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Characteristics of Changes in Karst Rocky Desertification in Southtern and Western China and Driving Mechanisms

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Abstract: The karst landform is a typical ecologically vulnerable region, and the problem of karst rocky desertification in southtern and western China has led to impoverishment and a degraded local ecological environment, which severely limits local socioeconomic development. An effective and appropriate control of karst rocky desertification in southtern and western China requires knowledge about its characteristics of variation and driving mechanisms. In this study, we chose eight regions in the southtern and western China as research areas and analysed the characteristics of the changes in karst ecosystem patterns and rocky desertification from 2000 to 2015. Based on these characteristics, we present the mechanisms that drive karst rocky desertification in the southtern and western China by utilizing the redundancy analysis (RDA) ordination method. The results show that the total area of rocky desertification in southtern and western China had been continuously decreasing from 2000 to 2015, revealing a positive development trend in rocky desertification. Rocky desertification variations were mainly affected by human activities. The reduction in farmland area improved farmland management and increased regional gross industrial product, which together with continuously rising gross domestic product of the tertiary industry caused a positive rocky desertification development. However, the local karst tourism has a certain effect on inducing slight rocky desertification.

Keywords: southtern and western China; karst; rocky desertification; change characteristics; driving mechanisms

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1 Introduction

Rocky desertification is an extreme form of land degradation, which leads to water shortages, reduced and barren soils, and the direct consequence of loss of land resources. Rocky desertification, together with desertification and water/soil loss, are three known types of land ecological disasters (Phillips, 2016; Veress 2020). Karst rocky desertification mainly occurs in the European Mediterranean basin (Lavee, 1998), Dinaric Karst (Gams and Gabrovec, 1999) and southern and western (Jiang et al., 2014). It is also distributed in other countries and regions in the world, such as Belize, Guatemala, Mexico, Israel, Ryukyu Islands (Ford and Williams, 2007), Indonesia (Sunkar, 2008), Caribbean island countries (Jiang et al., 2014) and Haiti (Williams, 2011). Karst landforms in China correspond to one-third of the total national land area and are contiguously exposed across 5.4 × 10^5 km^2 in 465 counties (cities and districts) in Guizhou, Yunnan, Guangxi, Hunan, Hubei, and Sichuan and Chongqing (Wu et al., 1998). Compared with other typical ecologically vulnerable regions

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such as the Loess Plateau and Tibetan Plateau, the karst region is constrained by its special geological background of easily dissolved carbonates. As a result, within the region, pedogenesis occurs extremely slowly, and the formed layer of soil is generally thin and discontinuous, resulting in rapid impacts of the soil layer to hydrological processes and severely damaged ground vegetation due to human activities. Severe erosion of soils results in the exposure of large areas of the bedrock, eventually driving the region to become mainly rocky and desertified and an ecologically vulnerable region in China (Qin et al., 2006).

The problem of rocky desertification severely limits the development of the local economy. Thus, it is important to study its spatiotemporal characteristics and its evolutionary pattern (Luo et al., 2021), which can assist with implementing targeted controls from a scientific perspective (Ma et al., 2015). Thus far, there have been a series of achievements in studying the spatiotemporal variations in karst rocky desertification in southern and western. By deploying a drone-based remote sensing technology, Wen and Li (2020) investigated both spatiotemporal distribution patterns and evolutionary patterns in the Guizhou rocky desertification region from 2004 to 2016. Based on the comprehensive index method, they analysed the rocky desertification distribution patterns in different ecological protection areas with karst landforms in southern and western, utilizing net primary productivity (NPP), the normalized difference vegetation index (NDVI), and slope indices. By utilizing MODIS (moderate resolution imaging spectroradiometer)-NDVI data from 2003 to 2016, Tian et al. (2017) analysed vegetation variations in rocky desertification areas of different grades in Guizhou in the most recent 14 yr based on the approach of linear trend analysis and interpolation. In addition, by adopting the comprehensive index method, Shi and Shu (2017) created a distribution map for rocky desertification areas with extreme, strong, medium, slight, potential, and no rocky desertification grades. Finally, by utilizing the NDVI and meteorological data, Wang et al. (2021) focused on discussing the NDVI spatiotemporal variation characteristics in rocky desertification areas in Chongqing based on trend analysis, coefficient of variation analysis, and partial correlation analysis.

The mechanism driving the evolution of rocky desertification is very important for rocky desertification control. It is commonly considered that the formation and development of rocky desertification in the karst region in southtern and western China are induced by both natural processes and human activities. Zhang (ang (2018) studied the relationship between vegetation coverage and rocky desertification evolution. Shi and Shu (2017) also investigated the spatiotemporal variation characteristics of rocky desertification in Guizhou and the associated key driving factors. Xu et al. (2019) analysed the contributions of human activities and climate change to the recovery from rocky desertification, which diversified the regional scale of related research. A number of previous studies have come to the conclusion that rocky desertification is the combined result of topography, formation lithology, geological structure, hydrology, meteorology, soil, and vegetation distribution (Wang et al. 2003; Cao et al. 2004; Li et al. 2005; Lv et al. 2007).

Geodynamics sculptured the steep and broken karst landscape, providing a dynamic potential energy for the formation of rocky desertification (Weng, 1995). Zhou and Huang (2003) found that limestone regions possess the largest area of rocky desertification with the highest rocky desertification degree, while marlstone regions rank the lowest in their rocky desertification area. Li et al. (2003) observed that rocky desertification is significantly correlated with lithology. Some scholars have proposed that regions with steeper slopes are more likely to experience water and soil loss, which intensifies rocky desertification (Ji, 2013). When the temperature is higher than a certain threshold value, the karstification in karst regions intensifies with increasing temperature. In addition, precipitation mainly occurs at relatively high temperatures from April to September. Thus, the dual effect of temperature and precipitation induces more severe soil loss in the karst region, where the original soil layer is already thin, thus accelerating the process of rocky desertification (Yuan, 1994; Su, 2002; Su et al., 2006). Zhang et al. (2012) concluded that regional variation in rocky desertification is mainly controlled by the type of material in the underlying surface (i.e., the number of ‘rocky mountains’). The early-to-middle period of the Qing dynasty is considered a critical transitional period for the effect of human activities on rocky desertification. During this period, natural factors started to play a less significant role in affecting rocky desertification compared with human activities, such that human economic activities became dominant in controlling rocky desertification (Han et al., 2006; Li et al., 2007). The ecological system in the karst region of southern and western is extremely vulnerable and sensitive to disturbances caused by human activities (Su, 2002). Since the founding of the People's Republic of China, the karst mountainous region has been trapped in a vicious circle of 'rapid population rise-excessive land reclamation-erosive soil degradation-rocky desertification spread' (Su and Zhou, 1995; Deng et al., 2009). Zhou and Huang (2003), Zhang et al. (2008) also reported a positive correlation between the occurrence of rocky desertification and population density in karst regions. Finally, deforestation exposes large areas of land, which also accelerates the process of rocky desertification (Huang et al., 2006).

The main natural factors that influence the evolution of rocky desertification include topography, formation lithology, hydrology, meteorology, and soil and vegetation distribution. In addition, human factors mainly include population density, land-use type, cultivation, grazing, and mining (Zhang et al., 2015; Tong et al., 2017). The dominant factor in controlling rocky desertification has gradually changed to human factors with socioeconomic development (Yan, 2018). However, previous studies on the characteristics of changes in karst rocky desertification in southern and western and driving mechanisms mainly focus on certain province, city or county, and there is no investigation on the whole area of southern and western. The time frame of previous studies is either narrow or long from now (Peng et al., 2013). In this study, we investigate the pattern of distribution of rocky desertification areas in the whole karst region of southern and western from 2000 to 2015 and determine the key factors, based on which we present the spatiotemporal variation characteristics of rocky desertification in the southern and western and the associated driving mechanisms.

2 Methods

2.1 Research area

The karst region in southern and western China includes 465 counties (cities and districts) in Guizhou Province, Yunnan Province, Guangxi Zhuang Autonomous Region, Hunan Province, Hubei Province, Sichuan Province, Guangdong Province and Chongqing City, as shown in Fig. 1. The karst region starts from the southern foot of the Qinling Mountains and reaches the Guangxi Basin in the south, the Hengduan Mountains in the west, and the west side of the Luoxiao Mountains in the east, with a total area of approximately 5.4 × 10^5 km^2 (Wu et al., 1998). The southtern and western karst region possesses abundant water resources, including the Yangtze, Pearl, and Lancang Rivers. Within this region, topography exhibits large vertical variations and diversity with rolling mountains and widely distributed carbonates. Topography is high in the northwest and low in the southeast with a large vertical gradient: the highest altitude above sea level is 7143 m, and the lowest altitude is −142 m. The karst region spans the south temperate zone, north subtropical zone, central subtropical zone, south subtropical zone, and plateau climatic zone, with the central subtropical monsoon and humid climate being prominent within the region. The population of this region contains a cluster of minority nationalities in China, including the Buyi, Miao, Gelao, and Yi. From National Bureau of Statistics of China (https://data.stats.gov.cn/), by the end of 2015, the gross domestic product of the eight southern and western regions had reached 21.8 × 10^{13} yuan (RMB), 75.03% higher compared with 2010. Specifically, the gross domestic product of the primary industry was 0.774 ×10^{13} yuan, an increase of 58.04%, the gross domestic product of the secondary industry was 3.58 × 10^{13} yuan, an increase of 59.05%, and the gross domestic product of the tertiary industry was 4.99 × 10^{13} yuan, an increase of 98.73%. Among the three industries, the tertiary industry has shown the fastest growth.

2.2 Approaches to assess rocky desertification changes

2.2.1 Assessing rocky desertification degree

According to previous research results (Lou, 2016), slope, vegetation coverage, and lithology are the three important factors that affect rocky desertification. This article evaluates the comprehensive characteristics of the three factors and divides rocky desertification into five levels, namely none rocky desertification, slight, medium, strong, and extreme intensity. The degree of rocky desertification in the three years of 2000, 2010 and 2015 will be evaluated separately (Table 1).

The main data of rocky desertification grade assessment has the following sources. The first is the slope data, which is based on the digital elevation model

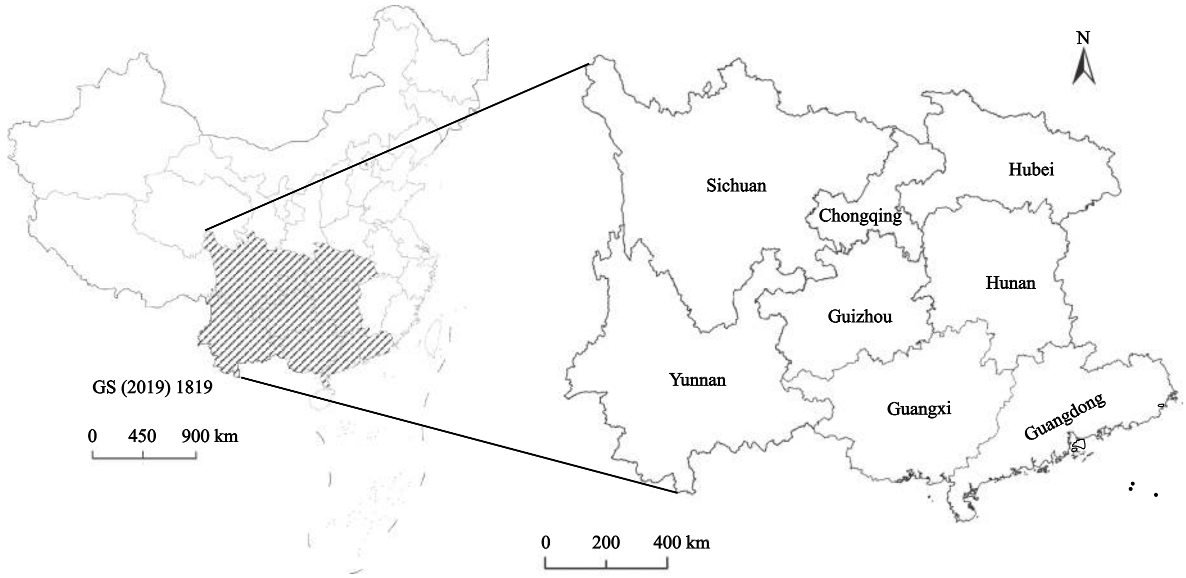

Fig. 1 The karst region in southtern and western China

Table 1 Classification of rocky desertification degree

Rocky desertification degree	Numerical value	Slope / (°)	Vegetation coverage / %	Lithology
None	0	< 5	> 80	Buried carbonatite
Slight	1	5–15	60–80	Sub-impure carbonate
Medium	2	15–25	40– 60	Impure carbonate
Strong	3	25–35	20–40	Dolomite
Extreme	4	> 35	< 20	Limestone and dolomite

(DEM) data with a resolution of 90 m downloaded by National Aeronautics and Space Administration of USA (NASA) (https://www.nasa.gov/), and the slope map is generated through the calculation of ArcGIS. The second is the vegetation coverage, which comes from the Institute of Aerospace Information Innovation of the Chinese Academy of Sciences and is retrieved from Moderate-resolution Imaging Spectrora diometer (MODIS), including three years of 2000, 2010 and 2015. The third is lithology data, which comes from the national geological map (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1566).

2.2.2 Assessing changes in rocky desertification areas

The land-use transfer matrix can be adopted to represent a dynamic process during which the areas with different land-use types are interchangeable at the beginning and end of a certain time period in a certain region. The matrix includes areas of different land-use types at a certain time point and the input and output areas of different land-use types at the beginning and end of a time period. Using ArcGIS, we utilized the land-use transfer matrix to calculate the transfer of rocky desertification areas in 2000, 2010, and 2015. In addition, we conducted a statistical analysis of areas with varied rocky desertification grades on both regional and provincial scales. The transfer matrix is shown as follows:

$$s_{ij} = \begin{bmatrix} s_{00} & s_{01} & \cdots & s_{0n} \\ s_{10} & s_{11} & \cdots & s_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ s_{n0} & s_{n1} & \cdots & s_{nn} \end{bmatrix} \tag{1}$$

where s is the area, n is the rocky desertification grade before and after the transfer, i and j ($i, j = 0, 1, \ldots, n$) represent the rocky desertification types before and after the transfer, and S_{ij} is the area of i rocky desertification type that transferred to j rocky desertification type. In the matrix, elements in each row represent the flow information about the transfer of i type rocky desertification, and elements in each column represent the sources of the transferred j type; $i = j$ corresponds to an unchanged i type rocky desertification area.

2.2.3 Assessing changes in rocky desertification grades

We adopted methods based on value assignment and difference to assess the spatial variation in rocky desertification between two periods. We divided rocky desertification into five degrees (Table 1), namely, none, slight, medium, strong and extreme, with numerical values of 0−4 respectively assigned to these degrees. After the assignment of numerical values to rocky desertification grids in ArcGIS, we conducted difference calculations to characterize changes in rocky desertification and grade classification based on the before-and-after rocky desertification changes. An improvement corresponds to the transfer from a high rocky desertification degree to a low degree, and vice versa. The absolute value of the before-and-after difference of 1−2 denotes a slight change (slight degradation and alleviation), 3−4 denotes a strong change (Strong degradation and alleviation), and 0 denotes no change in the rocky desertification degree (Table 2).

2.3 Driving mechanisms analysis method of rocky desertification changes

In this study, we adopted redundancy analysis (RDA) to investigate the rocky desertification process between 2000 and 2015. The RDA is a method that extracts and sums changes in a set of response variables, which can provide an explanation on the basis of a group of explanatory variables. First, we conducted detrended correspondence analysis (DCA) to compare the first axes of areas of different rocky desertification grades. If the axis length of the first axis was greater than 4.0, we adopted a nonlinear single-peak ordination method to conduct canonical correspondence analysis (CCA); if the value was smaller than 3.0, we then adopted a linear ordination method (e.g., principal components analysis (PCA) or RDA); and if the value was between 3.0 and 4.0, either RDA or CCA was adopted. When there were missing or abnormal data in the environmental gradients for any of the influencing factors, we adopted the DCA method to eliminate the data. Based on the DCA ordination method, the data arc effect was removed after the second axis.

RDA is a constraint ordination method based on the main component analysis, whose goal is to find a new variable as the best predicting indicator to predict the distribution of response variables. We assume that the new variable X (assuming it is the first axis) has a corresponding value in each sample and that the new variable has a value of X_i in the ith sample; we can predict the k type in the ith sample using the following equation:

$$Y_{ik} = b_{0k} + b_{1k}X_i + e_{ik} \tag{2}$$

where, X_i is the coordinate of the sample in the first axis, b_{1k} is the regression coefficient of each rocky desertification type and denotes the coordinate of the rocky desertification type in the first axis, and the other parameter b_{0k} represents the intercept of the regression line. e_{ik} is the random effects of species k in sample i.

The coordinate value X_i of the RDA sample can be obtained based on constraints and is a linear combination of environmental factors. Assuming that there are two measured environmental variables Z_{i1} and Z_{i2}, the value of the new variable X_i can be expressed using the linear combination of the environmental variables Z_{i1} and Z_{i2} using the following equation:

$$X_i = c_1 Z_{i1} + c_2 Z_{i2} \tag{3}$$

where, c_1 and c_2 are the correlation coefficients that represent the significance of the correlations between the environmental factors and the corresponding ordination axes.

The two steps above convert the RDA result to a multivariate, multielement regression equation set:

$$Y_{ik} = b_{0k} + b_{1k}c_1 Z_{i1} + b_{2k}c_2 Z_{i2} + e_{ik} \tag{4}$$

where, $b_{ik}c_j$ denotes the regression coefficient in the multivariate, multielement regression model, which describes the abundance of k-grade rocky desertification based on the degree of j environmental factor.

The influencing factor value can randomly assign variations to the rocky desertification grade without causing other effects. Based on data permutation, we obtained statistical test analytical results. The significance level test equation is shown below:

$$p = \frac{n_x + 1}{N + 1} \tag{5}$$

Table 2 Rocky desertification change grade division

Value difference	[−4, −3]	[−2, −1]	0	[1, 2]	[3, 4]
Difference-based rating	Strong degradation	Slight degradation	No change	Slight alleviation	Strong alleviation

where, p represents the significance test level, n_x represents the number of permutations that never lies below the number of random permutation analyses, and N represents the total number of permutations.

Partial ordination analysis assesses the contribution of each influencing factor variable to the change in rocky desertification by performing a partial Monte Carlo permutation test. Each influencing factor candidate is considered the only variable for analysis and the chosen factor(s) as covariate(s). Finally, based on the ordination model, a Monte Carlo permutation test is conducted to determine the main influencing factor.

The explanation of each influencing factor to response variables can be decomposed to a conditional explanatory variable and a marginal explanatory variable. The difference between the two explanatory variables can be used to determine the interaction between multiple influencing factors. The variance decomposition method can decompose a variable explanation to an unaffected factor explanatory part, an independent explanatory part, and a dependent explanatory part, whose values can be calculated based on the partial constraint analysis method.

2.4 Driving factors

2.4.1 Socioeconomic factors

To accurately analyse the rocky desertification pattern in southern and western region, we collected data relevant to economic activities from the statistical yearbooks (https://data.stats.gov.cn/) of the eight regions in southern and western China (gross domestic product (GDP), industrial product, population data, and agricultural population data). Economic activity, population, and human health data used in this study for exploring the mechanisms driving rocky desertification (ion (Table 3) were obtained on the basis of changes between the two periods. We present the data changes in percentage as our dependent variables.

Table 3 Selected socioeconomic driving factors of rocky desertification changes

Social and economic factors	Abbreviation	Unit
Gross domestic product	GDP	10^4 Yuan
Gross domestic product of primary industry	GDP1	10^4 Yuan
Gross domestic product of secondary industry	GDP2	10^4 Yuan
Gross domestic product of tertiary industry	GDP3	10^4 Yuan
Fixed-asset investment	FixInv	10^4 Yuan
Year-end population	PopYe	10^4

2.4.2 Topographic factors

Previous study on the mechanisms driving rocky desertification has pointed to a significant role of topographic condition (Qin et al., 2006). Thus, in ArcGIS, we chose each county as our research unit and extracted their mean altitude, terrain slope, terrain orientation, and mean topographic fractal dimension (Table 4). For analysing the causes of rocky desertification, we adopted changes (in percentage) in the county's topographic condition between two years as dependent variables. The DEM data in 30 m for provinces in China are from the Resources and Environmental Science Data Centre.

Table 4 Selected terrain driving factors of rocky desertification changes

No.	Terrain factors	Abbreviation	Unit
1	Elevation	ELEV	m
2	Slope	SLO	°
3	Topographic fractal dimension index	TPI	

To calculate changes in percentage in the county's topographic condition between two years, we adopted the rocky desertification areas of each county in 2000 and 2015 to obtain the means of the topographic factors in these rocky desertification areas, based on which we calculated the changes in percentage for each county. Among topographic factors, the topographic fractal dimension index is a critical factor that affects the spatial difference in the surface and is a comprehensive reflection of topography and elevation. During our analyses of topographic differences, we introduced the topographic fractal dimension index when a single elevation or terrain slope could not explain the phenomenon. In this study, we utilized the geographic information modelling method that combines elevation and terrain slope to extract the topographic fractal dimension index, which was able to better explain rocky terrain changes in the southtern and western region. The equation describing this yields:

$$T=\log\left[\left(\frac{E}{\overline{E}}+1\right)\times\left(\frac{S}{\overline{S}}+1\right)\right] \tag{6}$$

where T is the topographic fractal dimension index, E and S represent the elevation and slope of any point in space, respectively, and $\overline{E}$ and $\overline{S}$ represent the mean elevation and mean slope of a certain region, respectively.

The higher the elevation is, the steeper the slope and the larger the topographic fractal dimension index is, and vice versa. For cases with a high elevation but a shallow slope or with a low elevation but a steep slope, the topographic fractal dimension index has medium values.

2.4.3 Ecological Factors

Different ecological systems exhibit differences in soil erosion intensity, thus leading to differences in the distribution of ecological systems of different rocky desertification degrees. In addition, ecological system type plays a certain role in affecting the evolution of rocky desertification. For many years, China has conducted multiple ecological protection projects targeted ecological environmental problems, including the Returning Farmland to Forest project, the Natural Forest Protection project, and the Karst Rocky Desertification Control project, which are closely related to the control of rocky desertification in southern and western China. Thus, to investigate changes in rocky desertification, we chose county as our research unit and calculated changes in percentage in areas between 2000 and 2015 for different ecological systems as the influencing factors. There is no rocky desertification process in wetland, desert and bareland, as a result, wetland, desert and bareland were not considered in driving mechanisms analysis. The Resources and Environment Science and Data Center in China is a world-class research platform for land surface system science. The data used in this study are the remote sensing data for land use in China in 2000, 2010, and 2015 from The Resources and Environment Science and Data Center in China (https://www.resdc.cn/), which were classified based on the ecological system division scheme. The selected ecological system factors are summarized in Table 5.

Table 5 Selected ecosystem driving factors of rocky desertification changes

No.	**Ecosystem factors**	Abbreviation	Unit
1	Forest	FOE	km^2
2	Shrubland	SHE	km^2
3	Grassland	GRE	km^2
4	Farmland	FAE	km^2
5	City/town	TOE	km^2

3 Results

3.1 Changes in ecological system patterns in southern and western China

From 2000 to 2015, ecosystem area in the rocky desertification region in southern and western was significantly enhanced in towns, which increased by 48.42% and reached 1.810 × 10^4 km^2. On the other hand, the farmland area significantly decreased by approximately 2.220 × 10^4 km^2, corresponding to a 4.13% decrease (Fig. 2). In addition, areas of forest, grassland, wetland, and desert were enlarged by 0.210 × 10^4 km^2, 0.010 × 10^4 km^2, 0.190 × 10^4 km^2, and 0.100 × 10^4 km^2, respectively, corresponding to increases of 0.26%, 0.05%, 3.80%, and 6.13%, respectively, in 2000. In addition to the reduced farmland area, shrubland and bare land also decreased by 0.30% and 0.11%, respectively.

Except for bare lands, a total area of 5.570 × 10^4 km^2 of ecosystems experienced transformation in the southwestern region from 2000 to 2015. Specifically, the area of farmland that transformed to other ecosystems was the highest, that is followed by forest and shrubland. In addition, the transferred farmland area was 2.916 × 10^4 km^2, with contributions from town, forest, and shrubland areas of 1.401 × 10^4 km^2, 0.704 × 10^4 km^2, and

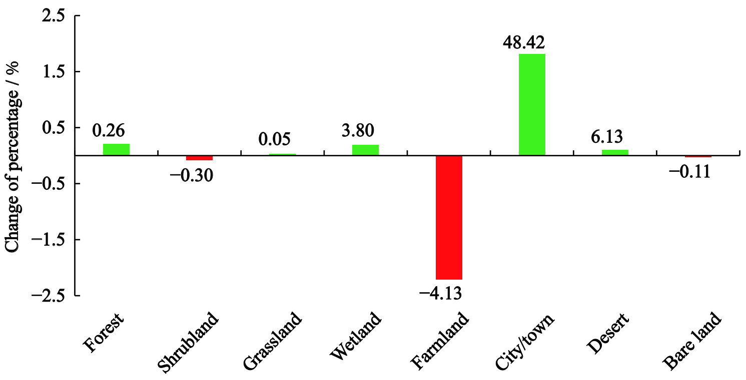

Fig. 2 Percentage changes in areas for different ecological systems from 2000 to 2015 in southtern and western China

0.343 × 10^4 km^2, respectively. The transformed forest area was 1.100 × 10^4 km^2, and the transformations of forest to farmland, shrubland and town were 0.331 × 10^4 km^2, 0.292 × 10^4 km^2, and 0.256× 10^4 km^2, respectively. The transferred shrubland area was 0.785 × 10^4 km^2, and the transformations of shrubland to forest, farmland, and city/town were 0.400 × 10^4 km^2, 0.162 × 10^4 km^2, and 0.126 × 10^4 km^2, respectively. Ecosystems with relatively high input transformation areas were town, forest, and shrubland. The transformed town area was 1.973 × 10^4 km^2, and the transformed forest and shrubland areas were also very large: 1.307 × 10^4 km^2 and 0.703 × 10^4 km^2, respectively. (Table 6).

3.2 Changes in area and grade of rocky desertification in southtern and western China

From 2000 to 2015, the rocky desertification area in southtern and western China continuously shrank, indicating an alleviated rocky densification condition. The rocky desertification area decreased from 13.200 × 10^4 km^2 in 2000 to 10.950 × 10^4 km^2 in 2010 and to 9.570 × 10^4 km^2 in 2015. Compared with 2000, the rocky desertification area decreased by 17.08% in 2010 and by 27.49% in 2015.

However, changes in rocky desertification areas of different degrees show inconsistent trends with respect to the overall rocky desertification trend in southtern and western China. Specifically, the area of slight rocky desertification first decreased by 33.15% from 2000 to 2010 and then increased by 0.370 × 10^4 km^2 in the following five years. The area of medium rocky desertification first increased by 10.48% from 2000 to 2010 and then decreased. As a result, its medium rocky desertification area in 2015 remained similar to that in 2000. On the other hand, strong and extreme rocky desertification areas show a trend consistent with the overall trend of rocky desertification in southtern and western China, which continuously decreased in area at an accelerated rate. The strong rocky desertification area decreased from 1.820 × 10^4 km^2 in 2000 to 1.630 × 10^4 km^2 in 2010 and then decreased by another 73.23% from 2010 to 2015. As a result, only 0.440 × 10^4 km^2 of strong rocky desertification area was remained in 2015. In 2000, the extreme rocky desertification area was 0.290 × 10^4 km^2, which decreased to 0.14 0× 10^4 km^2 in 2010, shrinking by 52.64% and further declining by 60.48% from 2010 to 2015, after which only a 0.050 × 10^4 km^2 area was remained (Fig. 3).

Table 7 shows the complexity and diversity in the process of rocky desertification in southern and western from 2000 to 2015 with a total of 24 transformation forms. The newly established rocky desertification area was 0.700 × 10^4 km^2, which was dominated by slight rocky desertification areas (83.61%). In addition, the newly established medium rocky desertification area corresponded to 14.85%, and the newly established strong and extreme rocky desertification areas were rare, only 1.54%. From 2000 to 2015, rocky desertification disappeared in a total area of 4.330 × 10^4 km^2 with varying rocky desertification degrees in the region. The area transformed from slight rocky desertification to no rocky desertification, which was the highest at 93.90%, while the areas transformed from medium, strong, and extreme rocky desertification to no rocky desertification were 4.83%, 1.54%, and 1.54%, respectively. The area transformed between different rocky desertification degrees (except the no rocky desertification degree) was 8.870 × 10^4 km^2 with 57.54%, maintaining their ini-

Table 6 Ecosystem transfer matrix of southtern and western China from 2000 to 2015 / 10^4 km^2

Year	Ecosystem	2015							
		Forest	Shrubland	Grassland	Wetland	Farmland	City/town	Desert	Out
2000	Forest	79.883	0.292	0.065	0.038	0.331	0.256	0.118	1.100
	Shrubland	0.400	26.917	0.030	0.047	0.162	0.126	0.020	0.785
	Grassland	0.125	0.044	20.591	0.024	0.038	0.065	0.005	0.301
	Wetland	0.012	0.007	0.013	4.876	0.070	0.112	0.006	0.220
	Farmland	0.704	0.343	0.200	0.230	50.673	1.401	0.036	2.916
	City/town	0.020	0.012	0.001	0.036	0.087	3.581	0.005	0.162
	Desert	0.043	0.005	0.001	0.014	0.012	0.013	1.557	0.089
	In	1.307	0.703	0.311	0.389	0.700	1.973	0.190	

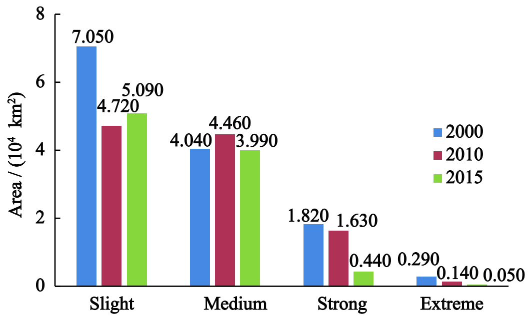

Fig. 3 Rocky desertification area in southern and western China in 2000, 2010 and 2015

tial rocky desertification degrees. The transformation of slight and medium rocky desertification areas from other degrees were 20.49% and 19.59%, respectively. In comparison, the transformed strong and extreme rocky desertification area was only 0.18%.

As shown in Table 8, the transformation of no rocky desertification to rocky desertification mostly occurred in Guizhou and Yunnan. Except of Guangdong, the other regions were dominated by transformations from no rocky desertification to slight rocky desertification. In comparison, Guangdong mostly experienced transformation from no rocky desertification to medium rocky desertification. From 2000 to 2015, among regions with disappearing rocky desertification areas, Guizhou, Sichuan and Hubei ranked the highest in disappearing areas. Among regions with unchanged rocky desertification areas, Guangdong and Guangxi and Chongqing had the highest percentages of medium rocky desertification areas, corresponding to 57.50%, 61.10%, and 55.24%, respectively. Among all types of rocky desertification transformations, the transformations to slight and medium degrees were dominating. Specifically, transformed slight rocky desertification was dominantly from medium rocky desertification with Hunan ranking the highest (54.72%). The transferred medium rocky desertification, on the other hand, was mostly from strong rocky desertification with Guangxi exhibiting the highest percentage (61.92%). Regarding the transformation of strong rocky desertification, Sichuan was the only region that mainly experienced degradation to extreme rocky desertification, while all other regions were dominated by transformations to medium rocky desertification. Finally, extreme rocky desertification was dominantly transformed to the strong degree.

As shown in Table 9, from 2000 to 2015, 11.25% of the rocky desertification area was further degraded in southtern and western China, corresponding to a total area of 1.130 × 10^4 km^2. Yunnan, Guizhou and Guangxi ranked the highest in their degraded areas: 0.467 × 10^4 km^2, 0.415 × 10^4 km^2, and 0.101 × 10^4 km^2, respectively. The degraded rocky desertification area was the lowest in Guangdong, with 0.008 × 10^4 km^2. A total of 5.106 ×10^4 km^2 did not experience any changes in rocky desertification grade, including 1.402 × 10^4 km^2 in Guizhou, which ranked the highest, followed by Yunnan and Guangxi with the areas of 1.199 × 10^4 km^2 and 1.104 × 10^4 km^2, respectively. From 2000 to 2015, a total area of 7.664 × 10^4 km^2 experienced alleviated rocky desertification in the region, including 2.084 × 10^4 km^2 in Guizhou, which ranked the highest; and 1.737 × 10^4 km^2 in Yunnan and 1.037 × 10^4 km^2 in Sichuan, which ranked second and third, respectively. Rocky desertification changes varied among the different regions. Specifically, rocky desertification conditions remained unchanged in Guangdong and Guangxi, while rocky desertification conditions were mostly alleviated in Sichuan, Hubei, Hunan, Guizhou, and Yunnan and in Chongqing. Among the regions with alleviated rocky desertification conditions, Sichuan ranked first in its rocky desertification area percentage at 78.35%, followed by Hubei at 68.50%.

From 2000 to 2015, a majority of rocky desertification areas were alleviated with a relatively small num-

Table 7 Process of changes in rocky desertification areas in southern and western China from 2000 to 2015 / 10^4 km^2

Year	Degree	2015				
		None	Slight	Medium	Strong	Extreme
2000	None	0	58.530	10.400	0.990	0.090
	Slight	40.660	15.440	12.060	0.750	0.040
	Medium	20.910	66.430	123.570	4.790	0.190
	Strong	4.760	9.990	54.890	13.360	0.450
	Extreme	0.690	0.830	6.900	2.710	2.140

Table 8 Transformation of rocky desertification in different degrees in southtern and western China from 2000 to 2015

Type	Grades transformation	Guangdong	Guangxi	Guizhou	Hubei	Hunan	Sichuan	Yunnan	Chongqing
New established	Area / 10^4 km^2	0.005	0.050	0.282	0.014	0.027	0.023	0.282	0.015
	0→1 /%	39.04	51.19	86.78	73.64	77.91	87.90	88.63	66.46
	0→2 /%	48.60	42.62	12.15	25.55	16.99	10.17	10.79	30.80
	0→3 /%	12.16	5.81	0.93	0.75	4.58	1.91	0.54	2.46
	0→4 /%	0.20	0.38	0.14	0.06	0.52	0.02	0.04	0.29
Disappear	Area / 10^4 km^2	0.013	0.251	1.216	0.471	0.396	0.821	0.900	0.258
	1→0 /%	65.18	85.73	93.61	97.87	93.26	94.59	93.97	96.00
	2→0 /%	17.65	10.42	5.28	1.76	5.59	4.12	4.90	3.16
	3→0 /%	13.74	3.41	0.99	0.34	1.03	1.12	0.93	0.75
	4→0 /%	3.43	0.44	0.12	0.02	0.12	0.17	0.21	0.09
Unchanged	Area / 10^4 km^2	0.051	1.104	1.402	0.255	0.505	0.252	1.199	0.339
	1→1 /%	34.75	33.18	64.63	51.17	55.17	54.30	58.60	43.79
	2→2 /%	57.50	61.10	33.27	47.85	37.45	32.53	33.38	55.24
	3→3 /%	7.56	5.59	2.03	0.93	7.03	4.00	7.26	0.90
	4→4 /%	0.20	0.14	0.07	0.05	0.35	9.17	0.75	0.06
Conversion	Area / 10^4 km^2	0.028	0.699	1.000	0.138	0.469	0.228	1.022	0.183
	2→1 /%	28.69	25.63	46.39	47.10	54.72	42.35	41.84	36.45
	3→1 /%	1.94	1.41	8.48	7.47	4.36	12.66	6.43	8.07
	4→1 /%	0.34	0.10	0.54	0.44	0.25	1.74	0.61	0.67
	1→2 /%	3.84	3.47	9.83	3.85	4.22	3.28	11.84	3.51
	3→2 /%	53.20	61.92	26.27	33.95	29.22	24.79	25.83	42.21
	4→2 /%	3.93	2.81	4.61	4.86	2.82	6.96	4.57	6.99
	1→3 /%	0.26	0.16	0.49	0.27	0.10	0.34	0.98	0.22
	2→3 /%	5.34	3.37	2.51	1.02	2.15	1.07	4.55	1.14
	4→3 /%	2.05	0.88	0.45	0.94	1.95	6.42	2.56	0.64
	1→4 /%	0.02	0.01	0.02	0.01	0.00	0.14	0.06	0.01
	2→4 /%	0.14	0.06	0.19	0.04	0.03	0.06	0.16	0.04
	3→4 /%	0.27	0.16	0.22	0.05	0.17	0.18	0.58	0.07

Note: 0, 1, 2, 3 ,4 are the rockey deserrification degree shown in Table 1

Table 9 Changes in rocky desertification in southern and western China from 2000 to 2015

Difference-based rating	Statistical	Guangdong	Guangxi	Guizhou	Hubei	Hunan	Sichuan	Yunnan	Chongqing	Total
Strong and slight degradation	Area /10^4 km^2	0.008	0.101	0.415	0.022	0.058	0.035	0.467	0.024	1.130
	Ratio /%	7.89	4.80	10.64	2.47	4.15	2.64	13.74	3.05	
No change	Area /10^4 km^2	0.051	1.104	1.402	0.255	0.505	0.252	1.199	0.339	5.106
	Ratio/%	52.83	52.44	35.94	29.03	36.17	19.02	35.23	42.61	
Strong and slight alleviation	Area /10^4 km^2	0.038	0.900	2.084	0.602	0.834	1.037	1.737	0.432	7.664
	Ratio /%	39.28	42.76	53.42	68.50	59.67	78.35	51.04	54.34	

ber of degraded areas. Regarding the spatial distribution (Fig. 4), degraded rocky desertification areas were mainly distributed in the southwestern part of Guizhou and south-eastern part of Yunnan; areas that experienced no change in rocky desertification grade were mostly distributed in Guizhou, the central and western

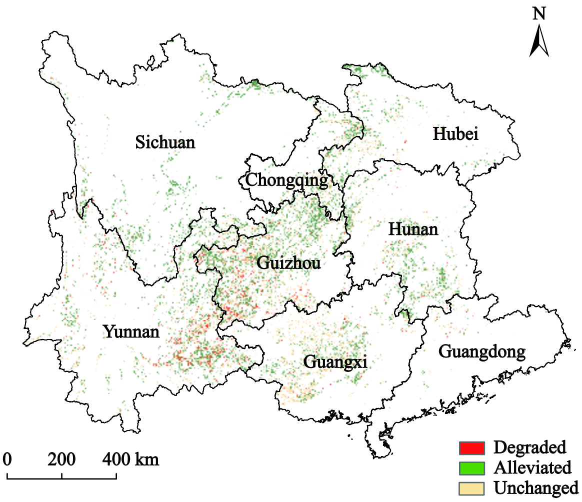

Fig. 4 Classification of rocky desertification changes in southern and western China from 2000 to 2015

part of Guangxi, and eastern Yunnan and at the junction of Chongqing, Hubei, and Guizhou.

3.3 Mechanisms driving rocky desertification changes in southern and western China

RDA ordination results show that among topographic factors, elevation, terrain slope, and topographic fractal dimension did not pass the Monte Carlo permutation test, indicating their low significance. In addition, socioeconomic factors are strongly correlated with rocky desertification changes, including GDP1 (Gross domestic product of primary industry), GDP (Gross domestic product), FixInv (Fixed-asset investment) and GDP3 (Gross domestic product of tertiary industry) (Table 10). Rocky desertification changes were not significantly correlated with Year-end population and gross domestic product of secondary industry. Regarding correlation with ecosystem factors, only farmland ecosystem and grassland ecosystem passed the significance test.

In this study, we adopt the RDA ordination plot to illustrate the correlations of the six ecological and socioeconomic factors with the change in rocky desertification grades obtained by the Monte Carlo permutation test (Fig. 5). Fig. 5 shows positive correlations between the first RDA axis (AX1) and farmland ecosystem factors and GDP1, thus indicating that AX1 mainly reflects changes in agricultural indices. In comparison, the second axis (AX2) is strongly correlated with FixInv and grassland.

Table 11 lists the eigenvalues and canonical coefficients of topographic and socioeconomic factors for the four ordination axes. The first four RDA ordination axes are able to explain 41.75% of the rocky desertification change. Specifically, the contribution of the first axis is the highest (34.90%), followed by the other three axes in decreasing order: 5.75%, 0.89%, and 0.21%, which were obtained from the cumulative percentage difference between the corresponding axis and the previous axis. These four axes are strongly correlated with environmental, socioeconomic, and ecological factors (Table 11). Among them, the first and second axes passed the significance test (Table 10).

RDA partial ordination analytical results show that

Table 10 Test results of influencing factors of rocky desertification changes in southern and western China

Factor	*F* value	*P* value
Gross domestic product	14.3	0.002**
Gross domestic product of primary industry	25.4	0.002**
Gross domestic product of secondary industry	2.9	0.054
Gross domestic product of tertiary industry	3.4	0.020*
Fixed-asset investment	7.2	0.002**
Year-end population	1.2	0.298
Forest	2.3	0.106
Shrubland	1.7	0.170
Grassland	7.1	0.002**
Farmland	78.3	0.002**
City/town	2.3	0.098
Topography fractal dimension index	0.7	0.526
Elevation	1.6	0.200
Slope	2.4	0.054

Notes: $^{*}P \le 0.05$, $^{**}P \le 0.01$, $^{***}P \le 0.001$

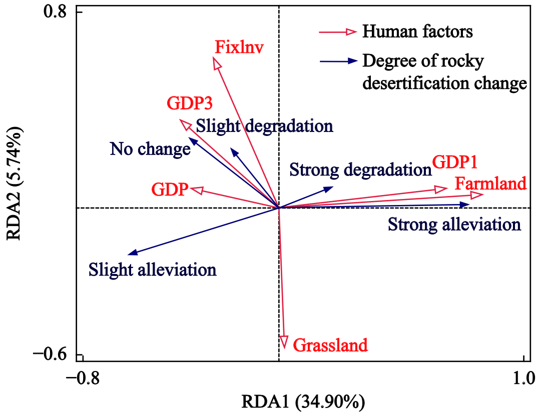

Fig. 5 Redundancy analysis (RDA) ordination of ecological factors, economic factors and rocky desertification changes

Table 11 Environmental explanation of the first four axes of the redundancy analysis (RDA)

RDA axes	1	2	3	4
Eigenvalue	0.3490	0.0575	0.0089	0.0021
Cumulative percentage of rocky desertification change variables /%	34.90	40.65	41.54	41.75
Relationship between rocky desertification and environmental factors	0.7962	0.4113	0.3366	0.2907
Cumulative percentage of environmental factors / %	83.53	97.28	99.42	99.91

ecosystem variables and socioeconomic factors can only explain 8.2% and 12.0% of the rocky desertification change, respectively, while the ecological system variables and socioeconomic factors can synergistically explain another 15.6% of the rocky desertification change. The explanatory ability of the socioeconomic variables is apparently significantly higher than that of the ecosystem variables, revealing that human activities (socioeconomic factor variables) play a more significant role in controlling rocky desertification changes than the ecosystem variables.

The arrow length for each factor in Fig. 5 can reflect the significance of the factor in influencing the rocky desertification change pattern, which reveals that the main factors were farmland ecosystem, GDP1, GDP3, GDP, and FixInv. In addition, the relationships between rocky desertification grade changes and the different factors can be assessed based on the cosine value of the corresponding angle: the smaller the angle is, the more significant the correlation is. When the angle is 90°, the correlation equals zero, and when the angle is greater than 90°, the correlation becomes negative. The different alleviated grades of rocky desertification are driven by different factors. The strongly alleviated grade of rocky desertification is positively correlated with farmland ecosystem factors and GDP1, mainly because the reduced farmland area and improved farmland management increased the agricultural product and furthermore reduced its disturbance on rocky desertification, both of which assisted with the alleviated development of rocky desertification. The slightly alleviated rocky desertification was the dominant form of changes that occurred in the southern and western region, as continuously increasing GDP and GDP3 were favourable for slight alleviation in rocky desertification.

The strong rocky desertification grade is strongly correlated with farmland variables and GDP1, almost uncorrelated with FixInv, and negatively correlated with GDP3 and GDP. The southern and western region is dominated by agricultural population and barren soils, which led to excessive land reclamation, severe water and soil losses, and eventually intensified rocky desertification. In addition, given the rapid development of the tertiary industry in the southern and western region compared with the primary industry, the development of the land-independent economy precluded strong degradation in rocky desertification. Slight rocky desertification is positively correlated with GDP3 and GDP. Economic development induced a certain negative effect on rocky desertification, possibly resulting from the development of tourism in the karst rocky desertification region, because tourism is the leading industry in the tertiary industry and plays an important role in the economic construction in southern and western (Wang, 2019). The negative correlations of the slightly degraded rocky desertification with GDP1 and farmland area indicate that agriculture has no influence on controlling slight rocky desertification degradation.

4 Discussion

About the evolution characteristics of karst rocky desertification, on the area of the research region, previous studies mainly focused on a certain county (Zhang et al., 2010; Pu et al., 2021), city (Hu et al., 2018; Pu et al., 2021) or province (Huang et al., 2006; Liu et al., 2008). southern and western, as a whole, boasts the largest rocky desertification area regions among the three largest karst regions in the world (Jiang et al., 2014; Jiang et al., 2020). As a result, it is more significant to in investigate the evolution characteristics of karst rocky desertification taking southern and western as a whole. As for the time frame of the study, either the time range of the study is narrow or it is long from now. For example, the time range is 4 years and 18 years far from now (Peng et al., 2013). Since 2000, China has paid more attention to rocky desertification in southern and western and adopted a series of control measures (Jiang et al., 2016). It is more meaningful to study the evolution law in a closer and wider time range for further guiding the control of rocky desertification. As a result, the investigation in this paper, in which the research area covers the whole southern and western region and the time covers 2000−2015, is more helpful for the further control of rocky desertification southern and western. From 2000 to 2015, rocky desertification in southern and western presented a benign development trend, which is consistent with the research conclusions of others (Jiang et al., 2016). In the driving mechanism of karst rocky desertification in southern and western, the change of rocky desertification is mainly influenced by human activities, which is also consistent with other researches (Wang, 2018). The population density of karst rocky desertification area is high, which is more than 1.5 times of the national average (http://www.forestry.gov.cn/main/3457/20181214/161611806917453.html). As a result, it is significantly important to control and transfer the population, and to achieve the moderate population goal in harmony with the law of ecological and economic development. Moreover, based on the ecological background of karst rocky desertification area, it is also significantly important to develop ecological agriculture and green industry, and to establish their own industrial clusters. From the driving mechanism of karst rocky desertification, it can be found that the karst tourism has a negative influence on the rocky desertification. The proportion of tertiary industry in the gross national product of southern and western is also gradually increasing, among which tourism is the leading industry of tertiary industry (Wang, 2019). The karst tourism should be programmed scientifically and developed moderately, and a long-term mechanism should be established to realize the value of ecological product.

5 Conclusions

In this study, we analysed the changes in the karst ecosystem and changes in the characteristics of rocky desertification in eight regions in southern and western China from 2000 to 2015. By considering socioeconomic, topographic, and ecological factors, we established a method to assess changes in the rocky desertification area and grade with the goal of revealing the mechanisms for karst rocky desertification in southtern and western China. Based on our analytical results, the following conclusions were drawn:ere drawn:

1) From 2000 to 2015, the areas of forest, grassland, wetland and desert increased in the southtern and western China; the areas of farmland, shrubland and bare land decreased; the city/town area significantly increased; and the area of farmland significantly decreased. In addition, the rocky desertification area continuously decreased during this period, corresponding to a benign development trend in rocky desertification, which is related to the rocky desertification control measures taken since 2000.

2) No strong correlations of rocky desertification change with topographic factors but did observe strong correlations with ecosystem and socioeconomic factors. These findings reveal that rocky desertification change is mainly controlled by human activities and that socioeconomic factors exhibit a stronger capability in explaining the dynamics of rocky desertification than ecosystem variables, which is consistent with other researches.

3) Reduced farmland area and improved farmland management were favourable to the alleviation of rocky desertification, while regional GDP and continuous development of the tertiary industry helped slightly alleviate rocky desertification. Increase in the land-independent economy prevented the occurrence of any strong degradation in rocky desertification grade. However, the development of tourism in southern and western China induced some slight degradation in rocky desertification, because tourism plays an important role in the economy in southtern and western China.hina.

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