Land Use Policy 100 (2021) 104940

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

# Optimize and control territorial spatial functional areas to improve the ecological stability and total environment in karst areas of Southwest China

Sinan Li[a], Xiaoqing Zhao[a,*], Junwei Pu[b], Peipei Miao[a], Qian Wang[a], Kun Tan[a]

[a] College of Earth Science, Yunnan University, Kunming 650500, China
[b] Institute of International Rivers and Eco-Security, Yunnan University, Kunming 650500, China

ARTICLE INFO

*Keywords:*
Territorial spatial planning
Optimization of functional areas
Control approaches
Correction of the "double evaluations"
Karst areas
Southwest China

ABSTRACT

Optimizing and controlling territorial space have become national strategic issues for China. However, urban-agricultural-ecological functions have serious conflicts in karst areas, causing differences in regional development and leading to severe problems related to the ecological environment and poverty. In this study, based on evaluations of urban-agricultural-ecological suitability and resource and environment carrying capacity, we explored an optimization method for territorial spatial functional areas and amendment rules for unsuitable areas in karst areas, identified different territorial spatial function areas, and proposed territorial spatial control approaches taking the functional area control and rock desertification space control as cores. On the one hand, the results showed that the optimization of the territorial space was divided into three single functional areas (i.e., urban space, agricultural space, and ecological space) and four multifunctional areas (i.e., urban-agricultural space, urban-ecological space, agricultural-ecological space, and urban-agricultural-ecological space). Among those different functional areas, the largest was ecological space, which was primarily distributed in the northwest, southwest, and northeast with good ecological environments and the south and southeast with severe rocky desertification. The second was agricultural-ecological space, which was primarily distributed in the north with better ecology and the south and southeast with severe rocky desertification. This region was the most important multifunctional area of the karst areas. The smallest type was urban-ecological space, which was primarily distributed in the central and northeastern regions with higher ecological and residential values. On the other hand, in terms of territorial spatial control, the region formed control patterns of functional areas of the "trinity", which centered on classified protection, comprehensive improvement, and cluster development. Additionally, from the three aspects of control of deteriorating rocky desertification area, control of severe rocky desertification area, and control of corresponding policies, we explored new approaches and methods for the development and protection of rocky desertification space. The results of this research provide references for territorial spatial planning and management in karst areas.

## 1. Introduction

Chinese territorial spatial patterns have undergone dramatic evolution under the major functional area zoning strategies and the new urbanization development (Liu and Yang, 2012). Urban-rural construction land has been expanding, while agricultural and ecological land has become condensed. This phenomenon has increased oppositions among urban, agriculture, and ecology, and it disrupted territorial spatial development patterns. Many derivative problems (e.g., conflicts of people and land, inefficient use of land resources, environmental pollution, imbalanced urban-rural development) have become increasingly apparent and have introduced large challenges for Chinese territorial spatial development (Liu et al., 2014; Fan, 2015; Liu et al., 2017). The sustainable development of territorial space in this chaotic situation has become an important question and a heavily researched topic in regional development research (Wang et al., 2016). Yunnan Province, Guizhou Province, and Guangxi Province in Southwest China are the most concentrated areas of the karst distribution in China. Rocky desertification is known as the source of disasters and poverty, and it is one of the three major land degradation problems in China. The serious rocky desertification conditions increase pressure on ecological protection (Bai et al., 2013; Fan et al., 2015) and affect regional sustainable development (Yang et al., 2016). The "urban disease" and "rural disease" (Liu, 2018) caused by the chaotic expansion of urban areas and unreasonable allocation of urban-rural resources have further triggered a series of ecological and poverty problems in karst areas.

* Corresponding author.
*E-mail address:* xqzhao@ynu.edu.cn (X. Zhao).

https://doi.org/10.1016/j.landusepol.2020.104940
Received 11 January 2020; Received in revised form 24 May 2020; Accepted 17 July 2020
Available online 28 July 2020
0264-8377/ 

Land use is the physical manifestation and core subject of territorial space (Fan, 2015), and its changes have been identified as a primary determinant of global change, having major impacts on ecosystems, climate change, and human vulnerability (Foley, 2005; Verburg et al., 2009). Relevant research has shown that changes in land use will strongly affect the rocky desertification in karst areas (Jiang et al., 2009). Therefore, optimization and control of the territorial space can effectively promote improvement of the rocky desertification and enhance the quality of regional ecological environments.

Previous studies of territorial space have mainly focused on the optimization and regulation of territorial spatial structures based on the relationship between land systems and the internal environment of natural systems (Zhou et al., 2016; Hersperger et al., 2012). And the partitioning and adjustment of regional territorial space are studied from the aspect of multifunctional land characteristics (Verburg et al., 2009) (e.g., ecosystem service value (Scolozzi et al., 2012), climate change (Wende et al., 2010)). Concurrently, some studies have focused on regional socioeconomic sustainable development to analyze the internal mechanism (Groot, 2006) and the interrelationship (Wiggering et al., 2003) between territorial spatial structures and regional sustainable development. With the implementation of major functional area planning in China, some studies have addressed the partitioning and optimization of territorial space for major functional areas and extensively explored the partition frameworks, indicator systems, and partitioning methods (Fan, 2015; Lin and Li, 2014). Based on the regional functional suitability and resource and environment carrying capacity (Liu et al., 2017), methods for optimizing and controlling territorial spatial patterns are constantly developing. Some researchers have also analyzed the functional characteristics of territorial space in terms of niche theory (Du et al., 2016) and suitability theory (Ma et al., 2015), as well as exploring different coupling relationships between different functions using different mechanism combinations (e.g., urbanization-ecological environment (Zhang et al., 2018), economy-environment (Bertinelli et al., 2008), and population-land-industry (Yang et al., 2015)). In terms of practical applications, according to different land structures and the utilization needs in different regions, the combined patterns of territorial space (Fan et al., 2018), partitioning of the "three-lines" (i.e., urban growth boundary, basic farmland protection red lines, and ecological protection red lines) (Tayyebi et al., 2014; Ran et al., 2018), and layout of spatial optimization (Zhao et al., 2019a; 2019b) have been extensively studied. Simultaneously, theoretical research (e.g., systems (Zhao et al., 2019c), approaches (Zhao et al., 2019a), and policies (Lin et al., 2019)) of territorial spatial control has gradually emerged.

However, the coordination, carrying capacity, and suitability of territorial space have been seriously overlooked, and the contradictions and conflicts among urban, agriculture and ecology persist in current regional development (Zhou et al., 2016). These issues affect the stability of territorial spatial structures. Thus, the Chinese government proposed a territorial spatial planning strategy that was dominated by urban-agricultural-ecological functions, and evaluations of urban-agricultural-ecological suitability and the resource and environment carrying capacity (i.e., the “double evaluations”) (Wang et al., 2019) have become important foundations and indispensable contents of territorial spatial planning. Existing studies have accumulated experiences for the in-depth optimization and control of territorial spatial functional areas, but the application and implementation of the results of "double evaluations" in the optimization of territorial spatial functional areas are in the exploration stage, and the research methods and ideas have not been determined. Additionally, studies of territorial spatial control are only general theoretical frameworks, lacking practical exploration and analysis. Especially in karst areas with severe spatial conflicts, the study of territorial space has received limited attention.

This study took Guangnan County as a study area, it’s a typical karst county in karst areas of Southwest China (this county is located in a karst continuous patch in Southwest China. The karst landform has a high continuousness degree, and it’s area accounts for 3/5 of the total area. The rocky desertification situation is severe, and the ecological environment is fragile. This county can reflect the characteristics of karst areas in Southwest China and has representativeness and typicalness). The social-ecological complexity of territorial space systems with a large proportion of rock desertification space in karst areas was taken into consideration. Based on the land use data and socioeconomic data for 2000, 2010, and 2018, the cell of $30\,m \times 30\,m$ was used as the evaluation unit, the urban-agricultural-ecological suitability and resource and environment carrying capacity in karst areas were evaluated, and the application of the evaluation results in the optimization of territorial spatial functional areas was explored. In addition, the types and functions of different functional areas were identified and analyzed, and the control approaches were proposed for the territorial space in karst areas. The objectives of this study were as follows: (1) to explore optimization methods for territorial spatial functional areas of karst areas by evaluating the urban-agricultural-ecological suitability and resource and environment carrying capacity; (2) to establish patterns of territorial spatial functional areas of karst areas and analyze different types of territorial spatial functional areas; (3) to discuss control approaches for territorial space in karst areas; and (4) to use the research results to provide the possibility for the coordinated development of urban function, agricultural function, and ecological function in karst areas of Southwest China, and use the research methods and ideas to provide reference for territorial spatial planning and management in other karst areas.

## 2. Materials and methods

### 2.1. Study area

Guangnan County, ranging from 23°29′N to 24°28′N and 104°31′E to 105°39′E, is a typical mountainous county with karst rocky desertification and located in Yunnan Province, Southwest China (Fig. 1). The county is located on the slope of the Yunnan-Guizhou Plateau and extends to East Guangxi; it is a part of the karst plateau in Southeast Yunnan and is a hilly area of the mountain plateau. The terrain is sloped from a higher altitude in the southwest to a lower altitude in the northeast. The county covers an area of $7730.09\,km^2$ with 94.7 % mountainous and semimountainous areas and ranks third in size in Yunnan Province. Guangnan County belongs to the Yunnan-Guangxi-Guizhou karst rocky desertification areas. The karst landform is distributed widely, accounting for three-quarters of the total area of the county and mainly consisting of severe rocky desertification, which is difficult to manage and has high ecological vulnerability. Simultaneously, this county is a border minority area that is dominated by the agricultural industry and has a poor economic situation and low productivity. It is also a county of Chinese national poverty. The unreasonable pattern of territorial space has led to environmental deterioration problems and poverty intensification, thereby seriously threatening the regional ecological environment and socioeconomic sustainable development.

### 2.2. Data source and processing

Landsat 5 T M data with 30 m spatial resolution for 2000 and 2010 and Landsat 8 OLI data with 15 m spatial resolution for 2018 were used. All remote sensing images were freely collected at http://www.gscloud.cn/ and subjected to atmospheric and geometric correction.

According to the spectral characteristics, textural features, and shapes of remote sensing images, we combined auxiliary materials such as the Forest Resources Survey Map, the second Chinese national land survey data, and the Google Image Map, and used man computer interactive interpretation method to achieve the visual interpretation of remote sensing images through ENVI 5.1 software and ArcGIS 10.2 software. And land use data sets (including paddy field, dry land,

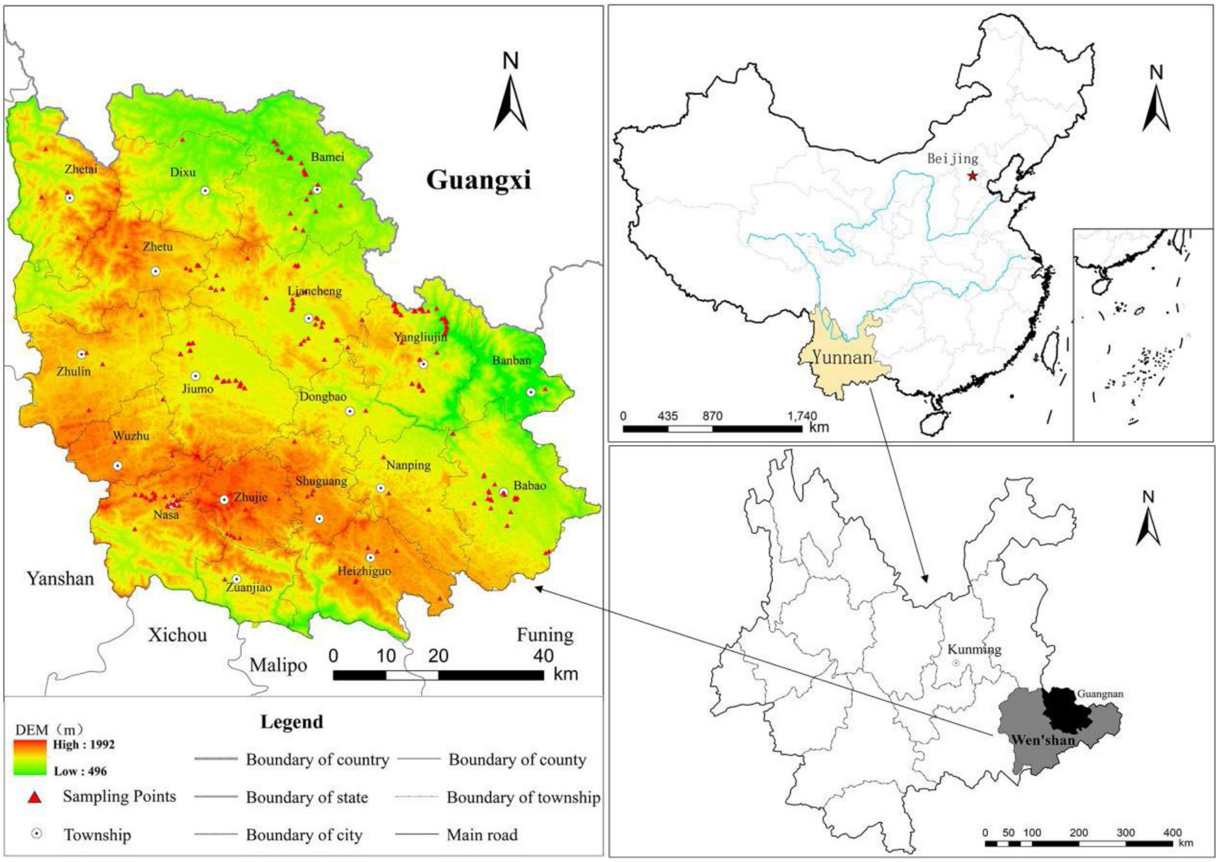


**Fig. 1.** Location of the study area in Southwest China and the 18 townships around the area.

garden, forestland, grassland, urban construction land, rural settlement, waters, and unutilized land) were constructed for the study area in 2000, 2010, and 2018. Concurrently, we performed field work in the study area and collected 220 sample points of land use types (the sample points covered the entire area, mainly involving land use types that were difficult to distinguish and that changed considerably). Through the comparison of the field results of the sample points and the classification results, the accuracy was 90.45 %. The classification results for 2000 and 2010 were tested by Kappa, Kappa of land use types in 2000 and 2010 were 0.85 and 0.86, respectively. All results met the needs of research.

Based on the lithology characteristics of karst areas, we divided rock of the study area into two types (i.e., carbonate rock and non-carbonate rock). The carbonate areas were divided into karst areas, and the non-carbonate areas were divided into non-karst areas. At the same time, in karst areas, according to classification standards of rocky desertification levels in karst areas of Southwest China in relevant literature (Xiong et al., 2012; Wang et al., 2017) and the actual situation of the study area, we used the rock exposure rate and fractional vegetation cover to divide rocky desertification levels (Table 1). And rocky desertification data sets (including no rocky desertification, potential rocky desertification, mild rocky desertification, moderate rocky desertification, and severe rocky desertification) were constructed for the study area in 2000, 2010, and 2018. Additionally, we collected 184 sample points of rocky desertification types (the sample points covered entire karst areas, mainly involving rocky desertification types that changed considerably) to verify the division results of 2018, and the accuracy was 85.33 %. The reliability of the division was high.

**Table 1**
Classification standards of rocky desertification levels.

| Rocky desertification levels | Index | |
|---|---|---|
| | Rock exposure rate (%) | Fractional vegetation cover (%) |
| No rocky desertification | < 20 | > 70 |
| Potential rocky desertification | 20 – 30 | 50 – 70 |
| Mild rocky desertification | 30 – 50 | 35 – 50 |
| Moderate rocky desertification | 50 – 70 | 20 – 35 |
| Severe rocky desertification | > 70 | < 20 |

Additionally, the Land Use General Plan (2006–2020), Environmental Protection General Plan (2016–2020), Ecological Civilization General Plan (2016–2025), Forestland Protection General Plan (2016–2020), meteorological data, lithology distribution data, geological disaster data, and soil physical and chemical data were collected from the government departments of the study area. These data could not be found on any website, and we obtained the consent of the local government to use them in our study.

The workflow of our study is shown in Fig. 2.

### 2.3. Evaluation of urban-agricultural-ecological suitability

According to the actual conditions of the study area, the evaluation index systems were constructed from three perspectives: urban development suitability, agricultural development suitability, and ecological protection suitability. Based on the short board principle (Chang et al., 2018), entropy weight method (Pan et al., 2015), and comprehensive evaluation method (Yang et al., 2018), we evaluated the land use suitability of urban, agriculture, and ecology, and divided the suitability levels into the following four levels: most suitable, basic suitable, unsuitable, and most unsuitable.

After the literature review (Bathrellos et al., 2017; Allam et al., 2015; Silvia et al., 2015) and field investigations, we constructed the index system for each suitability type. The index system of urban

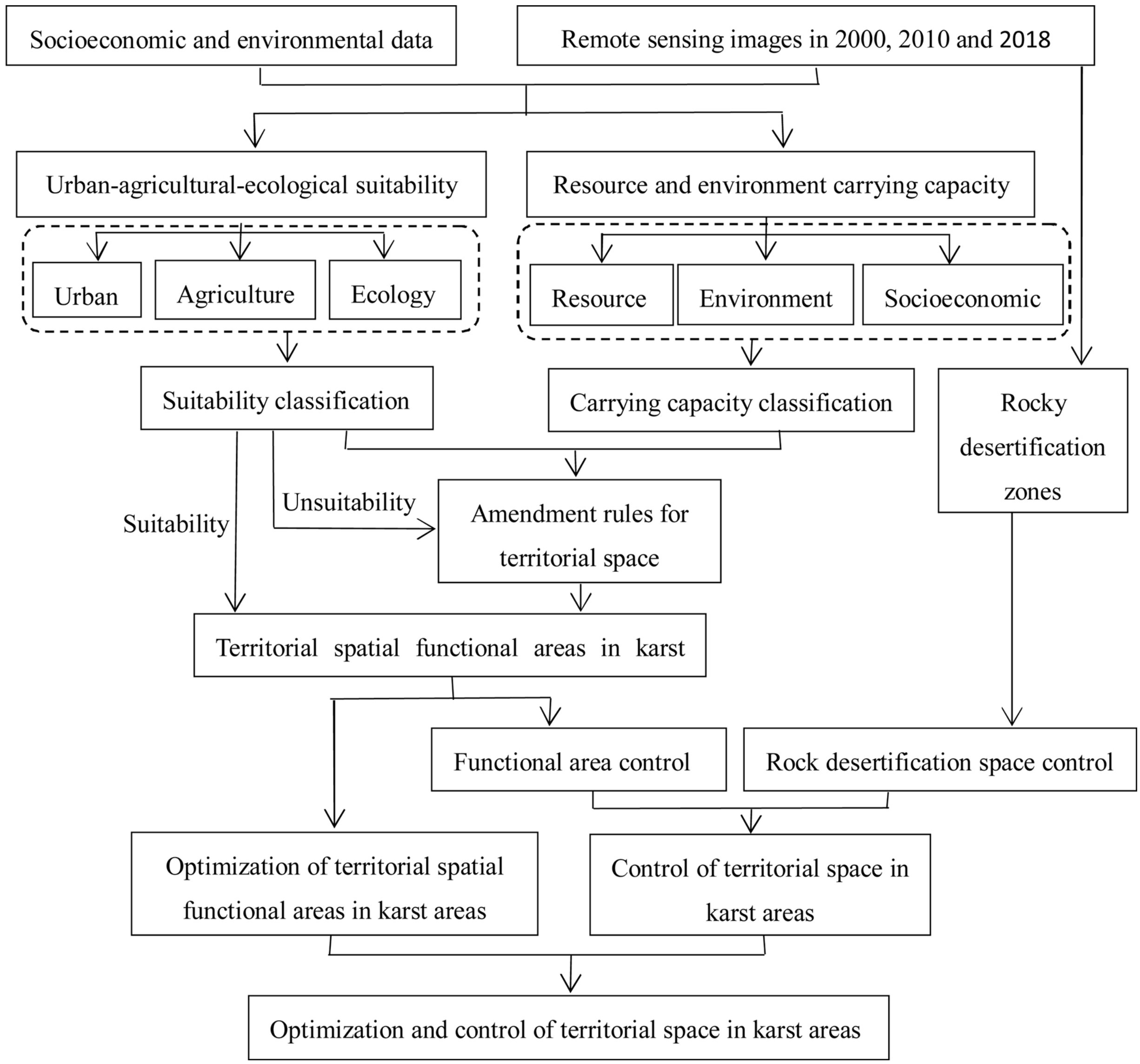


**Fig. 2.** Workflow of our study.

**Table 2**
Index system of urban development suitability.

| Objective | Category | Index | Trend | Weight |
|---|---|---|---|---|
| Urban development suitability | Conditional constraints | Slope | – | −0.0864 |
| | | Prone area types of geological disaster | – | −0.0537 |
| | | Affected area types of active fault | – | −0.0539 |
| | | Prone area types of karst collapse | – | −0.0545 |
| | | Occupied area types of the mine | + | 0.0536 |
| | | Ecological protection red lines | – | −0.0547 |
| | | Basic farmland protection red lines | – | −0.0540 |
| | | Current land use types | + | 0.0790 |
| | Location support | Distance to the county | – | −0.1501 |
| | | Distance to construction land | – | −0.1206 |
| | | Distance to rural settlement | – | −0.0566 |
| | | Distance to the main road | – | −0.1258 |
| | | Distance to the traffic branch | – | −0.0571 |

development suitability was constructed from the perspective of conditional constraints and location support (Table 2). The index system of agricultural development suitability was constructed from the perspective of soil management conditions, location support, site conditions, climatic conditions, soil nutrient conditions, soil profile and physical-chemical properties, and policy conditions (Table 3). The index system of ecological protection suitability was constructed from the perspective of ecological sensitivity, ecological importance, and policy conditions (Table 4). However, in those index systems, there were many indexes (e.g. prone area types of geological disaster, affected area types of active fault, prone area types of karst collapse, current land use types) that could not directly obtain the value of every

**Table 3**
Index system of agricultural development suitability.

| Objective | Category | Index | Trend | Weight |
|---|---|---|---|---|
| Agricultural development suitability | Soil management conditions | Irrigation guarantee rate | + | 0.1090 |
| | Location support | Distance to residential areas | – | −0.0140 |
| | | Distance to roads | – | −0.0783 |
| | | Distance to current cultivated land | – | −0.0129 |
| | Site conditions | Slope | – | −0.0516 |
| | | Aspect | + | 0.0417 |
| | | Elevation | – | −0.0427 |
| | Climatic conditions | Annual accumulated temperature above 10 °C | + | 0.1252 |
| | | Annual rainfall | + | 0.0557 |
| | Soil nutrient conditions | Organic matter | + | 0.0240 |
| | | Total nitrogen | + | 0.0217 |
| | | Available phosphorus | + | 0.1000 |
| | | Available potassium | + | 0.0654 |
| | | Available zinc | + | 0.0628 |
| | | Water-soluble boron | + | 0.0467 |
| | Soil profile and physical-chemical properties | Soil texture types | + | 0.0206 |
| | | Soil thickness | + | 0.0827 |
| | | Profile configuration types | + | 0.0218 |
| | | pH | + | 0.0232 |
| | Policy condition | Basic farmland protection red lines | + | / |

**Table 4**
Index system of ecological protection suitability.

| Objective | Category | Index | Trend | Weight |
|---|---|---|---|---|
| Ecological protection suitability | Ecological sensitivity | Soil erosion amount | + | 0.1068 |
| | | Geological disaster sensitivity | + | 0.0082 |
| | | Rocky desertification sensitivity | + | 0.1066 |
| | Ecological importance | Water conservation amount | + | 0.1275 |
| | | Soil conservation amount | + | 0.1913 |
| | | Ecological quality index | + | 0.1383 |
| | | Nature reserves types | + | 0.0967 |
| | | Nonprofit forest area types | + | 0.0399 |
| | | Net primary productivity | + | 0.1849 |
| | Policy condition | Ecological protection red lines | + | / |

spatial unit, so we obtained their values of spatial units through the following methods: based on the Landsat remote sensing images, we obtained current land use types of spatial units by the artificial visual interpretation; based on DEM data, we used the spatial analysis function of ArcGIS 10.2 software to get aspect types of spatial units; for other indexes, we obtained their vector data of spatial distribution from the government departments of the study area, and got spatial unit values of those indexes after rasterizing them by ArcGIS 10.2 software. Among them, we obtained the spatial distribution data of prone area types of geological disaster, affected area types of active fault, prone area types of karst collapse, and occupied area types of the mine from the Natural Resources Bureau; we obtained the spatial distribution data of soil texture types and profile configuration types from the Agriculture Bureau; and we obtained the spatial distribution data of nature reserves types and nonprofit forest area types from the Forestry Bureau. After obtaining the spatial unit value of each index, we divided them into four suitable intervals, and assigned units of four levels of the most unsuitable, unsuitable, suitable, and most suitable as 1, 2, 3, and 4, respectively (Table 5).

To obtain comprehensive suitability results for territorial spatial development, we first divided the two types of cells into ecological suitable area according to the status and change of rock desertification: one type was the cells in the current severe rocky desertification area, and the other type was the cells converted from no rocky desertification, potential rocky desertification, and mild rocky desertification to moderate rocky desertification. The former had the worst ecological environment and should be strictly protected; the ecological environment of the latter was better than the former, but it's rocky desertification degree was constantly increasing, and there was a tendency to develop into severe rocky desertification, so it should also be strictly ecologically protected. Simultaneously, considering that the study area was classified as a key ecological function area in the "Main Functional Area Planning of Yunnan Province", and combining with policies of protecting the high-quality arable land and restricting the disordered expansion of urban in karst areas, we determined the division principles of territorial space types for the priority of ecology, the protection of arable land, and the control of urban scope. Then, based on those principles and the suitability of cells, we divided territorial space types of the remaining cells: (1) for the cell that urban suitability, agricultural suitability, and ecological suitability were different suitable levels, which suitable type had the highest suitable level, the cell was classified as a suitable area for this suitable type; (2) for the cell that three suitable types were the most suitable level, it was classified as a ecological suitable area according to the principle of the priority of ecology; (3) for the cell that two suitable types were the most suitable level, if the ecological suitability was the most suitable level, it was classified as a ecological suitable area according to the principle of the priority of ecology; if the ecological suitability was not the most suitable level, according to the principles of the protection of arable land and the control of urban scope, the cell inside the urban function land was classified as a urban suitable area, and the cell around the urban function land was classified as a agricultural suitable area; (4) for the cell that two or three suitable types were the suitable level, it was classified as a multifunctional suitable area with multiple functional clusters; (5) for the cell that three suitable types were the unsuitable level or the most unsuitable level, it was classified as a unsuitable area, and it was determined the territorial space type in the subsequent optimization of the "double evaluations". Finally, we obtained seven

**Table 5**
Assignment criteria of type indexes for suitability.

| Suitable type | Index | Assignment interval | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Urban development suitability | Prone area types of geological disaster | High prone area | Medium prone area | Low prone area | Non-prone area |
| | Affected area types of active fault | Severe affected area | Moderate affected area | Mild affected area | Stable area |
| | Prone area types of karst collapse | High prone area | Medium prone area | Low prone area | Non-prone area |
| | Occupied area types of the mine | Collapsed land | Mining wasteland | Mining farm, mining transit field, mine building | Non-mine land |
| | Current land use types | Waters | Forestland, grassland | Paddy field, dry land, garden, unutilized land | Urban construction land, rural settlement |
| Agricultural development suitability | Aspect types | Shady slope | Semi-shady slope | Semi-sunny slope | Sunny slope |
| | Soil texture types | Silt loam, clay soil, clay loam | Sandy loam | Sandy soil, light loam | Heavy loam, medium loam |
| | Profile configuration types | A-G | A-C, A-C1-C2, A-W-G, A-P-W-G | A-AB-B, A-AB-B-C, A-B, A-B-C, A-P-C, A-P-C-D, A-C-D | A-P, A-W, A-P-W |
| Ecological protection suitability | Nature reserves types | / | / | Non-nature reserve | National nature reserve, provincial nature reserve |
| | Nonprofit forest area types | / | / | Non-nonprofit forest area | National nonprofit forest area, provincial nonprofit forest area |

suitable areas of territorial space functions (i.e., urban suitable area, agricultural suitable area, ecological suitable area, urban-agricultural suitable area, urban-ecological suitable area, agricultural-ecological suitable area and urban-agricultural-ecological suitable area) and one unsuitable area of territorial space functions.

Additionally, we divided different territorial space types based on seven suitable areas of territorial spatial functions: Urban suitable area was divided into urban space; agricultural suitable area was divided into agricultural space; ecological suitable area was divided into ecological space; urban-agricultural suitable area was divided into urban-agricultural space; urban-ecological suitable area was divided into urban-ecological space; agricultural-ecological suitable area was divided into agricultural-ecological space; urban-agricultural-ecological suitable area was divided into urban-agricultural-ecological space. Thereby the territorial space structures and territorial space spatial patterns of the urban-agricultural-ecological suitability evaluation were constructed (Fig. 3).

### *2.4. Evaluation of resource and environment carrying capacity*

In this study, the resource and environment carrying capacity was defined as: under the specific development stage, the economic and technological level, the production and life style, and the ecological protection goal, based on maintaining a virtuous cycle of the ecosystem, the factors of resource and environment can provide the maximum support capacity and the highest guarantee degree for human activities such as urban construction and agricultural production in a certain geographic area. The resource and environment carrying capacity is premised on the self-sufficiency in a spatial-temporal range, the long-term circulation in a regional system, and the coordinated development under technical conditions, and it is formed by the interaction of the natural environment and the human social system. Therefore, the evaluation of the resource and environment carrying capacity needs to integrate various indicators, and it is necessary to comprehensively consider the development status of different attributes (e.g. resource, environment, social economy) within a region. Among them, the resource is represented by water resource, land resource, mineral resource, tourism resource, etc.; the environment is represented by ecological environment, geographical environment, water environment, etc.; and the social economy is represented by social factors and economic factors.

Based on the above analysis, considering the particularity of the resource-environmental and socioeconomic conditions in karst areas, we used the resource carrying capacity, environment carrying capacity, and socioeconomic carrying capacity as subsystems in the evaluation of the resource and environment carrying capacity (Table 6), and we evaluated the resource and environment carrying capacity of the study area.

Concomitantly, to match the results of the resource and environment carrying capacity with those of the urban-agricultural-ecological suitability, the fuzzy comprehensive evaluation method (Wang et al., 2015) was used to determine the threshold value (Wang et al., 2015) of each index, and the resource and environment carrying capacity was divided into seven levels (I - VII from small to large). The membership degree (Lane et al., 2014) of each level of the spatial areas was calculated by the semitrapezoid distribution function (Wang et al., 2015), and the comprehensive evaluation results of the resource and environment carrying capacity were obtained by integrating the membership degree results.

### *2.5. Optimization of territorial space based on "double evaluations"*

In the development of territorial space, different territorial space types have different requirements on the background of regional resource and environment (Huang et al., 2020; Hao et al., 2019). Among them, urban space has the highest requirements on carrying capacity,

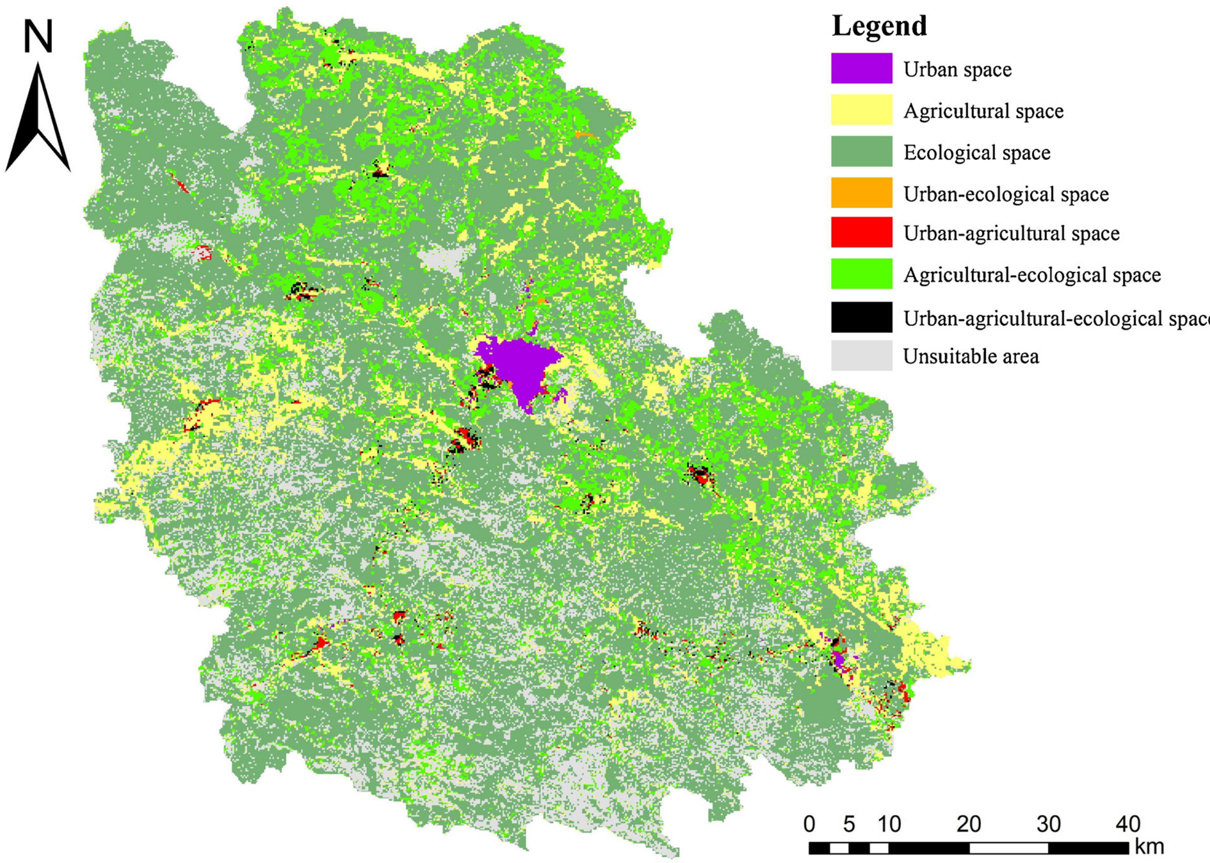


**Fig. 3.** Partitions of territorial space types based on the urban-agricultural-ecological suitability evaluation.

followed by agricultural space, and ecological space has the smallest requirements. Therefore, based on the development orientation of territorial space functions in karst areas and the carrying capacity of different territorial space types, we constructed amendment rules for the territorial space (Table 7). Then, we superimposed the unsuitable area of territorial space functions and the results of resource and environmental carrying capacity, and used amendment rules to determine territorial space types of unsuitable area. Finally, we integrated the division results of territorial space that were based on the urban-agricultural-ecological suitability evaluation and the correction results of unsuitable area, and obtained the optimization results for the territorial spatial functional areas under "double evaluations" in karst areas.

### 2.6. Control approaches for the territorial space

#### 2.6.1. Control of the territorial spatial functional areas

Based on the optimization results of the territorial spatial functional areas, with the goal of ecological protection and rocky desertification governance, we constructed control pattern of functional areas of the “trinity” for the three major functional spaces of urban, agricultural, and ecological space. Additionally, the control pattern was divided into the following three parts: classified protection, comprehensive improvement, and cluster development.

#### 2.6.2. Control of rocky desertification space

Rocky desertification in karst areas is the result of both natural factors and human influences (Zhang et al., 2011). Rocky desertification space is one of the most important components of the territorial space in karst areas, and its development has a huge impact on the stability of the regional territorial space. Therefore, we analyzed the levels and distributions of the rocky desertification of the study area in 2000, 2010, and 2018, and we explored control approaches for the rocky desertification space from the aspects of rocky desertification deteriorating areas, severe rocky desertification areas, and the corresponding policies.

## 3. Results

### 3.1. Optimization of territorial spatial functional areas in karst areas based on "double evaluations"

#### 3.1.1. Quantity structures

According to the evaluations of the urban-agricultural-ecological suitability and the resource and environment carrying capacity, based on the amendment rules of the territorial space, the optimization results of the territorial functional regions of karst areas were obtained. Different functional areas exhibited large gaps in quantity structures (Fig. 4). Among them, the area of the ecological space was the largest, and the area of the urban-ecological space was the smallest, with values of 5235.59 and 24.74 km$^2$, respectively. In other functional areas, areas from large to small were agricultural-ecological space, agricultural space, urban space, urban-agricultural space, and urban-agricultural-ecological space, which were 1219.04, 1108.49, 60.29, 47.93, and 34.01 km$^2$, respectively.

#### 3.1.2. Spatial distribution

Different territorial spatial functional areas displayed significant differences in spatial distribution (Fig. 5). (1) Urban space: This space was mainly distributed in the center and southeast with good geographical conditions and clear location advantages; those areas were the non-karst areas and areas with good rocky desertification. This distribution mode could effectively reduce the threat of natural disasters to human life and alleviate the pressure of human activities on the ecologically fragile mountainous areas in the cities and towns. (2)

**Table 6**
Index system of the resource and environment carrying capacity.

| Objective | Category | Index | | Trend | Weight |
|---|---|---|---|---|---|
| | | First-level index | Second-level index | | |
| Resource and environment carrying capacity | Resource carrying capacity | Water resources | Water resources per capita | + | 0.0207 |
| | | | Water supply ratio | + | 0.0295 |
| | | | Water supply and demand ratio | + | 0.0185 |
| | | | Water-saving rate | – | −0.0884 |
| | | Land resources | Cultivated land ratio | + | 0.0371 |
| | | | Construction land ratio | + | 0.0173 |
| | | Mineral resources | Determined mineral resource value | + | 0.0336 |
| | | Travel resources | Attraction of travel resources | + | 0.0368 |
| | | Location resource | Distance to roads | + | 0.0772 |
| | | | Distance to waters | + | 0.0384 |
| | Environment carrying capacity | Ecological environment | Ecosystem service value | – | −0.0309 |
| | | Geographical environment | Geomorphic environment suitable area ratio | + | 0.0545 |
| | | | Geological environment suitable area ratio | + | 0.0488 |
| | | Environment of water loss and soil erosion | Soil erosion amount | – | −0.0109 |
| | | | Rocky desertification sensitivity | – | −0.0351 |
| | | Water environment | Surface water environmental quality | + | 0.0110 |
| | | | Per capita sewage discharge | – | −0.0106 |
| | | Atmospheric environment | $SO_2$ | – | 0.0050 |
| | | | $NO_2$ | – | 0.0105 |
| | | | CO | – | 0.0104 |
| | | | $O_3$ | – | 0.0099 |
| | | | $PM_{10}$ | – | 0.0132 |
| | | | $PM_{2.5}$ | – | 0.0533 |
| | Socioeconomic carrying capacity | Social factors | population density | – | −0.0550 |
| | | | Urbanization rate | + | 0.0252 |
| | | | Labor force ratio | + | 0.0156 |
| | | | Index of per capita food production | + | 0.0235 |
| | | Economic factors | Per capita net income | + | 0.0161 |
| | | | GDP Per capita | + | 0.0387 |
| | | | Added value of the primary industry | + | 0.0537 |
| | | | Added value of the secondary industry | + | 0.0463 |
| | | | Added value of the tertiary industry | + | 0.0243 |

**Table 7**
Amendment rules for the territorial space.

| Level of resource and environment carrying capacity | Interval of resource and environment carrying capacity | Functional direction | Potential development type |
|---|---|---|---|
| I | 4.5 − 5.0 | Key urban development area | Urban space |
| II | 4.0–4.5 | Overall control development area | Urban-agricultural-ecological space |
| III | 3.5 − 4.0 | Urban-agricultural comprehensive development zone | Urban-agricultural space |
| IV | 3.0–3.5 | Urban development and ecological protection area | Urban-ecological space |
| V | 2.5 − 3.0 | Key agricultural development area | Agricultural space |
| VI | 2.0–2.5 | Agricultural development and ecological protection area | Agricultural-ecological space |
| VII | 1.0–2.0 | Key ecological protection area | Ecological space |

Agricultural space: This space was mainly distributed in the east and west, demonstrating a small continuous distribution in the south and southwest. It was concentrated in non-karst areas, no rocky desertification areas, and potential rocky desertification areas, and it was rarely observed in moderate and severe rocky desertification areas. (3) Ecological space: This space was the most widely distributed type of territorial spatial functional area in the whole territory, the highest connectivity was located in the northwest, southwest, and northeast. Especially in the severe rocky desertification areas in the south and southeast, there were mainly ecological space and spatial types related to ecology. (4) Urban-ecological space: This space integrated the residents' daily rest and environmental protection, and it was mainly distributed in the center and northeast, but the distribution scale was small. This type of functional area had good ecological environment, high vegetation cover index, and good ecological and residential values. (5) Urban-agricultural space: This space was mainly distributed around the urban space in the center and southeast, and the areas in the southwest that were connected to agricultural space. This type could effectively alleviate the impact of urban space on agricultural space. (6) Agricultural-ecological space: This space was distributed throughout the territory and was the second largest spatial type in the distribution. It was mainly distributed in the north with the best vegetation growth, followed by the southeast and south with heavy rocky desertification. Additionally, this multifunctional area could provide a good ecological barrier for the governance of rocky desertification and the interruption caused by human activity interference in karst areas. (7) Urban-agricultural-ecological space: This space integrated the construction of urban space, development of agricultural space, and protection of ecological space, and it was mainly distributed around areas of human activity in the center and southeast. Excluding the urban space, this

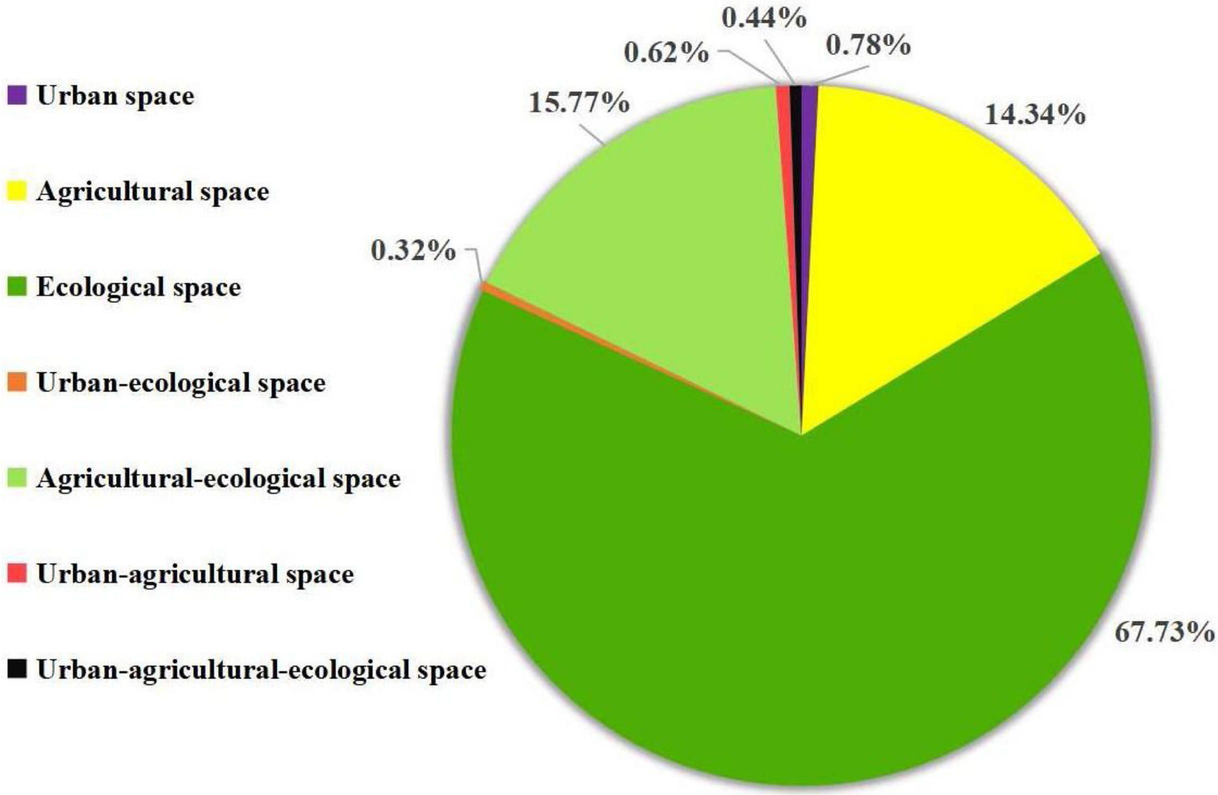


**Fig. 4.** Quantity structure ratio of the territorial spatial functional areas.

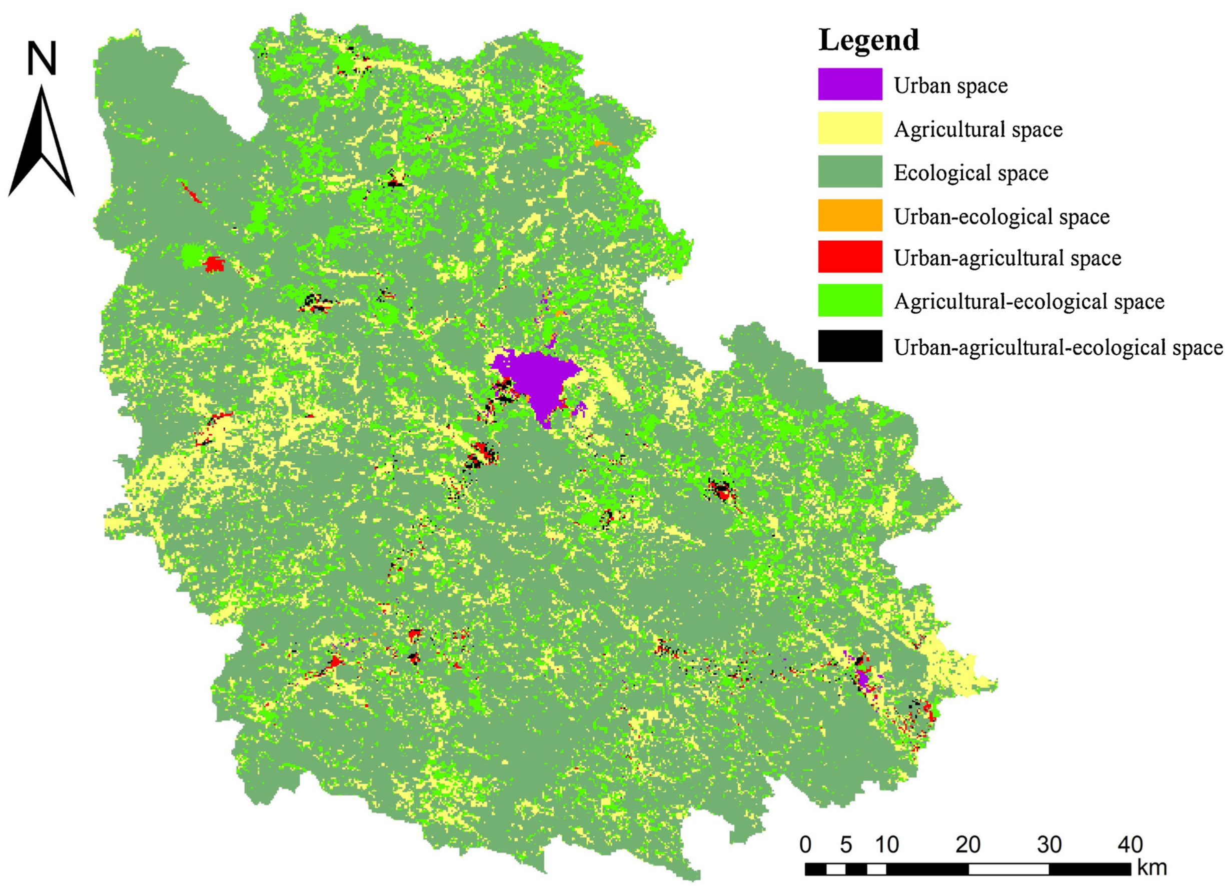


**Fig. 5.** Optimization of territorial spatial functional areas in karst areas based on "double evaluations".

functional area type had the highest requirements for background resources and the environment. However, it could alleviate contradictions between the increasing demand for urban space and agricultural space and their insufficient supply.

### 3.2. Control of the territorial space

#### 3.2.1. Control of the territorial spatial functional areas

The urban-agricultural-ecological functions are the cores of the Chinese territorial spatial planning strategy. In our optimization results of the territorial spatial function areas (Fig. 5), whether the territorial spatial function areas were single or multiple, they were independent or combined types of the three major functions. Therefore, based on the optimization results, the three major functional areas were taken as the control objects, and the control approaches for the territorial spatial functional regions of the karst areas were analyzed from aspects of classified protection, comprehensive improvement, and cluster development.

(1) Classified protection

According to the features and development directions of the three major functional areas, the control methods for territorial spatial classified protection in karst areas were respectively proposed.

1) Urban space: On the one hand, through the effective implementation of planned land standards and related regulatory requirements, the urban space in the center and southeast should strictly control the development intensity and land use efficiency inside the space, and guide the refined growth of urban space. To protect and create green and open urban space, the overall layouts of infrastructure corridors (e.g., transportation, energy, water conservancy, communications) and ecological corridors are also good strategies. On the other hand, for those multifunctional areas that are dominated by urban space in the center, southeast, and northeast, they should mainly be used for strategic and cutting-edge industrial development on the basis of the constraints of the total development intensity and assessment of ecological environment impact.
2) Agricultural space: For the agricultural space in the west and east, the occupation of non-agricultural construction should be stringently prevented to achieve consistency of the quality and amount of occupied and supplemented agricultural space in the balance of occupation and compensation. Simultaneously, the basic farmland should be scientifically divided to rationally guide the adjustment of agricultural structures, especially in severe rocky desertification areas. Additionally, the residential land in agricultural space should focus on ordered advancement of hollow village renovation and village integration. And the rural residential land should be reasonably arranged to properly allow the construction of regional infrastructures, support of ecological environmental protection projects, and development of ecotourism. However, the scope of the influence of non-agricultural activities must be strictly controlled during the process.
3) Ecological space: For ecological space with severe rocky desertification and prominent environmental problems in the west and south, it is important to protect the quality of the atmosphere, water, and soil. Subsequently, the development and construction activities, which conflict with ecological protection and have great impacts on rocky desertification, should be guided and gradually phased out by the adjustment of industrial structures and delimitation of prohibited human activities, thereby restoring the original ecological functions. For the ecological space with good environmental quality in the north, ecological protection red line areas should be scientifically delineated, and layouts of infrastructures, urban-rural construction, industrial development, and public service facilities should be prohibited in this area. Concurrently, it is strictly prohibited to increase development and construction activities that conflict with ecological functions outside ecological protection red line areas. However, without prejudice toward ecosystem functions and their integrity, the eco-industrial models could be appropriately developed to increase the economic output.

(2) Comprehensive improvement

According to the characteristics of low resource utilization efficiency, large patch fragmentation, and low ecological environment quality in karst areas, the approaches of territorial spatial comprehensive improvement were constructed from three aspects of the efficient use of resources, compact spatial layout, and ecosystem restoration.

1) Efficient use of resources

The efficient use of resources mainly involves urban and agricultural space. In the urban space, the rectification of idle and activation of inefficient construction land can help the region promote intensive use of regional territorial space. The agricultural space should improve the efficiency of spatial utilization in rural construction areas, sort out broken fields, and manage ecological fragile lower-level agricultural planting space (e.g., sloping fields, barren arable land, arid arable land, flooded arable land) to form food production areas and improve crop yield benefits.

2) Compact spatial layout

Taking the improvement of the connectivity of spatial layout as the core, areas with high plaque fragmentation in each functional area should be subjected to centralized remediation and management, and classified into functional areas with high connectivity surrounded by a suitable carrying capacity. Thereby, the layout compactness and utilization efficiency will be increased between different functional areas in karst areas, and new intensive patterns will be constructed for regional territorial space.

3) Ecosystem restoration

Urban space with high ecological sensitivity and poor living environment, agricultural space with poor planting conditions and low output efficiency, and ecological space with a fragile ecological environment and severe rocky desertification should be managed centrally by relying on the natural repair ability and artificial ecological engineering technologies. Additionally, the sequential construction of five ecological improvement projects (i.e., landform remodeling, soil reconstruction, vegetation reconstruction, landscape improvement, and biodiversity reorganization) are also good ways to improve the overall ecological landscape quality.

(3) Cluster development

Based on the optimization result of territorial space function areas, we separately selected two areas with the highest concentration degree of territorial space types that were related to urban function, agricultural function, and ecological function, and enclosed those six areas in circles by delineating circles. This method could separate six areas from areas with low concentration degree around them, and promote the formation of cluster development areas that were dominant by three territorial space functions. However, because of the differences of the sizes of those ares, the sizes of six circles were different.

According to the layout characteristics of different territorial space types in the optimization results, combining with the socio-economic development level, agricultural planting environment, and ecological environment quality of the study area, from the perspective of the three main function spaces (i.e. urban space, agricultural space, and ecological space), the development characteristics of regional territorial

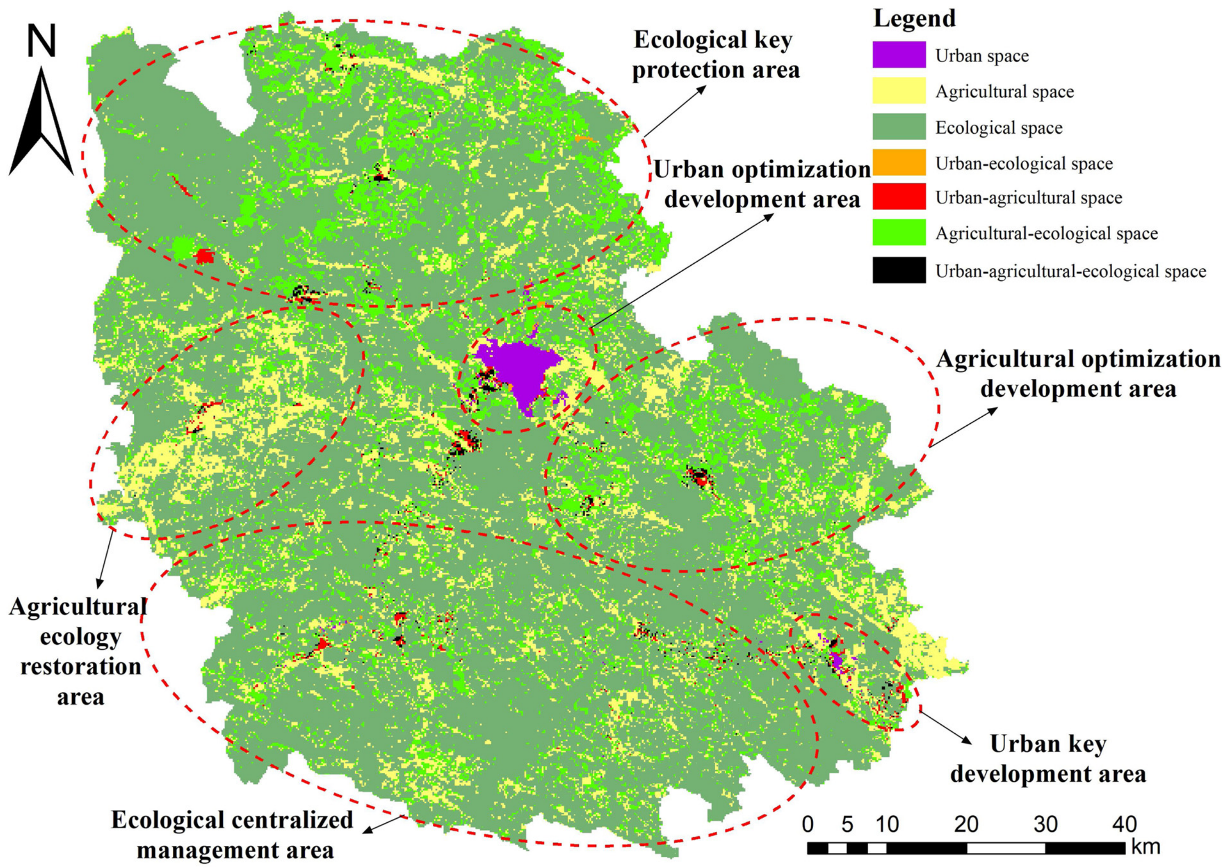


**Fig. 6.** Partitions of territorial spatial cluster development in karst areas.

space were highlighted, and the development priorities and planning directions of territorial space in all positions were set separately. Thereby further promoting the scale development of territorial space and the comprehensive improvement of rocky desertification situation in karst areas. Based on this, the urban space, agricultural space, and ecological space were divided into six cluster development areas: urban optimization development, urban key development, agricultural optimization development, agricultural ecology restoration, ecological key protection, and ecological centralized management (Fig. 6). Six cluster development areas had six development circles, and different circles were served as the boundaries of different cluster development areas. At the same time, for the development scopes in each circle, there were differences in different cluster development areas: Among them, the scopes of urban optimization development area and urban key development area were all territorial space types that were related to the urban function in those two circles, including urban space, urban-ecological space, urban-agricultural space, and urban-agricultural-ecological space; the scopes of agricultural optimization development area and agricultural ecology restoration area were all territorial space types that were related to the agricultural function in those two circles, including agricultural space, urban-agricultural space, agricultural-ecological space, and urban-agricultural-ecological space; the scopes of ecological key protection area and ecological centralized management area were all territorial space types that were related to the ecological function in those two circles, including ecological space, urban-ecological space, agricultural-ecological space, and urban-agricultural-ecological space.

1) The urban optimization development area was distributed in the center and had a good ecological environment foundation and a high degree of concentration. This area should focus on optimizing the population distribution, industrial structures, and urban layout. Simultaneously, it should change the methods of development and utilization, promote intensive and compact urban development, and improve the efficiency of territorial spatial development. Finally, the urban optimization development area should be enabled to extensively participate in the regional cooperation and competition.
2) The urban key development area was distributed in the southeast and had a small scope of urban spatial distribution. However, considering the needs of the population and the future development, this area should also be developed and constructed as urban space. During the development of this area, it should focus on improving the level of agglomeration development and strengthening infrastructure construction and environmental protection, while advancing new industrialization processes and improving the agglomeration capability of the population and industry.
3) The agricultural optimization development area was distributed in the east where the karst spatial type was non-karst area and had better farming and site conditions. In this area, based on the regional characteristics, it is necessary to adjust the planting and distribution of the agricultural industries and improve the planting and economic efficiency of the agricultural industries. Those methods will ensure regional food security and the effective supply of important agricultural products.
4) The agricultural ecology restoration area was distributed in the west where the karst type consisted of potential and severe rocky desertification areas. The ecological environment of the area was fragile. Thus, its development should focus on ecological protection and ease of rocky desertification, as well as using ecological agricultural products to replace the cultivation of crops with greater impacts on the ecological environment.
5) The ecological key protection area was distributed in the north and had the ecological space with the best overall vegetation coverage, the highest quality of ecological environment, and the highest

protection value. This area should protect the regional ecological space by building nature reserves and delineating ecological protection red line areas and prohibiting the development and construction of other types of functional areas.

6) The ecological centralized management area was distributed in the south where the karst type was mainly moderate and severe rocky desertification areas. Because this area demonstrated the greatest pressure on the ecological environment and had the highest ecological fragility, it should focus on the advancement of ecological restoration projects (e.g., afforestation program, grain-to-green program) while preventing human interference, as well as regulating the ecological environment and managing rocky desertification in a natural restoration-based manner.

### 3.2.2. Control of the rocky desertification space

(1) Control of the rocky desertification deteriorating areas

According to the changes in rocky desertification from 2000 to 2018, the study area was divided into the rocky desertification improvement area, rocky desertification deteriorating area, rocky desertification unchanging area, and non-karst area (Fig. 7). This study further mainly proposed control approaches for the rocky desertification deteriorating area. As shown in Fig. 7, this area was mainly distributed in the center, west, and northeast, and it was mainly located in the agricultural and ecological space, especially their junctions. Therefore, ecological strategies focusing on governance should be adopted for the rocky desertification deteriorating area. On the one hand, human interference should be reduced by limiting the population and transferring the surplus labor. On the other hand, the terracing project should be accelerated to improve agricultural production conditions and increase the cultivated land carrying capacity. Additionally, to meet people's needs for food and clothing, it will be necessary to actively implement ecological conservation projects (e.g., the conversion of cropland to forest or grassland projects, the afforestation project) to prevent further occupation of rocky desertification landscapes and promote stable development of the ecological environment pattern in karst areas.

(2) Control of the severe rocky desertification area

The severe rocky desertification area was the region with the worst environmental conditions and development trends in the study area, and it was mainly distributed in the south and west (Fig. 8). The ecological benefits of the severe rocky desertification area were close to zero, and the interior of the landscape type had stabilized. This region had a high cost of ecological restoration and small effect, while the relationship between the people and the environment was seriously imbalanced. This dilemma finally formed a vicious cycle of "poverty-resources plundering- environmental degradation-increased poverty". Therefore, in the severe rocky desertification area, it is first necessary to alleviate the ecological pressure of the population, reduce the predatory development of resources by human beings, and allow the ecology a chance to recover. Second, based on the combination of natural recovery and ecological protection areas, the ecological immigration project, the afforestation project, the project of closing hillsides to facilitate afforestation, and the terracing project should be vigorously implemented. In addition, the use of ecological technologies will promote positive vegetation succession, accelerate the restoration of the ecological environment, and decelerate the spread of the severe rocky desertification area.

(3) Control of corresponding policies

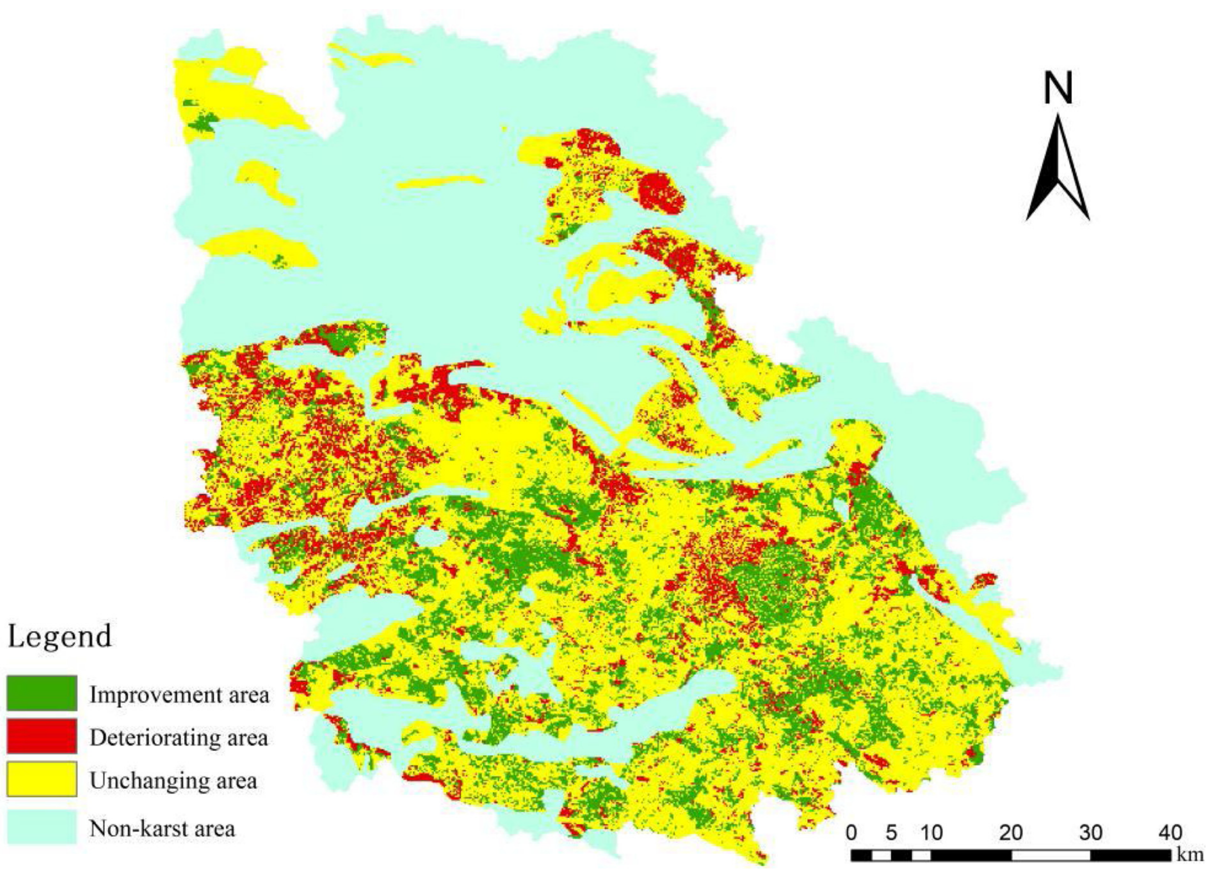


**Fig. 7.** Distribution of the change in rock desertification space from 2000 to 2018.

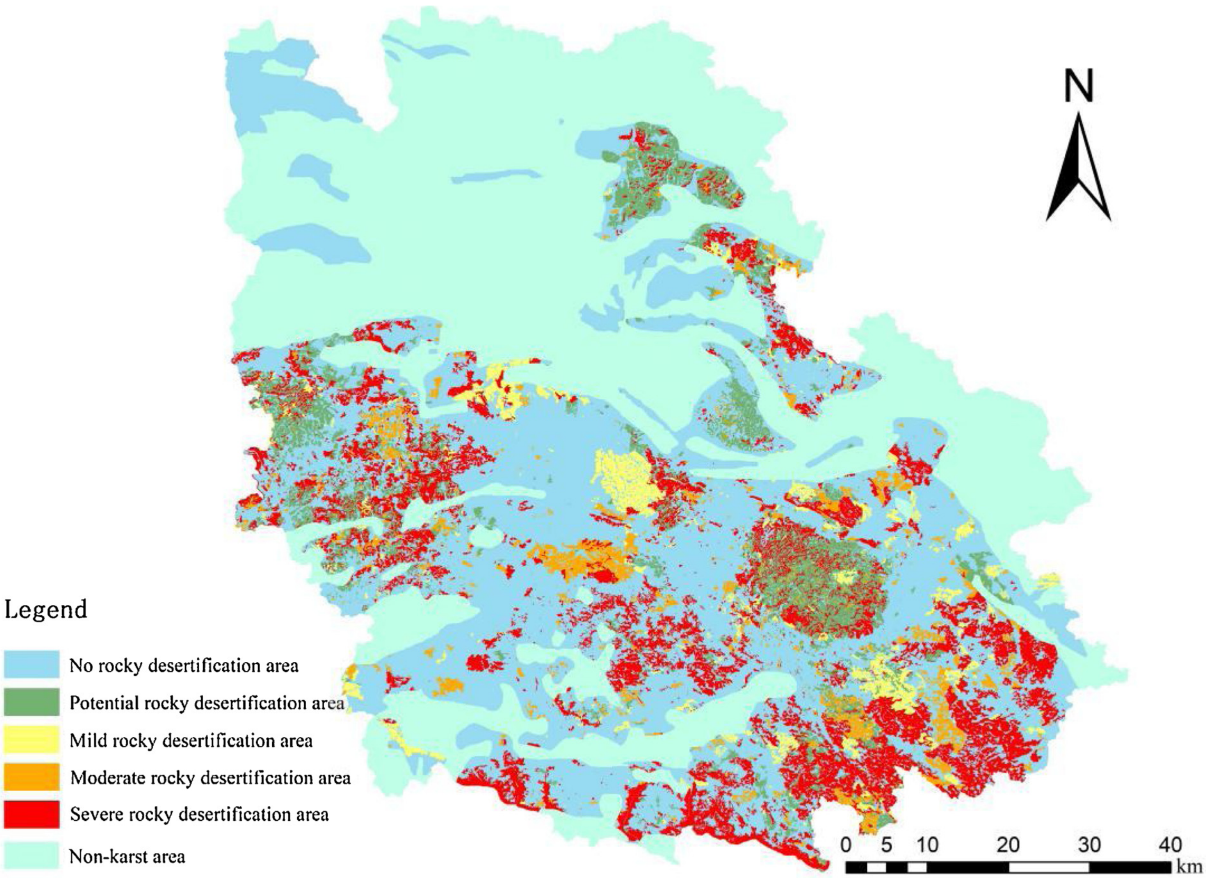


**Fig. 8.** Distribution of the current situation in rock desertification space in 2018.

To ensure ecological quality restoration of rocky desertification deteriorating area and severe rocky desertification area, the introduction of strict supporting control policies is important. 1) The excessive consumption of ecological environmental consumers should be restricted by establishing ecological compensation systems: who develops, who protects; who destroys, who restores; who benefits, who compensates; who pollutes, and who pays. 2) Monitoring and evaluation systems should be constructed to protect rocky desertification deteriorating area and severe rocky desertification area, and form real-time, dynamic, and stereoscopic surveillance systems. 3) Cadre evaluation systems should be improved, and strict systems of source protection, penalty for damages, and accountability should be established. 4) Local publicity systems should be implemented. The relevant personnel should visit the townships on a regular basis to publicize the necessity and urgency for the protection of rocky desertification deteriorating area and severe rocky desertification area. Such tactics will increase the awareness of all sectors of society and the public regarding the protection of relevant areas.

## 4. Discussion

### *4.1. Optimization method for territorial spatial functional areas*

In current regional development, urban expansion has led to the loss, fragmentation, transformation, and isolation of agricultural and ecological landscapes. This phenomenon disrupts the sustainability of agricultural production (Jin et al., 2016; Zhong et al., 2017) and takes adverse effects on the climate, soil, and biodiversity (Davis et al., 2016; Kurz et al., 2008). The solution to the contradictions between urban, agricultural, and ecological space in the process of territorial spatial sustainable development has been a recent focus of researchers. The "double evaluations", oriented by evaluations of urban-agricultural-ecological suitability and the resource and environment carrying capacity, have become an important foundation and core content of territorial spatial planning (Wang et al., 2019). The idea of "double evaluations" has been widely used in researches related to territorial space (e.g., delineation of the urban growth boundary (Zhang et al., 2019a; 2019b), assessment of functional areas (Wei et al., 2019)). These studies have provided a scientific basis for the adjustment and optimization of the structures of regional territorial functional areas.

This study explored the suitability and carrying capacity of the three functional orientations (i.e., urban construction, agricultural development, and ecological protection) in the study area by evaluating the urban-agricultural-ecological suitability and the resource and environment carrying capacity. And it established the scientific logic of the "dual evaluations" to the optimization of territorial spatial functional areas, and proposed optimization approaches for territorial spatial functional areas based on the integration of "dual evaluations". With the introduction of territorial spatial amendment rules based on the directivity of the resource and environment carrying capacity to the intensity of human activities (Liu et al., 2017), we constructed a complete "dual evaluations" optimization system for the territorial spatial functional areas to rationally plan the distribution of different functional areas. Especially in karst areas, this optimization method fully considered the background of resources and environment and the degree of spatial suitability, which can fundamentally improve the chaotic situation of the territorial spatial pattern and promote regional green development.

Concurrently, we attempted to adjust and optimize the pattern of territorial spatial function areas in karst areas through urban-agriculture-ecological functions coordination described in other studies (Zhao et al., 2019b). In practice, it has been shown that the results can promote the sustainable development of territorial space in karst areas. However, the method of urban-agricultural-ecological functions coordination mainly relies on the application of models and adjustment of rules to optimize the structures of territorial spatial functional areas. The construction of models and rules is very complicated. The method used in this study mainly relied on the selection of index systems to adjust the structures of the territorial spatial functional areas through assessments of the urban-agricultural-ecological suitability and the resource and environment carrying capacity. Compared with the former, this method is not only simpler in terms of local government use and field promotion, but it also has more practical value.

### 4.2. Exploration on territorial spatial control approaches in karst areas

The proposal of the Sustainable Development Goals (SDGs 2030) of the United Nations in 2015 has gradually caused the optimization and control of territorial space to become a hot issue in the study of global change and sustainable development (Gao and Bryan, 2017; Steffen et al., 2015). Optimization is the basis of control, and control is the realization of optimization (Chen and Zhu, 2015). Simultaneously, with the future expansion of cities around the world, rapid growth of urban space will have a prominent impact on farmland ecosystems, biodiversity, and carbon accumulation in the ecosystem (Seto et al., 2012). This growth requires strengthening the control of the territorial space, coordinating the relationship between functional areas, and reducing the negative impact of territorial spatial changes on the ecological environment. In karst areas in particular, because of their own ecological and environmental problems, it is more important to understand the background and appropriateness of resources and implement effective measures for territorial spatial control (Zhang et al., 2015; Xiao and Weng, 2007).

In the Chinese "National Land Planning Outline (2016–2030)", the overall control pattern of the classified protection, comprehensive improvement, and cluster development has been proposed as the main body, and the system of territorial spatial development and protection based on land use control has been established. However, strong doubts persist regarding how this is to be achieved (Zhang et al., 2019c). Based on the actual situations in karst areas, we comprehensively considered the resources, environment, and socioeconomic status of the study area, proposed territorial spatial control approaches taking control of the territorial spatial functional areas and control of the rocky desertification space as the core, and explored how to achieve better and faster regional development under the premise of protecting the ecological environment. Our control approaches restructured the territorial spatial pattern in karst areas by reshaping the construction and development systems, farmland ecosystems, and natural ecosystems (Pretty et al., 2018; Davis et al., 2017), as well as adjusting the governance focus of the rocky desertification space for rocky desertification deteriorating area and severe rocky desertification area. Those approaches will improve the food productivity and the ecological carrying capacity. Our analysis also showed that the control mode could become an important future strategy for territorial spatial sustainable development in karst areas.

### 4.3. Implications and significance for territorial spatial planning and management

In this study, we used the "dual evaluations" method to divide the territorial space into seven functional areas (Fig. 5) that were contacted with different social-ecological systems and showed significant spatial clustering in karst areas. These distinct patterns can be explained by historical social ecological interactions among people and nature (Bennett and Gosnell, 2015 Ostrom, 2009). In karst areas, because of the complexity of the resource environment, determining and identifying different functional areas is not only an effective strategy for territorial spatial planning and management (Bennett et al., 2009), but it also has important significance for the restoration of the ecological environment.

Our results showed that different functional areas had different aggregation patterns and development directions. On the one hand, for the regions with a better ecological environment and higher carrying capacity, the degree of urbanization was high. It is important for these regions to focus on economic construction and industrial development according to their functional orientations. Thus rationally regulating the relationship between development and protection and achieving intensive use through the combination of modern industrial expansion and traditional industrial cluster development (Jin et al., 2016). However, in this process, we must prevent all kinds of non-point source pollution from posing a huge threat to territorial spatial sustainable development (Shen et al., 2014) and retain a certain amount of green space to promote the stability of ecological functions (Stott et al., 2015). Additionally, building ecological corridors between agglomerated urban space and agricultural space is also an effective way to increase ecological security. On the other hand, for regions with a poor ecological environment and low carrying capacity, human activities have seriously affected the stability of the ecological system and disrupted the balance of the ecological environment. These regions demonstrated the largest gap between socioeconomic development and ecological environmental protection. It is necessary to implement the functional transition of the territorial space to reduce the pressure on limited natural resources (Izquierdo and Grau, 2009) and take full account of the food security and ecological resilience in strategic territorial spatial planning. Concurrently, green infrastructure planning as a land sharing approach (Baró et al., 2016) should be considered in regional development planning, because it can improve the environment and promote the positive succession of rocky desertification.

Additionally, the territorial space should adjust the development cores of each functional area in various aspects according to the characteristics of regional resources and environment, and reasonably delineate the patterns of territorial spatial functional areas. The transfer of high-intensity human activity areas and the increase of green space and ecological agriculture in severe rock desertification area are also effective ways to coordinate territorial spatial functional areas. Such methods fully consider the positive developmental needs of each functional area, and their implementation can be closely linked to promote positive directions of socioeconomic promotion, improvement of agricultural industry, and ecological governance. Thus, they can alleviate the impact of the development and construction of various functional regions of karst areas on vegetation net primary productivity (Milesi et al., 2003) and agricultural planting structures (Wahyunto et al., 2012), as well as improving the development and governance efficiency of territorial space. In rocky desertification deteriorating area and severe rocky desertification area, a reliance on the ecological environment self-repair capacity is the best governance method (Cairns, 1999). It is also a good choice to prevent human interference and implement effective ecological engineering. However, future large challenges are faced in ecological engineering (Jones, 2012). This engineering needs to formulate and implement effective corresponding policies of rocky desertification space for different regions.

## 5. Conclusions

In this study, according to the characteristics of urban-agricultural-ecological suitability and the resource and environment carrying capacity in karst areas of Southwest China, we explored the optimization method for territorial spatial functional areas under "dual evaluations" and optimized patterns of regional territorial spatial functional areas. In the optimization results, the territorial space was divided into seven functional areas: urban space, agricultural space, ecological space, urban-agricultural space, urban-ecological space, agricultural-ecological space, and urban-agricultural-ecological space. Their areas accounted for 0.78 %, 14.34 %, 67.73 %, 0.62 %, 0.32 %, 15.77 %, and

0.44 % of the total area, respectively. Because of the advantages of the geographical and local conditions, the center and southeast of the study area were the most suitable for the development of the functional area types related to urban function (i.e., urban space, urban-agricultural space, urban-ecological space, and urban-agricultural-ecological space). The agricultural space was mainly distributed in the east and west. The east should adjust agricultural structures based on economic development and regional characteristics, while the west should focus on the construction of ecological agricultural areas. The ecological space had higher connectivity in the northwest, southwest, and northeast. Areas with severe rocky desertification in the south and southeast especially displayed all spatial types related to the ecological space. The agricultural-ecological space was the most important multifunctional area in karst areas and was mainly distributed in the north, south and southeast. It could provide a good ecological barrier for the governance of rocky desertification and interruption of human activities. However, other multifunctional areas would also contribute to the sustainable development of territorial space.

In addition, we proposed control approaches for territorial space in karst areas from two aspects of the control of territorial spatial functional areas and of rocky desertification space. In the former case, we constructed control patterns of territorial spatial functional areas of the "trinity" that centered on classified protection, comprehensive improvement, and cluster development. Finally, three development directions of classified protection and three optimization targets of comprehensive improvement were formed while dividing into six areas of cluster development. In the latter case, we explored the control methods of rocky desertification deteriorating area dominated by the restriction of the population size and the implementation of ecological engineering, governance models of severe rocky desertification area combined natural restoration with the construction of ecological reserves, and control approaches for the policy centering on the implementation of corresponding policies. The optimization method for the territorial spatial functional areas under "dual evaluation" and exploration of territorial spatial control approaches could provide a scientific basis for the enhancement of rocky desertification and improvement of the ecological environment in karst areas in Southwest China.

## CRediT authorship contribution statement

**Sinan Li:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Xiaoqing Zhao:** Conceptualization, Methodology, Formal analysis, Resources, Writing - review & editing, Funding acquisition. **Junwei Pu:** Software, Resources, Writing - original draft, Project administration. **Peipei Miao:** Validation, Investigation, Writing - original draft. **Qian Wang:** Validation, Data curation, Visualization, Project administration. **Kun Tan:** Data curation, Visualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This research was supported by the Joint Fund of Yunnan Provincial Science and Technology Department and Yunnan University [2018FY001(-017)]; National Natural Science Foundation of China [41361020]; Science Research Fund of Yunnan Provincial Education Department [2020Y0030]; Project of Innovative Talents Cultivation for Graduate Students of Yunnan University [C176230200]; and Project of First-class Discipline Construction of Yunnan University-Geography [C176210103; C176210215].

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.landusepol.2020.104940.

## References

Allam, A., Amr, F., Tawfik, A., Chihiro, Y., Aiman, E.S., 2015. A simulation-based suitability index of the quality and quantity of agricultural drainage water for reuse in irrigation. Sci. Total Environ. 536, 79–90. https://doi.org/10.1016/j.scitotenv.2015.07.029.

Bai, X.Y., Wang, S.J., Xiong, K.N., 2013. Assessing spatial-temporal evolution processes of karst rocky desertification land: indications for restoration strategies. Land Degrad. Develop. 24, 47–56. https://doi.org/10.1002/ldr.1102.

Baró, F., Palomo, I., Zulian, G., Vizcaino, P., Haase, D., Baggethun, E.G., 2016. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: a case study in the Barcelona metropolitan region. Land Use Policy 57, 405–417. https://doi.org/10.1016/j.landusepol.2016.06.006.

Bathrellos, G.D., Skilodimou, H.D., Chousianitis, K., Youssef, A.M., Pradhan, B., 2017. Suitability estimation for urban development using multi-hazard assessment map. Sci. Total Environ. 575 (575), 119–134. https://doi.org/10.1016/j.scitotenv.2016.10.025.

Bennett, D.E., Gosnell, H., 2015. Integrating multiple perspectives on payments for ecosystem services through a social-ecological systems framework. Ecol. Econ. 116, 172–181. https://doi.org/10.1016/j.ecolecon.2015.04.019.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12 (12), 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Bertinelli, L., Strobl, E., Zou, B.T., 2008. Economic development and environmental quality: a reassessment in light of nature's self-regeneration capacity. Ecol. Econ. 66 (2-3), 371–378. https://doi.org/10.1016/j.ecolecon.2007.09.013.

Cairns, J., 1999. Balancing ecological impairment and repair for sustainability. Hydrobiologia 416 (4), 77–83. https://doi.org/10.1023/A:1003867411895.

Chang, T.Q., Kong, D.P., Hao, N., Xu, K.H., Yang, G.Z., 2018. Solving the dynamic weapon target assignment problem by an improved artificial bee colony algorithm with heuristic factor initialization. Appl. Soft Comput. 70, 845–863. https://doi.org/10.1016/j.asoc.2018.06.014.

Chen, H.Y., Zhu, T., 2015. The complexity of cooperative governance and optimization of institutional arrangements in the Greater Mekong Subregion. Land Use Policy 2016 (50), 363–370. https://doi.org/10.1016/j.landusepol.2015.09.030.

Davis, A.Y., Jung, J., Pijanowski, B.C., Minor, E.S., 2016. Combined vegetation volume and "greenness" affect urban air temperature. Appl. Geogr. 71, 106–114. https://doi.org/10.1016/j.apgeog.2016.04.010.

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nature Geosci. 10 (12), 919–924. https://doi.org/10.1038/s41561-017-0004-5.

Du, G.M., Sun, X.B., Wang, J.Y., 2016. Spatiotemporal patterns of multi-functionality of land use in Northeast China. Prog. Geogr. 35 (2), 232–244 (In Chinese).

Fan, J., 2015. Draft of major function oriented zoning of China. Acta Geographica Sinica. 70 (2), 186–201 (In Chinese).

Fan, Z.M., Li, J., Yue, T.X., Zhou, X., Lan, A.J., 2015. Scenarios of land cover in Karst area of southwestern China. Environ. Earth Sci. 74 (8), 6407–6420. https://doi.org/10.1007/s12665-015-4223-z.

Fan, Y.T., Jin, X.B., Gan, L., Jessup, L.H., Pijanowski, B.C., Yang, X.H., et al., 2018. Spatial identification and dynamic analysis of land use functions reveals distinct zones of multiple functions in eastern China. Sci. Total Environ. 642, 33–44. https://doi.org/10.1016/j.scitotenv.2018.05.383.

Foley, J.A., 2005. Global consequences of land use. Science 309 (5734), 570–574. https://doi.org/10.1126/science.1111772.

Gao, L., Bryan, B.A., 2017. Finding pathways to national-scale land-sector sustainability. Nature 544 (7649), 217–222. https://doi.org/10.1038/nature21694.

Groot, R.D., 2006. Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Landsc. Urban Plan. 75 (3-4), 0–186. https://doi.org/10.1016/j.landurbplan.2005.02.016.

Hao, Q., Deng, L., Feng, Z.M., 2019. Carrying capacity reconsidered in spatial planning:concepts, methods and applications. J. Nat. Resour. 34 (10), 2073–2086 (In Chinese).

Hersperger, A.M., Langhamer, D., Dalang, T., 2012. Inventorying human-made objects: a step towards better understanding land use for multifunctional planning in a peri-urban Swiss landscape. Landsc. Urban Plan. 105 (3), 0–314. https://doi.org/10.1016/j.landurbplan.2012.01.008.

Huang, A., Xu, Y.Q., Lu, L.H., Liu, C., et al., 2020. Research progress of the identification and optimization of production-living-ecological spaces. Prog. Geogr. 39 (03), 503–518 (In Chinese).

Izquierdo, A.E., Grau, H.R., 2009. Agriculture adjustment, land-use transition and protected areas in Northwestern Argentina. J. Environ. Manage. 90 (2), 858–865. https://doi.org/10.1016/j.jenvman.2008.02.013.

Jiang, Y.J., Li, L.L., Groves, C., Yuan, D., Kambesis, P., 2009. Relationships between rocky desertification and spatial pattern of land use in typical Karst area, Southwest China. Environ. Earth Sci. 59 (4), 881–890. https://doi.org/10.1007/s12665-009-0083-8.

Jin, X.B., Zhang, Z.H., Wu, X.W., Xiang, X.M., Sun, W., Bai, Q., et al., 2016. Co-ordination

of land exploitation, exploitable farmland reserves and national planning in China. Land Use Policy 57, 682–693. https://doi.org/10.1016/j.landusepol.2016.06.036.
Jones, C.G., 2012. Grand challenges for the future of ecological engineering. Ecol. Eng. 45, 80–84. https://doi.org/10.1016/j.ecoleng.2012.02.023.
Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., et al., 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452 (7190), 987–990. https://doi.org/10.1038/nature06777.
Lane, M., Dawes, L., Grace, P., 2014. The essential parameters of a resource-based carrying capacity assessment model: an Australian case study. Ecol. Model. 272, 220–231. https://doi.org/10.1016/j.ecolmodel.2013.10.006.
Lin, J.Y., LI, X., 2014. MFOZ planning of Dongguan based on spatial autocorrelation by using genetic algorithms. Geogr. Res. 33 (2), 349–357 (In Chinese).
Lin, J., Wu, T., Zhang, Y.X., Zhao, Y., 2019. Thoughts on unifying the regulation of territorial space use. J. Nat. Resour. 34 (10), 2200–2208 (In Chinese).
Liu, Y.S., 2018. Research on the urban-rural integration and rural revitalization in the new era in China. Acta Geographica Sinica 73 (4), 637–650 (In Chinese).
Liu, Y.S., Yang, R., 2012. The spatial characteristics and dormation mechanism of the county urbanization in China. Acta Geographica Sinica 67 (08), 1011–1020 (In Chinese).
Liu, Y.S., Fang, F., Li, Y.H., 2014. Key issues of land use in China and implications for policy making. Land Use Policy 40, 6–12. https://doi.org/10.1016/j.landusepol.2013.03.013.
Liu, J.L., Liu, Y.S., LI, Y.R., 2017. Classification evaluation and spatial-temporal analysis of "production-living-ecological" spaces in China. Acta Geographica Sinica 72 (7), 1290–1304 (In Chinese).
Ma, L.B., Niu, S.W., Shi, P.J., Guo, X.D., 2015. The functional zoning of territorial space and the developmental pattern of future space-based on the framework of the major function oriented zoning. Econ. Geogr. 35 (6), 68–77 (In Chinese).
Milesi, C., Elvidge, C.D., Nemani, R.R., Running, S.W., 2003. Assessing the impact of urban land development on net primary productivity in the Southeastern United States. Remote Sens. Environ. 86 (3), 401–410. https://doi.org/10.1016/S0034-4257(03)00081-6.
Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325 (5939), 419–422. https://doi.org/10.1126/science.1172133.
Pan, G.B., Xu, Y.P., Yu, Z.H., Song, S., Zhang, Y., 2015. Analysis of river health variation under the background of urbanization based on entropy weight and matter-element model: a case study in Huzhou City in the Yangtze River Delta. China. Environ. Res. 139, 31–35. https://doi.org/10.1016/j.envres.2015.02.013.
Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J., et al., 2018. Global assessment of agricultural system redesign for sustainable intensification. Nat. Sustain. 1 (8), 441–446. https://doi.org/10.1038/s41893-018-0114-0.
Ran, N., Jin, X.B., Fan, Y.T., Xiang, X.M., Liu, J., Zhou, Y.K., et al., 2018. 'Three Lines' delineation based on land use conflict identification and coordination in Jintan District, Changzhou. Resour. Sci. 40 (2), 284–298 (In Chinese).
Scolozzi, R., Morri, E., Santolini, R., 2012. Delphi-based change assessment in ecosystem service values to support strategic spatial planning in Italian landscapes. Ecol. Indic. 21, 134–144. https://doi.org/10.1016/j.ecolind.2011.07.019.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109 (40), 16083–16088. https://doi.org/10.4081/gh.2012.99.
Shen, Z.Y., Qiu, J.L., Hong, Q., Chen, L., 2014. Simulation of spatial and temporal distributions of non-point source pollution load in the Three Gorges Reservoir Region. Sci. Total Environ. 493, 138–146. https://doi.org/10.1016/j.scitotenv.2014.05.109.
Silvia, F., Sandra, P.A., Carolina Miranda, D.F., 2015. Salvadora persica agro-ecological suitability for oil production in Argentine dryland salinity. Sci. Total Environ. 538, 844–854. https://doi.org/10.1016/j.scitotenv.2015.08.082.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al., 2015. Planetary boundaries:guiding human development on a changing planet. Science 347 (6223), 736–746. https://doi.org/10.1126/science.1259855.
Stott, I., Soga, M., Inger, R., Gaston, K.J., 2015. Land sparing is crucial for urban ecosystem services. Front. Ecol. Environ. 13 (7), 387–393. https://doi.org/10.1890/140286.
Tayyebi, A., Perry, P.C., Tayyebi, A.H., 2014. Predicting the expansion of an urban boundary using spatial logistic regression and hybrid raster-vector routines with remote sensing and GIS. Int. J. Geogr. Inf. Sci. 28 (4), 639–659. https://doi.org/10.1080/13658816.2013.845892.
Verburg, P.H., van de Steeg, J., Veldkamp, A., Willemen, L., 2009. From land cover change to land function dynamics: a major challenge to improve land characterization. J. Environ. Manage. 90 (3), 1327–1335. https://doi.org/10.1016/j.jenvman.2008.08.005.
Wahyunto, W., Supriatna, W., Agus, F., 2012. Land use change and recommendation for sustainable development of peatland for agriculture: case study at kubu raya and pontianak districts, west kalimantan. Diabetes Care 11 (1), 32. https://doi.org/10.1093/cvr/cvt116.
Wang, Y., Li, Y., Liu, W., Gao, Y.B., 2015. Assessing operational ocean observing equipment (OOOE) based on the fuzzy comprehensive evaluation method. Ocean Eng. 107, 54–59. https://doi.org/10.1016/j.oceaneng.2015.07.032.
Wang, X., Zhao, X.L., Zhang, Z.X., Yi, L., Zuo, L.J., Wen, Q.K., et al., 2016. Assessment of soil erosion change and its relationships with land use/cover change in China from the end of the 1980s to 2010. Catena 137, 256–268. https://doi.org/10.1016/j.catena.2015.10.004.
Wang, L.J., Li, R., Sheng, M.Y., 2017. Distribution of soil organic carbon related to environmental factors in typical rocky desertification ecosystems. Acta Ecol. Sin. 37 (05), 1367–1378 (In Chinese).
Wang, Y.F., Fan, J., Zhou, K., 2019. Territorial function optimization regionalization based on the integration of "Double Evaluation". Geogr. Res. 38 (10), 2415–2429 (In Chinese).
Wei, X.H., Kai, X., Wang, Y., Yu, H.W., 2019. Discussions on the methods of "three zones and three lines" implementation at the spatial levels of city and county based on "double evaluations". City Plan. Rev. 43 (07), 10–20 (In Chinese).
Wende, W., Huelsmann, W., Marty, M., Penn-Bressel, G., Bobylev, N., 2010. Climate protection and compact urban structures in spatial planning and local construction plans in Germany. Land Use Policy 27 (3), 864–868. https://doi.org/10.1016/j.landusepol.2009.11.005.
Wiggering, H., Müller, K., Werner, A., Helming, K., 2003. The concept of multi-functionality in sustainable land development. Sustainable Development of Multifunctional Landscapes. Springer, Berlin Heidelberg, pp. 3–18. https://doi.org/10.1007/978-3-662-05240-2_1.
Xiao, H.L., Weng, Q.H., 2007. The impact of land use and land cover changes on land surface temperature in a karst area of China. J. Environ. Manage. 85 (1), 245–257. https://doi.org/10.1016/j.jenvman.2006.07.016.
Xiong, K.N., Li, J., Long, M.Z., 2012. Features of soil and water loss and key issues in demonstration areas for combating karst rocky desertification. Acta Geographica Sinica. 67 (07), 878–888 (In Chinese).
Yang, R., Liu, Y.S., Long, H.L., 2015. The study on non-agricultural transformation co-evolution characteristics of "population-land-industry": case study of the Bohai Rim in China. Geogr. Res. 34 (03), 475–486 (In Chinese).
Yang, Q.Y., Zhang, F.W., Jiang, Z.C., Yuan, D.X., Jiang, Y.J., 2016. Assessment of water resource carrying capacity in karst area of Southwest China. Environ. Earth Sci. 75 (1), 1–8. https://doi.org/10.1007/s12665-015-4816-6.
Yang, W.C., Xu, K., Lian, J.J., Bin, L.L., Ma, C., 2018. Multiple flood vulnerability assessment approach based on fuzzy comprehensive evaluation method and coordinated development degree model. J. Environ. Manage. 213, 440–450. https://doi.org/10.1016/j.jenvman.2018.02.085.
Zhang, M.Y., Wang, K.L., Zhang, C.H., Chen, H.S., Liu, H.Y., Yue, Y.M., et al., 2011. Using the radial basis function network model to assess rocky desertification in northwest Guangxi. China. Environ. Earth Sci. 62 (1), 69–76. https://doi.org/10.1007/s12665-010-0498-2.
Zhang, M.Y., Wang, K.L., Liu, H.Y., Zhang, C.H., Wang, J., Yue, Y.M., et al., 2015. How ecological restoration alters ecosystem services: an analysis of vegetation carbon sequestration in the karst area of northwest Guangxi, China. Environ. Earth Sci. 74 (6), 5307–5317. https://doi.org/10.1007/s12665-015-4542-0.
Zhang, Y., Liu, Y.F., Zhang, Y., Liu, Y., Zhang, G.X., Chen, Y.Y., 2018. On the spatial relationship between ecosystem services and urbanization: a case study in Wuhan, China. Sci. Total Environ. 637-638, 780. https://doi.org/10.1016/j.scitotenv.2018.04.396.
Zhang, N.G., Wang, N., Yin, J., 2019a. Shenyang's practice and optimizing exploration of "Three Control Lines" in territorial spatial planning. J. Nat. Resour. 34 (10), 2175–2185 (In Chinese).
Zhang, S.Y., Liu, X.P., Yan, S.Z., Zhan, Q., Liu, T.Q., 2019b. Delimitation of urban development boundaries using two basic evaluations and FLUS-UGB: a case study of Changchun. Trop. Geo. 39 (03), 377–386 (In Chinese).
Zhang, Y.N., Long, H.L., Tu, S.S., Ge, D.Z., Li, M., Wang, L.Z., 2019c. Spatial identification of land use functions and their tradeoffs/synergies in China: implications for sustainable land management. Ecol. Indic. 107, 105550. https://doi.org/10.1016/j.ecolind.2019.105550.
Zhao, X.Q., Li, S.N., Tan, K., Miao, P.P., Pu, J.W., et al., 2019a. Land use optimization of plateau lake basin based on town-agriculture-ecological spatial coordination. Trans. CSAE 35, 296–307 (In Chinese).
Zhao, X.Q., Li, S.N., Pu, J.W., Miao, P.P., Wang, Q., et al., 2019b. Optimization of the national land space based on the coordination of urban-agricultural-ecological functions in the karst areas of Southwest China. Sustainability 11, 6752. https://doi.org/10.3390/su11236752.
Zhao, K., Xu, J.Q., Shen, C., 2019c. Research on the compiling thinking of city and county territorial spatial master planning regulations based on the perspective of human behaviors. J. Nat. Resour. 34 (10), 2234–2243 (In Chinese).
Zhong, T.Y., Mitchell, B., Scott, S., Huang, X.J., Li, Y., Lu, X., 2017. Growing centralization in China's farmland protection policy in response to policy failure and related upward-extending unwillingness to protect farmland since 1978. Environ. Plan. C 35 (6), 1075–1097. https://doi.org/10.1177/0263774X16682958.
Zhou, D., Xu, J.C., Lin, Z.L., 2016. Conflict or coordination? Assessing land use multi-functionalization using production-living-ecology analysis. Sci. Total Environ. 577, 136–147. https://doi.org/10.1016/j.scitotenv.2016.10.143.