	109.99	22.00	−105.88	−21.18	−142.80	−28.56
SRD	51.11	10.22	119.10	23.82	−123.39	−24.68	−79.26	−15.85
ESRD	25.34	5.07	23.67	4.73	−30.88	−6.18	−26.12	−5.22

Table 5. Reversal area and evolution speed of long-term rocky desertification.

	2000–2010		2005–2015		2010–2020		2000–2020	
	ΔS	ΔV	ΔS	ΔV	ΔS	ΔV	ΔS	ΔV
NRD	−140.82	−14.08	−6.72	−0.67	401.71	40.17	222.08	44.42
PRD	−81.45	−8.14	7.99	0.80	83.57	8.36	34.59	6.92
LRD	−84.30	−8.43	6.14	0.61	23.06	2.31	−8.50	−1.70
MRD	87.36	8.74	4.11	0.41	−248.68	−24.87	−142.80	−28.56
SRD	170.21	17.02	−4.30	−0.43	−202.65	−20.26	−79.26	−15.85
ESRD	49.00	4.90	−7.22	−0.72	−57.00	−5.70	−26.12	−5.22

Note: "ΔS" in Note: "ΔS" in Tables 4 and 5 represents the area of change in the development or reversal of rocky desertification. "ΔV" represents the annual change rate of rocky desertification development or reversal during the monitoring period.

From a long-term perspective, the evolution rate of rocky desertification presents the characteristics of fast, slow, and changeable in different time periods. The evolution speed of rocky desertification is different at all levels. From 2000 to 2010, the order was: SRD > NRD > MRD > LRD > PRD > ESRD. From 2005 to 2015, the evolution speed of rocky desertification was slow, and its development/reversal speed at different levels had little difference. From 2010 to 2020, the evolution rate of rocky desertification reached the fastest in 20 years. Equally, the increase rate of NRD reached the highest (40.17 km^2). MRD and SRD also decreased the fastest.

3.3. Change of Rocky Desertification Types before and after Relocation

The transition matrix is used to describe the state transition of objective things, which can clearly represent the real situation of rocky desertification changes. It is conducive to studying the change process of rocky desertification. Based on the maps of five rocky desertification types in Panzhou City in 2000, 2005, 2010, 2015, and 2020. By using the tabulate area in ArcGIS software, the rocky desertification transfer matrix of Panzhou City in 2000–2005, 2005–2010, 2010–2015, and 2015–2020 is calculated. The transfer map of rocky desertification type and the statistical map of the transfer area are made by using Origin Software (Figure 6). Before the implementation of the relocation project, the transition from LRD to MRD and from MRD to SRD was the most obvious during 2000–2005. The transformation areas are 134.14 km^2 and 118.91 km^2, respectively. The second is the transition from MRD to NRD, covering an area of 71.45 km^2. The conversion area between other types is relatively small.

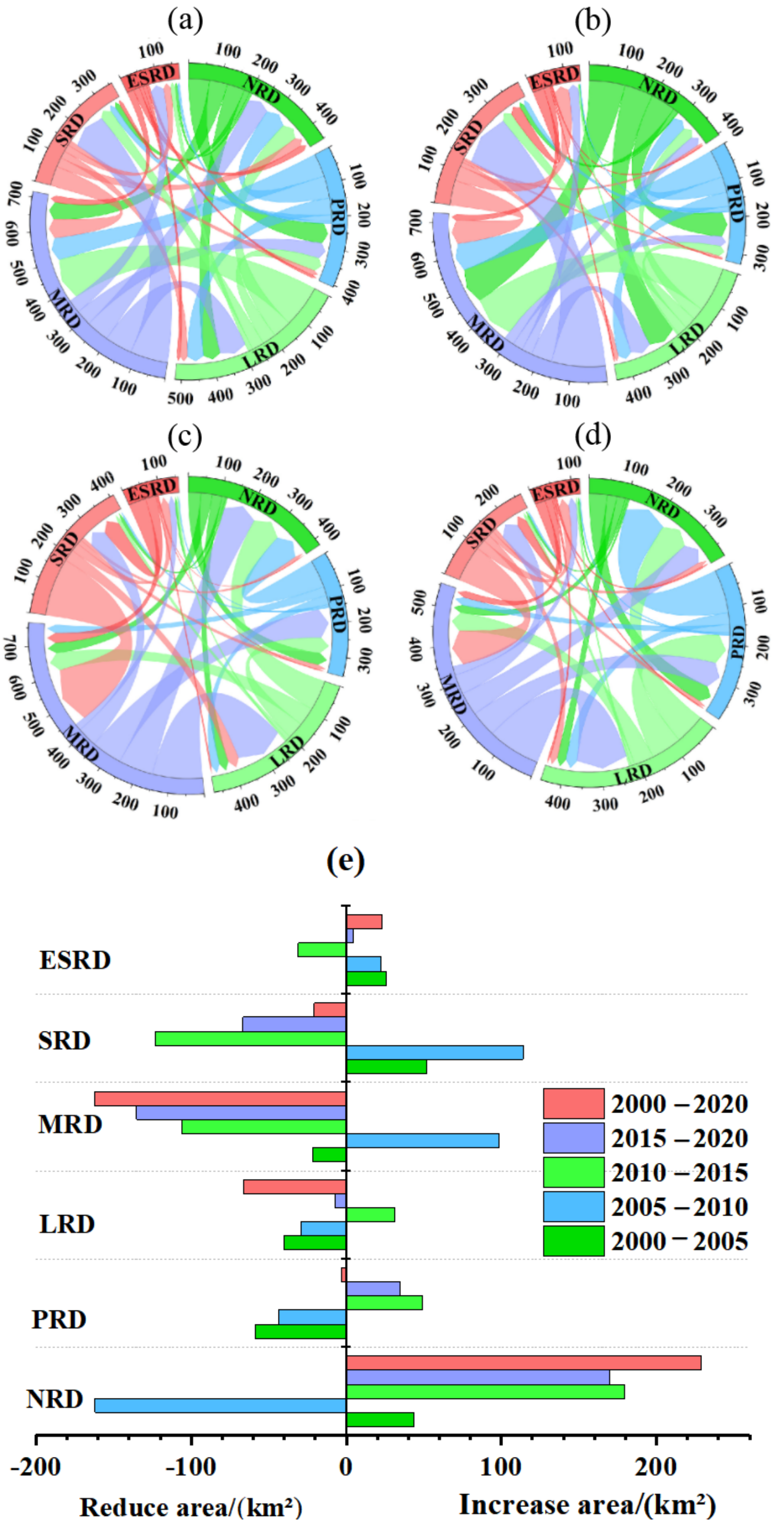

Figure 6. Rocky desertification transfer in different periods and transfer area statistics: (**a**) 200–2005, (**b**) 2005–2010, (**c**) 2010–2015, (**d**) 2015–2020, (**e**) area statistics.

The increased types of net rocky desertification areas are mainly NRD (43.76 km^2), SRD (51.56 km^2), and ESRD (25.61 km^2). From 2005 to 2010, the main trend was the change from SRD, LRD, PRD, and NRD to MRD. The areas are 71.68 km^2, 133.75 km^2, 81.65 km^2, and 106.29 km^2, respectively. At the same time, the transformation from MRD to SRD is the most significant, with an area of 160.16 km^2. On the whole, rocky desertification is deteriorating. The largest net transfer area of rocky desertification is the SRD, with an area of 116.93 km^2. The largest net transfer out area is NRD, which covers an area of 162.03 km^2. It shows that in this period, the control of rocky desertification is weaker than that of interference and destruction. In the duration 2010–2015, the transition from SRD to MRD was the most prominent. In addition, MRD has changed greatly to LRD, PRD, and NRD. The transformation areas are 153.89 km^2, 94.19 km^2, and 106.54 km^2, respectively. The area of rocky desertification above moderate level is decreasing. The main body of rocky desertification improvement is NRD and MRD; improved areas are 138.63 km^2 and 71.56 km^2, respectively. The main contribution comes from PRD (115.01 km^2) and MRD (80.62 km^2), respectively. The area of LRD and above types has an obvious reduction trend. Rocky desertification in only a few areas shows an increasing trend. The MRD and SRD area decreased by 201.82 km^2, and the ESRD area increased by 4.49 km^2. Combined with Figure 7, it can be seen that the area of ESRD increased during 2000–2020, and the types of increasing rocky desertification in the study area are NRD and ESRD. The increased area is 228.72 km^2 and 23.26 km^2, respectively. It shows that in recent 20 years, the achievements of rocky desertification control in Panzhou City have coexisted with the destruction of the ecological environment.

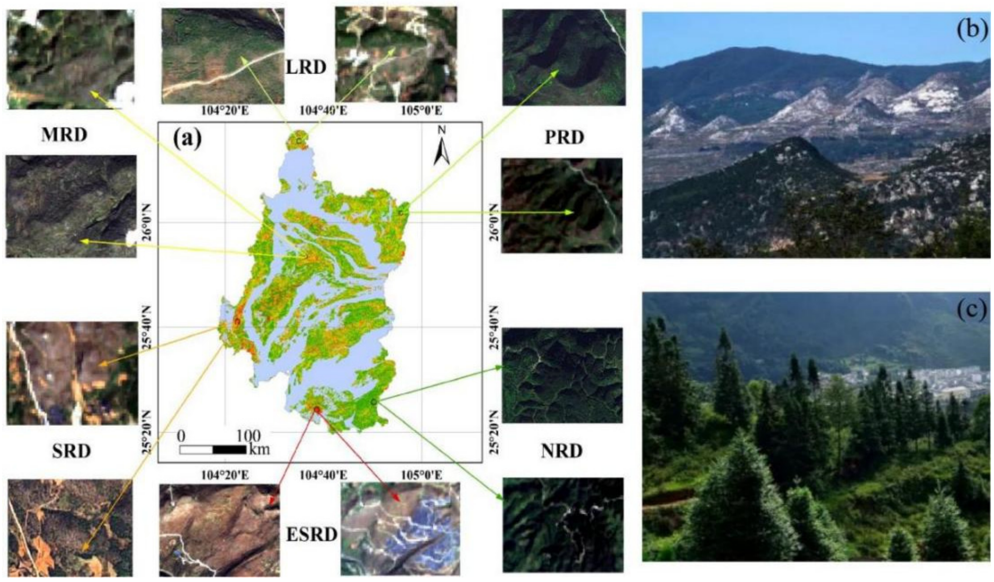

Figure 7. Interpretation result verification: (**a**) comparison between rocky desert resolution and actual images, (**b**) before treatment; (**c**) after treatment.

3.4. Analysis of Coupling Coordination Degree between Ex Situ Poverty Alleviation and Relocation and Rocky Desertification

During the whole relocation period, the spatial distribution of the relocated population in Panzhou City showed a spatial pattern of "less in the middle and more in the north and South". The relocated population is concentrated in Wumeng, Pingdi, Pugu, Jichangping and Jiuying in the northeast of the study area and Yingwu, Minzhu, Dashan, and Baotian in the southeast. Among them, the relocated population of Pingdi, Pugu, Yingwu, and Dashan all exceeded 1000 people. Accounting for 5.31%, 7.59%, 7.74%, and 15.3% of the total relocated population in Panzhou. Based on data integrity and availability, 266 administrative villages were selected in Panzhou City as the research unit. Using the coupling coordination degree model, measure the coupling degree C and coupling coordination degree D of the population density of relocation and the increment of different types of rocky desertification in the research unit (Figure 8).

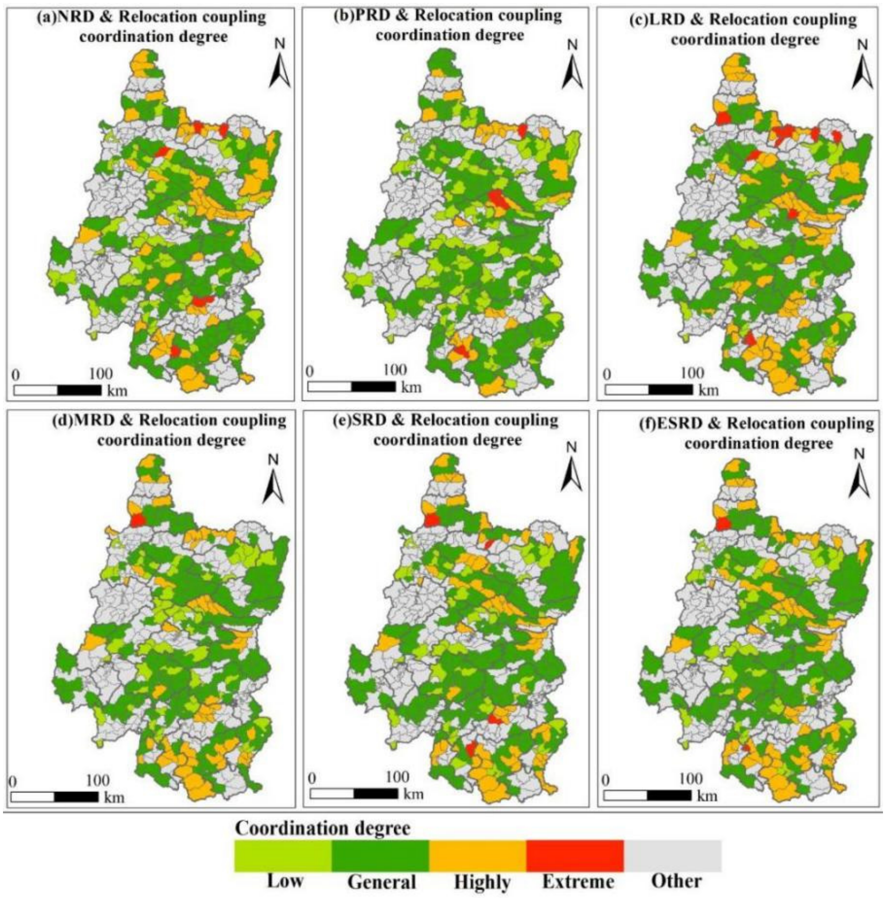

Figure 8. Coupling coordination degree of rocky desertification increment and relocated population.

The coupling coordination degree of PRD, LRD, MRD, SRD, and ESRD area improvement and the number of relocated population in the study area is dominated by general coupling coordination as a whole. The greater the relocation intensity, the more obvious the improvement effect of the rocky desertification area in the village, and the corresponding level of coupling coordination is higher. It can be seen from Figure 8 that the coupling coordination degree between the type of NRD and the relocated population is high-quality coordination in six administrative villages. These areas are scattered in Lemi, Shuiba, Bendai, Yujie, Zaojiaoshu, and Gao Xiang, and 53 villages have reached a high level of coordination. The proportion of administrative villages whose coupling coordination degree value is above the general coupling degree accounted for 76.32%. The number of coupling and coordination degrees of potential rocky desertification types in each research unit has reached a high level, or higher is 29. Dam, Gaoxing, Luojiatian, and Badaohe Village are extremely coupled. The number of administrative villages with the coupling degree between LRD and the number of relocated people is the highest, and there are 10 altogether. In addition, the coupling degree between 160 villages and 68 administrative villages is general coupling and high coupling. Among the 266 administrative villages in the study area, only 28 villages are in a state of low coupling. There are 163 administrative villages with a general coupling level between MRD and relocation, accounting for 60.15%, ranking first among the six types of rocky desertification. The number of administrative villages with high-quality coupling coordination is the least. The coupling coordination degree of MRD, SRD, and ESRD is followed by 80.45%, 83.46%, and 83.08%. Among them, 160 villages in both SRD and ESRD have reached the general coupling level. The number of administrative villages with a high degree of coupling and coordination is also the same, accounting for 60.15%. It can be seen that the change of land use mode caused by easy relocation and the reduction of the disturbance and damage of human activities on the land have significant effects on the improvement of local rocky desertification. It plays a key role in promoting the sustainable development of the ecosystem in the study area and improving and protecting the local ecological environment.

3.5. Future Scenario Prediction of Rocky Desertification

At present, the expansion trend of rocky desertification in the study area can be controlled to a certain extent. However, there is still a gradual deterioration in some areas, which needs to be controlled urgently. The evolution of rocky desertification is a gradual process, and various influencing factors will not change significantly. The development trend of rocky desertification in Panzhou City will largely continue the change law from 2015 to 2020. Therefore, through the interactive operation of ArcGIS 10.3 and IDRISI Selva 17.0, the spatial analysis of the distribution map of rocky desertification in Panzhou City in 2015 and 2020 was carried out. To study the evolution of rocky desertification grades in Panzhou from 2015 to 2020. Thus, the regional characteristics of rocky desertification changes can be analyzed. Meanwhile, the CA-Markov model is adopted to predict the future development trend of rocky desertification in Panzhou (Figure 9).

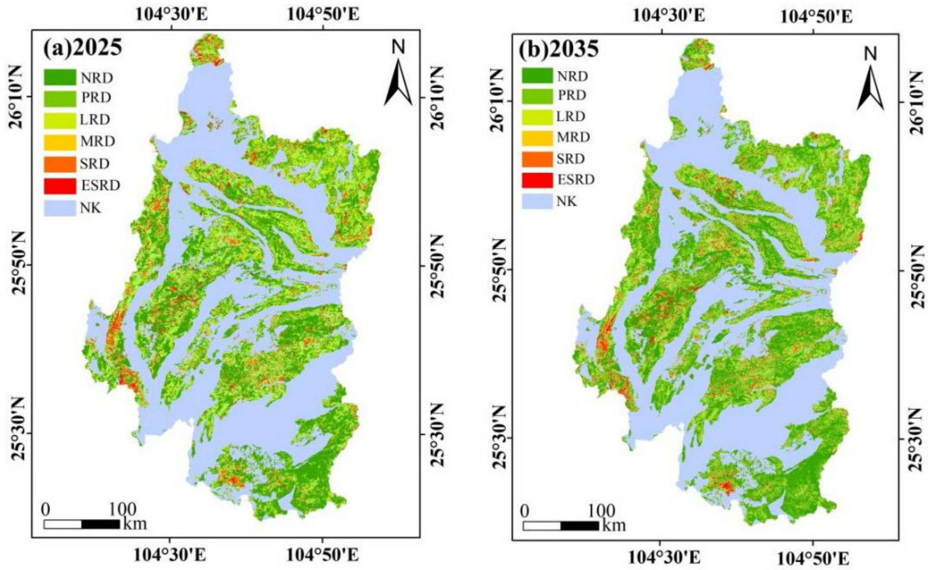

Figure 9. Prediction map of rocky desertification. (**a**,**b**) show the prediction results for 2025 and 2035, respectively.

In 2025, the NRD area of Panzhou City will increase from 934.23 km^2 in 2020 to 968.50 km^2 (Table 6), reaching 48.10%. Secondly, MRD reduced the area most, which reduced from 416.76 km^2 to 315.34 km^2, a total reduction of 101.42 km^2. High-grade rocky desertification (MRD, SRD, ESRD) is mainly distributed in the north and southwest of the study area. Among them, Wumeng, Baoji, Shengjing Street, Jichangping, and other towns are mostly distributed. From 2025 to 2035, NRD and PRD will increase by 9.76 km^2 and 82.68 km^2, accounting for 51.16% and 15.88%, respectively. The remaining types of rocky desertification are all decreasing. The reduction trend of the MRD area is the most obvious, with a total reduction of 54.91 km^2. The second is SRD, and the reduction amount is 31.10 km^2. At the same time, the LRD and ESRD landscapes will not change much between 2025 and 2035. The proportion difference was 1.48% and 1.32%, respectively. In 2035, the proportion of rocky desertification landscapes in the total area of the study area is in the order of NRD > PRD > LRD > MRD > SRD > ESRD. Among the rocky desertification types that have occurred, LRD has the largest proportion, and ESRD has the smallest. The evolution of rocky desertification is not achieved overnight but is a complex and gradual process. From the absolute value of the change rate of rocky desertification increase (Table 6), the maximum change rate is the ESRD, with a change rate of 38.98%. The rate of change of PRD is the second, which is 34.86%, and the LRD is the smallest (9.31%). It is easy to see that the type of rocky desertification with the greatest decrease or increase is not necessarily the one with the greatest rate of change. It indicates that some areas are in a situation of deteriorating at the same time during the process of ecological restoration of rocky desertification. In addition, the ecological restoration of rocky desertification should not only pay attention to the areas where rocky desertification has occurred but also take note of the areas where rocky desertification has not occurred. We should strive to improve rocky-desertification-worsening areas and prevent rocky desertification areas.

Table 6. Prediction results of rocky desertification in Panzhou City in 2025 and 2035.

Type	2025		2035		2025–2035	
	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Amount of Change/km^2	Rate of Change (%)
NRD	968.5	48.1	1028.26	51.06	59.76	6.17%
PRD	237.16	11.78	319.84	15.88	82.68	34.86%
LRD	320.16	15.9	290.35	14.42	−29.81	−9.31%
MRD	315.34	15.66	260.43	12.93	−54.91	−17.41%
SRD	104.18	5.17	73.08	3.63	−31.1	−29.85%
ESRD	68.3	3.39	41.68	2.07	−26.62	−38.98%

Note: "Ratio" represents the proportion of different rocky desertification grades in the total rocky desertification area of each grade.

4. Discussion

The implementation effect of ex situ poverty alleviation and relocation is a hot issue of great concern to academia and the government [46]. This study explores the response relationship between the temporal and spatial evolution of rocky desertification and the relocation policy for poverty alleviation and relocation through coupling coordination degree and other methods. The results show that the total area of rocky desertification in the study area has changed significantly from 2000 to 2020. Rocky desertification presents a changing trend of "improvement deterioration improvement". At the same time, the improvement rate of rocky desertification reached the fastest during 2015–2020. After the implementation of the relocation project, the area without rocky desertification has increased significantly. In addition, the greater the relocation in the study area, the more obvious the improvement effect of the rocky desertification area in the village, and the higher the corresponding coupling coordination level. The carbonate rocks widely distributed in Panzhou are hard in texture and low in water permeability. Precipitation falls into such areas, and part of it flows off in the form of runoff, which becomes the carrier of soil particle transportation and provides good geological basic conditions for the development of rocky desertification [47]. Due to the arid habitat, more stones, and less soil, it is difficult for vegetation to breed. Once subjected to production and living activities that are easy to damage the ecological environment, such as human reclamation, grazing, and firewood collection, the habitat could easily deteriorate sharply and fall into a vicious circle of vegetation and land degradation. The more fragile the local ecosystem is, the more likely rocky desertification is to occur or tend to deteriorate [48]. If natural conditions are regarded as the internal cause, unreasonable human activities are the external cause of rocky desertification [49]. If there is no external factor, only driven by internal factors, the evolution of rocky desertification will be extremely slow. The superposition of active human production and construction activities and natural background accelerates the evolution of rocky desertification. After the implementation of the relocation project, the population relocation has alleviated the contradiction between humans and land in ecologically fragile areas from the source. Fewer human construction activities greatly reduce the bearing pressure on the ecological environment in the relocation area. The land and vegetation have been maintained, and the natural ecological recovery is good, which is conducive to the restoration and enhancement of the function of the natural ecosystems.

As a policy of benefiting the people in a specific historical period, relocation for poverty alleviation in other places has achieved good implementation results [50]. The benefit evaluation of relocation involves economic, social, and ecological benefits. At this stage, the research mainly focuses on social and economic development, which is not conducive to highlighting the comprehensive effect of relocation. This study makes a quantitative study on the evolution direction and rate of rocky desertification in the study area from two dimensions of time and space. Figures 4 and 6 show that after relocation, the area of rocky desertification is significantly improved, and the overall transfer of the population in the relocation area is helpful in promoting the natural restoration of the ecological environment. After the relocation, the old houses are demolished, the homestead is reclaimed and greened, and the ecological restoration of slope farmland above 25 degrees is carried out by using the policy of returning farmland to forest, which greatly improves the forest coverage in the study area and conserves water sources, so as to effectively reduce rocky desertification. This is the same as the ecological benefit assessment conclusions of Baolu [51] and Li Peilin [52] after the relocation of rural residents. Separately, it is worth noting that in 2010, the rocky desertification-free land in most areas of the study area was continuously eroded by rocky desertification, and the rocky desertification was serious. Regional water resources and the ecological environment are affected by the change in precipitation. Continuous drought leads to the expansion of regional rocky desertification areas at a certain rate every year [53]. In 2009–2013, under the background of a weak south branch trough, less water vapor transport in the Bay of Bengal, and a weak polar vortex, the Arctic Oscillation negative abnormal cold air path was eastward, and the precipitation dropped sharply, resulting in severe drought in most areas of Guizhou [54], which is an important reason for the serious rocky desertification in Guizhou in 2010 [55].

In addition, the evolution of rocky desertification is affected by many factors, such as lithology, geological structure, slope, precipitation, etc. [4,5,9,14]. Among them, there are obvious differences between rocky desertification of different grades and different land use types. correlation [56]. After the implementation of the ex situ poverty alleviation and relocation project, the land use pattern in Panzhou City has changed, and different land use methods have different interference effects and interference processes on different land ecosystems. The karst rocky desertification land degradation process, degree of degradation, and characteristics of degraded communities are different, which are ultimately manifested in the differences in restoration methods and restoration difficulty. However, this study focuses on the effect of the reduction of human disturbance on the restoration of rocky desertification in Panzhou City, and the main influencing factor of land use is not considered in the classification and evaluation of rocky desertification. This is also a shortcoming of this study, and we will continue to explore this issue in the future.

China's long-term goal is clear. By 2035, China will fundamentally improve its ecological environment. Therefore, in order to make sure the improvement of rocky desertification in Panzhou City enters a virtuous circle by 2035, after initially curbing the development of rocky desertification, it is still necessary to vigorously implement ecological projects focusing on vegetation restoration and continuously track and monitor the dynamic changes of rocky desertification. The ecological benefits of ex situ poverty alleviation and relocation include not only the ecological restoration of the emigration place but also the improvement of the ecological environment of the emigration place. In the process of urbanization, the influx of a large number of people has a great impact on the surface ecological environment [57], and the concentration of the population has increased the interference with environmental factors, resulting in the destruction of the stability of the quasi-native environment [58]. This problem should be paid attention to, and ecological benefits should be discussed from a more comprehensive perspective.

5. Conclusions

(1) In the past 20 years, the vegetation coverage in Panzhou City has generally improved, and the implementation of ex situ poverty alleviation and relocation projects has significantly promoted the reduction of rocky desertification areas and their degree. After relocation (2015–2020), the improvement rate of rocky desertification accelerated, and the ecological environment continued to improve.

(2) Before the relocation, from 2000 to 2005, the main direction of rocky desertification transfer was from LRD to MRD and SRD. After the relocation, all types of rocky desertification changed to NRD. The improvement effect of rocky desertification is remarkable, and the main contribution comes from PRD and LRD.

(3) The greater the relocation intensity, the more obvious the improvement effect of the rocky desertification area in the village, and the higher the corresponding coupling coordination level. Among them, the coupling coordination degree between LRD and relocation intensity is the most significant, and the coupling coordination degree between PRD and relocation intensity is the lowest.

(4) The forecast shows that the rocky desertification in Panzhou will continue to improve by 2025 and 2035, and relevant policies and measures will continue to play an important role in improving local rocky desertification.

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