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Spatial and Temporal Evolutionary Characteristics of Landscape Pattern of a Typical Karst Watershed based on GEE Platform

WEI Qingqing[1], HE Wen[1,2,*], WANG Jinye[1,3], ZHOU Xinran[1], YAO Yuefeng[2]

1. School of Tourism and Landscape Architecture, Guilin University of Technology, Guilin, Guangxi 541006, China;
2. Guangxi Key Laboratory of Plant Conservation and Restoration Ecology in Karst Terrain, Guangxi Institute of Botany, Guangxi Zhuang Autonomous Region and Chinese Academy of Sciences, Guilin, Guangxi 541006, China;
3. Nanning Institute of Technology, Nanning 530000, China

Abstract: Given the high degree of fragmentation and poor resistance to disturbance in karst landscapes, it is important to clarify the spatial and temporal dynamics of landscape patterns in karst areas when designing karst ecological protection strategies. Using the Li River Basin as the study area, the spatial distribution and dynamic evolution of landscape patterns in the basin were analyzed at the levels of landscape utilization, landscape type dynamics and landscape pattern indices based on the Landsat series images for 2000 to 2020 obtained from the GEE platform as the data source. The results show three important aspects of this typical karst watershed. (1) There are large differences in landscape structure and landscape type trends between the karst and non-karst areas in the Li River Basin. (2) The comprehensive landscape type dynamic attitude of the Li River Basin is 0.22%, and the composite index of landscape type use varies from 239.49 to 244.88. The degree of landscape use is higher in karst areas than in non-karst areas, and the rate of landscape change in karst areas is more intense. The integrated index of landscape use in karst areas ranges from 262.32 to 270.50, and in non-karst areas it spans 225.28 to 227.01. The integrated landscape type motility in the karst areas is 0.31%, which is about twice as high as that in non-karst areas. (3) The overall landscape evolution of the Li River Basin shows trends of increasing fragmentation, decreasing connectivity, decreasing dominance and increasing heterogeneity, and these trends are particularly prominent in the karst areas. The results of this study can provide a scientific basis for realizing the construction goals of the National Sustainable Development Innovation Demonstration Zone in Guilin, and a technical reference for the ecological environmental management of the karst watershed.

Key words: degree of landscape use; landscape pattern index; landscape type dynamic attitude; karst landscape; Li River Basin

1 Introduction

Karst areas have fragile ecological environments (Li et al., 2002), serious ecological problems such as rock desertification and soil erosion, and weak resistance to disturbances. With the accelerated industrialization and urbanization in the 21st century, human activities that disturb ecological processes have increased (Zhao et al., 2018), and the accumulated disturbances act directly on the structures and compositions of ecosystems (Zeng and Liu, 1999), leading to even greater ecological and environmental problems (Xi

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First author: WEI Qingqing, E-mail: 1220236805@qq.com
***Corresponding author:** HE Wen, E-mail: hw@gxib.cn

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et al., 2019). Studies of landscape pattern evolution can indicate the environmental context, reveal the ecological processes, and reflect the type and level of ecological services, so they provide an important way to evaluate ecological and environmental effects (Costanza et al., 2017). When changes in landscape patterns occur, they are often accompanied by changes in the structure and function of the regional ecosystems, and the ecological and environmental effects triggered by them often have a certain lag (Han et al., 2017). Therefore, understanding environmental changes in karst regions through landscape pattern evolution not only provides feasible directions for their ecological risk assessment and prediction, but it also has important implications for ecological environmental protection in karst regions that are undergoing rapid economic development.

The quantitative study of landscape patterns began in the late 1970s, thanks to the development of remote sensing image technology, and the research in that period focused on the use of remote sensing images to extract information on landscape patterns in different time periods and to carry out dynamic change analysis (Nagaike and Kamitani, 1999; Zhou, 2000). At the end of the 20th century, with the continuous in-depth research and deepening of our understanding, researchers began to conduct more comprehensive and detailed studies on the various elements of landscape pattern changes and their influencing factors (Burgi et al., 2004). Based on landscape feature indices, with the help of landscape pattern assessment, driving and prediction models (Sun and Yan, 2014; Zhang et al., 2020), the transfer of elements within the landscape, the degree of change, and the rate of change have been explored in depth. For example, Huang et al. analyzed the spatial pattern characteristics of the wetland landscape in the Yalong River basin and its changes (Huang et al., 2012), while Song et al. studied the trends, areas, and rates of change, as well as the specific transformation types, in the middle reaches of the Shiyang River basin landscape types (Song et al., 2010). At present, the use of remote sensing image data to analyze changes in landscape patterns is quite common, and most of the existing studies are based on the use of RS and GIS platforms to obtain landscape classification results. After half a century of development, the GEE (Google Earth Engine) cloud platform (Dong et al., 2016; Gorelick et al., 2017) has emerged. It is based on cloud computing, the Internet of Things, big data and artificial intelligence technologies to process remote sensing data, and the platform's built-in Image Collection(), filterDate(), map(), median() and other algorithms can quickly and efficiently integrate and process massive amounts of remote sensing information data within a certain time period. The built-in cloud processing module of satellite series data such as Landsat, MODIS and Sentinel is especially powerful, which is a great help in the cloudy and foggy weather conditions in southern China. In the remote sensing application research of large scale and long time series (Wu et al., 2023), GEE is gradually becoming a new tool for the dynamic analysis of landscape patterns.

Based on the GEE platform, this study extracted information on the landscape pattern of the Li River Basin and analyzed the relationships between the temporal changes of the landscape pattern and the ecological environmental changes. Currently, there are many studies on the spatial and temporal dynamics of landscape patterns at the watershed scale, but as the most typical karst landscape river in the world, the Li River has special topographic and geomorphological conditions that make its landscape pattern evolution very different from other regions. In particular, the rapid economic development of the Li River Basin since 2000, including tourism development, infrastructure construction and reforestation, have all had an impact on the landscape pattern of the region. An accurate and objective description of the changes in the landscape pattern of the region, and their relationship with economic and social development, are important scientific issues that need to be addressed for the sustainable development of the Li River Basin and Guilin City. Therefore, exploring the spatial and temporal evolutionary characteristics of landscape patterns in the karst and non-karst areas of the Li River Basin will not only provide technical guidance and a basis for ecological environmental protection and management decision-making in the basin, but it will also provide a reference for the management of similar basin ecosystems.

2 Study area and data sources

2.1 Study area

The Li River Basin (geographical coordinates 24°38'–25°56'N, 110°05'–110°44'E) is located in the northeast of Guangxi, within the territory of Guilin. It belongs to the Pearl River system, originating from the Cat's Hill in Huajiang Township, Xing'an County, with an overall long strip flowing from north to south, with a total length of about 214 km and a total basin area of more than 5800 km^2 (Fig. 1). The climate is characterized by a subtropical monsoon climate, with long summers and short winters, abundant rainfall, high light and heat intensities, an average annual temperature of 19.3 ℃ and an annual rainfall of 1838 to 1942 mm. The high mountains are mainly located in the north, east and west of the basin, bordered by the Yuecheng Ridge in the north and the Ocean Mountain in the east; while the central part of the mountain is relatively flat, showing a topographic distribution that is high around the edges and low in the middle. The Li River Basin karst landform covers about 2393.65 km^2, accounting for 41% of the whole basin area. It is an important element of the Guilin karst and one of the most representative karst landforms in the world.

2.2 Data sources and processing

All of the remote sensing data used in this study were called

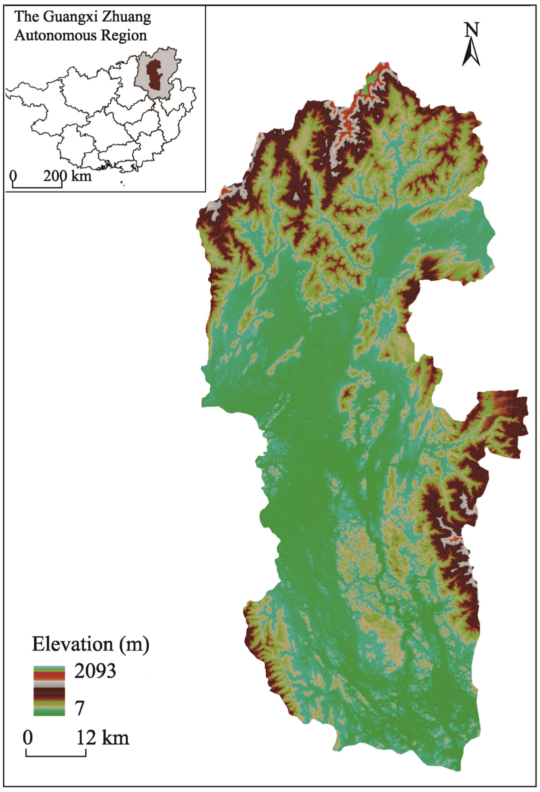

Fig. 1 Map of the Li River Basin location and topography

and processed online by the GEE platform, including Landsat-5, Landsat-8 surface reflectance data and SRTM digital elevation data. Based on the GEE platform, the filterDate() and filterBounds() functions were used to filter all the Landsat 5/8 images within the study area and within the target time period (2000 to 2020). Landsat 5/8 images (41 views in 2000, 35 views in 2005, 37 views in 2010, 34 views in 2015, and 45 views in 2020) were filtered using the GEE platform, and the median values of all images filtered in each year were combined according to the QA (quality assessment) band of the Landsat series to remove cloud effects; and these were then stitched together to form the complete study area data. The digital elevation model was selected from SRTM with a spatial resolution of 30 m, and the elevation and slope were extracted using the ee.Algorithms.Terrain() function.

3 Research methods

3.1 Landscape type extraction based on the GEE platform

3.1.1 Landscape type extraction process

According to the basic process shown in Fig. 2, with the support of the GEE platform, the required remote sensing image data information was collected using the ee.ImageCollection() function, and after declouding, the sample points were selected by combining the high-definition images provided by GEE and the expert's a priori knowledge. Then the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Normalized Building Index (NDBI) were selected for calculating the relevant vegetation indices from the collected remote sensing images, while the digital elevation model data were collected and slope conversion was carried out. After that step, the images, vegetation indices and elevation information were combined into a composite multi-band remote sensing dataset; then the sampleRegions() function was applied to extract the multi-band remote sensing information into the sample points, and the sample points were allocated in the ratio of 7:3, with 70% being used for model training and 30% for model validation. Finally, the modeling was carried out based on the random forest algorithm, and the Overall Accuracy (OA) and Kappa coefficient were used for accuracy validation. Larger values of the OA and Kappa coefficients indicate greater accuracy; and if the accuracy verification meets the requirements, the classification results are output, but if not, the sample points are reselected.

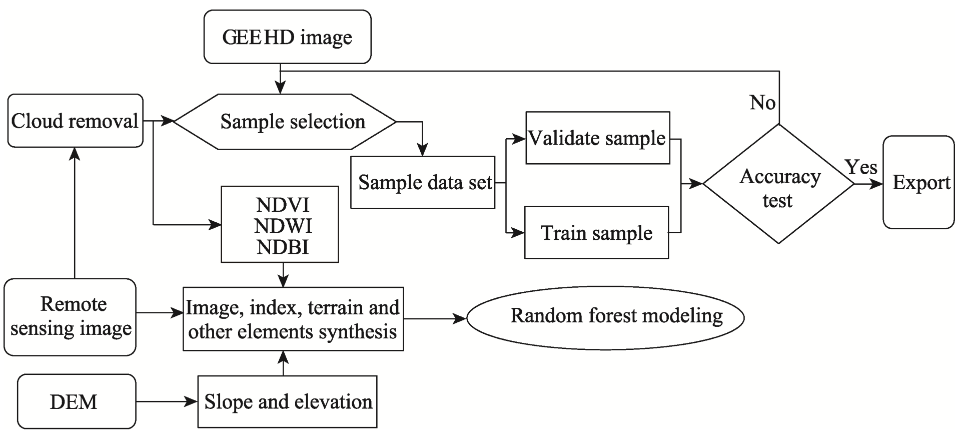

Fig. 2 Flow chart of landscape pattern extraction based on the GEE platform

3.1.2 Landscape types and accuracy

Based on the GEE platform, the random forest algorithm was used to extract landscape type information from 2000 to 2020 in the Li River Basin based on the classification standards of existing studies as well as experts' a priori knowledge. The main landscape types were forest land, cropland, grassland, waters and construction land, as shown in Fig. 3. The Overall Accuracy of the extraction of landscape types for each year was above 0.94, and the Kappa coefficients were above 0.92 (Table 1). The classification accuracy was significantly higher than that of Qiao et al. for the extraction of vegetation information of the East Dongting Lake wetlands (OA: 87.69%) (Qiao et al., 2013), and similar to that of Chen et al. for the classification of surface cover in Hunan Province using GEE (OA: 95%–96%) (Chen et al., 2021). Therefore, the accuracy of landscape type classification based on the GEE platform is high and suitable for analyzing changes in the landscape patterns in the study area from 2000 to 2020.

Table 1 Accuracy of landscape patch classification results

Indicators	2000	2005	2010	2015	2020
OA (%)	96.36	97.81	94.48	94.07	96.35
Kappa	0.95	0.97	0.93	0.92	0.95

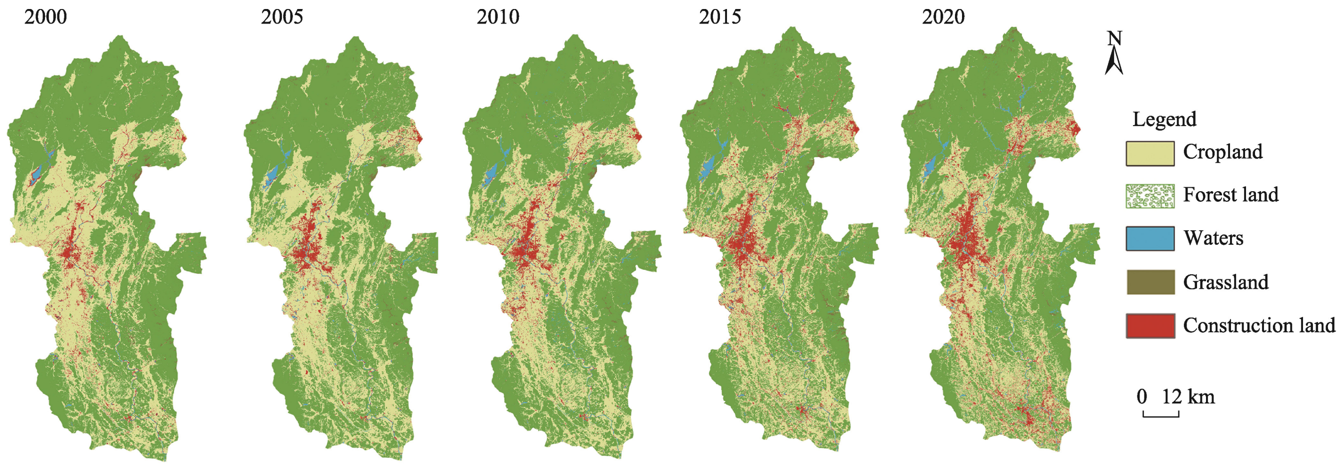

Fig. 3 Distribution of landscape types in the Li River Basin

3.2 Landscape pattern characterization

3.2.1 Extent of use of the landscape types

The degree of landscape type use is a composite expression of the strength of human activities in disturbing the natural landscape (Han et al., 2006). In this study, a composite index of landscape type use (L_j), i is the landscape type, $i \in j$, the index of the amount of change in the degree of landscape use (L_{b-a}) and the rate of change index (R) were characterized by the expressions:

$$L_j = 100 \times \sum_{i=1}^{n} A_i \times C_i \quad (1)$$

$$L_{b-a} = L_b - L_a = 100 \times \left[\sum_{i=1}^{n} (A_i \times C_{ib}) - \sum_{i=1}^{n} (A_i \times C_{ia}) \right] \quad (2)$$

$$R = \frac{\sum_{i=1}^{n} (A_i \times C_{ib}) - \sum_{i=1}^{n} (A_i \times C_{ia})}{\sum_{i=1}^{n} (A_i \times C_{ia})} \quad (3)$$

where L_j is the composite index of the j regional landscape type use, L_{b-a} is an index of the amount of change in landscape use, R is the index of the rate of change in the extent of landscape use, and A_i is the graded index of the i landscape types, with the gradated index referring to the studies of Liu and Li (Liu, 1992; Li et al., 2011). C_i is the percentage area of the i graded landscape type, n is the number of landscape type gradations, L_b, L_a are the composite indices of the landscape type utilization in periods b and a, respectively, and C_{ia}, C_{ib} are the percentage areas of the i graded landscape type extent in period b and period a, respectively. When $L_{b-a} > 0$ or R>0, the area is increasing in the degree of use of the landscape patches; otherwise, it is decreasing.

3.2.2 Rate of change in the landscape types

The rate of landscape type change is expressed in terms of single landscape type dynamics (S_{single}) and combined landscape type dynamics (S_{total}) (Zhu et al., 2001), based on the expressions:

$$S_{single} = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (4)$$

$$S_{total} = \frac{\sum_{i=1}^{n} \Delta LU_i}{2\sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\% \quad (5)$$

where U_b, U_a are the numbers of a landscape types at the end and beginning of the study, respectively, and T is the length of the study. LU_i is the area of the i landscape type at the beginning of the study, and ΔLU_i is the absolute value of the area transferred out at the end of the study for the i landscape type.

3.2.3 Landscape pattern indices

The selection of landscape pattern indices can effectively identify and summarize the landscape spatial pattern information and express its structural distribution characteristics (Wu et al., 2021a). In this study, according to the principles of landscape pattern index selection, four landscape pattern indices were used to analyze the landscape spatial pattern of the Li River Basin from the landscape level, including Patch Density index (*PD*), Area-weighted mean patch Fractal dimension index (*FRAC_AM*), Contagion index (*CONTAG*) and Shannon's Diversity index (*SHDI*) (Zhang et al., 2020; Wu et al., 2021b). Each landscape index was calculated using Fragstats 4.2 software.

$$PD_j = \sum_{i=1}^{n} \frac{n_i}{A} \times 10^6 \tag{6}$$

$$FRAC\_AM_j = \sum_{i=1}^{n} \left\{ \frac{2\ln 0.25 \times P_{ij}}{\ln a_{ij}} \times \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right\} \tag{7}$$

$$CONTAG_j = \left\{ 1 + \frac{\sum_{i=1}^{n}\sum_{k=1}^{n} P_i \times \frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}} \times \ln P_i \times \frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}}}{2\ln n} \right\} \times 100 \tag{8}$$

$$SHDI_j = -\sum_{i=1}^{n} P_i \times \ln P_i \tag{9}$$

where n_i denotes the number of patches in the i landscape type, A denotes the total landscape area, P_{ij} denotes the perimeter of the j patch in the i type landscape, a_{ij} denotes the area of the j patch in the i type landscape, P_i denotes the proportion of the area occupied by i land, g_{ik} denotes the number of connected pixels between the landscape types i and k, and m is the total number of landscape types.

PD, the number of patches per unit area, is used to measure the degree of fragmentation of the landscape; and the higher the value, the greater the fragmentation of the landscape and the lower the degree of landscape security. *FRAC_AM* is used to characterize the complexity of the landscape patch shape, and takes a value ranging from 1 to 2; and the smaller the value, the simpler the shape, while the larger the value, the more complex the shape. In most cases, landscapes with a high intensity of human interference have more complex shapes. *CONTAG* indicates the degree of aggregation or extension of the landscape type, and its value ranges from 0 to 100. A small value indicates the existence of many small patches and a high degree of landscape fragmentation, while a larger value indicates that there are dominant patches with a high degree of connectivity in the landscape. For *SHDI*, the higher the value, the richer the landscape patches and the more resistant the ecosystem is to disturbance.

4 Results and analysis

4.1 Analysis of dynamic changes in landscape types

4.1.1 Analysis of changes in the number of landscape types

According to Fig. 3, forest land and arable land are the main landscape types of the Li River Basin, with the area of arable and forest land accounting for over 90% of the basin. Forest land is mainly distributed in the northern and eastern parts of the basin, while arable land is mainly distributed in the low hill areas in the western part of the basin. The grassland area is relatively small and mainly scattered in the northern part of the basin, while construction land is mainly distributed in the middle and western parts of the basin. According to Table 2, the areas of arable land, forest land and grassland in the Li River Basin show decreasing trends from 2000 to 2020, while the areas of water and construction land show increasing trends. Arable land decreased by a total of 136.37 km^2, of which the decrease from 2000 to 2010 was 136.69 km^2, and the arable land remained basically the same from 2010 to 2020. Forest land decreased by a total of 105.82 km^2, of which the increase was obvious from 2000 to 2010, with a total increase of 33.40 km^2, but a decrease was obvious from 2010 to 2020, with a total decrease of 139.22 km^2. Grassland decreased by a total of 11.90 km^2, with a slight increase of 3.87 km^2 from 2000 to 2010. The areas of water and construction land showed continuous increases, with a rapid increase in water from 2000 to 2010 and a rapid increase in construction land from 2010 to 2020. The latter represented a total increase of 146.48 km^2, which exceeded the amount of construction land in 2000. The continuous expansion of construction land is associated with the decrease in arable land, and there is encroachment on arable land.

4.1.2 Landscape type transfer analysis

Table 3 shows the transfer matrix of each landscape type in the Li River Basin from 2000 to 2020.The areas of arable land, forest land, water, construction land, and grassland transferred out from 2000 to 2020 accounted for 10.37%, 7.88%, 0.06%, 1.2%, and 0.60% of the total area of the Li River Basin, respectively, total 1171.22 km^2. Of that area, the transfers of arable land and forest land were the largest, with the area of cropland converted to forest land accounting for 5.61% of the total area of the watershed, and the area of forest land converted to cropland accounting for 7.00% of the total area of the watershed, and frequent interconversions between cropland and forest land. The increase in water area mainly came from forest land, cultivated land and

Table 2 Areas of the landscape types in the Li River Basin (Unit: km^2)

Year or period	Arable land	Forest land	Grassland	Waters	Construction land
2000	2077.50	3538.65	43.24	36.17	130.56
2005	2018.68	3548.55	52.09	65.69	141.10
2010	1940.81	3572.05	47.11	75.86	190.29
2015	1888.79	3552.75	45.27	77.24	262.06
2020	1941.13	3432.83	31.34	84.05	336.77
2000–2010	–136.69	33.40	3.87	39.69	59.73
2010–2020	0.32	–139.22	–15.77	8.19	146.48
2000–2020	–136.37	–105.82	–11.90	47.88	206.21

Table 3 Transfer matrix of each landscape type in the Li River Basin from 2000 to 2020 (Unit: %)

2020	2000						
	Arable land	Forest land	Waters	Construction land	Grassland	Total	Total transfers in
Arable land	25.28	7.00	0.02	0.78	0.23	33.31	8.02
Forest land	5.61	52.86	0.20	0.06	0.36	58.92	6.07
Waters	0.26	0.26	0.56	0.36	0.00	1.44	0.88
Construction land	4.49	0.24	0.01	1.05	0.00	5.79	4.74
Grassland	0.01	0.38	0.00	0.00	0.15	0.54	0.40
Total	36.65	60.72	0.62	2.25	0.78	100.00	
Total transfers out	10.37	7.88	0.06	1.20	0.60		20.11

construction land, accounting for 0.26%, 0.26% and 0.36% of the total watershed area, respectively. The expansion of construction land was mainly converted from cropland, with the area of cropland converted to construction land accounting for 4.49% of the total area of the watershed. The increased area of grassland mainly came from forest land, accounting for 0.38% of the total area of the watershed.

4.1.3 Extent and rate of change in each landscape type

The results of the rate of change calculations for landscape types in different periods in the Li River Basin are shown in Table 4. There are obvious temporal and spatial differences in the combined landscape type dynamic attitudes of the four periods in the Li River Basin. The data show an S_{total} of 0.22% from 2000 to 2020 with the most drastic change in landscape type from 2015 to 2020, which has an S_{total} of 0.46%, or more than twice the 0.21% from 2000 to 2005. In terms of single landscape type dynamics, the most drastic changes in landscape types in the Li River Basin from 2000 to 2020 were in construction land and water, with dynamics of 3.06% and 2.85% respectively; followed by grassland with –1.9%, and relatively stable changes in cultivated land and forest land, with dynamics of –0.35% and –0.15% respectively. The changes in each landscape type varied significantly in different stages, with construction land changing at a positive rate of greater than 5% after 2005 due to the accelerated urbanization. Changes in water areas fluctuated, with the most dramatic change from 2000 to 2005, when S_{single} reached 16.9%, and a significant drop from 2010 to 2015, when S_{single} was only 0.36%. The changes in arable land and forest land were not very volatile, with S_{single} remaining below 0.8%. The change in grassland fluctuated more, with a positive change at a rate of 4.09% from 2000 to 2005 and negative growth after 2005, and the greatest rate of decline was an S_{single} of 6.15% from 2015 to 2020.

4.1.4 Analysis of the extent of landscape use

The data in Table 5 show that the range of the combined index of landscape type use in the Li River Basin for the five years is 239.49 to 244.88, which is higher than that of the northern Black River Basin (2005, 197.76) (Li et al., 2011) but similar to the combined index of landscape type use in the whole Guangdong Province (2005, 235.78) (Wu et al., 2012), so the degree of land use in the Li River Basin is generally high. According to the amount of change in landscape use (L_{b-a}) and the rate of change (R), both L_{b-a} and R in the Li River Basin were negative from 2000 to 2005, and the degree of landscape use decreased. The L_{b-a} and R for 2005 to 2010, 2010 to 2015, and 2015 to 2020 were positive with increasing values, especially the index increase from 2015 to 2020 which reached 3.46, indicating the deepening of land use in the Li River Basin.

Table 4 The rates of change landscape patch types in the Li River Basin (Unit: %)

Time period	2000–2005	2005–2010	2010–2015	2015–2020	2000–2020
Arable land	–0.59	–0.77	–0.54	0.55	–0.35
Forest land	0.06	0.13	–0.11	–0.68	–0.15
Grassland	4.09	–1.91	–0.78	–6.15	–1.90
Water area	16.46	3.09	0.36	1.76	2.85
Construction land	1.98	6.97	7.54	5.70	3.06
Integrated landscape type dynamic attitude (S_{total})	0.21	0.28	0.25	0.46	0.22

Table 5 Landscape type utilization degree in the Li River Basin

Year	2000	2005	2010	2015	2020
Composite index of landscape type use (L_j)	240.14	239.49	239.84	241.42	244.88
Time period	2000–2005	2005–2010	2010–2015	2015–2020	2000–2020
Amount of change in landscape use (L_{b-a})	–0.65	0.35	1.58	3.46	4.74
Rate of change in landscape use (R)	–0.003	0.001	0.007	0.014	0.020

4.2 Analysis of the changing spatial pattern of the landscape

Four major landscape pattern indices were selected at the landscape level to analyze the characteristics of landscape spatial pattern changes in the Li River Basin (Table 6). From 2000 to 2020, the landscape Patch density index (*PD*) increased from 8.77 in 2000 to 12.63 in 2020, an increase of 43.94% and a significant increase, indicating that the degree of landscape fragmentation in the Li River Basin had increased rapidly with the continuing rapid economic development. The area-weighted mean patch fractal dimension (*FRAC_AM*) did not change significantly, but it shows a generally increasing trend, indicating that the Li River Basin landscape was subjected to increased anthropogenic action and the landscape shape was becoming increasingly complex during the study period. The Contagion index (*CONTAG*) shows a decreasing trend, indicating that the number of small patches in the Li River Basin was increasing and the landscape connectivity was becoming less connected. The Shannon's Diversity Index (*SHDI*) continues to increase, indicating that the landscape types were gradually becoming more complex, heterogeneous and diverse as tourism development in the Li River Basin increased. In summary, the Li River Basin landscape has been in a process of transformation from 2000–2020, with overall trends of increasing fragmentation, decreasing connectivity, decreasing dominance and increasing heterogeneity, all of which indicate a risk of declining ecological safety in the Li River Basin.

Table 6 Landscape pattern indices in the Li River Basin

Year	*PD* (pcs km^{-2})	*FRAC_AM*	*CONTAG* (%)	*SHDI*
2000	8.77	1.32	66.23	0.82
2005	11.11	1.32	63.90	0.85
2010	10.19	1.32	63.34	0.87
2015	11.42	1.32	61.46	0.90
2020	12.63	1.33	59.85	0.93

4.3 Karst landscape features and variation

4.3.1 Karst landscape structure and quantitative differences

The karst landscape of the Li River Basin is prominent, and it accounts for 41% of the total area of the study area. The data in Table 7 show that most of the arable land in the study area is distributed in the karst areas, and the area of arable land in karst areas is about twice that in non-karst areas. The arable land in karst and non-karst areas during the study period accounted for about 21.77% to 23.49% and 10.65% to 12.30% of the total area of the basin, respectively. Forest land was mainly found in non-karst areas, representing three times as much as the Forest land in karst areas. The forest land in non-karst and non-karst areas accounted for 43.65% to 45.00% and 15.28% to 16.52% of the total watershed area respectively. Grassland and water areas were mainly located in the non-karst areas. The sizes of construction land in the karst and non-karst areas were relatively close from 2000 to 2015, but the gap widened in 2020, when the area of arable land in karst areas was 202.24 km^2 and that in non-karst areas was 134.53 km^2.

4.3.2 Differences in the degrees and rates of change in the karst landscapes

The range of the integrated index values of landscape use in karst areas from 2000 to 2020 was 262.32 to 270.50 (Table 8), and the corresponding range in non-karst areas was 225.28 to 227.01, with a significantly higher degree of landscape use in the karst areas of the Li River Basin. According to the rate of change of landscape use (R), all the R values in karst areas are positive, indicating that the degree of landscape use in karst areas has deepened year by year, while the R values in non-karst areas are negative from 2000 to

Table 7 Quantitative characteristics of the different geographical types

Type of landform	Year	Arable land		Forest land		Grassland		Water area		Construction land	
		Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)
Karst landscapes	2000	1361.06	23.36	945.64	16.23	14.44	0.25	7.13	0.12	65.38	1.12
	2005	1368.43	23.49	930.26	15.97	7.54	0.13	18.05	0.31	69.39	1.19
	2010	1316.53	22.60	950.56	16.32	5.87	0.10	23.62	0.41	97.08	1.67
	2015	1268.59	21.77	962.65	16.52	0.42	0.01	23.66	0.41	138.34	2.37
	2020	1283.11	22.02	889.98	15.28	1.59	0.03	16.74	0.29	202.24	3.47
Non-karst landscapes	2000	716.44	12.30	2593.00	44.51	28.80	0.49	29.04	0.50	65.17	1.12
	2005	650.25	11.16	2618.29	44.94	44.56	0.76	47.65	0.82	71.71	1.23
	2010	624.27	10.72	2621.48	45.00	41.25	0.71	52.24	0.90	93.21	1.60
	2015	620.21	10.65	2590.10	44.46	44.85	0.77	53.58	0.92	123.72	2.12
	2020	658.02	11.29	2542.85	43.65	29.74	0.51	67.31	1.16	134.53	2.31

2005, but then turn positive, indicating that the degree of landscape use in non-karst landscapes shows a trend of first decreasing and then increasing. In addition, from the amount of change in landscape use (L_{b-a}), the increase in L_{b-a} in karst areas is larger, while the increase in L_{b-a} in non-karst areas is smaller. This difference was especially notable from 2015 to 2020, when the L_{b-a} in karst areas reached 5.95, but it was only 1.73 in non-karst areas, indicating that the degree of landscape use in karst areas in the Li River Basin is not only higher than that in non-karst areas, but also the index increases significantly; which indicates that the influence of human activities on the karst areas of the Li River Basin has been increasing in recent years.

The integrated landscape dynamics of karst areas (S_{total}) has been growing year by year (Table 9). It showed the slowest change from 2000 to 2005, with an S_{total} of 0.31%, and the fastest change from 2015 to 2020, with an S_{total} of 0.67%. Meanwhile, the integrated landscape dynamics of non-karst areas shows a trend of fast, then slow and then fast changes, which included the fastest change from 2000 to 2005, with an S_{total} of 0.39%, and the slowest change from 2005 to 2010, with an S_{total} of 0.17%. Although the rates of landscape change differ between karst and non-karst areas at different time periods, the rate of landscape change in karst areas is generally faster than in non-karst areas. In terms of the rates of change of the individual landscape types, forest land and arable land in both karst and non-karst areas showed negative growth from 2000 to 2020, with differences in the rates of negative growth and significant differences in different stages. Grassland showed negative growth in karst areas, with a kinetic attitude of –40.3% and a large negative variation, but positive growth in non-karst areas, with a kinetic attitude of 0.16% and large variations in different stages. Water areas showed positive growth at rates of around 3% in both karst and non-karst areas, while the rate of change not only varied significantly but also fluctuated greatly from stage to stage. The kinetic attitude values of building land were 1.22%, 7.98%, 8.50% and 9.24% in the four stages in the karst areas and 2.01%, 6.00%, 6.55% and 1.75% in the non-karst areas. Clearly, the rate of change of construction land in karst areas continued to increase gradually, and by 2020 it far exceeded that of non-karst areas.

4.3.3 Differences in the spatial patterns of changes in karst landscapes

From 2000 to 2020, the *PD* index was clearly higher in karst areas than in non-karst areas (Table 10), indicating that karst landscapes are more prone to fragmentation than non-karst areas. Comparing the *FRAC_AM* indices of the two landscapes, the *FRAC_AM* index values are slightly higher in karst areas, indicating that karst landscapes are more susceptible to anthropogenic disturbance, resulting in greater complexity in the shapes of the landscape patches. Similarly, the *SHDI* Index is higher in karst areas compared to non-karst landscapes, indicating that the landscape patches are more heterogeneous and the dominant patches decline more rapidly in karst areas. The *CONTAG* index values of karst landscape areas are lower than non-karst areas, indicating that landscape patches in karst areas are less connected. Therefore, the comparison of these four landscape pattern indices shows that compared with non-karst areas, the landscape patches in karst areas are more fragmented, more complex in shape and less connected; resulting in a significant increase in the uncertainty faced by the entire ecosystem and a decrease in its ability to withstand risks.

5 Discussion

The land-use types in the study area during each of the five phases were dominated by arable land and forest land, which covered more than 90% of the entire watershed. From 2000 to 2020, arable land, forest land and grassland showed

Table 8 The degrees of landscape utilization in different geographical types

Type of landform	Year	Composite index of landscape type use (L_j)	Time period	Amount of change in landscape use (L_{b-a})	Rate of change in landscape use (R)
Karst landscapes	2000	262.32	2000 to 2005	0.65	0.002
	2005	262.97	2005 to 2010	0.14	0.001
	2010	263.11	2010 to 2015	1.45	0.005
	2015	264.56	2015 to 2020	5.94	0.022
	2020	270.50	2000 to 2020	8.18	0.031
Non-karst landscapes	2000	224.67	2000 to 2005	–1.55	–0.007
	2005	223.12	2005 to 2010	0.50	0.002
	2010	223.62	2010 to 2015	1.66	0.007
	2015	225.28	2015 to 2020	1.73	0.008
	2020	227.01	2000 to 2020	2.34	0.010

Table 9 The rates of change of landscape patch types in different geographical types (unit: %)

Type of landform	Speed of change	2000 to 2005	2005 to 2010	2010 to 2015	2015 to 2020	2000 to 2020
Karst landscapes	Arable land	0.11	–0.76	–0.73	0.23	–0.30
	Forest land	–0.33	0.44	0.25	–1.51	–0.31
	Grassland	–9.56	–4.43	–18.56	55.74	–40.30
	Water area	30.63	6.17	0.04	–5.85	2.87
	Construction land	1.22	7.98	8.50	9.24	3.38
	Integrated landscape type dynamic attitude (S_{total})	0.19	0.45	0.45	0.67	0.31
Non-karst landscapes	Arable land	–1.85	–0.80	–0.13	1.22	–0.44
	Forest land	0.20	0.02	–0.24	–0.36	–0.10
	Grassland	10.94	–1.49	1.74	–6.74	0.16
	Water area	12.81	1.93	0.51	5.13	2.84
	Construction land	2.01	6.00	6.55	1.75	2.58
	Integrated landscape type dynamic attitude (S_{total})	0.39	0.17	0.21	0.36	0.16

Table 10 Landscape pattern index values of the different geographical types in the Li River Basin

Type of landform	Year	*PD* (pcs km^{-2})	*FRAC_AM*	*CONTAG* (%)	*SHDI*
Karst landscapes	2000	12.00	1.29	63.79	0.84
	2005	14.27	1.30	62.03	0.85
	2010	12.70	1.29	61.00	0.87
	2015	14.65	1.29	58.82	0.92
	2020	16.47	1.31	56.72	0.95
Non-karst landscapes	2000	7.02	1.27	72.01	0.70
	2005	9.52	1.28	70.00	0.72
	2010	9.05	1.28	69.52	0.73
	2015	9.91	1.29	67.73	0.76
	2020	10.79	1.29	66.65	0.79

decreasing trends, while waters and construction land kept increasing (Wang and Zhou, 2019), with a notably large increase in construction land, for which the area in 2020 was 3.56 times larger than in 2000. The landscape type shift matrix revealed that the increase in construction land was mainly dependent on the transfer of cropland, with frequent transitions between cropland and forest land. The results of this study are consistent with those of Mao et al. (Mao et al, 2014) in their study of land use change in the Li River Basin. This shift in landscape type is closely related to the economic activities led by tourism and ecological conservation projects in the Li River Basin. In 2010, the number of tourists in the Li River Basin reached an unprecedented 200000, and the area of construction land increased rapidly to cater to the tourism development. On the other hand, since 2000, the Chinese government has responded to the challenge of deforestation that accompanied the rapid economic growth by setting up programs to convert sloping arable land to forest and to subsidize farmers with central government funds to withdraw from farming. The Li River Basin was one of the first areas to implement these programs, and the autonomous government issued the “Regulations on Ecological Protection of the Li River” in 2011 as a way to ensure the Li River Basin’s forest coverage. The implementation periods of the related projects resulted in frequent shifts between landscape types.

The overall degree of land use in the Li River Basin was high from 2000 to 2020, and its composite index of landscape type use ranged from 239.49 to 244.88. These values are 1.07 to 1.09 times higher than the average of Guangxi (224.87) (Gao et al., 2014), and the composite landscape type movement attitude of the Li River Basin was about 0.22% during the 20 years, which was similar to the value in Hu et al.'s study on the Li River Basin from 1973 to 2013 (Hu et al., 2017). The degree of landscape type utilization is a comprehensive expression of the strength of interference with the natural landscape from human activities, and the degree of landscape exploitation is generally higher in areas with concentrated residential settlements and intensive industrial and agricultural production activities. Guilin ranks third (after Nanning and Liuzhou) among the 14 prefecture-level cities in Guangxi in terms of economic development, and the Li River Basin is the core area of tourism development in Guilin, so its degree of landscape utilization is higher than the average level in Guangxi. In addition, our statistical analysis of the *PD* index, *FRAC_AM* index, *CONTAG* index and *SHDI* index revealed that the Li River Basin landscape as a whole shows trends of increasing fragmentation, decreasing connectivity, decreasing dominance and increasing heterogeneity in the process of transformation, which all indicate that the ecological safety of the Li River Basin is at risk of decreasing (Bi et al., 2019).

The phenomenon of heterogeneous changes in landscape patterns between the karst and non-karst areas in the Li River Basin may be more related to the geographical environmental characteristics of the region. The Li River Basin is bordered by the Yue Cheng Ling in the north and the Ocean Mountain in the east, with a higher elevation and less disturbance by human activities, which is the main distribution area of the non-karst landforms. The lush vegetation in this area creates favorable conditions for the maintenance and protection of ecological diversity, ecosystem health and stability in the region. The central and southern areas of the Li River Basin, which belong to the impact river valley zone with a low elevation, are endowed with a large amount of arable land and construction land landscape, which is the main coverage area of the karst landform. In general, the landscape patches of construction land and cultivated land are utilized to a higher extent than the woodland and grassland landscapes, so the landscape in the Li River flow karst area is utilized to a greater extent. Furthermore, in addition to the poorer ecological stability of karst landscapes themselves (Li et al., 2021), the Li River Basin karst area is also an area for concentrated human activities such as tourism and agricultural production (Mao et al., 2014), resulting in higher fragmentation, more complex shapes and poorer landscape connectivity of the landscape patches in the karst area. Overall, the evolution of landscape patterns in the Li River Basin shows a high degree of spatial heterogeneity that is influenced by the geographic feature factors and human activities in the study area. Therefore, when implementing restoration and protection of the Li River Basin landscape, the topographic and geomorphological characteristics of the karst region need to be fully considered. Particular attention should be paid to preventing the formation of high-risk areas in the karst region of the Li River Basin, and if necessary, the measures for returning farmland to forest and grass need to be increased through mandatory policies. The investment in integrated soil and water conservation management and rock desertification management needs to be strengthened, and the patches of other landscape types such as woodland and grassland need to be appropriately increased to reduce *PD*, *FRAC_AM*, and *SHDI*, increase *CONTAG*, slow down the degree of landscape fragmentation and enhance the level of landscape stability, while strictly limiting the unnecessary expansion of construction land in the process of urbanization, in order to achieve the purpose of protecting the fragile karst ecological environment. In addition, the issues of economic and social development and ecological environmental management in the Li River Basin should be properly handled. For the economic activities of tourism, agriculture and forestry in the Li River Basin, the impacts of other human activities on the ecological landscape pattern should be reduced in an integrated manner, in order to enhance human welfare and promote the healthy development of the ecosystem.

6 Conclusions

Based on the GEE platform, this paper presents a quantitative analysis of the spatial and temporal evolutionary characteristics of the landscape pattern in the Li River Basin from 2000 to 2020. The analysis found that there are significant differences in the spatial and temporal evolution of the landscape patterns between the karst and non-karst areas in the Li River Basin. Three main conclusions are as follows.

(1) Forest land and arable land are the main landscapes of the Li River Basin, but they showed a negative growth trend from 2000 to 2020, and positive changes in waters and construction land. Forest land is mainly distributed in non-karst areas, and arable land is mainly distributed in karst areas. The chord diagram of landscape type shifts shows that the increase in construction land mainly came from arable land, implying that a large increase in construction land occured in the karst areas. The karst areas in the Li River Basin are gradually becoming more disturbed by human activity.

(2) As influenced by the special physical and geographical environment of the river basin as well as social and economic development and other comprehensive factors, the landscape patterns of karst and non-karst areas in the Li River Basin have evolved very differently. The differences are mainly apparent in the following ways: the degree of landscape use is higher in karst areas than in non-karst areas; there are significant differences in the trends of landscape

type changes and the rates of landscape type changes between karst and non-karst areas; and the landscape patches in karst areas are more fragmented, more complex in shape and less connected.

(3) Based on the GEE platform, this study used the random forest algorithm to extract the landscape pattern of the Li River Basin from 2000 to 2020, which greatly improves the work efficiency and the accuracy of the extracted data.

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基于 GEE 平台的典型喀斯特流域景观格局时空演化特征研究

魏青青[1]，何　文[1,2]，王金叶[1,3]，周馨冉[1]，姚月锋[2]

1. 桂林理工大学旅游与风景园林学院，广西桂林 541006；
2. 广西壮族自治区/中国科学院广西植物研究所，广西喀斯特植物保育与恢复生态学重点实验室，广西桂林 541006；
3. 南宁理工学院，南宁 530000

摘　要：喀斯特景观破碎化程度高、抗干扰能力差，厘清喀斯特区景观格局时空动态变化对喀斯特生态环境保护具有重要意义。本文以漓江流域为研究区，基于 GEE 平台获取的 2000–2020 年 5 期 Landsat 系列影像作为数据源，从景观利用程度、景观类型动态度以及景观格局指数层面分析研究流域景观空间分布及动态演化。结果表明:（1）漓江流域喀斯特地区和非喀斯特地区景观结构、景观类型变化趋势均存在较大差异。（2）漓江流域综合景观类型动态度为 0.22%，景观利用综合指数范围在 239.49–244.88，喀斯特地区景观利用程度比非喀斯特地区更高，景观变化速率更加激烈。喀斯特地区景观利用综合指数为 262.32–270.50，非喀斯特地区景观利用综合指数为 225.28–227.01，且喀斯特地区的综合景观类型动态度为 0.31%，是非喀斯特地区的 2 倍左右。（3）漓江流域景观演化整体表现为破碎度增加、连通性减弱、优势度下降、异质化增强的趋势，其中喀斯特地区尤为突出。研究结果可为桂林市国家可持续发展创新示范区建设目标的实现提供科学依据，为喀斯特流域生态环境治理提供技术参考。

关键词：景观利用程度；景观格局指数；景观类型动态度；喀斯特景观；漓江流域