Human–desertification coupling relationship in the karst region

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Abstract: Forward and reverse successions of karst rocky desertification (KRD) occur simultaneously, and are linked to human activity, thus presenting a mutual feedback loop. Previous studies have focused on the unilateral human-driven mechanism of KRD or the impact of KRD on social-economic activities. These lack quantitative measurement and in-depth understanding of interactions involved. Therefore, this study builds and applies a novel model for measuring the coupling relationship and degree between KRD and social-economic activity in the Guizhou karst region of China. Results show an overall improvement but local deteriorations in KRD from 2000 to 2011; conversely, social-economic activity intensities increased during that time period. With their spatio-temporal variations, positive and negative human–desertification coupling relationships with an increased coupling degree are found. Different coupling relationship types between KRD and social-economic development, including urbanization, economic development and household income, are shown. KRD is found to be high positively coupled with specific human behavior intensities such as population movement, steep slope cultivation and ecological restoration. An inverted U-shaped curve is observed in the coupling index of KRD and urbanization within different development levels. Negative coupling at a low urbanization level indicates the limitation of the karst physical environment on social-economic development. Positive coupling with increasing urbanization implies a conflict between environment protection and social-economic development. A return to negative coupling in several counties with high urbanization levels indicates a win-win for ecology and economy. The effectiveness of the proposed coupling model is demonstrated, informing differentiated strategies for combating KRD and improving social-economic development.

Key words: desertification, human activity, interaction, coupling index, karst region

1 Introduction

Karst rocky desertification (KRD), the most serious ecological and environmental degradation problem in Southwestern China, threatens regional social-economic development (Jiang et al., 2014; Wang, Liu, et al., 2004). In turn, human behavior has significantly changed the KRD succession process (Yan & Cai, 2015). The interaction and positive feedback between KRD and human activity has historically caused a vicious circle (Wang, Lee, et al., 2004; Zhou et al.,

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2014). Residents in the karst region face the dual pressures of poverty and a fragile karst environment, where KRD intensifies poverty, and poverty aggravates KRD (Huang et al., 2008; Wang, Liu, et al., 2004).

The scarcity of flat land available in the karst region leads farmers to expand arable land to steep slopes, which causes soil erosion and aggravates KRD. This worsens cultivated soil properties and impoverished resident livelihoods in the karst region (Li et al., 2016). Meanwhile, social-economic development can motivate the government and residents to pay attention to the environment and provide more funds for controlling and combating KRD (Yang et al., 2014; Zhang et al., 2016). Under karst special physical conditions, the regional forward and reverse KRD succession processes are intertwined with complex social-economic activity (Mick, 2010; Xu & Zhang, 2014b; Zhao et al., 2021). This requires an in-depth understanding of the complex interactions between them, in order to achieve sustainable human-environment development in the karst region.

Recent researches have quantified the effect of the multiple driving factors on KRD using statistical methods. Human activities combined with special physical karst environments have been proved to cause transformation of different KRD classes (Bai et al., 2013; Xu & Zhang, 2014a). Human disturbance or restoration activities can accelerate or reverse the KRD succession process (Yan & Cai, 2015). Anthropogenic unreasonable development activities, including steep slope cultivation, deforestation and reclamation, overgrazing and mining of mountains, tend to accelerate KRD expansion (Wu et al., 2011; Yang et al., 2011). On the other hand, urbanization enables rural population migration, which can alleviate the pressure of the rural population on the environment and control KRD (Cai et al., 2014). The implementation of ecological protection and restoration projects in Southwestern China, such as returning farmland to forests, natural forest protection and closing hills to facilitate afforestation, has helped to combat KRD (Qi et al., 2013; Tong et al., 2017; Zhang et al., 2015). With population growth and economic development, the impact of humans on the land surface intensifies, and can alter the KRD succession process over a short time period.

The mutual succession processes of different KRD classes have also significantly influenced the production and living activities and conditions in the karst region (Li et al., 2019). KRD can easily encroach on the limited flat-land resources in the karst region and cause prominent competition among multiple land uses. The loss of flat arable lands and decrease of land suitability reduce agricultural productivity and farmers' income (Li et al., 2016; Xu & Zhang, 2016). Meanwhile, KRD could easily cause geological disasters and lead to economic losses (Guo et al., 2013; Huang et al., 2008). Conversely, a decrease in KRD can improve the regional environment and benefit production and living conditions. For example, increasing the vegetation cover and thus lowering bedrock exposure decreases the local temperature, favoring crop growth and yield (Yang et al., 2019). In the environment restoration process, combating KRD and alleviating poverty are closely linked with the increase of ecological and economic benefits (Li &

Xiong, 2020; Zhang et al., 2016). Implemented ecological poverty alleviation policies can relieve the anthropogenic pressure on the environment to control KRD, and also promote regional social-economic development (Deng & Jiang, 2011).

Thus, KRD succession interacts with social-economic development in the karst region; however, whether they mainly restrict or promote each other is still uncertain (Zhao et al., 2021). Moreover, whether their coupling relationships change in response to the urbanization process is still unclear. Kuznets curves are used to hypothesize the complex relationship between environmental pollution and economy growth (Dinda, 2004; Stern, 2004). Economic growth can lead to environmental pollution in the early stages, but the trend reverses, and a high income results in environmental improvement above some threshold of income. Whether the coupling relationship between KRD and human activity is consistent with the Kuznets curve is questionable. Understanding how they interact and feed back with each other would support combating KRD and also enhance sustainable social-economic development (Li et al., 2016; Zhao et al., 2021). To solve these problems, this study proposes a coupling model between KRD and human activity. It quantifies the spatio-temporal coupling relationship between KRD and social-economic activity, thus supporting investigation of the changes in the coupling relationship with social-economic development process.

The objectives of this paper are to: (1) propose a coupling model to detect the coupling relationship and coupling degree between KRD and social-economic activity and (2) explore their interaction dynamically with the social-economic development process. As a case study, the novel model is applied to the Guizhou Province in China, which has the most serious KRD in Southwestern China. The coupling model gives an approximation for the coupling relationship between KRD and human activity and explores how the relationship responds to different social-economic development levels. This can help to enhance understanding of the interaction and support policy design decision making.

2 Materials and methods

2.1 Study region

Guizhou Province is a typical karst landform area (Wang, Liu, et al., 2004; Zhang et al., 2010), comprising considerable karst landform types with peaks and depressions. The exposed karst area accounts for 61.92% of the total territorial area, and it is the province with the largest area of KRD in China.[1] It is in the subtropical humid monsoon climate zone, with an average annual temperature of ca. 15 °C, and an average annual precipitation of ca. 1200 mm. The terrain is high in the northwest and low in the southeast, with an average elevation of ca. 1100 m. The province consists of considerable mountains and hills but few flat areas and no plains.

As KRD is a special land-degradation type that occurs only in karst environments, the study of KRD can be conducted only in counties/cities/districts that include a karst environment. In this

[1] State Council of the People's Republic of China. 2008. A General Outline of Plan Program about Comprehensively Taming Karst Rocky Desertification (2006–2015) (in Chinese).

paper, these administrative units are unified and termed a “karst county”. There are 78 karst counties in Guizhou Province, which is taken as the study area in this paper (Figure 1). The study area covers 154,027 km^2 with a karst area of 109,083 km^2. All of the karst counties in Guizhou Province are listed in the scope of the National Rocky Desertification Comprehensive Control Pilot County Project. Under the specific karst environment combined with intense human disturbance and KRD improvement projects, different KRD classes mutually transform each other in the study area (Bai et al., 2013). In addition, the regional societies and economies have different development rates in different counties. Thus, the Guizhou karst region is an ideal research area for studying the coupling relationship between KRD and social-economic activity.

2.2 Data sources and pre-processing

2.2.1 Data sources

To explore the spatio-temporal interaction between KRD and social-economic activity, data for two different years (2000 and 2011) were collected in the Guizhou karst region. The KRD map in 2000 was sourced from the Atlas of Comprehensive Prevention and Control of Karst Rocky Desertification in Guizhou Province (2006-2050) (Chen et al., 2007). The KRD map in 2011 was sourced from the second national rocky desertification monitoring result from the National Forestry Bureau[1]. Both of these were produced by the same KRD classification system with six KRD classes according to the same bedrock rate classification standard. The six KRD classes were: no KRD, potential KRD, slight KRD, moderate KRD, severe KRD and extremely severe KRD. The two KRD maps were scanned, digitized and resampled with a spatial resolution of 100 m using ArcGIS 10.0. Then, the changes between the two years were examined and corrected using visual interpretation based on Landsat 4-5 Thematic Mapper images. According to the classification standard of the two KRD maps and previous studies (Bai et al., 2013; Chen et al., 2007; Xu et al., 2015), the KRD classification standard in this study was based on bedrock exposure and color characteristics in the false-color composite of remote-sensing images (Table 1).

The social-economic data of 78 Guizhou karst counties in 2000 and 2011 were collected from the Statistical Yearbook of Guizhou Province (2001 and 2012), Social and Economic Statistics Yearbook in Counties of China (2001 and 2012), and 5^{th} and 6^{th} national census in Counties of China. Land-use data with a spatial resolution of 30 m were provided by the Resource and Environment Science and Data Center.

2.2.2 Comprehensive characterization of karst rocky desertification

The data for social-economic activity indicators were collected at the county scale, but the KRD distributions were mapped at the grid scale. To compare them and quantify their coupling relationship, the KRD characteristics needed to be characterized at the county scale. Considering the six KRD classes representing the different KRD succession stages and degrees of

[1] National Forestry Bureau. 2012. The bulletin of national karst rocky desertification monitoring status (2^{nd}) (in Chinese).

desertification (Xu & Zhang, 2014b), a class-weighted KRD area method was used to calculate a comprehensive KRD index using the following equation:

$$CKI^j = \sum_{i=1}^{6} \omega_i \times A_i^j \tag{1}$$

where CKI^j is the class-weighted KRD index for county j; j ranges from 1 to 78 in this study (in km^2); i means the six KRD classes, ranging from 1 to 6, representing no KRD, potential KRD, slight KRD, moderate KRD, severe KRD and extremely severe KRD, respectively; ω_i means the class weight of KRD class i, which is assigned as 0.10, 0.25, 0.40, 0.60, 0.80 and 0.95 for the six KRD classes according to the average value of bedrock exposure rate (Table 1); and A_i^j is the area of KRD class i at county j (in km^2). A higher CKI^j indicates a more serious KRD for this county.

2.2.3 Indicator selection of social-economic activity

The indicators of social-economic activity selected in this study focused on the main aspects that KRD influences the social-economic development and specific human behavior[1], which also, in turn, affect the KRD succession process. Human pressure alleviation and ecological restoration are the main human factors contributing to the KRD improvement (Wu et al., 2011). In addition, regional poverty causing unreasonable activity, especially steep slope cultivation, is a key factor in aggravating KRD (Li et al., 2016). Along with the KRD succession process, the above-mentioned socio-economic factors will be affected by the feedback of KRD. The occurrence of KRD exacerbates regional poverty and affects urban–rural population mobility, economic development and the income of local farmers (Li & Xiong, 2020; Zhang et al., 2016; Zhou et al., 2014). Therefore, this study selected six social-economic activity indicators covering the two aspects of social-economic development and specific human behavior (Table 2). Indicators of social-economic development were the urban population proportion, per capita gross domestic product (GDP) and rural per capita net income. Indicators of specific human behavior were the migrant population proportion, sloping cropland area of >25°, and afforestation area. The values of GDP and rural per capita net income in 2011 were transformed as the constant price based on the price in 2000.

2.2.4 Data standardization

To quantify the coupling relationship between KRD and social-economic activity, all the data were standardized in the range [0, 1] due to the significant difference in magnitude and dimension for different indicators. The equation is as follows:

[1] National Forestry Bureau. 2012. The bulletin of national karst rocky desertification monitoring status (2nd) (in Chinese).

$$x' = \frac{\ln(x)_{\max} - \ln(x)}{\ln(x)_{\max} - \ln(x)_{\min}} \qquad (2)$$

where x' is the standard value of any indicator; and ln(*x*), $\ln(x)_{max}$ and $\ln(x)_{min}$ are the specific value, maximum and minimum of the logarithmic function of original data. The logarithmic function was used to deal with the obvious skewed distribution of data.

2.3 Coupling model between karst rocky desertification and social-economic activity

2.3.1 Revised coupling relationship index

The coupling relationship refers to the phenomenon that two or more objects influence each other through various interactions. The concept of coupling is used to describe the degree of interaction between systems or elements (Liu, Liu, et al., 2018; Sheng & ZHong, 2009). Its definition has been expanded and widely used in climate and environment change studies (Liu, Jiao, et al., 2018; Wang, Ma, et al., 2014; Xu et al., 2019). The coupling relationship of two objects can be calculated as follows:

$$C = \frac{\sqrt{K \times S}}{(K + S)/2} \qquad (3)$$

where C is the coupling relationship index, ranging 0 to 1; and K and S are the standard values of object 1 and object 2.

However, the coupling relationship index calculated using equation (3) is not sufficient for quantifying very large or small standardized values, resulting in an overestimation of the positive relationships (Sheng & ZHong, 2009). An absolute difference correction factor, measuring the difference between two objects, is proposed in this paper to revise the coupling relationship index in equation (3):

$$C_{ks} = \frac{\sqrt{K \times S}}{(K + S)/2} \times (1 - |K - S|) \qquad (4)$$

where C_{ks} is the revised coupling relationship index measuring KRD and social-economic activity; and K and S are the standard values of KRD and social-economic activity in this study, respectively. A value of C_{ks} greater than 0.5 means there is a positive coupling relationship between two objects. A value less than 0.5 means there is a negative coupling relationship between the two objects. When $C_{ks} > 0.5$, the closer it is to 1, the stronger the positive coupling relationship; when $C_{ks} < 0.5$, the closer it is to 0, the stronger the negative coupling relationship. According to C_{ks}, the coupling relationship of two objects can be divided into five types: high positive coupling (0.8–1.0), moderate positive coupling (0.6–0.8), weak coupling (0.4–0.6), moderate negative coupling (0.6–0.8) and high negative coupling (0.8–1.0).

2.3.2 Coupling degree index

Having complex coupling relationships at different units, it calls for comprehensively quantifying the coupling degree by combining them all to measure the coupling degree of KRD and human activity. Based on equation (4), the coupling degree between the KRD and social-economic activity can be calculated as follows:

$$I_{K\leftrightarrow S} = \sum_{c=1}^{n_c} \left| C_{ks} - 0.5 \right| \quad (5)$$

where $I_{K\leftrightarrow S}$ is the coupling degree index between KRD and social-economic activity; and c is the number of counties, $n_c = 78$ in this study. A higher $I_{K\leftrightarrow S}$ means a larger coupling degree.

2.3.3 Control variable method of coupling relationship responding to different social-economic development levels

The spatio-temporal variations of KRD and social-economic activity were calculated using remote-sensing image interpretation and statistical data collection. Then, their coupling relationship was measured for the 78 karst counties of Guizhou Province. A control variable method was used in this paper to explore the changes in the coupling relationship responding to the different social-economic development levels. The social-economic development indicator was used as the independent variable, and the coupling relationship index (C_{ks}) was used as the dependent variable. Function fitting was performed to quantify how the dependent variable changed with the change in the independent variable, i.e. how the change in C_{ks} responded to different social-economic development levels.

3 Results

3.1 Spatio-temporal variation of karst rocky desertification and social-economic activity

The KRD maps in 2000 and 2011 present a relatively similar spatial distribution (Figure 2). The KRD degree in the Guizhou karst region was greater in the western areas but lower in the eastern areas. The southwestern and northwestern areas were affected by the most serious KRD, where areas with severe and extremely severe KRD classes were widely distributed. The no KRD class was the base of the study area in 2011, where its areas covered 37.33% of the total area and 52.71% of the total karst area. The area of potential KRD class ranked second, accounting for 23.05% of the total karst area. The moderate and light KRD classes ranked third and fourth, covering 10.92% and 9.23% of the total karst area, respectively. The areas of severe and extremely severe KRD classes were relatively small. Based on the class-weighted KRD area at county scale (Figure 2c, d), the spatial difference of KRD characteristics were intuitively displayed between 78 karst counties.

The KRD expansion trend did not fundamentally reverse in Guizhou karst region from 2000 to 2011, showing a global improvement in the entire region but considerable locally marked deteriorations. The class-weighted KRD index of 48 counties decreased, but that of 30 counties slightly increased. The areas of the no KRD class increased in this period, from 45269 km^2 in 2000 to 57498 km^2 in 2011 with an increase rate of 27.01%. Areas of potential, light and extremely severe KRD classes decreased at rates of 20.91%, 45.31% and 5.88%, respectively. Conversely, areas of moderate and severe KRD classes increased by 22.87% and 18.58%, respectively. Complex mutual transformations occurred among different KRD classes. The potential, light and moderate KRD classes are the intermediate stages in the forward and reverse KRD succession processes in this period.

The socio-economic development level has significantly developed in the Guizhou karst region (Table 3). The urbanization population proportion increased from 24.15% in 2000 to 31.74% in 2011, where over two million people moved from rural areas to urban areas. The GDP and rural per capita net income significantly increased in this period, that nearly tripled and doubled, respectively. Meanwhile, specific human behavior intensified during this period. The migrant population proportion increased from 12.10% in 2000 to 34.38% in 2011, which resulted in different changes of population pressure in different areas. Ecological restoration also significantly expanded in the 78 counties, with the afforestation area increasing from 6.76 km^2/county to 21.39 km^2/county. With the implementation of the Grain for Green Project since 2002, the steep slope cultivation area decreased by 2.68% between 2000 and 2011, thus showing a slight decrease.

The spatial distributions of each socio-economic indicator were mapped and analyzed at the county scale. Two indicators for 2000 and 2011 are displayed as examples (Figure 3), showing the different spatial distributions for the different years. The urbanization population proportion presented a high value in the central and northern areas but a low value in western areas. It also showed a larger increased rate in the central and northern areas from 2000 to 2011. Due to the similar distribution of urban population proportion to GDP and rural per capita net income with correlation coefficients of 0.86 and 0.84, both presented a similar spatial distribution to that of urbanization level. Analyzing the spatial distribution of specific human behavior, the high afforestation areas were mainly located in the northwest and southeast and low values were scattered over the study area. Conversely, the spatial distributions of the afforestation areas were relatively similar for the two years. The spatial distributions of other indicators were also mapped and used in the coupling model.

3.2 Coupling characteristics between karst rocky desertification and social-economic activity

The present coupling model was used to analyze the interaction of KRD degree and social-economic activity with their spatio-temporal differences at 78 counties. The C_{ks} between the class-weighted KRD index and the social-economic activity indicator was calculated for the 78 Guizhou karst counties (Figures 4 and 5). The county proportions of five coupling relationships were calculated (Table 4). The KRD degree and social-economic development level showed a complex coupling relationship. Different values of C_{ks} between KRD and urbanization level were obtained for different counties. Positive coupling relationships with $C_{ks} > 0.6$ were found in more than half the counties in 2011, which were mainly located in the central and northern regions (Figure 4a). Weak coupling relationships with $0.4 \leq C_{ks} \leq 0.6$ and negative coupling relationships with $C_{ks} < 0.4$ were scattered throughout the study area. In particular, the counties with high negative coupling relationships with $C_{ks} < 0.2$ were located in several social-economic developed counties. In contrast, the number of positive coupling relationships decreased and that of weak and negative coupling relationships increased in 2000 (Figure 4b). Counties with weak coupling relationships covered over one-third of the total number. Values of C_{ks} in 2000 in the west and north were smaller than those in 2011, where counties in the west showed a negative coupling relationship and counties in the north presented a weak coupling or moderate positive coupling relationship. Due to a distribution of urban population proportion similar to those of GDP and rural per capita net income, the spatial distribution of C_{ks} for KRD and two other social-economic development indicators showed similar distributions to that for KRD and urbanization level (Figure 4c,d). There were more counties with negative coupling relationships for GDP and rural per capita net income in 2000, located in the less-developed and serious KRD counties (Figure 4c,e).

Compared to C_{ks} for KRD and social-economic development (Figure 4), C_{ks} for specific human behavior showed an obvious spatial difference (Figure 5). The spatial distributions of C_{ks} for three indicators were similar with a positive coupling relationship within most counties. In particular, the county proportions of high positive coupling relationships for migrant population proportion, sloping cropland area of >25°, and afforestation area were 70.51%, 71.79% and 60.26%, respectively. There was a limited number of counties with negative coupling relationships. Their average C_{ks} values were 0.82, 0.84 and 0.82 in 2011, respectively. The C_{ks} of three indicators in 2000 showed a similar distribution to those in 2011, with average C_{ks} values of 0.65, 0.82 and 0.82, respectively. Negative coupling relationships between KRD and migrant population proportion were found in counties with relatively serious KRD, which implied that serious KRD would limit population movement.

The coupling degree index $I_{K \leftrightarrow S}$ between KRD and social-economic activity in 2000 and 2011 was calculated and compared (Table 5). The $I_{K \leftrightarrow S}$ of KRD and social-economic development levels increased by a rate of nearly 50%. The $I_{K \leftrightarrow S}$ values were ca. 0.20 in 2000 and ca. 0.30 in 2011, indicating an intensive interaction between KRD and social-economic development during the 2000–2011 period. Weak coupling relationships in part of counties turned into moderate or high positive coupling relationships from 2000 to 2011. In contrast, the coupling degrees of KRD and specific human behavior stayed relatively stable. The $I_{K \leftrightarrow S}$ for the population movement increased from 0.25 to 0.31, $I_{K \leftrightarrow S}$ for steep slope cultivation decreased from 0.34 in 2000 to 0.30 in 2011, but $I_{K \leftrightarrow S}$ for ecological restoration measurement did not change.

3.3 Change of coupling relationships between karst rocky desertification and social-economic activity within the urbanization process

Compared to the high positive coupling relationships between KRD and specific human behavior (Figure 5), the complex coupling relationship types were found between KRD and social-economic levels (Figure 4). Thus, the change of C_{ks} responding to different social-economic development levels was further explored. Owing to the similar distribution between the urban population proportion and GDP or rural per capita net income, this paper analyzed only the changes of C_{ks} for urbanization level (Figure 6). The figure shows that C_{ks} is an inverted U-shaped curve of urbanization level, which was fitted as a quadratic function with a determination coefficient of 0.64, at a significance level of 99%. The urbanization level was low in the study area in 2000, but significantly increased from 2000 to 2011, presenting a shift from negative coupling relationships in counties with low urbanization levels to counties with high urbanization levels. Poor resource and environment endowment with severe KRD restricts urbanization and social-economic development, resulting in a negative coupling relationship between them (red square in Figure 6). For urbanization, the environment is sacrificed to obtain social-economic development, resulting in a positive coupling relationship (yellow square in Figure 6). In counties with high urbanization levels, social-economic development, instead of being a threat to the environment, was the means to eventual environmental improvement and KRD restoration (blue square in Figure 6).

The inverted U-shaped curve between C_{ks} and urbanization level indicates the different coupling relationships in karst counties. Examining the KRD related to urbanization in different counties (Figure 6), the top ten counties with the lowest urbanization level in 2000 had an average value of standard class-weighted KRD index of 0.82, which was significantly higher than the average value in the study area. Thus, their average value of C_{ks} was 0.30, indicating a negative coupling relationship between KRD and social-economic development. These counties experienced an increased urbanization proportion and a slight decreased KRD index from 2000 to 2011 in these counties, resulting in an increased C_{ks} and a turn to moderate or weak coupling relationships. Meanwhile, the top ten counties with the highest urbanization level in 2011 presented a KRD improvement trend. These counties had an average value for the standard class-weighted KRD index of 0.30, which was much lower than the average of 0.66 in the study area. The C_{ks} in these counties decreased from 0.51 in 2000 to 0.29 in 2011, where positive coupling relationships or weak coupling relationships became negative coupling relationships during this period.

The social-economic development responding to KRD succession was also analyzed from another angle. Among the top ten counties with KRD improvement, the average urbanization population proportion was 52.18%, which was much higher than the average value of 31.74% in all karst counties. Although the increased rate of urbanization in these cities was close to the average value in the study area, the coupling relationship between KRD and urbanization changed from positive coupling to weak or negative coupling. In contrast, there was a low urbanization population proportion of 22.53% in the top ten counties with deteriorated KRD aggravation, much lower than the average value of 31.74% in the study area. The contradiction between environment protection and social-economic development at this stage meant a higher increased rate of urbanization level of over 50% increased KRD. The positive coupling relationship with an average C_{ks} of 0.71 implies that urbanization with unreasonable development activities could easily damage the environment and aggravated KRD.

4 Discussion

Based on remote-sensing image interpretation and statistical data, a revised coupling model has been built to measure the coupling relationship and coupling degree between KRD and social-economic activity (C_{ks} and $I_{K\leftrightarrow S}$) in the Guizhou karst region. Previous unilateral studies have focused on human activity driving KRD (Li & Xiong, 2020; Wu et al., 2011; Xu et al., 2013; Yan & Cai, 2015) or KRD influencing social-economic activity (Shi et al., 2019; Zhang et al., 2016; Zhao et al., 2021). However, this study has quantified the complex spatio-temporal interactions using a novel coupling model. Different coupling relationship types and an intensified coupling degree between KRD and social-economic development were found in the study area. The positive and negative feedbacks between KRD and social-economic activity, which have not been quantified in previous studies (Xu et al., 2011; Zhou et al., 2014), lead to their complex interaction. This study has built the proposed coupling model and demonstrated that C_{ks} and $I_{K\leftrightarrow S}$ are indicative indicators for detecting complex interactions between KRD and social-economic activity (Figures 4 and 5).

An inverted U-shaped curve between C_{ks} and urbanization level was found in this study (Figure 6). This implied that the coupling relationship between KRD and social-economic development with different karst counties should be diagnosed according to their different urbanization levels. The shift process of “negative coupling→positive coupling→negative coupling” was hypothesized as the complex relationship between KRD and urbanization. The turn from positive coupling to negative coupling was consistent with the Environmental Kuznets Curve (Stern, 2004), but the negative coupling in less-developed areas indicated the limitation of the specific karst fragile environment (Wang, Liu, et al., 2004). A negative but not positive coupling relationship was found in counties with low urbanization levels (red square in Figure 6). Within the fragile karst physical environment, resources and environmental capacity are a prerequisite for human living and production (Jiang et al., 2014; Xu & Zhang, 2014b). In counties with serious KRD, the ecological environment is severely damaged and has limited available land resources conducive to population aggregation and urbanization development. Reclaiming steep slopes can cause serious soil erosion and thus an increase in KRD, giving a vicious circle of poverty and KRD (Wang, Lee, et al., 2004; Zhou et al., 2014).

The positive coupling relationship between KRD and social-economic development indicates that the society and economy develop at the expense of the environment, and KRD aggravated with unreasonable development activities within the urbanization process (yellow square in Figure 6) (Liu et al., 2014). With continuous urbanization, the negative coupling relationship between KRD and social-economic development and a win-win for environment protection and social-economic development can be achieved in several developed counties of the study area (blue square in Figure 6). The developed counties with high urbanization levels were located mainly in areas with high proportions of flat-land resources, which benefit soil conservation and aid KRD control. Urbanization has guided the rural population to agglomerate in cities and towns, relieving the pressure on the environment (Zhang et al., 2016). With social-economic development, efficient production and sufficient ecological restoration funds can enhance KRD control (Zhang et al., 2016; Zhao et al., 2021). The inflection point from positive coupling to negative coupling emerged in an urbanization level of about 50%–60% in this study. Rather than being a threat to the environment, social-economic growth could be the means to eventual environmental improvement (Stern, 2004).

Three indicators of specific human behavior had a positive coupling relationship with KRD (Figure 5). Without soil and water conservation measures, steep slope cultivation can easily cause soil erosion and further aggravated KRD (Wang, Zou, et al., 2014), where a higher area proportion of sloping cropland area of >25° along with a more serious KRD. It is generally recognized that the population migration relieving the pressure to the environment and the ecological restoration projects benefiting for the KRD control (Chen et al., 2012; Qi et al., 2013); however, a positive coupling relationship was found in this study. This was attributed to the influence of KRD in different counties on the human behavior choice. On the one hand, KRD improvement and a better ecological environment are conducive to attracting populations, and the migrant population proportion is also low. In turn, the KRD aggravation will destroy people's living environment and stimulate population migration (Cai et al., 2014). On the other hand, the difference in KRD degrees between counties is the strategy design basis of ecological restoration projects. Thus, a more serious KRD would lead to a larger afforestation area, showing a positive coupling relationship between them (Xiao et al., 2020). However, the feedback of these two behaviors on the KRD is combined with the positive and negative effects of other considerable human activities (Yan & Cai, 2015). For example, among the 39 counties in the top 50% of the afforestation area, most of them were located in the west region with severe KRD (Figure 3). However, there were 15 counties with slightly deteriorated KRD from 2000 and 2011, where the average C_{ks} for KRD and urbanization at these counties reached 0.77. Thus, even if the ecological restoration projects were implemented, it is difficult to control and decrease KRD without control of unreasonable human activity along with the urbanization process.

The uncertainty improvements and model applications can be tested in future work. The coupling relationships were classified as five types with an equal classification interval of [0, 1] in this study. Whether the classification threshold is reasonable and indicative needs to be validated using more case studies, especially for the highly positive and negative coupling relationships. The statistical significance of C_{ks} and $I_{K\leftrightarrow S}$ in this proposed model can be further tested. With the complex coupling relationship between KRD and social-economic development measured in this study, it is suggested that these be incorporated into model simulations for KRD succession and social-economic development (Abdollahian et al., 2015; Helldén, 2008; Xu & Zhang, 2018). In particular, the inverted U-shaped curve for C_{ks} within different urbanization levels need to be considered for improving the model accuracy.

The coupling indices C_{ks} and $I_{K\leftrightarrow S}$ calculated in the proposed model can quantify the different coupling characteristics, which provide the information necessary to specify strategies for combating KRD and increasing social-economic development (Chen et al., 2012; Wang et al., 2019). The results demonstrated an increased number of counties with a positive coupling relationship between KRD and social-economic development and a smaller number of counties with a negative coupling relationship along with a highly developed level (Figures 4 and 6). This implies the importance and necessity of reversing the positive coupling relationship and pursing a win-win for environment improvement and social-economic development (Zhang et al., 2016). Areas with positive coupling require more attention, especially the areas deviating from the inverted U-shaped curve. These counties were mainly located in the central region, presenting a relatively high urbanization level but also a high positive coupling relationship. Unreasonable human activity still occurred in these areas and KRD was still serious, and so the human disturbance on the environment needs to be controlled (Zhao & Hou, 2019). Within the less-developed areas with negative coupling or weak coupling relationships in the northeastern and western regions, looking for a green development path that does not sacrifice the environment to achieve future social-economic development is necessary. In addition, larger afforestation areas were positively coupled with KRD, but failed to control KRD in several counties. It is suggested that KRD improvement projects restore areas affected by serious KRD but also pay more attention to poverty alleviation in the region. Thus, increasing household income and promoting industrial development can realize the negative coupling relationship between KRD and social-economic development and break the vicious circle of poverty and KRD (Wang, Lee, et al., 2004; Zhao et al., 2021).

5 Conclusion

KRD interacts with human activity with positive and negative feedback, calling for an in-depth understanding of their complex coupling relationships. This study has proposed a novel coupling model to measure the coupling relationship and coupling degree between KRD and social-economic activity using C_{ks} and $I_{K\leftrightarrow S}$. A class-weighted KRD index representing the KRD degree and six indicators of social-economic development and specific human behavior representing the social-economic activity were calculated using the proposed coupling model. Results showed an overall decrease in KRD improvement but considerable local KRD aggrvations from 2000 to 2011, with 48 counties having a decreased class-weighted KRD index and 30 counties having a slightly increased index. Except for steep slope cultivation, other indicators of social-economic activity have increased. According to the calculated C_{ks}, a complex coupling relationship between KRD and social-economic development level was found with different numeral intervals of C_{ks}. In contrast, a positive coupling relationship between KRD and specific human behavior intensity with an average C_{ks} of ca. 0.8 in the 78 karst counties. The $I_{K\leftrightarrow S}$ indicated that the coupling degree between KRD and social-economic development level increased by nearly 50%. In contrast, the coupling degree of KRD and specific human behavior stayed relatively stable. The C_{ks} between KRD and urbanization was found to be an inverted U-shaped curve of development level. There was a shift process of "negative coupling→positive coupling→negative coupling" between KRD and urbanization. Negative coupling relationships in counties with serious KRD and low urbanization levels indicate the limitation of the karst physical environment. Turning to positive coupling relationships occurred with the urbanization process in most counties, implying the conflict between environment protection and social-economic development. A return to negative coupling relationships occurred in several counties with a high urbanization level and light KRD degree. Specified strategies to combat KRD and increase social-economic have been suggested according to the calculated coupling indices C_{ks} and $I_{K\leftrightarrow S}$. An increased number of positive coupling relationships between KRD and social-economic development calls for further attention to the study area. The results have demonstrated the effectiveness of the proposed model for measuring the complex coupling relationship between KRD and human activity, supporting a way for exploring win-win for decreasing KRD and improving socio-economic development.

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Tables

Table 1 Karst rocky desertification classification standard

Classification of KRD[1] type	Percent of bedrock exposure (%)	Landsat 4-5 TM image with false color composite[2]	Assigned KRD class-weight value
No KRD	< 20	Scarlet	0.10
Potential KRD	20-30	Shocking pink	0.15
Light KRD	31-50	Pink	0.40
Moderate KRD	51-70	Green in red	0.60
Severe KRD	71-90	Gray in red	0.80
Extremely severe KRD	> 90	White, grey	0.95

Note: [1] KRD means karst rocky desertification;

[2] Landsat 4-5 TM image bands 4, 3, 2 were assigned as red, green, and blue channels

636 Table 2 Indicator system of social-economic activities in Guizhou karst region

	Category	Indicator	Data processing
Social-economic development	Urbanization level	Urban population proportion	Urban population / Total population
	Economic development level	Per capita gross domestic product	Obtained from the statistical yearbook
	Household income level	Rural per capita net income	Obtained from the statistical yearbook
Specific human behavior	Population movement	Migrant population proportion	[Immigrant population - (resident population - registered population)]/ Total population
	Steep slope cultivation	Sloping cropland area of >25°	Area of sloping croplands of > 25°
	Ecological restoration measurement	Afforestation area	Area of increased forests except for Grain for Green forests in the last decade of base year

Table 3 Average statistics of social-economic activity indicator in Guizhou karst region

	Category	Indicator	2000	2011	Change rate (%)
Social-economic development	Urbanization level	Urban population proportion (%)	24.15	31.74	31.43
	Economic development level	Per capita gross domestic product (Yuan)	3151.96	9758.63	209.61
	Household income level	Rural per capita net income (Yuan)	1521.29	3022.59	98.69
Specific human behavior	Population movement	Migrant population proportion (%)	12.10	34.38	184.13
	Steep slope cultivation	Sloping cropland area of >25° (km^2/county)	53.37	51.94	-2.68
	Ecological restoration measurement	Afforestation area (km^2/county)	6.76	21.39	212.42

Table 4 Number proportion of coupling relationships between karst rocky desertification and social-economic activities in Guizhou karst region

Category		Indicator	Year	Coupling relationship with karst rocky desertification				
				High negative coupling	Moderate negative coupling	Weak coupling	Moderate positive coupling	High positive coupling
Social-economic development	Urbanization level	Urban population proportion	2000	8.97	11.54	37.19	20.51	21.79
			2011	7.69	11.54	17.95	29.49	33.33
	Economic development level	Per capita gross domestic product	2000	10.26	20.51	35.9	19.23	14.10
			2011	7.69	7.69	14.10	32.05	38.47
	Household income level	Rural per capita net income	2000	8.97	17.95	39.74	23.08	10.26
			2011	5.13	7.69	28.21	21.79	37.18
Specific human behavior	Population movement	Migrant population proportion	2000	3.85	7.69	24.36	37.18	26.92
			2011	1.28	1.28	7.69	19.24	70.51
	Steep slope cultivation	Sloping cropland area of >25°	2000	1.28	1.28	7.69	24.37	65.38
			2011	1.28	1.28	6.41	19.24	71.79
	Ecological restoration measurement	Afforestation area	2000	1.28	1.28	5.13	24.36	67.95
			2011	2.56	1.28	12.82	23.08	60.26

Table 5 Coupling relationship intensity of karst rocky desertification and social-economic activities in Guizhou karst region

Indicator		Coupling relationship intensity with karst rocky desertification		
		2000	2011	Change
Social-economic development	Urban population proportion	0.21	0.28	0.08
	Per capita gross domestic product	0.20	0.30	0.10
	Rural per capita net income	0.19	0.31	0.12
Specific human behavior	Migrant population proportion	0.25	0.31	0.06
	Sloping cropland area of >25°	0.34	0.30	-0.04
	Afforestation area	0.34	0.34	0.00

Figure captions

Figure 1 Location of Guizhou karst region

Figure 2 Karst rocky desertification map in Guizhou karst region at a) grid scale in 2000, b) grid sale in 2011, c) county scale in 2000, d) county sale in 201

Figure 3 Examples of spatial distribution of social-economic activities in Guizhou karst region. a) urban population proportion in 2000, b) urban population proportion in 2011, c) afforestation area in 2000, d) afforestation area in 2011

Figure 4 Spatial distribution of coupling relationships between karst rocky desertification (KRD) and social-economic development. a) urbanization in 2000, b) urbanization in 2011, c) economic development in 2000, d) economic development in 2011, e) household income in 2000, f) household income in 2011

Figure 5 Spatial distribution of coupling relationships between karst rocky desertification (KRD) and specific human behavior. a) population movement in 2000, b) population movement in 2011, c) steep slope cultivation in 2000, d) steep slope cultivation in 2011, e) ecological restoration measurement in 2000, f) ecological restoration measurement in 2011

Figure 6 Changes of coupling relationships between karst rocky desertification and urbanization within different urbanization levels