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Research article

Urban landscape sustainability in karst mountainous cities: A landscape resilience perspective

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ABSTRACT

In the context of the rapid progress of global urbanization, the massive encroachment of social landscapes into ecological and productive landscapes has led to a series of environmental problems. Furthermore, analyzing the landscape resilience could effectively reveal the sustainable development ability of the urban landscape. This study establishes a social-ecological productive landscape resilience (SEPLR) evaluation system and reveals trade-offs and synergies between different landscape types and resilience. Finally, this study provides landscape management zonings based on the spatial and temporal dynamic characteristics of landscape resilience and subsystem resilience. The findings showed that: (1) The CUAG has significant landscape heterogeneity and change drastically, which is mainly manifested by the massive encroachment of social landscape into productive landscape. (2) The SEPLR of CUAG decreased slightly by 0.75 % over the decade, with significant changes of spatial distribution. (3) The comprehensive remediation areas and social development areas are the dominant management zones. The findings could be incorporated into the decision-making of land use trade-off development in CUAG to promote the coordinated development of social-ecological productive systems and improve the sustainability of urban landscape.

1. Introduction

Over the past decades, drastic human activities have led to irreversible changes in global ecosystems, resulting in the reduction of global biodiversity and the degradation of ecosystems [1]. The Millennium Ecosystem Assessment indicates that over 60 per cent of the world's ecosystems are in a state of continuing degradation and remain on a trend of degradation [2]. In addition, the coexistence of pressing economic development and the necessary ecological civilization building needs has led to a complex flow of interactions between urban social landscapes (SL), ecological landscapes (EL), and productive landscapes (PL), which inevitably poses a serious threat to the ecological health and sustainability of the landscapes [3–5]. Unsustainable landscape pattern changes often preceded by dramatic urbanization and serious ecological problems such as habitat fragmentation, desertification, soil erosion and loss of biodiversity [6–8]. Therefore, in the context of China's rapid urbanization and ecological restoration in parallel, how to enhance landscape sustainability has gradually become a hotspot of sustainability science research [9–11].

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Landscape as a complex adaptive system, whose sustainability depends on resilience that arises from adaptive capacity [10]. Human activities directly affect the functioning of the planet, modifying its ability to recover [12,13]. Currently, resilience has been developed for use in many fields, and a growing amount of research demonstrates the need for an integrated methodology to enhance resilience in social, ecological, and multiple fields [14–16]. The resilience of social-ecological systems has been extensively studied [4, 17–19], however, social-ecological systems could not fully reflect the sustainability of urban development, and more complex dimensions and intuitive scales need to be taken into account [20]. Landscape resilience is a complex indicator that integrates the resilience of different systems based on larger scales in space, and as one of the key issues of concern in landscape sustainability science, it could be an effective measure of the sustainability of regional landscapes [10,11,21]. Meanwhile, enhancing landscape resilience could effectively respond to environmental change and maintain landscape ecological health and sustainability [10]. Therefore, how to evaluate and enhance landscape resilience has become an essential issue for sustainable landscape development [1, 10]. Urban areas, as areas of high population concentration, face a wide range of problems [22,23]. Particularly in the context of rapid urbanization, urban landscape resilience has been applied as a transformative approach to urban planning, to enhance the resilience of cities to external pressures and natural disasters [24,25]. Therefore, planning for sustainable urban development has become an essential goal of current urbanization [26,27]. Concurrently, maintaining landscape resilience is recognized as an objective of environmental management and planning strategies [28–30]. The quantitative evaluation of landscape resilience is currently in an exploratory period. The earliest research framework was established in the study of Ciftcioglu [1] in North Cyprus, in which landscape resilience was categorized into three sub-systems (social systems, ecosystems, and productive systems), a participatory approach method for data collection was used, and finally, the evaluation of landscape resilience was implemented for the region. Based on the social-ecological productive landscape resilience (SEPLR) model, some Chinese scholars have explored the model and studied the spatial and temporal changes in landscape resilience, the driving mechanisms, and the impacts of different policies on landscape resilience in different regions [5,31–34]. However, most of the current studies have weaknesses: evaluations are conducted in administrative districts, the selection of indicators is not geographically specific and idiosyncratic, and data precision is low. Therefore,

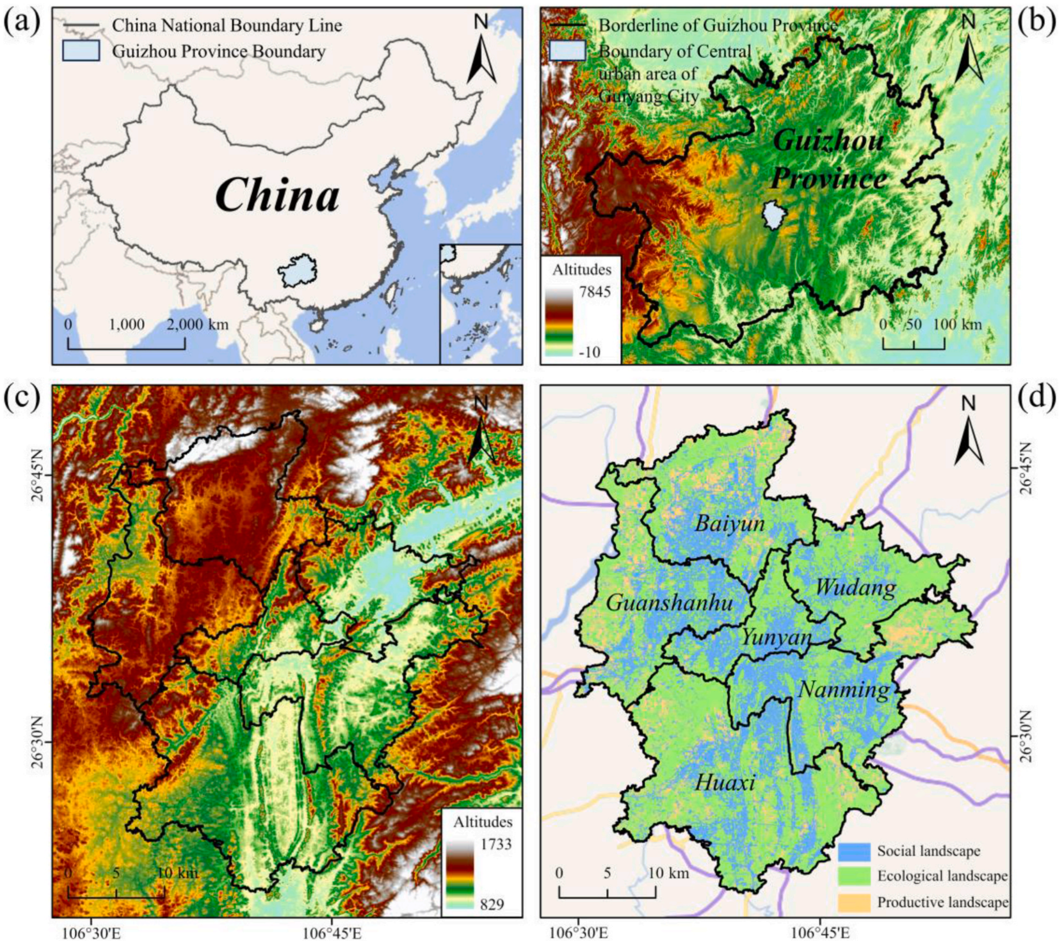

Fig. 1. Location of the central urban area of Guiyang city in China.
Notes: (a) Chinese national boundary; (b) Guizhou province boundary; (c) Altitude map of the study area; (d) Distribution of landscape types of the study area.

it is urgently needed to construct a more karst regional and highly accurate landscape resilience evaluation framwork to explore the impact of changes in karst mountain urban landscape pattern on landscape resilience, thereby obtaining a more accurate spatial distribution pattern and providing scientific guidance for the optimization of landscape pattern.

As the economic and cultural center of Guizhou Province, Guiyang City, with a gross domestic product (GDP) of about 24.1 % of the province, plays a decisive role in the socio-economic development of Guizhou Province. Meanwhile, as a typical karst mountain city in Southwest China, it has a fragile ecological environment background with a high degree of landscape heterogeneity and landscape fragmentation, which leads to more time required for the management of ecosystem degradation in this area compared with other regions [35]. In the last decade, urban expansion has led to drastic changes in landscape patterns, and the unavoidable encroachment of SL on EL in the process of urbanization has led to a series of ecological and environmental problems (e.g., soil and water erosion, ecosystem degradation, rocky desertification, etc.), which have further fragmented the already fragile environmental background [36]. However, it has benefited from a series of ecological restoration projects implemented by the Chinese government (e.g., Natural Forest Protection Project, the Public Welfare Forest Protection Project, the Karst Rocky Desertification Restoration Project), especially the Grain for Green program (GFGP), which is the largest ecological restoration project in the world [37,38], the degradation of the ecosystems in Guiyang City was restored, and simultaneously led to a significant reduction of the PL drastically reduced. Since CUAG is simultaneously in the context of high-intensity human activity interference and ecological environment restoration, as a typical region that is simultaneously in a state of destruction and restoration. Exploring its landscape pattern change and its impact on landscape resilience is significant for landscape sustainable development, and guiding significance for future urbanization of Guiyang City and optimization of landscape pattern.

To reveal how SEPLR is affected in the context of karst areas experienced simultaneous restoration and destruction, this study takes the central city of Guiyang as an example, selects indicators with regional characteristics according to the actual situation of the study area, and constructs a multi-level evaluation system based on the SEPLR model, aiming to answer the following questions.

(1) Direction of landscape type transformation in the study area in the last decade?
(2) Trends in landscape resilience in the study area over the last decade?
(3) How different landscape types affect landscape resilience?

The remainder of this manuscript is organized as follows: Section 2 introduces an overview of the study area and data sources, and the research methodology. Section 3 introduces the main findings of this study. Section 4 introduces the findings, shortcomings and limitations of this study. Section 5 summarizes this study and also the outlook.

2. Materials and methods

2.1. Study region

Guiyang City (26°11′-26°55′N, 106°07′-107°17′E) is located on the eastern slope of the Yunnan-Guizhou Plateau, the watershed of the Yangtze River and the Pearl River, and is strategically important as the “Two Rivers Barrier” (Fig. 1). As the capital of Guizhou Province, Guiyang has been strongly developing its central urban area, which covers an area of 1188 km approximately. The population has increased dramatically by 38.35 % during 2010–2020, while the urbanization has been progressing rapidly, with the urban area increasing by 45.26 %. Meanwhile, Guiyang city is located in the core of the karst region in the Guizhou province, which is a typical karst mountain city, and is also the area with wider rocky desertification in southwestern karst region [39]. The altitude of the study area gradually decreases from northwest to southeast, with an average altitude of 1180 m [40]. It has a subtropical humid monsoon climate, with year-round rainfall, and is known as "There are no three clear days in the sky", with an average annual temperature of 15.3 °C, an average annual precipitation of 1197–1248 mm, and an average annual relative humidity of 80 % [16].

The Central Urban Area of Guiyang City (CUAG) has a wide range of mountainous terrain with large topographic and geomorphic relief, resulting in a fragmented landscape and a fragile ecological background in the study area [36]. In recent years, the urbanization process of Guiyang City has been developing rapidly, and the landscape pattern of the CUAG has changed dramatically, resulting in increased landscape fragmentation, which has led to the reduction of the area of the internal habitat patches and the decrease of landscape connectivity, resulting in a series of ecological and environmental problems (e.g., ecosystem degradation, biodiversity loss, and ecosystem service reduction, etc.) [41]. Meanwhile, the Chinese government implemented a series of ecological restoration measures, in the context of both degradation and restoration, resulting in a drastic change in the landscape pattern of the CUAG. Overall, the CUAG is in a context of rapid urbanization and intensive implementation of ecological conservation and restoration measures., which makes it the best area for exploring changes in landscape resilience in the context of multiple contexts that lead to dramatic changes in landscape patterns.

2.2. Data sources and processing

In this study, the remote sensing images of central urban area of Guiyang city (CUAG) in 2010, 2015 and 2020 are selected, which are obtained from the high-resolution remote sensing images of Google Earth in 2010 and 2015 with good image quality and spatial resolution of 2 m, and from the high-resolution remote sensing images of Gaofen-1 satellite series in 2020 with good image quality and spatial resolution of 2 m. Based on China’s land use classification standard (GB/T 21010-2017), supplemented by field surveys, they are classified into 10 categories: residential land, forestland, grassland, transport land, farmland, warehousing land, under construction land, water and water conservancy facilities land, other land, and mountain. With reference to relevant research, the landscape types were classified by combining the actual land use situation in the study area (Table 1) [42,43]. The productive landscape only considered agricultural productive land due to the extremely rare presence of industrial productive land within the study area.

The rocky desertification intensity data are from Guizhou Forestry Bureau. The digital elevation model (DEM) data are from Geospatial Data Cloud (https://www.gscloud.cn). The fraction vegetation cover data were obtained from the National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) China Regional 250 m Normalized Vegetation Index Dataset (2000–2022). The GDP and population density (POP) data were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn). And other socio-economic data are from Guiyang City Statistical Yearbook, statistical yearbooks of districts and counties, and the National Economic and Social Development Statistical Bulletin. Eventually, all socio-economic data were extracted into a 900 m grid based on ArcGIS 10.5 software.

2.3. Landscape pattern dynamics analysis

2.3.1. Transfer matrix method

The spatial analysis tool of ArcGIS 10.5 software was used to extract and analyze the quantitative characteristics of different landscape types in the central urban area of Guiyang city during 2010–2015 and 2015–2020. The complex transfer trend between different landscape types during the 10-year period was revealed based on the transfer matrix method, the formula is as follows:

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

where: S_{ij} represents the landscape type status at the beginning and end of the study; n represents the number of types.

2.3.2. Identify landscape pattern dominance zones

The triangulation model, as a qualitative classification tool, was initially used to assess and analyze soil texture. In recent years, the model has been widely used in the fields of geography, economics, and environmental science [44,45]. The landscape advantage zone (LAZ) of the study area was divided based on the triangular model at the 900 m fishing net scale. Fig. 2 shows the shape of the social-ecological productive triangle model with SL, EL, PL as the three vertices. The 0–1 of each axis increases counterclockwise, and there are a total of seven zones in the triangular model, showing seven different LAZs, which are social landscape advantage zone (SLAZ), ecological landscape advantage zone (ELAZ), productive landscape advantage zone (PLAZ), social-ecological landscape composite zone (SELCZ), social-productive landscape composite zone (SPLCZ), ecological-productive landscape composite zone (EPLCZ), and social-ecological-productive landscape balance zone (SEPLBZ).

2.4. Social-ecological productive landscape resilience evaluation

2.4.1. Construction of social-ecological-productive landscape resilience evaluation system

The evaluation of urban landscape resilience through the construction of a multi-level indicator system has been recognized by numerous scholars. This study is based on the SEPLR model proposed by previous studies [1,5], and has borrowed the pressure-state-response (PSR) model [46], which is intended to provide a comprehensive evaluation of resilience at the level of the three subsystems: social, ecological, and productive. Based on the 2010, 2015 and 2020 basic land use data, socio-economic data and topographic data of CUAG, and combined with the actual situation of Guiyang city and the accessibility of the data, the evaluation index system shown in the table is constructed (Table 2). In addition, all the spatial data was then integrated to quantitatively identify the landscape resilience in the 900 m grid units, thus to resolve the limitation of administrative zones and to obtain a finer spatial distribution pattern.

(1) Ecosystem resilience

The maintenance and enhancement of ecosystem resilience (ER) plays a critical role in protecting biodiversity and enhancing ecosystem services, and is the basis for maintaining the stability of the SEPLR [1,5,34]. ER are characterized by ecological stresses, landscape patterns, and ecosystem function, and the ability of ecosystems to maintain their structure and function in the face of outside

Table 1
Classification of landscape types.

Types of urban landscape	Land type 1 level of classification	Land type 2 level of classification
Productive landscape	Agricultural production land	Farmland
Urban social landscape	Social living land	Warehousing land, Transport land, Residential land, Other land, Under construction land
Ecological landscape	Forestland and grassland ecological land	Grassland, Forestland
	Other ecological land	Water and water conservancy facilities land, Mountain

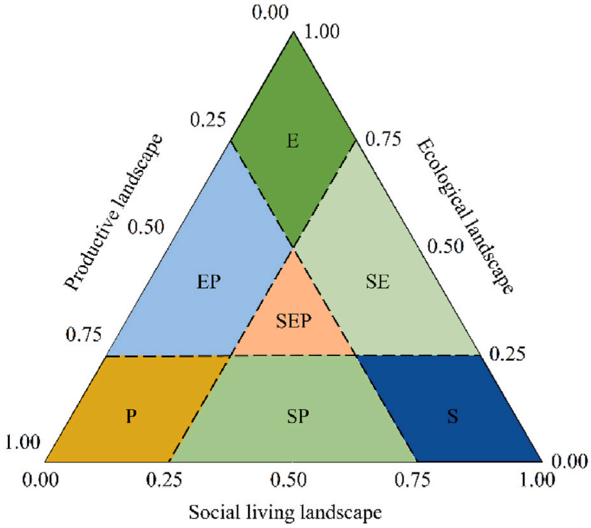

Fig. 2. Triangular model of the landscape advantage zone.
Notes: S, social landscape advantage zone; E, ecological landscape advantage zone; P, productive landscape advantage zone; SE, social-ecological landscape composite zone; SP, social-productive landscape composite zone; EP, ecological-productive landscape composite zone; SEP, social-ecological-productive landscape balance zone.

Table 2
Evaluation indicator system of social-ecological-productive landscape resilience.

Target Layer	Element layer (Weight)	Criterion Layer	Index Layer	Weight
Social-ecological Landscape resilience	Ecosystem resilience (0.3431)	Ecological stress	Rocky desertification Intensity	0.1675
			Land use intensity index	0.1638
		Landscape pattern	Landscape connectivity index	0.1727
			Landscape fragmentation index	0.1619
		Ecosystem function	Fraction vegetation coverage	0.1653
			Biological abundance	0.1688
	Social system resilience (0.3299)	Human activity intensity	Road density	0.1901
			POP	0.1763
		Industrial structure	Percentage of tertiary industry	0.2443
		Economic capacity	GDP	0.2431
			Total agricultural output	0.1462
	Productive system resilience (0.3269)	Topographic condition	Slope	0.2066
			Altitude	0.2063
		Labor force	Persons working in villages	0.1852
		Productive capacity	Cultivated land area index	0.2107
			Production of major crops	0.1912

pressures [5,47,48]. In this study, ecological pressure was characterized by land use intensity index and rocky desertification intensity. Landscape pattern was selected as landscape connectivity index and landscape fragmentation index. And ecosystem function was selected as fraction vegetation cover and biological abundance index. The calculation method of each index is as follows.

①Ecological stress indicators

The formula for the land use intensity index is as follow:

$$I = 100 \times \sum_{j=1}^{k} A_j \times C_j \tag{2}$$

where: j is the number of land use type classes, in this study $k = 4$; A_j is the index of the j_{th} class of land use degree; C_j is the proportion of the area of the j_{th} class of land in the region to the total area of the prefecture and city. Among them, the value of A_j corresponds to four major land use types, i.e., unutilized land, forestland, grass and water land, agricultural land and urban settlement land, and its index is 1,2,3 and 4, respectively.

The rocky desertification intensity data are classified into 5 levels: no rocky desertification, potential rocky desertification, mild rocky desertification, moderate rocky desertification and severe rocky desertification, which are assigned the values of 1, 2, 3, 4 and 5, respectively, and then normalized to obtain the rocky desertification intensity index.

②Landscape pattern

The landscape connectivity index is calculated as follow:

$$CONNECT = \frac{\sum_{j=k}^{n} C_{ijk}}{\frac{n_i(n_{i-1})}{2}} \times 100 \tag{3}$$

where: C_{ijk} is the connectivity status of patches j and k associated with patch type i within a critical distance; n_i is the number of patches of patch type i in the landscape. The connectivity index takes values in the range of [0, 100].

Seven landscape pattern indices were selected to calculate the landscape fragmentation index, and the first principal component cumulative contribution rate reached more than 90 % through principal component analysis. Therefore, the first principal component was selected to characterize the landscape fragmentation index. The calculation formula is as follow:

$$F = 0.1521 \times SHDI + 0.1509 \times NP + 0.1503 \times LPI + 0.1520 \times ED + 0.1517 \times DIVISION \tag{4}$$

where: $SHDI$ is the landscape diversity index; NP is the number of patches index; LPI is the maximum patch index; ED is the edge density index; and $DIVISION$ is the landscape separation index.

③Ecosystem function

The formula for calculating fraction vegetation cover is as follow:

$$F_i = (NDVI_i - NDVI_{\max}) / (NDVI_{\max} - NDVI_{\min}) \tag{5}$$

where: F_i represents the size of the vegetation cover index, and $NDVI_{\max}$ and $NDVI_{\min}$ represent the maximum and minimum values of regional vegetation cover.

The index of biological abundance was referenced from previous studies [31,49], and was calculated as follows:

$$F = \left(0.11 \times Area_a + 0.35 \times Area_f + 0.21 \times Area_g + 0.28 \times Area_w + 0.04 \times Area_r + 0.01 \times Area_u\right) \Big/ Area \tag{6}$$

where: F is the biological abundance index; $Area$ is the area of the region; $Area_a$, $Area_f$, $Area_g$, $Area_w$, $Area_r$, $Area_u$, represent the area of farmland, forestland, grassland, water, construction land, and unutilized land in the region, respectively.

(2) Social system resilience

Social system resilience (SR) characterizes the ability of a social system to maintain its structural and functional stability in the face of external stresses, and is characterized by the human activity intensity, industrial structure, and economic capacity [1,5,31,34,36]. Road density and population density indicators, Percentage of tertiary industry indicators, GDP and total agricultural output were selected to characterize them respectively. The calculation method of each index is as follows.

①Human activity intensity

POP data comes from the Resource and Environmental Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn).

Road density in the study area was quantified using patch density analysis in Fragstats software, the formula is as follow:

$$RD = \frac{NP}{A} \tag{7}$$

where: RD is the road density, NP is the number of patches, and A is the total area of the landscape or patch. The road density data within each grid was extracted using the ArcGIS zoning statistics tool.

②Industrial structure

The percentage of tertiary industry was obtained from the statistical yearbooks of Guiyang city districts and counties, etc.

③Economic Capacity

The GDP data obtained from the Resource and Environmental Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn). The total agricultural output data was obtained from Guiyang city districts and counties statistical yearbooks, etc.

(3) Productive system resilience

Productive system resilience (PR) plays a crucial role in the sustainability of agricultural production and is the bottom line for national food security. Three criterion layers of topography condition, labor force and production capacity were selected to characterize the PR [1,31,34,42]. Slope and altitude indicators, persons working in villages indicators, and indicators for the share of cultivated land area and production of major crops were selected to represent the three criterion Layer, respectively. The calculation method of each index is as follows.

①Topographic condition

Altitude data was obtained from the Geospatial Data Cloud (http://www.gscloud.cn). Slope indicators were extracted based on DEM data of the study area using ArcGIS 10.5 software.

②Labor force

The persons working in villages was obtained from Guizhou Provincial Statistical Yearbook, etc.

③Production capacity

The cultivated land area index was calculated from vectorised high-resolution remote sensing images. And the production of major crops was obtained from statistical yearbooks.

2.4.2. *Weight calculation based on global entropy value method*

The global entropy method is an objective evaluation method that can generalise multiple indicators in multiple regions and years [50,51]. Compared with the subjective assignment method, this method determines the weights of the indicators based on the information provided by the observational data of each indicator and avoids the influence of human factors [52–54]. To ensure the objectivity of the data, this study adopts the global entropy method to calculate the indicator weights between subsystems and within their subsystems. The specific steps are as follows.

(1) Data standardization:

Different indicators can have a positive or negative impact on the system: the larger the value of a positive indicator, the better; the smaller the value of a negative indicator, the better. Among them, landscape connectivity index, fraction vegetation cover, biological abundance, road density, population density, percentage of tertiary industry, GDP, total agricultural output, persons working in villages, cultivated land area index, and production of major crops are positive indicators; Rock desertification intensity, land use intensity index, landscape fragmentation index, slope and altitude are negative indicators. Since there are differences in the scales of different indicators, it is necessary to normalize the indicators before calculating the weights. The formula is as follows:

Positive indicators:

$$X = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{8}$$

Negative indicators:

$$X = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \tag{9}$$

(2) Weights Calculation:

The formula is as follows:

$$k = \frac{1}{\ln(n)} \tag{10}$$

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{11}$$

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{12}$$

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{n}(-e_i)} \tag{13}$$

where: k is a constant, n is the number of total data quantity; P_{ij} is the proportion of the value of the j_{th} indicator in the i_{th} evaluation object to the sum of all the values of this indicator, X_{ij} is the value of the j_{th} indicator in the i_{th} evaluation object; e_j is the entropy value of the j_{th} indicator; W_j is the weight of indicator j.

(3) Landscape resilience and subsystem resilience calculations

$$ER_i = \sum_{j=1}^{n} w_j I_{ij} \tag{14}$$

$$SR_i = \sum_{j=1}^{n} w_j I_{ij} \tag{15}$$

$$PR_i = = \sum_{j=1}^{n} w_j I_{ij} \tag{16}$$

$$SEPLR_i = a_1 ER_i + a_2 SR_i + a_3 PR_i \tag{17}$$

where: ER_i, SR_i, and PR_i represent ecosystem resilience, social system resilience, and productive system resilience of the i_{th} study unit; I_{ij} represents the j_{th} indicator of landscape resilience of the ith study unit; $SEPLR_i$ represents landscape resilience of the i_{th} study unit; a_1, a_2, and a_3 represent the ecosystem resilience, social system resilience, and productive system resilience respectively weights.

2.4.3. Correlation analysis for social-ecological productive landscape resilience

The changes in the area of different landscape types, landscape resilience, and sub-system resilience within the 900 m grid were quantitatively identified based on ArcGIS 10.5 software. And then, the correlation between various categories of landscape variations and SEPLR, SR, ER, PR were discovered using the spearman correlation analysis from 2000 to 2020. The spatial trade-off and synergistic relations analysis between the resilience of each subsystem and SEPLR was then realized by Matlab2022a to reveal the spatial correlation between the resilience of each subsystem and SEPLR.

2.5. Landscape management zoning methods

Based on the high and low values and the change trend of the SEPLR to classify the areas that need to be managed: attenuation areas and the sensitive-vulnerable areas, advantageous promotion areas (high-value and continuous increase), stable areas (high-value in stable state), attenuation areas (high-value in reduced state), emerging development areas (medium and low value in increased state), and sensitive-vulnerable areas (medium and low value in stable or decreased state) [34]. Among them, attenuation areas and sensitive-vulnerable areas are priority areas for landscape management. In addition, based on the tridimensional magic cube model, the SR, ER, and PR of different regions were classified, so as to construct a regional trade-off development model [42]. The subsystem resilience was categorized as high, medium, or low using the natural break-point method (Fig. 3), corresponding to numbers 1, 2, and

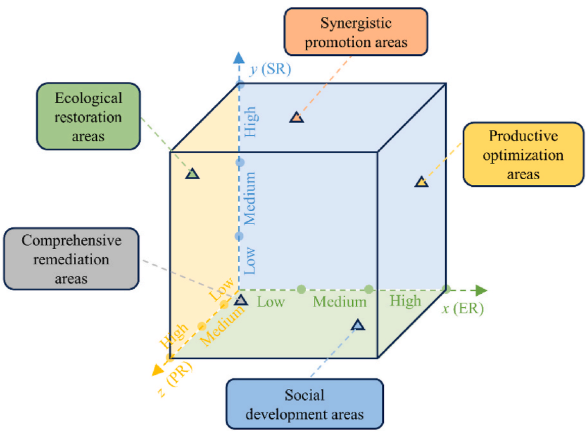

Fig. 3. Landscape management tridimensional magic cube model.
Notes: SR, social landscape resilience; ER, ecological landscape resilience; PR, productive landscape resilience.

3, which correspond to the three axes of the cube respectively. The regional trade-off development areas were formed (Table 3).

3. Results

3.1. Landscape pattern dynamics characterization

The landscape type of CUAG has changed significantly during the 10-year period (Fig. 4). The landscape types of the CUAG were dominated by SL and EL, which accounted for 73–90.34 % of the total area during 2010–2020. The EL always occupied the largest area and showed a continuous growth trend, increased from 591.22 km^2 to 671.70 km^2, with a growth rate of 13.61 %. The SL occupied the smallest proportion in 2010, with an area of 252.57 km^2, and the PL had an area of 307.80 km^2. During 2010–2020, the SL area showed a dramatic increase followed by a slow increase, with the area increased from 252.57 km^2 to 368.69 km^2, with a growth rate of 45.98 %. The EL area increased slightly, from 591.22 km^2 to 674.70 km^2, with amplification rate of 13.63 %. And the PL area continued to decrease significantly, from 307.80 km^2 to 111.20 km^2, with a decrease of 63.87 %. Meanwhile, the transfers between different landscape types showed significant variations (Fig. 4), the SL was predominantly transferred to the EL, with 107.27 km^2 in total, which accounted for 84.15 % of the transferred area in SL. The EL transferred to SL and PL were 130.95 km^2 and 80.91 km^2, respectively. The PL transferred to SL and EL was 111.75 km^2 and 185.08 km^2, respectively.

The spatial distribution pattern of landscape types in the central urban area of Guiyang City changed significantly from 2010 to 2020 (Fig. 5). In general, the spatial pattern of different landscape types was relatively stable over the 10-year period, but was accompanied by an outwardly expanding trend in both high and low value. The high-value of area proportion in SL was concentrated in the central region of the study area and the central region of each district. It was gradually expanding outwards, with the main direction of expansion being the north-western and south-eastern regions; The low-value of area proportion in SL was mainly distributed in the marginal region of the study area, with its extent gradually decreasing. The area proportion of EL showed staggered mosaics of high and low values, with small changes over the 10-year period. The increase region was mainly in the northern and southern regions, and the decrease region was mainly in the eastern region. The high-value of area proportion in PL was concentrated in the northern region, which had changed drastically during the 10-year period. The high-value of area proportion gradually disappeared, and in 2020, only a small part of it remained sporadically distributed at the fringe of the study area. And the low-value of area proportion was mainly concentrated in the central region, which gradually encroached into the high-value region.

3.2. Dynamic characterization of landscape dominance zones

Landscape dominance zones in the study area changed significantly over the 10-year period (Fig. 6). In 2010, the LAZs were dominated by the ELAZ and EPLCZ, and the number of PLAZ showed similarities to the number of SLAZ. In 2015, the EPLCZ and PLAZ decreased significantly, and the SELCZ increased significantly, the remained LAZ were relatively stable. Until 2020, the EPLCZ and PLAZ continued to decrease. Meanwhile, the SPLCZ also decreased significantly, and the SELCZ continued to increase significantly. Generally, the triangular model center of gravity showed a gradual transition to the right over the 10-year period, which represents a significant decrease in PL area in the study area and the LAZ gradually transformed to the SELCZ.

3.3. Spatial-temporal dynamics of social-ecological productive landscape resilience

The SR of CUAG was 0.2779, 0.2826, and 0.3042 in 2010, 2015, and 2020, respectively, which showed an increase trend yearly with a change rate of 9.44 %. The ER was 0.5724, 0.5577 and 0.5606, respectively, which showed a slow decrease with a change rate of −2.06 %. The PR was 0.3448, 0.3275 and 0.3200 respectively, which showed a decrease trend yearly with a change rate of −7.19 %. The SEPLR was relatively stable between 2010 and 2020, decreased from 0.3969 to 0.3939, with only a change rate of −0.75 %.

The spatial distribution pattern of resilience for each subsystem in the study area changed significantly over the 10-year period (Fig. 7). The distribution of SR showed a pattern of high in the center and low surrounding, with the high-value areas gradually clustered towards the central Yunyan district, the area bounded by the Nanming, Yunyan, and Guanshanhu district. The ER distribution pattern showed low center surrounded by high, with a trend of expansion outward in the low-value area. The PR primarily showed low in the center, and the high-values were concentrated in the farmland agglomeration area and had a significant decrease. The low-value aggregation area of SEPLR moved from the center to the outside, and the high-value aggregation area gradually moved from the southeast to the northwest, gradually developed from the distribution pattern of high around and low in the center to the trend of uniform distribution.

Table 3
Classification of landscape management zones.

Trade-Off Development Zones	Magic Cube Unit Combination
Synergistic promotion areas	(3,2,1) (3,3,2) (3,2,3) (2,3,3) (2,2,3) (2,3,2) (3,2,2) (2,2,2)
Social development areas	(3,1,3) (3,1,2) (2,1,3) (2,1,2)
Ecological restoration areas	(1,3,3) (1,2,3) (1,3,2) (1,2,2)
Production optimization areas	(3,3,1) (3,2,1) (2,3,1) (2,2,1)
Comprehensive remediation areas	(1,1,1) (1,1,2) (1,2,1) (2,1,1) (1,1,3) (1,3,1) (3,1,1)

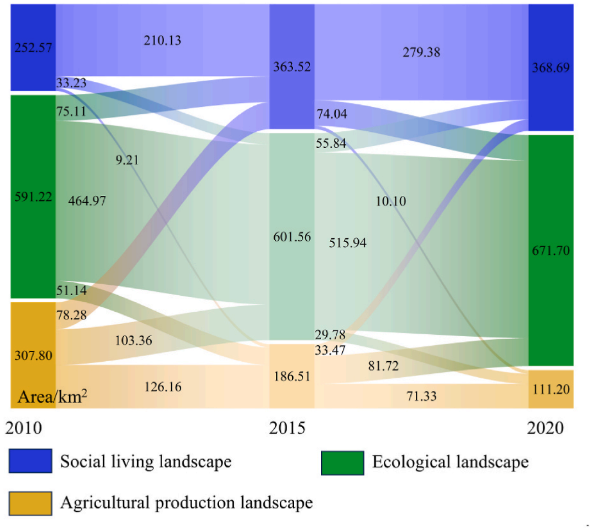

Fig. 4. Characteristics of quantity transfer in different landscape types.

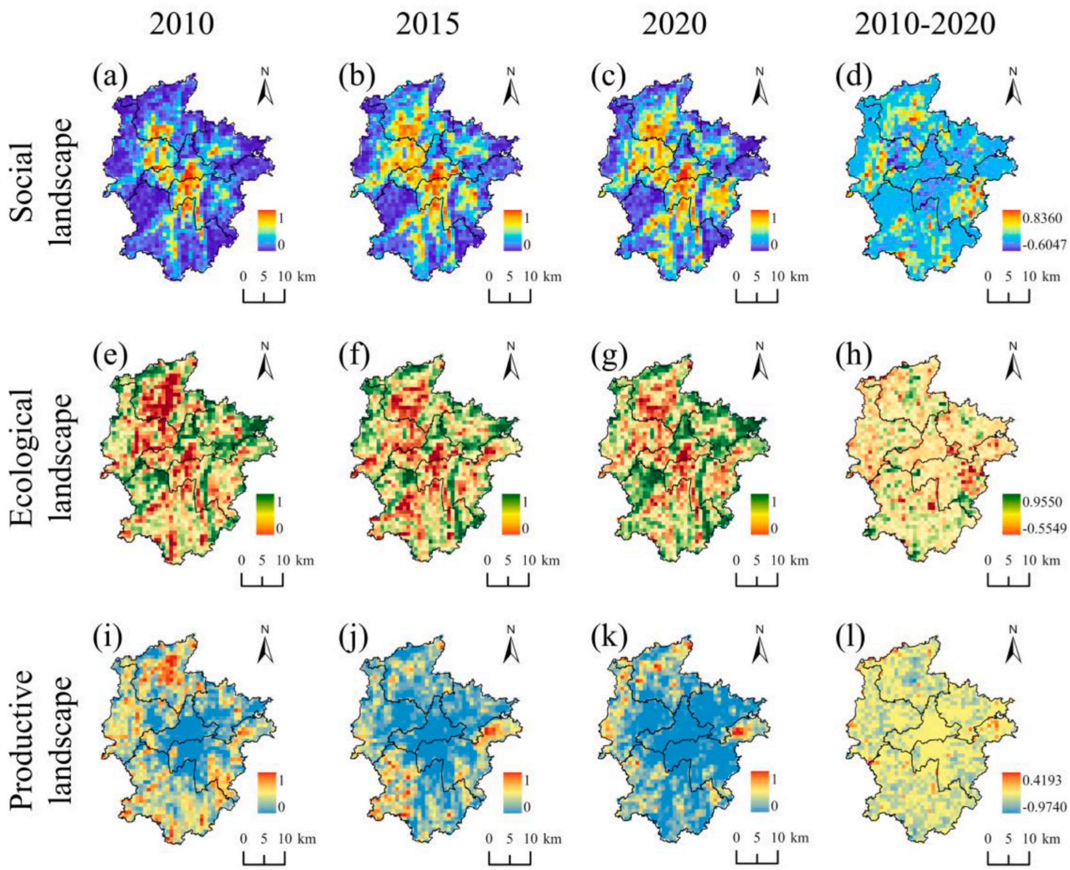

Fig. 5. Landscape area proportion normalized and change trends map.

Notes: (a), (b), (c), (d) represent the normalized distribution of the proportion of social landscapes in 2010, 2015, 2020 and the change in the landscape proportion index from 2010 to 2020, respectively; (e), (f), (g), (h) represent the normalized distribution of the proportion of ecological landscapes in 2010, 2015, 2020 and the change in the landscape proportion index from 2010 to 2020, respectively; (h), (i), (j), (k) represent the normalized distribution of the proportion of productive landscapes in 2010, 2015, 2020 and the change in the landscape proportion index from 2010 to 2020, respectively.

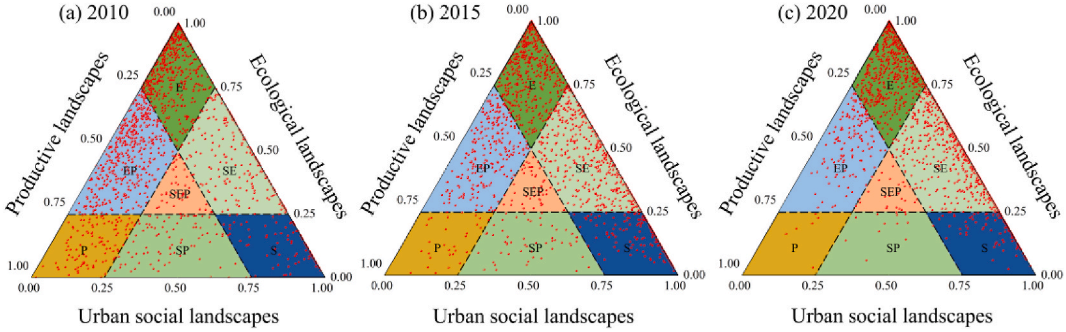

Fig. 6. Changes in landscape advantage zones.

Notes: S, social landscape advantage zone; E, ecological landscape advantage zone; P, productive landscape advantage zone; SE, social-ecological landscape composite zone; SP, social-productive landscape composite zone; EP, ecological-productive landscape composite zone; SEP, social-ecological-productive landscape balance zone; (a), (b), (c) represent the landscape advantage zones map for 2010, 2015, and 2020, respectively.

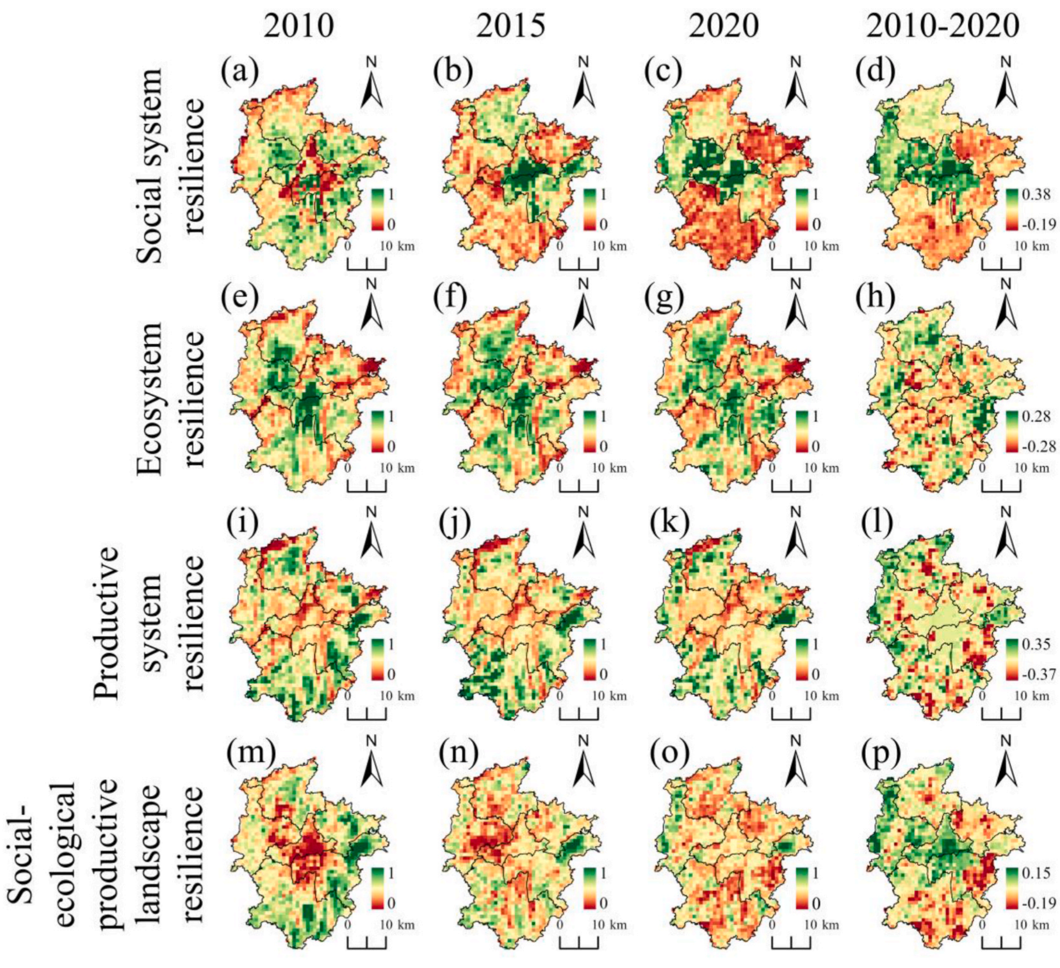

Fig. 7. Resilience normalized and change trends map.

Notes: (a), (b), (c), (d) represent the normalized distribution of the proportion of social system resilience in 2010, 2015, 2020 and the change in the resilience index from 2010 to 2020, respectively; (e), (f), (g), (h) represent the normalized distribution of the proportion of ecosystem resilience 2010, 2015, 2020 and the change in the resilience index from 2010 to 2020, respectively; (i), (j), (k), (l) represent the normalized distribution of the proportion of productive system resilience in 2010, 2015, 2020 and the change in the resilience index from 2010 to 2020, respectively; (m), (n), (o), (p) represent the normalized distribution of the proportion of social-ecological productive landscape resilience in 2010, 2015, 2020 and the change in the resilience index from 2010 to 2020, respectively.

In different LAZs (Table 4), the highest values of SR, ER and PR were distributed in SLAZ, ELAZ and PLAZ, with the values of 0.3380, 0.6618, and 0.5778 respectively. In contrast, the lowest values of SR, ER, PR were distributed in ELAZ, SPLCZ and SELCZ, with the values of 0.2535, 0.4666, and 0.4008 respectively. The highest and lowest values of SEPLR were distributed in PLAZ and SLAZ, with the values of 0.4935 and 0.3463 respectively.

3.4. Social-ecological productive landscape resilience trade-off and synergies

Correlations between different landscape types and different resilience showed significant variation (Fig. 8). The SL area showed a not-significant ($P > 0.1$) correlation with SR, and an extremely significant ($P < 0.05$) negative correlation with EL area ($R = -0.16$), PL area ($R = -0.58$), ER ($R = -0.71$), PR ($R = -0.44$), and SEPLR ($R = -0.58$). The EL area showed an extremely significant ($P < 0.05$) positive correlation with ER ($P < 0.05$), and a negative correlation with SL, PL, SR, PR, and SEPLR. The PL showed an extremely significant ($P < 0.05$) positive correlation with SR, ER, PR, and SEPLR ($P < 0.05$), and an extremely significant ($P < 0.05$) negative correlation with SL and EL. Between the different resilience, all showed extremely significant ($P < 0.05$) positive correlations, except SR and ER, which showed non-significant ($P > 0.1$).

The SEPLR, SR, ER, and PR exhibited different trade-offs and synergistic connections with each other spatially (Fig. 9). The SR and PR showed predominantly synergistic with SEPLR throughout the study area, and the ER was predominantly synergistic with SEPLR at the outside and synergistic at the inside of the study area. Between the different subsystem resilience, both SR-ER and ER-PR exhibited large trade-off effects spatially. In contrast, SR-PR showed a more even balance between trade-offs and synergies.

3.5. Landscape management zoning based on landscape resilience

The spatial distribution of the zones to be managed was extracted based on SEPLR, and its spatial distribution showed 3 main types: attenuation concentration zone, sensitive-vulnerable concentration zone, and sensitive-vulnerable-attenuation composite zone (Fig. 10). Based on the development trade-off conceptual model, which was divided into 5 management zones, i.e., social development area, ecological restoration area, production management zones, comprehensive remediation area, and synergistic promotion area. Specifically, the social development areas were primarily concentrated in the northeast part of the study area in the Wudang district and in numerous sporadic distributions within the Huaxi district (Fig. 11). The ecological restoration concentration area was primarily distributed in the northern part of the study area within the Baiyun district. The productive optimization area was predominantly distributed in the Guanshanhu district, and sporadically distributed in other districts and counties in the study area. The comprehensive remediation area was dominated in the Huaxi, Baiyun, and Wudang districts. Most areas in the Huaxi district manifested attenuation and sensitive-vulnerable areas, and which were classified as social development areas and comprehensive remediation areas. The Nanming District manifested a coexistence of multiple management areas.

4. Discussion

4.1. Social landscape expansion is a major manifestation of changing landscape patterns

Land resources are the basis for human survival and development, and are divided into SL, EL, and PL according to different functions [43,55]. Since the reform and opening up, China's urbanization has accelerated, and the landscape pattern has changed dramatically. Meanwhile, a series of problems have been exposed, e.g. conflict in human-land relations, ecological degradation, irrational exploitation and utilization of resources [56]. Furthermore, different interactions between people and the environment often led to a complex and diverse landscape pattern, showing significant landscape advantage areas in different regions. The sustainability of the landscape has been under serious threat recently due to the dramatic increase in population, the occupation of other landscapes by urbanization and the impact of various factors [10,57–60]. Moreover, landscape patterns directly affected ecosystems and were also linked to socio-economic processes and productive capacities, which were critical for landscape resilience and sustainability [10,61].

This study revealed the structure of the landscape pattern and its variation tendency in the CUAG. Moreover, the spatial landscape

Table 4
Mean values of resilience in different landscape advantage areas.

Landscape pattern zones	The average resilience			
	Social system resilience	Ecological resilience	Productive resilience	Social-ecological productive landscape resilience
SLAZ	0.3380	0.3807	0.3996	0.3463
ELAZ	0.2535	0.6618	0.3399	0.3900
PLAZ	0.3298	0.5272	0.5778	0.4935
SELCZ	0.3047	0.5025	0.4008	0.3682
SPLCZ	0.3211	0.4666	0.4956	0.4256
EPLCZ	0.2959	0.5913	0.5172	0.4424
SEPLBZ	0.3138	0.5142	0.4191	0.4190

Notes: SLAZ, social landscape advantage zone; ELAZ, ecological landscape advantage zone; PLAZ, productive landscape advantage zone; SELCZ, social-ecological landscape composite zone; SPLCZ, social-productive landscape composite zone; EPLCZ, ecological-productive landscape composite zone; SEPLBZ, social-ecological productive landscape balance zone.

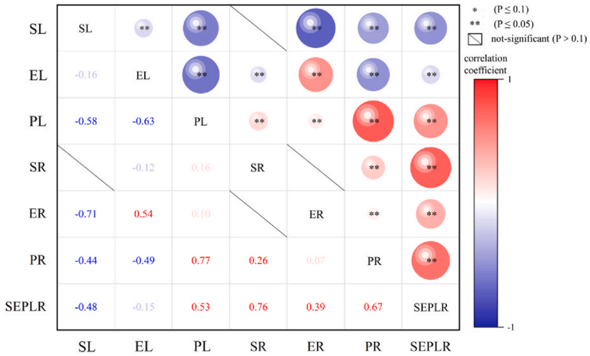

Fig. 8. Analysis of the correlation between different landscape types and landscape resilience.
Notes: SL, social landscape; EL, ecological landscape; PL, productive landscape; SR, social resilience; ER, ecological resilience; PR, productive resilience; SEPLR, social-ecological productive resilience.

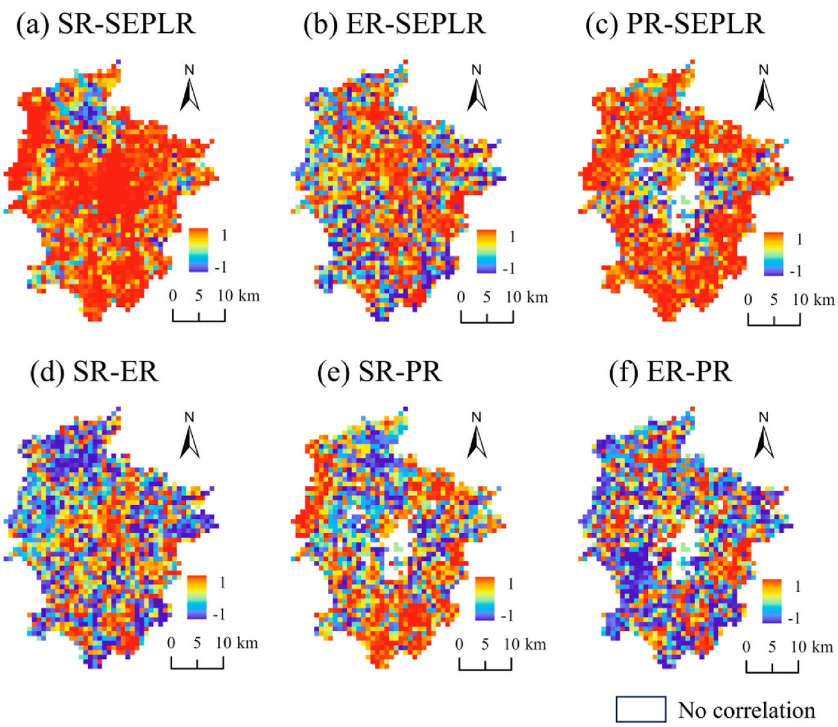

Fig. 9. Landscape resilience spatial trade-off and synergy.
Notes: SR, social resilience; ER, ecological resilience; PR, productive resilience; SEPLR, social-ecological productive resilience; (a), (b), (c) represent spatial trade-offs and synergy distributions for SR, ER, PR with SEPLR, respectively; (d), (e), (f) represent spatial trade-offs and synergy distributions between SR-ER, SR-PR and ER-PR, respectively.

pattern could be revealed more accurately based on the scale of grids, while the triangular model was used to identify the dominant areas of landscape pattern. Numerous studies have been established that rapid urbanization often leads to the encroachment of SL into other landscapes, thus enabling the expansion of urban land use area [62,63]. This study indicated that as the center of gravity of socio-economic development in Guiyang City, with rapid progress of urbanization, manifested clustered development of urbanization, which led to massive encroachment of SL into other landscape types. The SL continues to occupy more PL, leading to a number of ecological problems (habitat loss, landscape fragmentation and ecological function impairment within urban agglomerations) at CUAG [29,64]. Meanwhile, urban expansion also has a clear direction of center of gravity migration [43,65]. The CUAG had strong heterogeneity of landscape patterns. In recent years, there was rapid expansion of urbanization, and the SLAZ primarily distributed in the Yunyan, Nanming, and Guanshanhu district. The ELAZ was relatively uniformly distributed, which could be due to the wider mountainous distribution of CUAG, located in the karstic mountainous region, limiting the excessive encroachment of SL into the EL, and also limiting the development of the PL [36]. However, benefiting from a series of ecological restoration projects implemented by

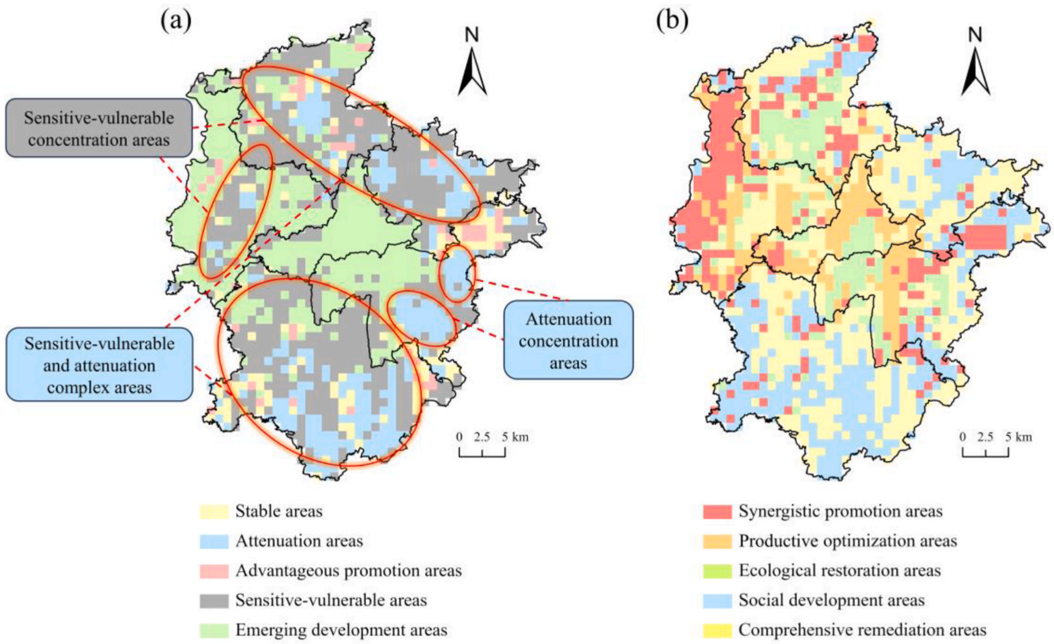

Fig. 10. Landscape management area extraction.
Notes: (a) Represents high and low values and trends in landscape resilience; (b) represents the regional distribution of extraction management for the three-dimensional magic cube model.

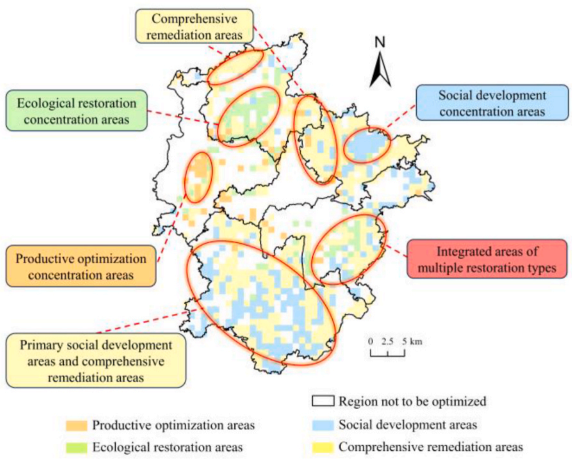

Fig. 11. Landscape management zones.

the Chinese government (rocky desertification control, GFGP, etc.), the area of EL has increased in recent years, which was mainly transferred from the PL to the EL [16]. The PLAZ rarely distributed in the Yunyan district, which was caused by that as the economic center of Guiyang City, the majority area was occupied by SL. Noteworthy was the dramatic decrease in the area of PL in recent years, mostly due to the GFGP policy of conversion to EL, and partly due to the encroachment of SL in the context of urban development.

Overall, the CUAG showed that rapid expansion of urbanization, ecological restoration measures in parallel, and a vigorous implementation of the GFGP in the last decade. This ultimately resulted in significant increases in SL, small increases in EL and significant decreases in PL, which was similar to previous studies [36,37,40]. As a result of the significant transfer out (SL encroachment) and in (PL transfer) of EL, there has been degradation of forestland and a decrease in the overall ecological quality of the CUAG [66,67].

4.2. Significant spatial and temporal heterogeneity in landscape resilience

Resilience can effectively evaluate the sustainability of different systems and has gradually become a research hotspot in the fields of landscape ecology, geography, and environmental sciences [1,34]. Evaluation and quantification of landscape resilience was still at an exploratory stage currently [10,68]. Based on the previous studies, this study constructs a more characteristic Karst region and more accurate evaluation system. In particular, the landscape fragmentation index, landscape connectivity index, rocky desertification intensity index, and fraction vegetation cover index could effectively reflect the vegetation lushness, habitat fragmentation, and fragile ecological background of karst mountain cities. Therefore, this study could more accurately reveal the spatial and temporal characteristics of the urban landscape resilience in karst mountainous regions [52–54].

The findings indicated that the CUAG had a significant increase in SR over the last decade, and there is a significant change in its spatial pattern. The high SR areas expanded to the west, which might be due to the shift in the center of development of Guiyang City in recent years, resulting in a yearly expansion of the high SR areas [69]. Urbanization encroachment on ecological lands tends to lead to reduced ecosystem resilience [66,67]. During the study period, the ER of CUAG showed a significant decrease followed by a small increase, which could be attributed to the destruction of ecosystems during urbanization, and then the ER improved due to the intense implementation of a series of ecological protection and restoration measures. Meanwhile, the GFGP had led to a significant reduction in the area of agricultural land and a significant reduction in the resilience of production systems [16,38,70,71]. The CUAG had been relatively stable in SEPLR recently, but the spatial pattern had changed significantly. Overall, CUAG had achieved an increase in urban SR at the expense of a small amount of ER and PR during the last decade of urbanization and development. In addition, the resilience of the different LAZ showed significant differences, with the PLAZ showing the strongest resilience, followed by the EPLCZ and SPLCZ. Therefore, we could conclude that excessive encroachment of social and ecological landscapes into productive landscapes generally resulted in landscape resilience being reduced. Spatial trade-offs and synergy analyzes showed the SR and SEPLR showed a synergistic relationship at large spatial scales, and part of the trade-off region might be caused by the encroachment of SL on PL ultimately leading to a significant reduction in PR [34]. Whereas the increase in ER essentially originated from return to forest, most of the decrease in ER is attributed to SL encroachment, and this complex and multifaceted combination of influences produces spatially complex trade-offs and synergistic correlations [5,31,32]. The PL had the largest impact on the PR, and the reduction of the PL was the direct reason for the reduction of the PR. Therefore, the PL showed a spatial synergistic effect with PR over a large area [70]. Some studies had shown that the development of social systems may negatively affect other systems, which is similar to the results in this study, where SR and ER were shown to be trade-off effects [20]. Meanwhile, productive systems and ecosystems had always been in a mutually reinforcing relationship, and human-induced conversion of forested land and reforestation activities are important causes of ecosystem health and production system stability [72]. In this study, a significant weak positive correlation was observed between ER and PR, which confirms the results of previous studies.

In summary, the CUAG has been in a multiple context of rapid urbanization and ecological conservation and restoration during the period 2010–2020. Under the influenced of multiple factors, the SEPLR had a complicated spatial-temporal variation. During this decade the SR improved significantly with the rapid progress of urbanization, and the EL area increased while the ER decreased slightly, which indicated a more fragile ecological environment in the CUAG and a decrease in habitat quality. The extremely large reduction in PL area led to a significant decrease in PR. The development of SEPLR should be carefully considered as a trade-off in the future urbanization process, and SR should be developed without sacrificing ER and ensuring basic PR.

4.3. Including landscape resilience in the landscape management zoning

Urban landscape resilience has been used as a transformational approach to urban planning to enhance the resilience of urban areas to external stresses and natural hazards in recent years (Giulia, 2023; Yamagata and Maruyama, 2016). Therefore, this study is based on the principle of multi-objectives, integrating social, ecological and production systems, and proposing landscape management zoning measures based on the spatial and temporal characteristics of landscape resilience and sub-systems resilience, so as to achieve the integration and coordination of multi-system development (Dai and Wang, 2023; Peng et al., 2019; Zhang et al., 2021).

Compared to similar studies, most of which manage areas based on the administrative district as a unit, grid-based landscape management would be able to identify the management areas more accurately, thus improve the landscape resilience and achieve the goal of sustainable landscape development. In this study, the landscape management zones were carried out for the attenuation areas and the sensitive-vulnerable areas in the sub-districts. Tridimensional magic cube model was divided the types of management into five subcategories: synergistic promotion zones, social development zones, production optimization zones, comprehensive remediation zones, and ecological restoration zones (Fig. 3) [34]. This study concluded that the 4 management zones of the CUAG accounted for 59. 68 % of the total area in the study area and were mainly distributed in the Baiyun, Huaxi, Nanming and Wudang districts (Fig. 12). Among them, the Huaxi and Wudang districts mainly took comprehensive remediation and social development. The Nanming and Baiyun districts dominated by comprehensive remediation, social development and ecological restoration, with production optimization as a supplement. The Guanshanhu district was the primary area for production optimization, and attention should be focused on farmland protection to protect the national bottom line of food production. The results of the management zones in the Yunyan district indicated that the region needs comprehensive remediation and ecological restoration and production optimization. Generally, the study indicated that karst mountain cities have a high resistance to development due to being in a fragile environmental background, which also leads to a high degree of regional landscape heterogeneity and a high degree of landscape fragmentation [73]. Therefore, it is also necessary to emphasize the rehabilitation of rocky desertification and biodiversity conservation, to adhere to the ecological red line and to rehabilitate degraded ecosystems [74]. Meanwhile, food security is an important

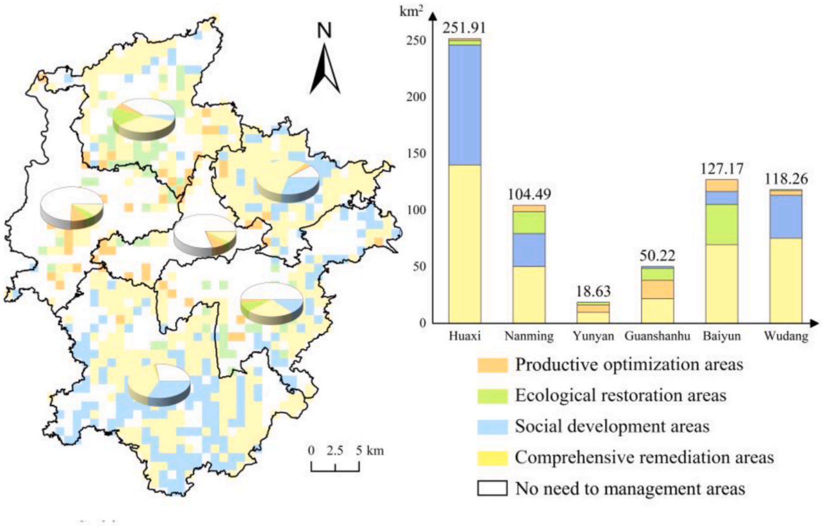

Fig. 12. Landscape management zones in different districts.

guarantee of national security, and attention should be paid to the protection of arable land to protect the bottom line of national food production [75–77].

To manage the landscape based on SEPLR spatial-temporal dynamics of CUAG in this study. However, in actual urban development planning, urban construction was normally organized in more distinct functional regions. Meanwhile, enhancing the resilience of different subsystems could also lead to conflicting situations, where measures to enhance the resilience of one subsystem may adversely affect another subsystem [22,78]. For future urbanization, the balance between the economic benefits of agriculture and the ecological and environmental effects should be considered fully. Areas with low ER values on the urban fringe could be regraded into PL, and enhanced ecological protection projects in areas with high ER values could help to increase landscape connectivity and guarantee national food security [77]. Meanwhile, it was needed to combine more urban development plans and functional areas to choose the best landscape management scheme.

4.4. Limitations and future work

The evaluation of SEPLR is still in the development stage at present, and the evaluation in different areas should be chosen as a more suitable indicator for the study area [10,34,68]. Meanwhile socio-economic data with high spatial and temporal resolution can more accurately identify the dynamic characteristics of SEPLR. In this study although the data were sufficient, data inaccessibility, uncertainty, and low spatial resolution remained a limiting factor in exploring SEPLR. Meanwhile, the consideration of productive landscapes only for agricultural production could be inapplicable in different regions. In addition, more indicators should be considered in future studies to reveal the mechanism of urban SEPLR changes more precisely, and to explore the trade-offs and synergistic mechanisms among different subsystems in a deeper way. However, for the uncertainty and diversity of influences on the sustainability of urban landscapes, this study does not dissect the specific driving mechanisms [10,68]. While explore what landscape configurations and landscape patterns in urban development can lead to higher landscape resilience. In future studies, urban development planning should be considered in conjunction with the results of the SEPLR distribution study, so as to achieve sustainable development of urban landscapes. Notably, in the context of the construction of national ecological civilization and the rapid progress of urbanization, how to combine the complex relationship of social-ecological productive landscape intertransformation, the trade-offs and synergies between SR, ER, and PR, to formulate a reasonable response for the landscape pattern configuration and the optimization of the distribution of spatial pattern in order to achieve the goal of the sustainable development of the urban landscape needs to be further explored [23,79].

5. Conclusion

We concluded that the EL was the predominant landscape type in the CUAG, meanwhile the landscape pattern had changed significantly, with significant urbanization trends. The massive encroachment of SL and EL into PL has led to a significant reduction in the area of PL. The SEPLR of CUAG declined slightly, over the past decade, with reduction of only 0.75 %, which This is reflected in a significant increase in SR, a small decrease in ER and a significant decrease in PR. The high-value areas of different systems resilience are distributed in the landscape dominance areas of this category. Among the different landscape types, only PL have a promoting effect on SEPLR. The results of landscape management zones based on landscape resilience indicate that comprehensive remediation, and social development needs are high priority in the future landscape. The finding could provide scientific guidance for coordinating regional economic development, ecological restoration, and farmland protection in areas with fragile ecosystems, promoting sustainable landscape development, and having a guiding significance for the future urban development in karst mountainous cities or similar mountainous regions.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Chao Wu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuan Su:** Supervision, Project administration, Funding acquisition. **Zhijie Wang:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

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.

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