sustainability

Article

Landscape Evolution and Its Driving Forces in the Rapidly Urbanized Guangdong–Hong Kong–Macao Greater Bay Area, a Case Study in Zhuhai City, South China

Miaomiao Liu [1,2], Guishan Chen [1,2], Guanhua Li [1,2,*], Yingyu Huang [1,2], Kaiwei Luo [1,2] and Changfa Zhan [2]

[1] Guangdong Provincial Key Laboratory of Marine Disaster Prediction and Protection, Institute of Marine Sciences, Shantou University, Shantou 515063, China; 22mmliu@stu.edu.cn (M.L.)
[2] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519000, China
[*] Correspondence: ligh1986@gmail.com

Abstract: Over the past four decades, urban expansions driven by rapid economic development and climate change have exerted profound impacts on land-use dynamics in the Guangdong–Hong Kong–Macao Greater Bay Area. However, our understanding of the interplay of different urban landscape patterns in this rapid urbanization zone remains limited. This study examines remote sensing data from 1999, 2009, and 2019 to analyze the spatial heterogeneity of the urbanization impact on landscape patterns, as well as driving forces, in Zhuhai City, in the western part of the Great Bay. The findings reveal that land-use changes in Zhuhai City are primarily characterized by the conversion of cultivated land and water areas into construction land and forest land, particularly in the western part of the city. These changes may result from rapid urbanization, leading to increased fragmentation and spatial aggregation of landscape patterns. Landscape pattern changes in Zhuhai City were related to both socio-economic development and natural environment change. The urbanization has promoted the agricultural transformation with a loss of cultivated land and water areas. Additionally, this study suggests that the coordination of land use along with the protection and construction of the ecological environment is urgently needed to achieve sustainable development in the region.

Keywords: land-use change; landscape patterns; principal component analysis; grey relation analysis; driving factors; Guangdong–Hong Kong–Macao Greater Bay Area (GBA)

Citation: Liu, M.; Chen, G.; Li, G.; Huang, Y.; Luo, K.; Zhan, C. Landscape Evolution and Its Driving Forces in the Rapidly Urbanized Guangdong–Hong Kong–Macao Greater Bay Area, a Case Study in Zhuhai City, South China. *Sustainability* **2023**, *15*, 13045. https://doi.org/10.3390/su151713045

Academic Editors: Kaifeng Duan, Jiajia Li, Jianing Zhou and Lei Chen

Received: 5 July 2023
Revised: 7 August 2023
Accepted: 23 August 2023
Published: 30 August 2023

1. Introduction

Land is a precious and finite resource that provides essential services for humanity and the planet [1,2]. With the global industrial and economic development, unreasonable land use and urban expansion have caused various problems, such as ecosystem degradation, food crisis, biodiversity loss, and climate change, threatening the sustainability of human society and the well-being of future generations [3]. Land-use change refers to the change in landscape, coverage, and utilization caused by changes in the characteristics of the land itself and changes in the way individuals or groups of people interact with it [4–6]. Changes in landscape are the most direct manifestation of human activities affecting regional ecosystems, and they are a crucial factor influencing the alteration of ecosystem services [7–11]. The areas where there are sharp contradictions between human and land relationships have been the recent focus of land-use research, characterized by fragile ecological environments associated with climate change, rapid industrialization, and urbanization [12–15]. Urbanization since especially the past century has had a significant impact on landscape and land-use patterns, leading to changes in land use and alterations in the surrounding environment [16,17]. Recognizing the importance of sustainable landscape variability is crucial for maintaining the functionality of ecosystems, preserving biodiversity, and ensuring the long-term well-being of both humans and the environment [18,19]. Landscape pattern refers to the types, sizes, numbers, spatial distribution, and configuration of different landscape composition units caused by land-use transformation [4,20]. It is not only a comprehensive expression of landscape heterogeneity in space and time but also the result of the joint action of various ecological processes at different scales [17,21]. As the most intuitive expression of land-use change, studying the spatio-temporal dynamic of landscape patterns caused by land-use change is still an important issue in current landscape-ecology assessment [17,22,23]. Recent studies in landscape ecology and landscape planning paid particular attention to the spatial structure of landscapes in examining the relationships between land uses and urbanization at various scales [17,24–26]. Using the analysis of regional landscape pattern indices, the state of land-use change can be accurately retrieved, which has significant implications for the rational planning of future regional land resources and the protection of the ecological environment [21,27–30].

Over the last four decades, China has witnessed remarkable urbanization and noteworthy transformations in land use, with the most significant changes in landscape occurring in urban areas and their surrounding regions, particularly in eastern China [31,32]. Numerous studies have paid great attention to quantifying the spatial-temporal pattern of urbanization with certain general patterns along the urban–rural gradient in some metropolitan cities [33–35]. The increasing works from China have immensely promoted land-use research under rapid urbanization. Based on landscape metrics, the change in land-use types was closely related to the characteristics of human activities, presenting an ecologically fragile landscape with a complex diffusion–coalescence pattern along the rural–urban transect [33,34]. The rapid urbanization has also resulted in significant landscape transformation and triggered a series of ecological and environmental issues, particularly in the Pearl River Delta (PRD) region, where the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) is located [36–41]. With the rapid economic development, industrialization, and urbanization process, coupled with the adjustment of industrial structure, the excessive exploitation of land resources has led to the occupation of a large amount of ecological space and the continuous deterioration of ecological resources, making the PRD region a hotspot for land-use change research in China [13,42]. The recent progress in land-use and landscape changes within the PRD and its surroundings gave rise to an improved understanding of urbanization expansion and its ecological impact with changes in spatial positions as well as tradeoffs between ecosystem services caused by land-use/land-cover changes [32,42]. However, the current research on the dynamic changes in land-use and landscape patterns in the PRD mainly focuses on single landscape structures such as coastal wetlands, forests, and transportation land or the spatial pattern characteristics of rural and small towns [28,32,43]. Comparatively, there is still a lack of sufficient attention on the interplay of different urban landscape patterns in the rapidly developing economic zones in the PRD [33,34], where such a topic is urgently needed. The urban gradient analysis and landscape metrics were widely applied to analyze the changes in landscape patterns [44], and such efforts are expected to improve the understanding of the dynamic changes in urban and rural land use. Zhuhai City, as one of the core metropolises on the west bank of the PRD, has certain representativeness of land-use and landscape pattern changes in the GBA. In recent years, the rapid urbanization has led to prominent issues such as an increase in demand for construction land and a large-scale loss of ecological land [32,45–49]. Nevertheless, there is still a dearth of spatial heterogeneity of the urbanization impact on landscape patterns in Zhuhai City in addition to ecological landscape variations. On account of this, the purpose of this study is to analyze the spatial heterogeneity of the urbanization impact on landscape patterns in Zhuhai City based on remote sensing data from 1999 to 2019 with the following main research objectives: (1) to use landscape metrics to identify the characteristics of landscape patterns in Zhuhai City from 1999 to 2019; (2) to analyze the landscape change patterns in the context of rapid urbanization; and (3) to examine the driving factors of landscape pattern changes. This study is expected to provide a reference for land-use planning and ecological restoration in Zhuhai and achieving sustainable development in the coastal GBA region.

2. Materials and Methods

2.1. Study Area

The PRD is one of the three largest river deltas in China formed by fluvial sediments at the mouth of the Pearl River between 112°45′–113°50′ E longitude and 21°31′–23°10′ N latitude [50] (Figure 1). The PRD is geologically located in the transitional zone between the elevated landscape of the catchment basin and the deposition center of the northern continental shelf of the South China Sea [51]. Due to the collision between the Indian plate and the Eurasian plate approximately 34 million years ago, the upland region has experienced gradual uplift, while the continental shelf has undergone subsidence [52]. As a result, the Pearl River has been depositing sediment onto the subsiding continental shelf. The composite delta with fertile soil formed by the extensive deposition of material carried by rivers has nurtured the ancient civilization of Nanyue for thousands of years. It is also one of the key factors that have contributed to the prosperous development of the GBA urban agglomeration today [53]. The majority of the PRD lies within the south subtropical zone and experiences a subtropical marine monsoon climate. The region has an average annual temperature ranging from 21.4 to 22.4 °C, along with an average annual precipitation of 1600 to 2300 mm [45]. The PRD region has experienced rapid urbanization and industrialization, leading to the conversion of agricultural and natural land into urban and industrial areas over the past four decades [54]. One of the most notable changes in land use in the PRD has been the expansion of urban areas. This has a significant impact on the environment, including air and water pollution, as well as on the social and economic landscape of the region [37–39,54,55]. Another important change in land use in the PRD was the growth of industrial areas [55]. The region has become one of the largest manufacturing centers in the world, with many factories and industrial parks located in the region. This has led to the conversion of agricultural and natural land into industrial areas, which has significant environmental impacts, including pollution and habitat loss [56,57]. In addition to urbanization and industrialization, the PRD also experienced changes in agricultural land use with a decline in the amount of agricultural land with a shift from traditional agriculture to more intensive forms of agriculture, such as aquaculture and horticulture [30]. Overall, the changes in land use in the PRD have had a significant impact on the environment, economy, and society in the region. Zhuhai City is in the western part of the PRD with a total land area of c.1725 km^2 along with a sea area of c. 5965.2 km^2. Zhuhai City has a maximum horizontal distance of approximately 135 km from east to west and a maximum vertical distance of approximately 81 km from north to south. The annual temperature is relatively high, reaching 22.4 °C with monthly average temperatures of between 15 °C and 28 °C [48]. The rainfall is abundant, with an average annual precipitation of 1700 mm–2200 mm. The city is topographically characterized by mountains, terraced fields, hills, and plains with inland areas dominated by hills, followed by plains. The city is divided into three districts: Xiangzhou, Doumen, and Jinwan, with the study area's geographic location shown in Figure 1. Amidst rapid urbanization in the GBA, Zhuhai has experienced significant shifts in population composition and economic structure. In this context, the urbanization has brought about substantial changes to Zhuhai, including construction area expansion and the transformation of natural landscapes. Therefore, in consideration of these transformations, it is important to recognize the landscape evolution and driving forces in the rapidly developing area of Zhuhai City to shape the urban ecological environment.

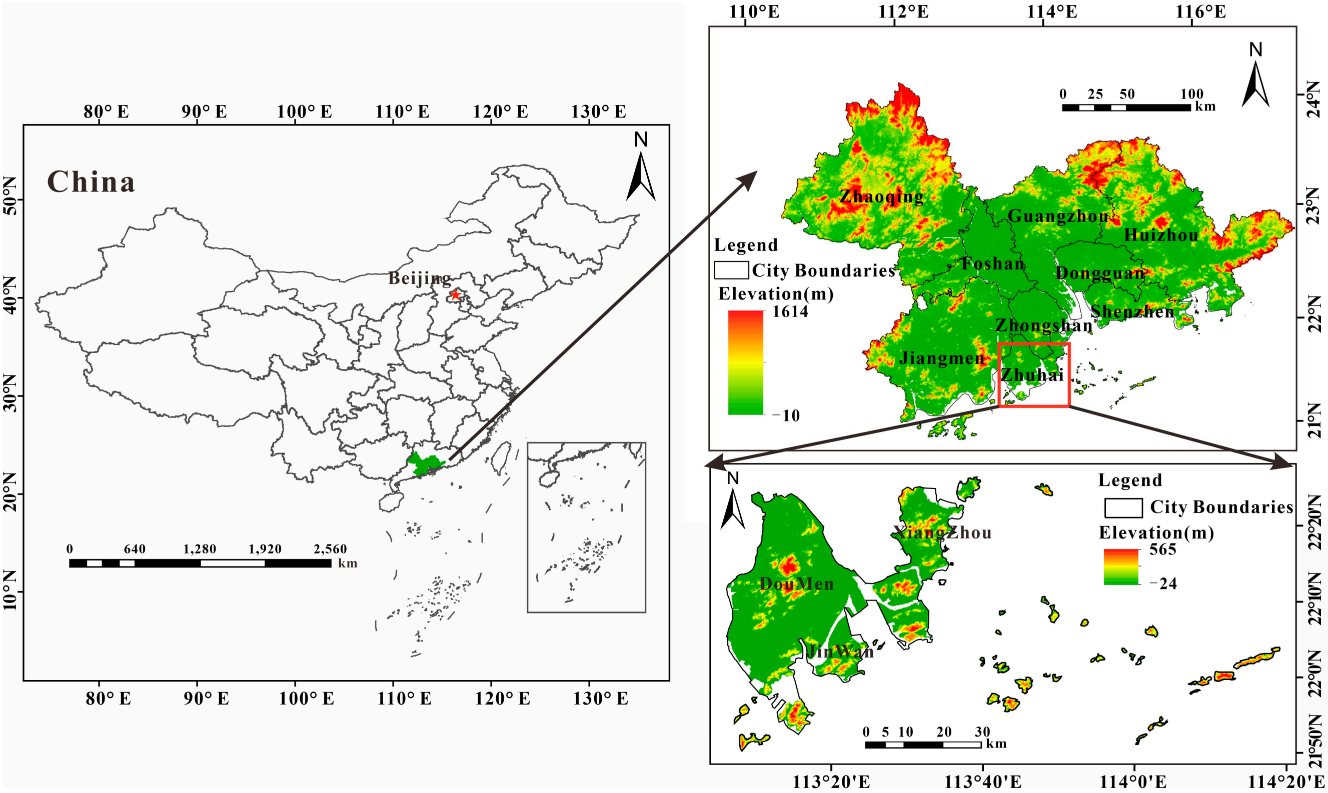

Figure 1. Topographic sketch map showing the location of Pearl River Delta and Zhuhai City. Reprinted/adapted with permission from Ref. [58]. Copyright year 2022, copyright owner U.S. National Geophysical Data Center.

2.2. Methodological Framework

The entire research process of this study is divided into three parts. Based on data preprocessing and landscape classification, ArcGIS 10.2 and Fragstats 4.2 software are used to analyze the characteristics of land use and landscape pattern changes. Finally, principal component analysis and grey relation analysis are employed to quantitatively analyze the driving mechanisms of land use and landscape pattern changes in Zhuhai City from three aspects: socio-economic factors, agricultural factors, and natural factors. The methodological framework used in the study is shown in Figure 2.

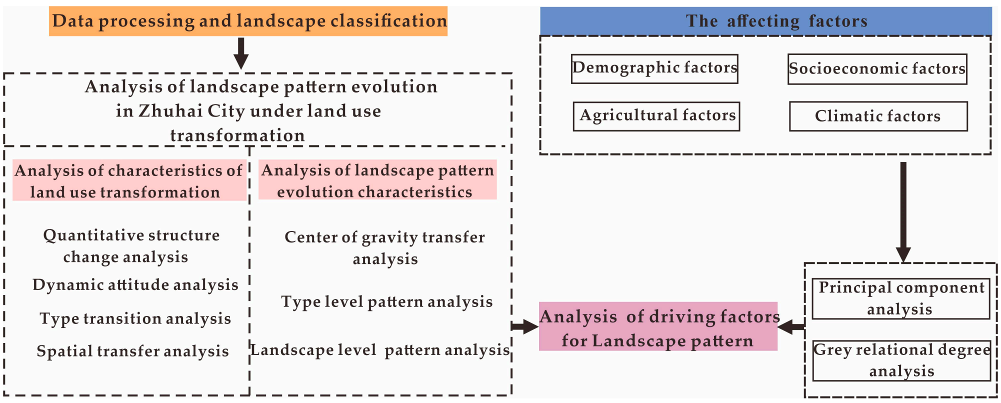

Figure 2. Methodological framework diagram.

2.3. Data Source and Processing

The remote sensing image data in this study include Landsat-7 ETM from 6 December 1999, Landsat-5 TM from 11 January 2009, and Landsat-8 OSL from 20 September 2019, with a resolution of 30 m and a cloud cover of less than 1% (https://www.gscloud.cn/, accessed on 13 January 2023) (Table 1). Considering that Zhuhai is a coastal city with frequent summer foggy weather, there may be fewer remote sensing images available for the study area. Fortunately, since Zhuhai belongs to a subtropical climate with evergreen seasons, remote sensing images from different months in the autumn and winter seasons can also be selected to achieve enough available images. The non-remote sensing image data mainly include 16-level Tianditu used to extract and verify accuracy samples, vector data of Guangdong Province and Zhuhai's districts and counties, Zhuhai's DEM elevation data (http://www.resdc.cn/, accessed on 13 January 2023), and Zhuhai's statistical yearbooks from 1999 to 2019 (http://stats.gd.gov.cn/gdtjnj, accessed on 20 January 2023). ENVI5.2 was used to perform preprocessing on the remote sensing images of Zhuhai in 1999, 2009, and 2019, including image stitching, radiometric calibration, and FLAASH atmospheric correction.

Table 1. List of data used in this study.

Data Types	Resolution (m)	Acquisition Time	Data Sources
Landsat 7 ETM	30	06/12/1999	Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (https://www.gscloud.cn/)
Landsat 5 TM	30	11/01/2009	
Landsat 8 OSL	30	20/09/2019	
DEM	30	-	Resource and Environment Science and Data Center, Chinese Academy L of Sciences (http://www.resdc.cn/)
Administrative division	-	-	

According to the "Classification of Land Use Status" (GB/T 21010-2017) released in China in 2017, the land-use types in Zhuhai are classified into five categories: cultivated land (paddy field, irrigated land, dry land), forest land (deciduous forest land, bamboo forest land, shrub forest land), water area (river surface, lake surface, reservoir surface, pond surface), built-up land (urban land, compulsory town land, village land, tourism land), and unused land (mudflat, swamp), as shown in Table 2 [59]. The classification above was also combined with the resolution assessment of remote sensing images, spectral characteristics of land cover, and field investigations, referring to the previous classification standards of land use in Zhuhai. By combining spectral characteristics of different land-cover types and historical images in the region, five land-cover types were selected for processing samples, followed by supervised classification performance using the maximum likelihood method.

To ensure the authenticity and reliability of the data, the classification accuracy was validated using a confusion matrix and field surveys [60]. In this study, the accuracy of the classification results was verified by combining field survey data with high-spatial-resolution remote sensing images obtained from the BIGEMAP map downloader. Partial high-resolution images within the study area were selected, and 50 random validation samples were extracted for each land-use type. The error matrix was established using ENVI 4.2 software, and the overall accuracy and Kappa coefficient of the classified images for each time period were calculated. The results showed that the classification accuracy of the three time periods exceeded 85%, and the Kappa coefficients were all above 0.8, indicating that the classification results can be used for subsequent research [61].

Table 2. Introduction to land-use categories.

Numbers	Land-Use Categories	Contents
1	Cultivated land	Including paddy field, dry land, irrigated land, and so on
2	Forest	Including arbor woodland, bamboo woodland, shrub woodland, other woodland, and garden land, etc.

Table 2. *Cont.*

Numbers	Land-Use Categories	Contents
3	Water	Including rivers, reservoirs, lakes, pits, and so on
4	Construction Land	Including urban land, compulsory town land, village land, transportation land, and special land
5	Unused land	Including coastal flats, swamps, bare rock, and so on

2.4. Land-Use Dynamic Model

The land-use dynamic model considers the transitions between different land-use types during the study period, focusing on the process of change. It primarily reflects the intensity of land-use change in the study area, facilitating the identification of hotspots of land-use change at different spatial scales [62]. The land-use dynamic model includes single land-use dynamics and comprehensive land-use dynamics [63].

Single land-use dynamics analyzes the change in the quantity and rates of change in a specific land-use type within a designated research area over a certain period of time [64]. The formula for single land-use dynamics was described as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

In the formula for single land-use dynamics, K represents the dynamic degree of a certain land-use type during the study period. U_a and U_b denote the number of a certain land-use type at the beginning and end of the study period, respectively. T indicates the length of the study period. When T is set to a year, K represents the annual change rate of a certain land-use type.

The comprehensive land-use dynamics can reflect the annual rate of change in all land within a given region [65]. The formula for comprehensive land-use dynamics was described as follows [66]:

$$K_{total} = \frac{\sum_{i=1}^{n} |u_{bi} - u_{ai}|}{2\sum_{i=1}^{n} u_{ai}} \times \frac{1}{T} \times 100\% \tag{2}$$

In the formula, u_{ai} is the area of the ith land-use type at the beginning of the monitoring period. $|u_{bi} - u_{ai}|$ represents the absolute value of the area converted from the ith land-use type to a non-ith land-use type during the monitoring period. T denotes the length of the monitoring period. When T is set to a year, K_{total} represents the annual change rate of a certain land-use type.

2.5. Land-Use Transfer Matrix

Land-use transfer matrix is a mathematical model that reveals the structural characteristics of land use along with the transformation situation and direction among different types. By constructing the transfer matrix, we can not only understand the loss direction of each type of land at the beginning of the study period but also study the source and composition of each type of land use at the end of the study period [63]. The transfer matrix is

$$S = S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2n} \\ S_{31} & S_{32} & S_{44} & \cdots & S_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ S_{n1} & S_{n2} & S_{n3} & \cdots & S_{nn} \end{bmatrix} \tag{3}$$

S: area. i and j represent land-use types at the beginning and end of the study period, respectively. n: the number of land-use types.

2.6. Analysis of Land Landscape Patterns

The landscape index highly concentrates landscape pattern information, which is a simple quantitative indicator reflecting the characteristics of the landscape pattern structure, composition, and spatial configuration, including patch level, class level, and landscape level [67–69].

The selection of landscape indicators is generally based on theoretical analysis, expert knowledge, and previous published research results, so as to eliminate redundant or redundant indicators [70]. In terms of the urban landscape, the research on urban landscape pattern characteristics mainly focuses on size, density, shape, edge, connectivity, heterogeneity, and diversity. Therefore, based on the research needs and the most commonly used indicators in urbanization research, this paper aims to characterize and analyze the landscape pattern of Zhuhai City according to the characteristics of frequent human interference activities and dramatic landscape changes in the Pearl River Delta region. The landscape pattern is analyzed from the level of type indicators and landscape indicators. At the type level, we selected the CA, NP, AI, and LPI indicators, which show the spatial distribution of urban land patches from the perspective of size and quantity [68] and can indirectly reflect the direction and degree of human activity interference with land use. At the landscape level, we selected five indicators that can reflect the overall characteristics to analyze the changes in landscape pattern. The ED, LSI, SHEI, SHDI, and CONTAG indicators can better reflect the connectivity, heterogeneity, and diversity characteristics of the landscape pattern. All the indicators selected here are calculated using FRAGSTATS 4.2 software.

2.7. Spatial Centers of Gravity (SCG)

Gravity describes the focal point of the movement or influence of a specific feature within a region. SCG presents the evolutionary process of landscape types that can effectively mirror the spatial aggregation and migration trends of various landscape types [71].

$$Y_t = \sum_{i=1}^{n} (C_{ti} \times Y_{ti}) / \sum_{i=1}^{n} C_{ti} \tag{4}$$

$$X_t = \sum_{i=1}^{n} (C_{ti} \times X_{ti}) / \sum_{i=1}^{n} C_{ti} \tag{5}$$

where X_t and Y_t indicate the latitude and longitude coordinates of the centroid of a certain landscape type distribution in year t. X_{ti} and Y_{ti} denote the latitude and longitude coordinates of the gravity of the ith patch of a certain landscape type distribution in year t. Cti represents the area of the ith patch of a certain landscape type in year t.

2.8. Principal Component Analysis

As a multivariate statistical analysis method, principal component analysis involves linear transformation of multiple variables based on the idea of “dimension reduction”. With the premise of minimum information loss, multiple indicators are transformed into several complementary and correlated comprehensive indicators, which replace the original indicator information [72]. In this study, the principal component analysis method with SPSS 26 software was applied to analyze the driving factor regarding regional landscape evolution by selecting several important and relatively independent comprehensive factors through principal component analysis.

2.9. Grey Relation Analysis

Grey relational analysis is a scientific method that is based on the macro or micro geometric approximation between behavioral factors. The closer the array curves are, the stronger the relationship between the factors. It is commonly used to measure the degree of similarity or dissimilarity in the development trends among various influencing factors, in order to determine the level of closeness between the main behavioral factor and the rest of the behavioral factors, and thus identify the primary and secondary factors [73]. This study utilizes the DPS 7.05 software platform to calculate and analyze the grey correlation between 13 major indicators based on the social, economic, and natural aspects, as well as the 5 landscape index.

3. Results and Discussion

3.1. Analysis of Inter-Annual Land-Use Shift

3.1.1. Quantity Characteristic Analysis of Land-Use Change

As the core hub of the western GBA, Zhuhai City is divided into two parts, the eastern and western regions, by the Modaomen Waterway [46]. The eastern region is mainly composed of Xiangzhou District, while the western region is mainly composed of Doumen District and Jinwan District. Due to the influence of natural environment and location conditions, there are significant differences in the distribution of land-use types in the eastern, central, and western regions of Zhuhai City (Figure 1). Figure 3 shows the land-use changes and its spatial distribution. Cultivated land is mainly distributed in the fluvial plain and low-mountainous areas in the west, with concentrated distribution in patches [74]. Construction land is mainly concentrated in the coastal plain and hilly areas in the central region. Forest land is mainly composed of mountains, distributed in the Fenghuang Mountain and Xiaoshan-hengqin Mountain in the east, Huangyang Mountain in the west, and coastal low-mountainous areas in the north. Water bodies are mainly composed of river surfaces, lake surfaces, and pond surfaces and are mainly distributed in various towns in the west, interspersed with cultivated farmland. From 1999 to 2019, the cultivated land area in Zhuhai City decreased from 74,899.21 hm^2 to 43,318.23 hm^2, with a reduction area ratio of up to 19.91%, which is the most significant change among the five land-use types. At the same time, construction land and forest land increased relatively. The area of construction land increased by 25,134.79 hm^2, with an increment ratio of 15.85%. The area of water bodies and unused land decreased slightly, although the change is not significant. This new result is essentially consistent with previous findings from ecological and forest landscapes in this area [32,40,41,48].

3.1.2. Analysis of Land-Use Dynamics

Based on the single and comprehensive land-use dynamic models [64], the classification results of three image phases in the study area were statistically analyzed to evaluate the changes in land-use types in Zhuhai City. Results show that the land-use changes in the study area were relatively significant over the past 20 years, with a comprehensive annual change rate of 1.23% (Table 3). The annual variation rate of construction land was the highest among the three periods, reaching up to 13.70%, 4.12%, and 11.73%, respectively, indicating that the spatial transformation of construction land in Zhuhai City was the most prominent [74]. The water area was relatively stable in the past twenty years, with the lowest annual change rate of −1.37%, 0.13%, and −0.63%, respectively. Change in cultivated land was also significant, with an annual change rate of −2.11%. The forest land with an annual change rate of 2.52% exhibited a relatively active spatial transformation due to urbanization [35]. In sum, the land-use changes in Zhuhai City over the past 20 years were significant, mainly manifested as "two increases and three decreases" that were characterized by a continuous growth of construction land and forest land, the decrease in cultivated land and unused land, and first increasing and then decreasing in water area. This is consistent with the characteristics of rapid economic development and continuous urbanization in Zhuhai City [25,33,35].

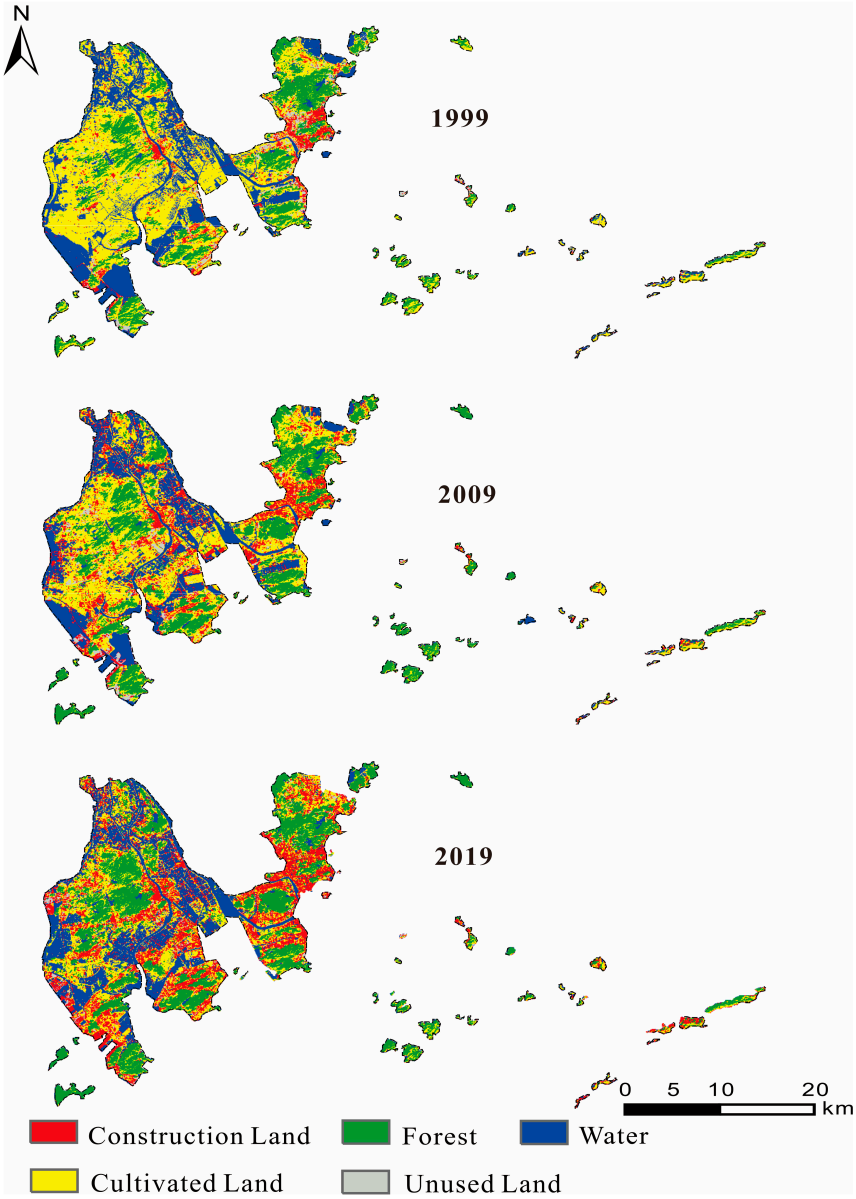

Figure 3. Land-use classification map of Zhuhai from 1999 to 2019.

Table 3. Change rate of land-use types in Zhuhai from 1999 to 2019.

Land-Use Type	1999–2009		2009–2019		1999–2019	
	Area Change/hm^2	k/%	Area Change/hm^2	k/%	Area Change/hm^2	k/%
Construction land	14,679.10	13.70	10,455.78	4.12	25,134.79	11.73
Forest	8610.59	3.15	5150.68	1.43	13,761.27	2.52
Water	5423.87	−1.37	440.51	0.13	4983.36	−0.63
Cultivated land	16,862.87	−2.25	14,718.11	−2.54	31,580.98	−2.11
Unused land	1002.85	−1.62	1328.85	−2.56	2331.70	−1.89
K_{total}	1.47		1.01			1.23

3.1.3. Analysis of Land-Use Type Transfer in Zhuhai City

The land-use transfer map intuitively elucidates the transformation relationship of various land-use types in spatial locations [24]. In this study, using the spatial analysis function of GIS, a spatial overlay analysis was conducted on the land-use data for 1999 and

2019. Based on Equation (3), the land-use spatial distribution map (Figure 4) and land-use type transition matrix (Tables 4–6) for Zhuhai City from 1999 to 2019 were obtained.

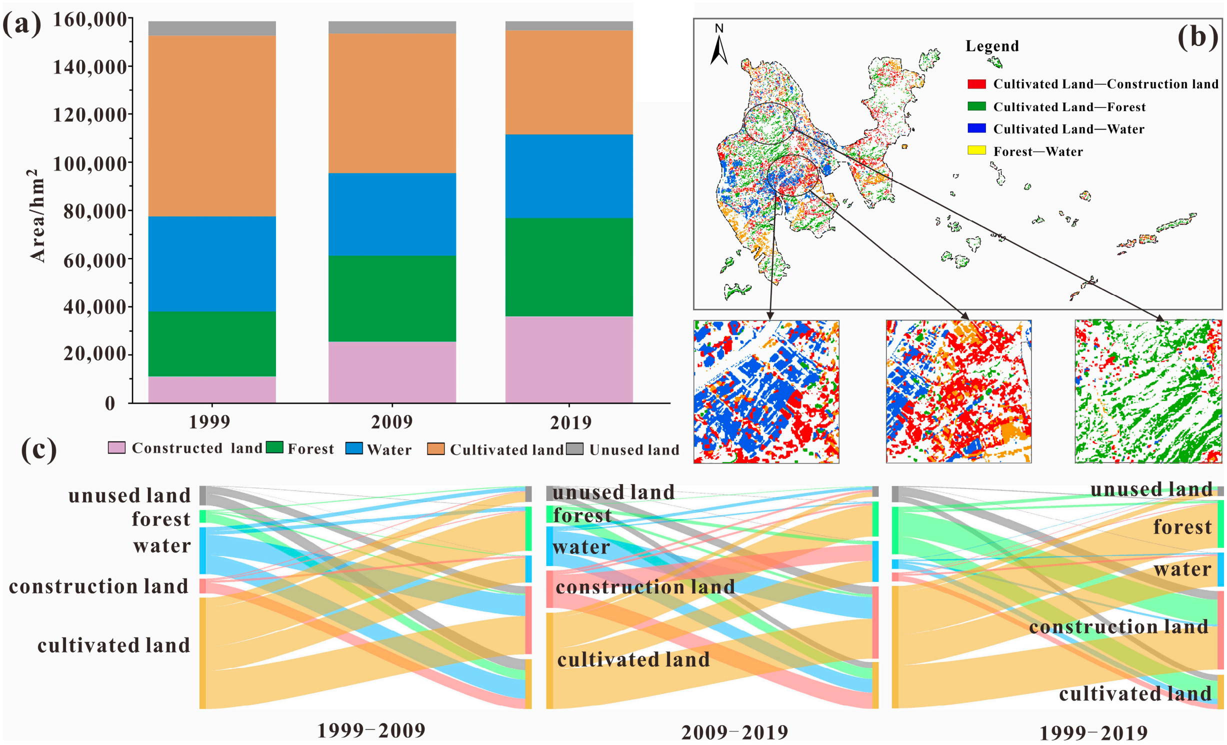

Figure 4. Map of land-use change in Zhuhai from 1999 to 2019. (**a**) The bar chart shows the area proportion of five land-use types. (**b**) Spatial transfer map of main land-use types in Zhuhai from 1999 to 2019. (**c**) Sankey diagram showing the magnitude and pathways of land-use changes in 1999–2019. The height of the vertical bars denotes the proportional area of a land type.

The increase in construction land in Zhuhai City has shifted from the Xiangzhou District in the east to the Doumen District and Jinwan District in the west, while the decrease in cultivated land is concentrated in the Doumen District and Jinwan District in the west, with sporadic distribution in the Xiangzhou District. From 1999 to 2009, the conversion of land use in Zhuhai City was concentrated in the western region, prevailingly characterized by the conversion of cultivated land to construction and forest land in Pingsha Town, Hongqi Town, and Qianwu Town. The increased construction land was primarily distributed on the banks of Huangyang River and Zhufeng Avenue in Doumen District and Zhuhai Avenue and the northwestern Sanjiao Town in Jinwan District. The increased construction land area during the study period was mainly concentrated in northeastern Tangjiawan and the northern Hengqin Island in Xiangzhou District, Jing'an Town and Baijiao Town in Doumen District, and the surrounding areas of Sanjiao Town in Jinwan District. The above analysis suggests that land-use transformation in Zhuhai has undergone a shift in the center of gravity in spatial distribution from the east to the west. The Zhuhai Municipal Committee and Municipal Government in 2004 proposed the urban development concept of "building the west city and enhancing the east city". Subsequently, in 2008, the strategy of "eastern transformation, central adjustment, and western development" was implemented [33]. This may be largely responsible for the land-use shift before 2009.

There were drastic changes in land-use types in Zhuhai from 1999 to 2019 (Table 6). The Sankey diagram (Figure 4c) shows that land-use classification generally elucidates the conversion of cultivated land and water areas to construction land and forest land, with cultivated land showing the most significant changes among the five land-use types [25]. Among them, 20.75% of cultivated land was converted to construction land, with 21.02% of cultivated land converted to forest land, resulting in a significant reduction in cultivated land. This is essentially in line with another ecological assessment in Zhuhai [25,35] in relation to urbanization and the national policy of returning farmland to forest [33]. Furthermore, the land-use classification may also be affected by the implementation of the "industrial westward expansion and urban westward expansion" strategy in Zhuhai City in 2003, which promoted the development of urban construction to the western regions [74]. The implementation of national key construction projects including transportation and energy aspects resulted in a large demand for construction land, which occupied a large amount of cultivated land, leading to a reduction in cultivated land area [75]. On the other hand, to increase income, farmers spontaneously converted some cultivated land into high-income orchards and aquaculture areas, gradually leading to a conversion of cultivated land to forest land and water areas [76,77]. Forest land increased by 8.68%, with original forest land being converted to cultivated land and construction land (Figure 4). The "three old" renovation project implemented in Zhuhai City from 2010 to 2014 with the expansion of green spaces may be responsible for the change in forest land. The unused land area is continuously decreasing, with a reduction of 3.15%, as a result of the conversion to cultivated land and construction land and some land being converted to forest land. The urban spatial development pattern of Zhuhai has been recently redefined by guiding the transformation of the eastern urban area, achieving the westward shift of the city's development focus, accelerating the urbanization pace of the western region, and developing the western region into the second main urban area of Zhuhai [33]. Therefore, the rapidly urbanizing areas will inevitably consume a large amount of non-construction land types to meet the expansion of the city, leading to an overall spatial trend of the land-use pattern transformation from the east to the west in Zhuhai.

Table 4. Land-use transfer matrix of Zhuhai City from 1999 to 2009.

		2009					
		Cultivated Land	**Construction Land**	**Forest**	**Water**	**Unused Land**	**Total**
1999	Cultivated land	44,309.16	10,500.57	10,809.72	6583.27	2696.50	74,899.21
	Construction land	2956.25	6647.88	269.07	586.44	254.46	10,714.10
	Forest	2610.29	478.87	23,762.16	216.76	272.35	27,340.44
	Water	5098.47	5686.29	988.25	26,659.95	1081.43	39,514.40
	Unused land	3062.17	2079.50	121.82	44.10	876.45	6184.04
	Total	58,036.34	25,393.11	35,951.03	34,090.53	5181.19	158,652.20

Table 5. Land-use transfer matrix of Zhuhai City from 2009 to 2019.

		2019					
		Cultivated Land	**Construction Land**	**Forest**	**Water**	**Unused Land**	**Total**
2009	Cultivatednland	29,347.20	11,857.34	9260.80	6177.16	1393.85	58,036.34
	Construction land	4951.05	14,275.24	601.13	4923.32	642.37	25,393.11
	Forest	3230.46	832.36	30,714.06	999.56	174.60	35,951.03
	Water	4011.40	6409.27	426.34	22,333.60	909.92	34,090.53
	Unused land	1778.12	2474.68	99.38	97.41	731.60	5181.19
	Total	43,318.23	35,848.89	41,101.71	34,531.04	3852.34	158,652.20

Table 6. Land-use transfer matrix of Zhuhai city from 1999 to 2019.

		2019					
		Cultivated Land	**Construction Land**	**Forest**	**Water**	**Unused Land**	**Total**
1999	Cultivated land	30,969.33	15,540.21	15,747.28	10,815.21	1827.18	74,899.21
	Construction land	1942.56	7560.68	317.25	686.97	206.64	10,714.10
	Forest	1973.16	744.48	23,945.12	512.08	165.60	27,340.44
	Water	6345.54	8763.07	788.04	22,404.82	1212.93	39,514.40
	Unused land	2087.64	3240.45	304.02	111.96	439.97	6184.04
	Total	43,318.23	35,848.89	41,101.71	34,531.04	3852.34	158,652.20

3.2. Landscape Change Pattern Analysis

3.2.1. Analysis of Landscape Gravity Center Migration

The spatial migration pattern of five land-use types in Zhuhai in 1999, 2009, and 2019 is illustrated in Figure 5. The analysis of landscape gravity center migration shows that the gravity center of construction land in Zhuhai shifted to the northwest from 1999 to 2019. During this period, Zhuhai City implemented a strategy of westward expansion and rapid urbanization development, promoting the increasing expansion of construction land in the western area [74]. At the same time, the gravity center of cultivated land has shifted to the southwest. Although the expansion of construction land in the west caused the occupation of a large area of cultivated land, a large amount of cultivated land was still distributed in Jinwan and Doumen Districts in western Zhuhai. The gravity center of forest land has shifted significantly during this period, as Zhuhai City was committed to building a northern mountainous ecological tourism belt [25]. The ecological condition in the northern part has been greatly improved with the increased forest land. For water bodies, the gravity center has essentially shifted to the eastern part which is opposite to that of construction land. Notably, the urban expansion in the western part of Zhuhai was also accompanied by large-scale soil erosion during the past 20 years [74]. On the contrary, protection of the mangrove wetland in the eastern coastal area resulted in the gradual eastward shift of the gravity center of water bodies [78]. Comparatively, the gravity center of unused land has shifted relatively slowly, mainly to the northwest. The continuous industrialization might give rise to an increase in land development intensity and possible low land-use efficiency [79], resulting in some land being left unused.

3.2.2. Analysis of Landscape Characteristics at the Type Level

Based on the analysis of the type-level landscape characteristic index [80] (Figure 6), the cultivated area of class area (CA) decreased annually, while the number of patches (NP) initially decreased and then increased from 1999 to 2019. This indicates a continuous reduction around cultivated land along with an increase in the degree of landscape fragmentation and human interference [25]. Meanwhile, the largest patch index (LPI) and aggregation index (AI) of cultivated land continued to decrease. The urbanization process and changes in land-use strategies in Zhuhai might have a certain impact on the area of cultivated land [33]. The CA, LPI, and AI indices of construction land increased annually, while the NP initially increased and then decreased. This indicates that the area of construction land was relatively small in the early stage followed by an increase in fragmentation. With the improvement in urbanization level, the dominance of construction land gradually increased with a gradual decrease in fragmentation, while spatial aggregation gradually increased [74]. For forest land, the CA and AI gradually increased together with a decreased NP, as the LPI index initially decreased and then increased, implying forest land has been increasing with a gradually decreased fragmentation and more concentrated spatial distribution. The variation in landscape indices for forest land is largely attributed to the management of ecological land use in Zhuhai City in recent years that may have a certain protective effect on forest land evolution [25]. The CA of water bodies decreased gradually to be more stable, while the NP and LPI initially decreased and then increased. Moreover, the AI index exhibited the opposite trend to the NP and LPI, indicating that water bodies, as the second dominant landscape type after cultivated land, have decreased due to the occupation of other land-use types, resulting in a decrease in fragmentation and a gradual decrease in spatial aggregation.

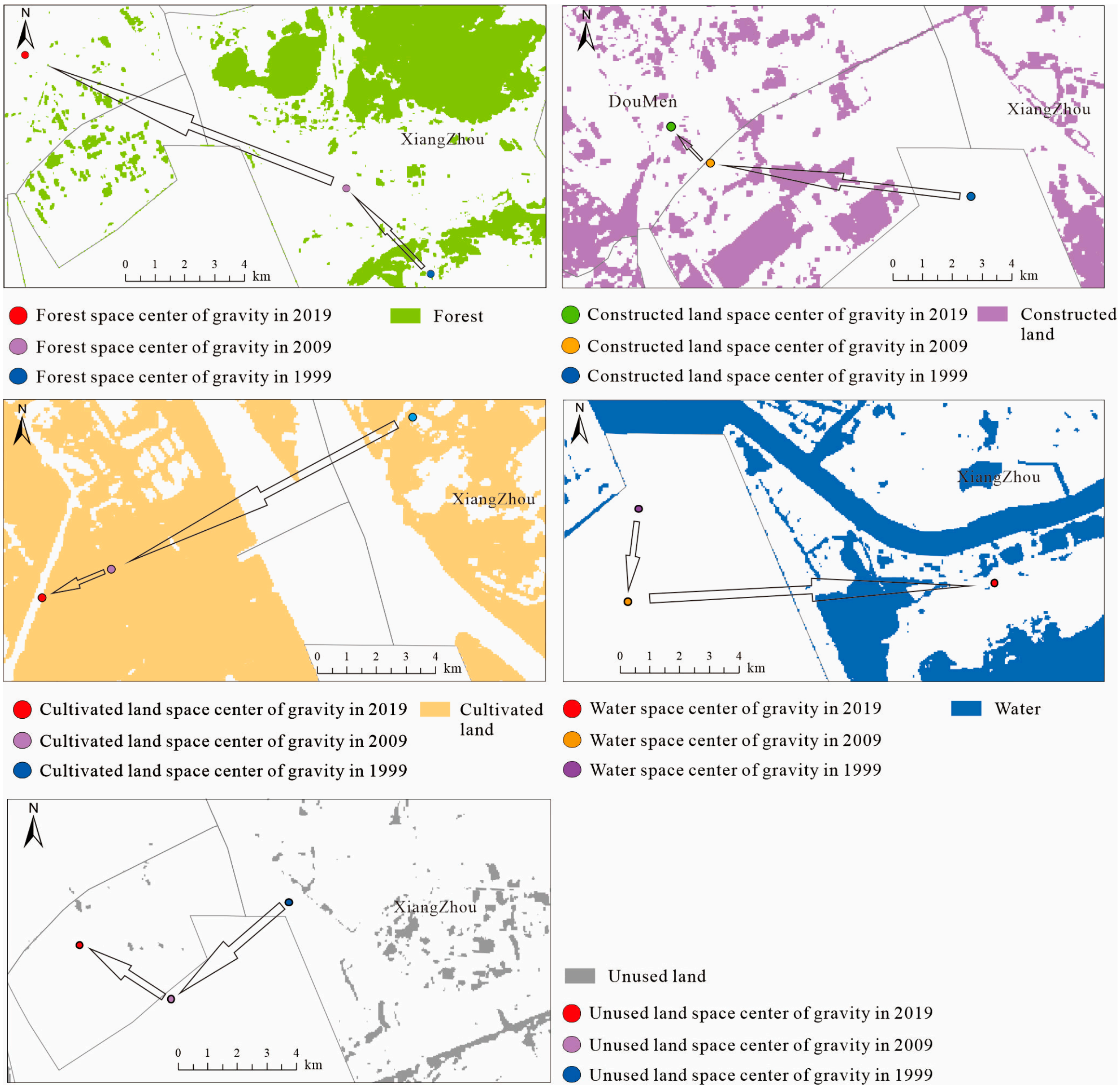

Figure 5. Direction map of gravity shift of landscape types in Zhuhai City from 1999 to 2019.

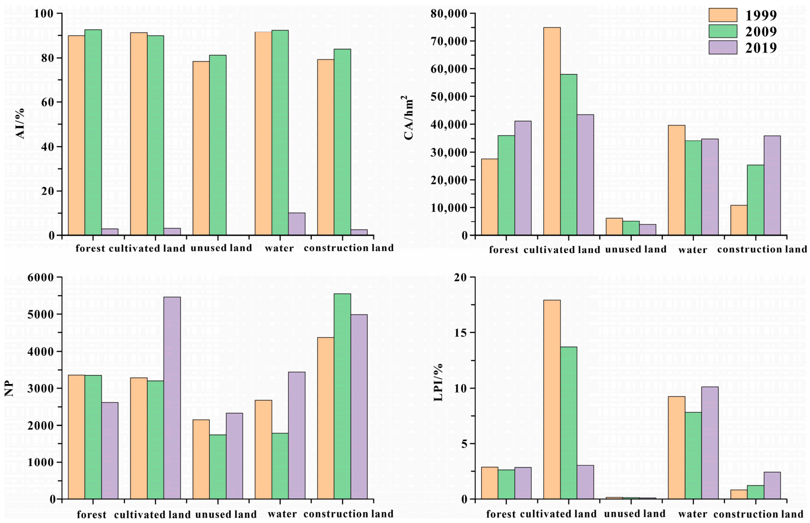

Figure 6. Changes in type-level landscape index in Zhuhai from 1999 to 2019.

The annual decrease in the conversion of unused land has led to a decline in the corresponding CA. On the other hand, the NP initially experienced a decrease but eventually showed an increase. Concurrently, the LPI showed a decreasing trend gradually approaching zero. Similarly, the AI witnessed an initial increase followed by a subsequent decrease. The type-level landscape index of unused land denotes that the unused land in Zhuhai is continuously decreasing with the relatively increasing fragmentation. Moreover, the spatial aggregation has been relatively decreasing during the past twenty years, suggesting that the spatial development layout of Zhuhai is gradually becoming more rational with a significantly improved land-use efficiency.

3.2.3. Analysis of Changes in Landscape Characteristics at the Landscape Level

Figure 7 illustrates the edge density (ED) and landscape shape index (LSI), which increased dramatically with a more significant change from 2009 to 2019, while the patch segmentation of different landscape types gradually increased. Moreover, the complexity of boundaries also showed a gradual increase, resulting in landscapes with increasingly irregular shapes. The contagion index (CONTAG) continuously decreased from 1999 to 2019, indicating that the increased number of small patches enhanced landscape fragmentation, thereby weakening the spatial aggregation and connectivity of the study area's landscape. During the past twenty years, Shannon's diversity index (SHDI) and Shannon's evenness index (SHEI) exhibited a continued increasing trend, indicating continuously enlarged inferior landscape patches, while the proportion of various landscape types' areas gradually decreased, indicating diversification and homogenization. Throughout the research period, the escalating level of human disturbance, positive macroeconomic conditions, and industrial growth in Zhuhai have contributed to the progressive conversion of scattered cultivated land, water areas, and unused land into construction sites. Consequently, there was a rise in the overall level of landscape fragmentation within the study area. The increased segmentation of small patches subsequently diminished the connectivity between these patches [35].

3.3. Analysis of Landscape Pattern Evolution Driving Forces

3.3.1. Driving Factors

Previous studies have categorized the driving forces in landscape pattern change into two main groups: natural and social [26,27,81–84]. Natural factors primarily contribute to alterations in land cover and exert a relatively consistent influence on land-use change as the environmental background. On the other hand, social systems, including technology, policies, and economic factors, directly exert an impact on land-use transformations within the decadal time scale by influencing the decision-making processes and social behavior of individuals regarding land utilization [85,86].

This study selects driving factor indicators from four aspects: economic development, population, agricultural level, and natural environment. Based on previous studies, since the reform and opening-up policy was implemented in China, especially in the densely populated and economically strong regions of Beijing–Tianjin–Hebei, Yangtze River Delta, and Pearl River Delta, population change and socio-economic development have been regarded as the main driving factors of land-use change due to the rapid increase in urbanization level [45,50,87]. As a core city of the Pearl River Delta region, Zhuhai should select driving factors by combining the findings of previous studies and the characteristics of this region, such as fast urbanization, large population mobility, and coastal location. Between 1999 and 2019, Zhuhai's economy maintained high-speed growth, and the industrial structure was continuously adjusted, which promoted the transfer of rural labor force to the secondary and tertiary industries. This resulted in rural population migration to urban areas. A large number of immigrants caused urban construction land expansion and cultivated land reduction [88,89]. Here, we choose urban population as a percentage of total resident population (PUP) and end-of-year resident population (RP) as the driving factors for population. The growth of infrastructure and housing construction will significantly increase fixed asset investment in the whole society. Therefore, this paper selects GDP, per capita GDP (PGDP), gross value of primary industry (PI), gross of secondary industry (SI), gross of tertiary industry (TI), per capita disposable income of city residents (PCIC), and per capita income of rural residents (PCIR) as the driving factors for economic development. Considering that Zhuhai is located in a coastal area with abundant wetland resources and a favorable hydrological environment that is suitable for various fish farming activities, we select the total output value of agriculture, forestry, animal husbandry, and fishery (AFAF) and end-of-year fruit area (FA) as the driving factors for agricultural level. Meanwhile, we select temperature (T) and precipitation (P) as natural factors. Since Zhuhai's terrain is mainly composed of hills and plains, this paper will not consider the impact of basic resource conditions such as elevation and slope on land-use change in this area. The socio-economic and agricultural driving factor data selected for this study are sourced from the Statistical Yearbook of Guangdong Province. (http://stats.gd.gov.cn/gdtjnj, accessed on 20 January 2023).

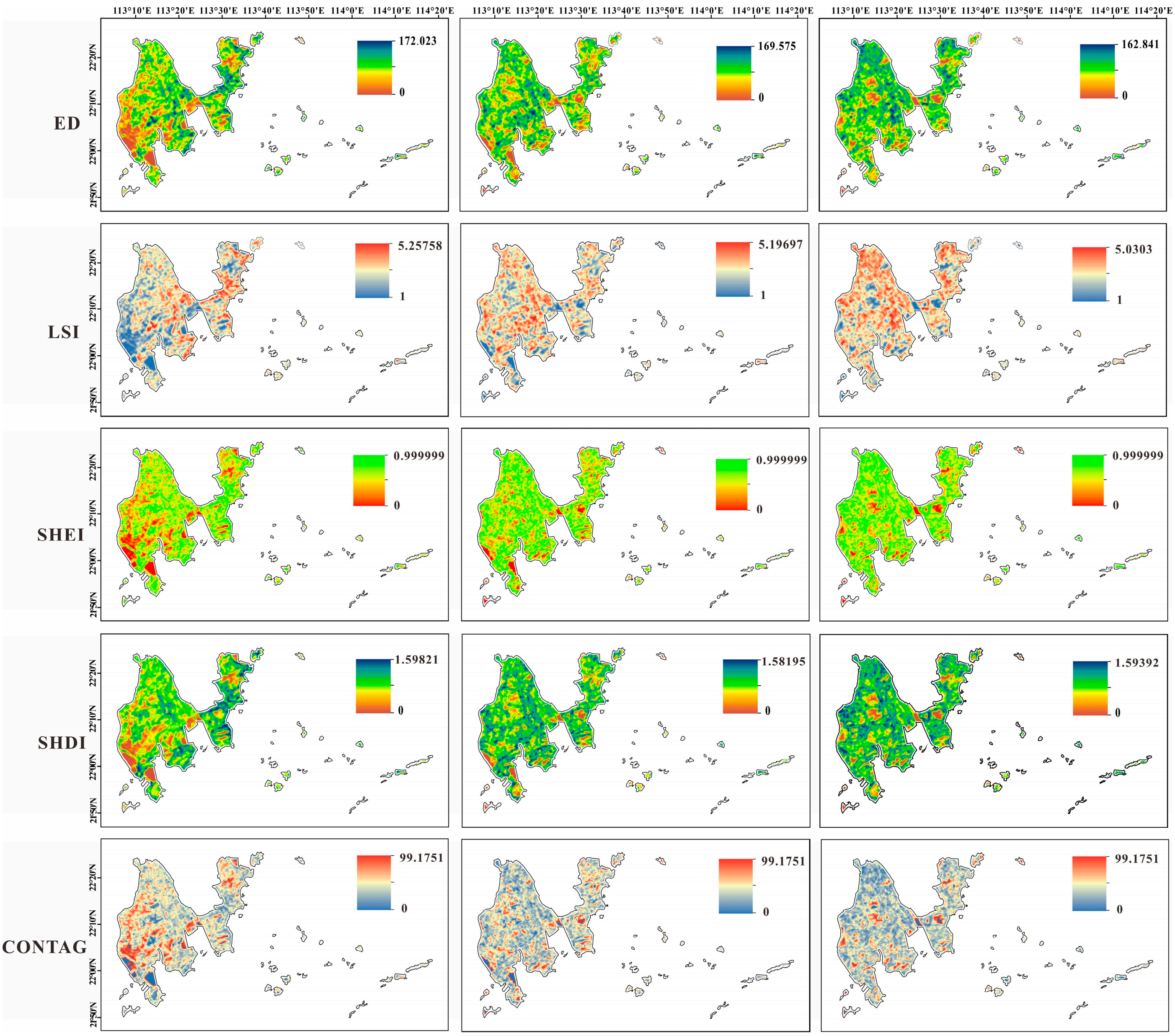

Figure 7. Spatial distribution map of landscape index in Zhuhai City from 1999 to 2019.

The result presents the extraction of two principal components with eigenvalues greater than 1, contributing to a cumulative variance of 91.21%. The analysis indicates that the two principal components can effectively represent the original 13 variables. Subsequently, the rotated component matrix was obtained using the maximum variance method. Table 7 highlights the variation of factors including per capita net income of rural residents (X9), gross value of secondary industry (X6), gross value of tertiary industry (X7), and GDP (X4). Higher loadings in the first component present socio-economic development. These factors are then defined as socio-economic development factors. The second component is predominantly characterized by a larger loading of end-of-year fruit area (X11) and precipitation (X12), which primarily signifies agricultural structural adjustments and climatic background (Table 7).

Table 7. Rotational component matrix.

Indicators	**Element**	
	1	**2**
End-of-year resident population	0.979	0.147
Proportion of urban population to the total resident population	0.963	0.032
Per capita GDP	0.989	0.020
Gross domestic product	0.999	−0.035
Gross value of primary industry	0.989	0.016
Gross value of secondary industry	0.998	0.013
Gross value of tertiary industry	0.995	−0.074
Per capita net income of rural residents	0.998	−0.136
Per capita disposable income of city residents	0.995	−0.074
Gross output of agriculture, forestry, animal husbandry, and fishery	0.981	0.014
End-of-year fruit area	0.143	0.797
Precipitation	0.230	−0.728
Temperature	0.889	0.149

In order to conduct a more in-depth study on the driving factors of the constructed landscape pattern in Zhuhai City, we utilized the analysis method of the grey correlation degree based on principal component analysis. This further enabled us to identify the significant driving factors that cause the spatiotemporal evolution of the landscape pattern in Zhuhai City and analyze their degree of correlation. As shown in Figure 8, the selected socio-economic factors, agricultural factors, and natural factors are strongly correlated with the six landscape indices. The change in land-use landscape pattern is the result of the interaction of multiple influencing factors. In this study, the climatic factors selected have a more obvious driving effect on the landscape indices than the socio-economic factors. This suggests that the change in landscape pattern in Zhuhai City is closely related to both socio-economic development and the natural environment. In terms of landscape shape and diversity, ED, LSI, SHEI, SHDI, and CONTAG are significantly correlated with temperature, precipitation, population, and end-of-year fruit area at the end of the year, with a correlation degree of 0.9. The increase in precipitation, population growth, and the development of agriculture, industry, and economy in the study area lead to a further increase in construction land demand, a decrease in cultivated land, and the continuous desertification of unused land, which further aggravates the landscape fragmentation in Zhuhai City.

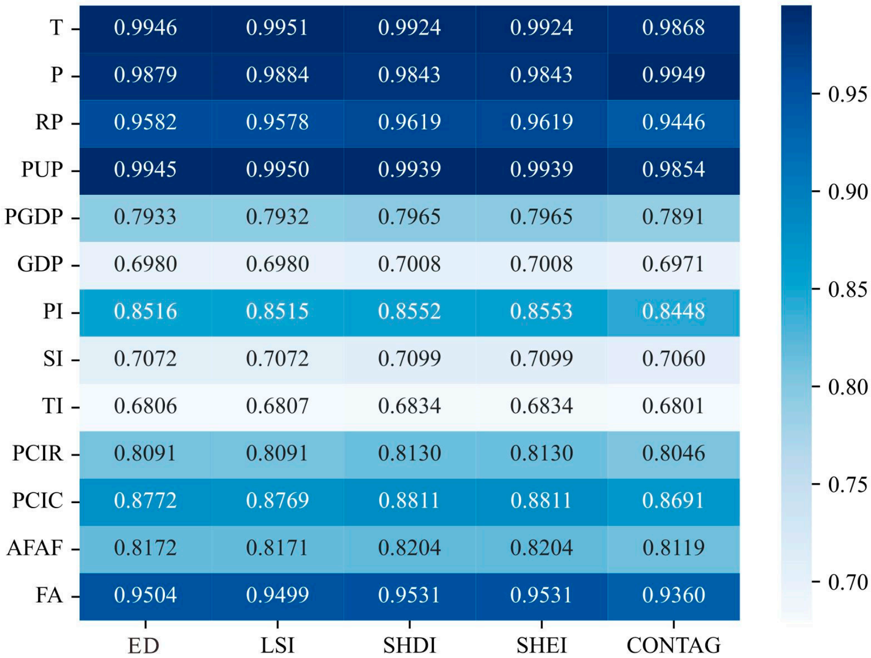

Figure 8. Gray correlation degree of indicators between social, economic, and natural indices and landscape index.

3.3.2. Driving Forces of Landscape Pattern Evolution and Suggestions

Studies have shown that the landscape pattern of Zhuhai City has undergone tremendous changes in the past 20 years, mainly reflecting the impacts of population, economic, and natural factors. Generally, in areas with high urbanization, the rapid expansion of built-up land is coupled with many socio-economic factors [90]. Such us in Tabriz metropolitan area of Iran, where GDP and population are considered as the main drivers of land use change [17]. In the Pearl River Delta region, there is a significant correlation among built-up area, GDP, and permanent population [50,87]. From 1999 to 2019, Zhuhai City experienced rapid economic development, with continuous increases in per capita GDP and regional production value. The secondary and tertiary industries developed rapidly, and the economic growth was accompanied by industrial structure transformation. The structure of the three industries changed from 4.4:51.2:40.0 in 1999 to 1.7:44.5:53.8 in 2019, with the tertiary industry gradually dominating (Figure 9). The permanent population increased year by year, and the rural population migrated to urban areas continuously. This development became the main reason for the increase in built-up land and the potential driving force for the reduction in cultivated land. At the same time, since the reform and opening-up, foreign investment has become a new driving force for urbanization in the Pearl River Delta region of South China. As a core city of the Pearl River Delta, adjacent to Hong Kong and Macao, Zhuhai was influenced by the radiation of Hong Kong and Macao on the mainland economy. In a short period of time, economic structure adjustment, rural industrialization, and an export-oriented economy emerged, making Zhuhai and Shenzhen on the east bank of the Pearl River estuary rapidly develop as a new center of economic growth [91,92]. This inevitably led to a strong encroachment on cultivated land and a vigorous development of unused land to meet the demand for built-up land. For a time, Zhuhai City presented a mixed pattern of cultivated land, built-up land, and residential land. This further aggravated the fragmentation degree of the landscape pattern in this area and significantly reduced spatial aggregation.

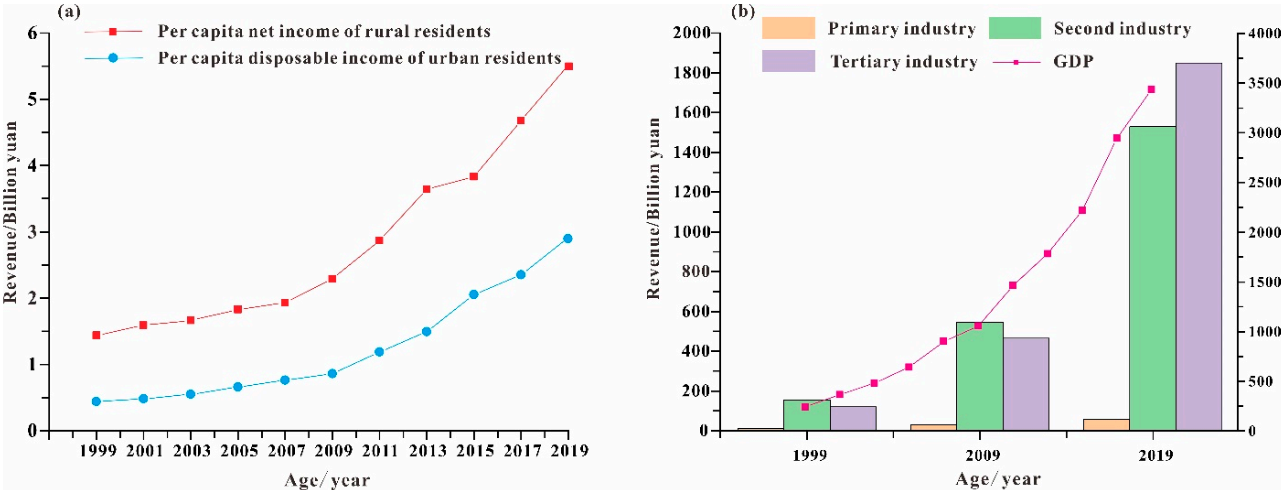

Figure 9. Changes in per capita income, GDP, and output value of various industries in Zhuhai City from 1999 to 2019. (**a**) Per capita income of Zhuhai City. (**b**) Industrial structure of Zhuhai City.

Agricultural adjustment is also a major factor driving the landscape pattern change of Zhuhai City. Zhuhai is located on the west bank of the Pearl River estuary, where the economic benefits of grain crops are far lower than those of aquaculture and fruit tree planting. Farmers developed forestry and fishery farming to increase their income, resulting in a large area of cultivated land being abandoned or converted to other land types, aggravating landscape fragmentation. Since the 18th National Congress of the Communist Party of China, following the call for ecological civilization construction such as "controlling development intensity, adjusting spatial structure", under the new situation of "adhering to the red line of cultivated land, saving and intensive land use", the Zhuhai municipal government actively implemented the national policy and formulated the "Zhuhai City Land Use Master Plan (2006–2020)", strictly protected cultivated land, implemented balance between the occupation and compensation of cultivated land, and carried out a land reclamation plan. Therefore, the decline rate of cultivated land slowed down from 2009 to 2019. However, with the implementation of Zhuhai City's development strategy of "western transformation, eastern development" in 2008 and the continuous improvement in urbanization level, built-up land increased significantly, and most of the area came from cultivated land.

In addition, climatic factors control the overall water and heat resources and further affect the basic pattern of land use by affecting plant growth, soil nutrient supply, and water bodies [93,94]. Zhuhai City has a warm and humid climate, with temperature rising continuously and precipitation fluctuating. Temperature and precipitation changes have a significant impact on the fragmentation degree and landscape diversity of Zhuhai City. The overall topography of Zhuhai City is relatively flat, mainly consisting of plains and hills. The city is crisscrossed by rivers and has abundant wetland resources such as paddy fields and ponds [95]. However, it is highly susceptible to the influence of temperature and rainfall. During dry and warm climates, wetlands may degrade and transform into non-wetlands, resulting in reduced connectivity between wetland patches. Conversely, a warm and humid climate environment is conducive to the restoration and development of water bodies and wetlands. During 20 years, SHEI and SHDI indices showed an upward trend. From 1999 to 2019, the cultivated land area in the study area continued to decrease, accompanied by the conversion to natural landscapes such as forest land and water area, which further increased landscape diversity. However, the CONTAG gradually decreases, and the landscape connectivity deteriorates. This indicates that although the wet and hot climatic conditions can have a positive regulatory effect on the landscape pattern, the increasing human activities gradually replace natural factors, leading to an increase in landscape fragmentation within the study area.

Since the initiation of the reform and opening-up in China, the GBA region has undergone a remarkable increase in urbanization and a sustaining rise in development and construction intensity, resulting in severe ecological damage in recent years [28,30,31]. Zhuhai City, as a core city in the western GBA, prominently experienced a rapid and extensive expansion of non-agricultural construction activities [33]. The haphazard mixing of urban and agricultural areas caused the fragmentation of ecological land use, triggering a range of ecological and environmental challenges [74]. While the "Coordination Development Plan of the Pearl River Delta Urban Agglomeration" has been implemented to enhance the protection of ecological resources, such as forest land and green spaces, across various cities and promote the coordinated development of urban and rural areas, it is essential to address the issues arising from the reduction in cultivated land and the loss of coastal mangrove wetlands [78]. This study contributes a new analysis of land-use changes in Zhuhai over the past twenty years as a case study of suburban landscape changes under recent rapid urbanization in developing counties. The landscape pattern change in Zhuhai such as encroachment on cultivated land, water areas, and undeveloped land should be paid great attention. Future efforts should focus on prudent planning of limited land resources, reinforcing ecological land use. It is crucial to discontinue the extensive mode of land use, cease the practice of acquiring cultivated land without proper utilization, and prevent the unchecked expansion of construction land [96]. In order to achieve sustainable development in the region, it is imperative to establish a harmonious balance between land use and the protection and construction of the ecological environment [97]. This requires coordinated efforts to promote sustainable practices, strike a balance between economic development and ecological preservation, and ensure the long-term well-being of the region.

4. Conclusions

This study employs remote sensing data and relevant landscape indices to analyze landscape pattern evolution in Zhuhai City, along with the driving factors of landscape pattern change. Based on the analysis above, we draw the conclusions as follows:

1. From 1999 to 2019, there was a significant change in land use in Zhuhai City, characterized by a decrease in cultivated land, unused land, and water area and an obvious increase in construction land. The landscape evolution was dominated by a conversion from cultivated land to construction land and forest land. The decreased cultivated land was mainly distributed in the western rural area of Zhuhai.
2. Urbanization gradually increased the fragmentation and the spatial aggregation degree of Zhuhai City overall. The fragmentation degree of landscape patterns increased in Zhuhai over the twenty years along with the enhancement of inferior landscape patches. Moreover, urbanization in the rural area brought about an increase in the fragmentation of the landscape patterns, with a continuous decrease in spatial aggregation.
3. Both socio-economic development and natural environment change factors controlled the landscape pattern change of Zhuhai City over the past twenty years. The improvement in urbanization level has promoted the agricultural transformation with cultivated land loss corresponding to a continuous increase in the per capita net income of rural residents. In addition, this study suggests that coordination of land use along with the protection and construction of the ecological environment is still urgently needed to achieve sustainable development in the region.

Author Contributions: Conceptualization, G.L.; methodology, M.L. and Y.H.; writing—original draft preparation, M.L. and G.C.; writing—review and editing, G.L.; visualization, K.L.; supervision, G.L. and C.Z.; funding acquisition, G.L. and C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number "41704069", Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), grant number "SML2020SP006", and the STU Scientific Research Start-Up Foundation for Talents, grant number "NTF21025".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all patients involved in the study. Written informed consent has been obtained from the patients to publish this paper.

Data Availability Statement: The data associated with this manuscript can be accessed in the text and data sources indicated. The processed data will also be shared in the MDPI journal database.

Acknowledgments: The authors thank Garrett Thompson from the Translation Department in the School of International Studies, Sun Yat-sen University, for language corrections. The authors are also grateful to the editor and three anonymous reviewers for their insightful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pfister, S.; Bayer, P.; Koehler, A.; Hellweg, S. Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environ. Sci. Technol.* **2011**, *45*, 5761–5768. [CrossRef]
2. Ellis, E. *Land Use and Land Cover Change*; Springer: Amestertam, The Netherlands, 2012. Available online: http://www.aughty.org/pdf/landuse_landcover.pdf (accessed on 20 February 2023).
3. Healy, R.G.; Rosenberg, J.S. *Land Use and the States*; Routledge: London, UK, 2013.
4. O'Neill, R.V.; Krummel, J.R.; Gardner, R.E.A.; Sugihara, G.; Jackson, B.; DeAngelis, D.L.; Milne, B.T.; Turner, G.; Zygmunt, B.; Christensen, S.W.; et al. Indices of landscape pattern. *Landsc. Ecol.* **1988**, *1*, 153–162. [CrossRef]
5. Lambin, E.F.; Geist, H.J.; Lepers, E. Dynamics of land-use and land-cover change in tropical regions. *Annu. Rev. Environ. Resour.* **2003**, *28*, 205–241. [CrossRef]
6. Hobbs, R.J. Land-use changes and invasions. *Invasive Speciesi Chang. World.* **2000**, 55–64.
7. Steffen, W.; Crutzen, J.; McNeill, J. The Anthropocene: Are humans now overwhelming the great forces of Nature? *Ambio* **2008**, *36*, 614–621. [CrossRef]
8. Andrew, M.E.; Wulder, M.A.; Nelson, T.A.; Coops, N.C. Spatial data, analysis approaches, and information needs for spatial ecosystem service assessments: A review. *GISci. Remote Sens.* **2015**, *52*, 344–373. [CrossRef]
9. Crespin, S.J.; Simonetti, J.A. Loss of ecosystem services and the decapitalization of nature in El Salvador. *Ecosyst. Serv.* **2016**, *17*, 5–13. [CrossRef]
10. Fu, Q.; Li, B.; Hou, Y.; Bi, X.; Zhang, X. Effects of land use and climate change on ecosystem services in Central Asia's arid regions: A case study in Altay Prefecture, China. *Sci. Total Environ.* **2017**, *607–608*, 633–646. [CrossRef]
11. Hasan, S.S.; Zhen, L.; Miah, M.G.; Ahamed, T.; Samie, A. Impact of land use change on ecosystem services: A review. *Environ. Dev.* **2020**, *34*, 100527. [CrossRef]
12. Creutzig, F.; d'Amour, C.B.; Weddige, U.; Fuss, S.; Edenhofer, O. Assessing human and environmental pressures of global land-use change 2000–2010. *Glob. Sustain.* **2019**, *2*, e1. [CrossRef]
13. Li, H.; Zhang, H.; Li, Q.; Zhao, J.; Guo, X.; Ying, H.; Deng, G.; Rihan, W.; Wang, S. Vegetation productivity dynamics in response to climate change and human activities under different topography and land cover in Northeast China. *Remote Sens.* **2021**, *13*, 975. [CrossRef]
14. Chatterjee, U.; Majumdar, S. Impact of land use change and rapid urbanization on urban heat island in Kolkata city: A remote sensing based perspective. *J. Environ. Manag.* **2022**, *11*, 59–71. [CrossRef]
15. Rabby, Y.W.; Li, Y.; Abedin, J.; Sabrina, S. Impact of land use/land cover change on landslide susceptibility in Rangamati municipality of Rangamati District, Bangladesh. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 89. [CrossRef]
16. Salvati, L.; Zambon, I.; Chelli, F.M.; Serra, P. Do spatial patterns of urbanization and land consumption reflect different socioeconomic contexts in europe? *Sci. Total Environ.* **2018**, *625*, 722–730. [CrossRef]
17. Dadashpoor, H.; Azizi, P.; Moghadasi, M. Land use change, urbanization, and change in landscape pattern in a metropolitan area. *Sci. Total Environ.* **2019**, *655*, 707–719. [CrossRef] [PubMed]
18. Woodroffe, C.D.; Nicholls, R.J.; Saito, Y.; Chen, Z.; Goodbred, S.L. Landscape variability and the response of Asian megadeltas to environmental change. In *Global Change and Integrated Coastal Management the Asia-Pacific Region*; Springer: Dordrecht, The Netherlands, 2006; pp. 277–314.
19. Chaves, L.F.; Hamer, G.L.; Walker, E.D.; Brown, W.M.; Ruiz, M.O.; Kitron, U.D. Climatic variability and landscape heterogeneity impact urban mosquito diversity and vector abundance and infection. *Ecosphere* **2011**, *2*, 1–21. [CrossRef]
20. McGarigal, K. *Landscape Pattern Metrics*; American Cancer Society: Atlanta, GA, USA, 2002. Available online: https://doi.org/10.1002/9781118445112.stat07723 (accessed on 20 February 2023).
21. Bell, S. *Landscape: Pattern, Perception and Process*; Routledge: London, UK, 2012.
22. Riitters, K.H.; O'neill, R.V.; Hunsaker, C.T.; Wickham, J.D.; Yankee, D.H.; Timmins, S.P.; Jones, R.H.; Jackson, B.L. A factor analysis of landscape pattern and structure metrics. *Landsc. Ecol.* **1995**, *10*, 23–39. [CrossRef]
23. PyšEK, P.; Hulme, P.E. Spatio-temporal dynamics of plant invasions: Linking pattern to process. *Ecoscience* **2005**, *12*, 302–315. [CrossRef]

24. Murakami, A.; Zain, A.M.; Takeuchi, K.; Tsunekawa, A.; Yokota, S. Trends in urbanization and patterns of land use in the Asian mega cities Jakarta, Bangkok, and Metro Manila. *Landsc. Urban Plan.* **2005**, *70*, 251–259. [CrossRef]
25. Deng, J.S.; Wang, K.; Hong, Y.; Qi, J.G. Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization. *Landsc. Urban Plan.* **2009**, *92*, 187–198. [CrossRef]
26. Darrel Jenerette, G.; Potere, D. Global analysis and simulation of land-use change associated with urbanization. *Landsc. Ecol.* **2010**, *25*, 657–670. [CrossRef]
27. Corry, R.C.; Nassauer, J.I. Limitations of using landscape pattern indices to evaluate the ecological consequences of alternative plans and designs. *Landsc. Urban Plan.* **2005**, *72*, 265–280. [CrossRef]
28. Zhao, S.M.; Ma, Y.F.; Wang, J.L.; You, X.Y. Landscape pattern analysis and network planning of Tianjin City. *Urban For. Urban Green.* **2019**, *46*, 126479. [CrossRef]
29. Huang, B.X.; Chiou, S.C.; Li, W.Y. Landscape pattern and ecological network structure in urban green space planning: A case study of Fuzhou city. *Land* **2021**, *10*, 769. [CrossRef]
30. Dong, J.; Jiang, H.; Gu, T.; Liu, Y.; Peng, J. Sustainable landscape pattern: A landscape approach to serving spatial planning. *Landsc. Ecol.* **2022**, *37*, 31–42. [CrossRef]
31. Chuai, X.; Huang, X.; Wu, C.; Li, J.; Lu, Q.; Qi, X.; Zhang, M.; Zuo, T.; Lu, J. Land use and ecosystems services value changes and ecological land management in coastal Jiangsu, China. *Habitat Int.* **2016**, *57*, 164–174. [CrossRef]
32. Hu, Y.; Zhang, Y. Spatial–temporal dynamics and driving factor analysis of urban ecological land in Zhuhai city, China. *Sci. Rep.* **2020**, *10*, 16174. [CrossRef]
33. Li, J.; Li, C.; Zhu, F.; Song, C.; Wu, J. Spatiotemporal pattern of urbanization in Shanghai, China between 1989 and 2005. *Landsc. Ecol.* **2013**, *28*, 1545–1565. [CrossRef]
34. Li, H.; Peng, J.; Yanxu, L.; Yi'na, H. Urbanization impact on landscape patterns in Beijing City, China: A spatial heterogeneity perspective. *Ecol. Indic.* **2017**, *82*, 50–60. [CrossRef]
35. Long, H.; Liu, Y.; Hou, X.; Li, T.; Li, Y. Effects of land use transitions due to rapid urbanization on ecosystem services: Implications for urban planning in the new developing area of China. *Habitat. Int.* **2014**, *44*, 536–544. [CrossRef]
36. Lin, G.C. Metropolitan development in a transitional socialist economy: Spatial restructuring in the Pearl River Delta, China. *Urban Stud.* **2001**, *38*, 383–406. [CrossRef]
37. Fan, Q.; Ding, S. Landscape pattern changes at a county scale: A case study in Fengqiu, Henan Province, China from 1990 to 2013. *Catena* **2016**, *137*, 152–160. [CrossRef]
38. Fang, C.; Li, G.; Wang, S. Changing and differentiated urban landscape in China: Spatiotemporal patterns and driving forces. *Environ. Sci. Technol.* **2016**, *50*, 2217–2227. [CrossRef] [PubMed]
39. Wang, S.; Wu, M.; Hu, M.; Xia, B. Integrating ecosystem services and landscape connectivity into the optimization of ecological security pattern: A case study of the Pearl River Delta, China. *Envion. Sci. Pollut. Res.* **2022**, *29*, 76051–76065. [CrossRef]
40. Li, L.; Huang, X.; Wu, D.; Yang, H. Construction of ecological security pattern adapting to future land use change in Pearl River Delta, China. *Appl. Geogr.* **2023**, *154*, 102946. [CrossRef]
41. Wu, J.; Wu, C.; Zhang, Q.; Zhuang, M.; Xiao, H.; Wu, H.; Ouyang, L.; Liu, Y.; Meng, C.; Song, C.; et al. Spatiotemporal Evolution of Urban Agglomeration and Its Impact on Landscape Patterns in the Pearl River Delta, China. *Remote Sens.* **2023**, *15*, 2520. [CrossRef]
42. Liu, W.; Zhan, J.; Zhao, F.; Yan, H.; Zhang, F.; Wei, X. Impacts of urbanization-induced land-use changes on ecosystem services: A case study of the Pearl River Delta Metropolitan Region, China. *Ecol. Indic.* **2019**, *98*, 228–238. [CrossRef]
43. Yang, R.; Zhang, J.; Xu, Q.; Luo, X. Urban-rural spatial transformation process and influences from the perspective of land use: A case study of the Pearl River Delta Region. *Habitat Int.* **2020**, *104*, 102234. [CrossRef]
44. Luck, M.; Wu, J. A gradient analysis of urban landscape pattern: A case study from the Phoenix metropolitan region, Arizona, USA. *Landsc. Ecol.* **2002**, *17*, 327–339. [CrossRef]
45. Chen, X.; Li, F.; Li, X.; Hu, Y.; Hu, P. Quantifying the Compound Factors of Forest Land Changes in the Pearl River Delta, China. *Remote Sens.* **2021**, *13*, 1911. [CrossRef]
46. Sheng, N.; Tang, U.W. Zhuhai. *Cities Int. J. Urban Policy Plan.* **2013**, *32*, 70–79. [CrossRef]
47. Wu, Z.; Wang, J.; Zhuo, M.; Wan, H. Spatial distribution and landscape ecological impact degree assessment of quarry in Zhuhai City. *J. Appl. Ecol.* **2004**, *15*, 283–286.
48. Cui, N.; Feng, C.C.; Wang, D.; Li, J.; Guo, L. The effects of rapid urbanization on forest landscape connectivity in Zhuhai City, China. *Sustainability* **2018**, *10*, 3381. [CrossRef]
49. Liu, Y.; Cui, N.; Han, R.; Guo, L. Establishing ecological security patterns based on reconstructed ecosystem services value in rapidly urbanizing areas: A case study in Zhuhai City, China. *Sustainability* **2020**, *12*, 6629. [CrossRef]
50. Chen, S.; Zhu, Z.; Liu, X.; Yang, L. Variation in vegetation and its driving force in the Pearl River Delta region of China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10343. [CrossRef] [PubMed]
51. Zong, Y.; Huang, K.; Yu, F.; Zheng, Z.; Switzer, A.; Huang, G.; Ning, W.; Tang, M. The role of sea-level rise, monsoonal discharge and the palaeo-landscape in the early Holocene evolution of the Pearl River delta, southern China. *Quat. Sci. Rev.* **2012**, *54*, 77–88. [CrossRef]
52. Aitchison, J.C.; Ali, J.R.; Davies, A.M. When and where did India and Asia collide? *J. Geophys. Res. Solid Earth* **2007**, *112*, B05423. [CrossRef]

53. Weng, Q. A historical perspective of river basin management in the Pearl River Delta of China. *J. Environ. Manag.* **2007**, *85*, 1048–1062. [CrossRef]
54. Li, X.; Luo, Y.; Wu, J. Decoupling relationship between urbanization and carbon sequestration in the Pearl river delta from 2000 to 2020. *Remote Sens.* **2022**, *14*, 526. [CrossRef]
55. Wu, X.; Huang, Y.; Gao, J. Impact of industrial agglomeration on new-type urbanization: Evidence from Pearl River Delta urban agglomeration of China. *Int. Rev. Econ. Financ.* **2022**, *77*, 312–325. [CrossRef]
56. Fu, J.; Mai, B.; Sheng, G.; Zhang, G.; Wang, X.; Xiao, X.; Ran, R.; Cheng, F.; Peng, X.; Wang, Z.; et al. Persistent organic pollutants in environment of the Pearl River Delta, China: An overview. *Chemosphere* **2003**, *52*, 1411–1422. [CrossRef]
57. Zhao, X.; Zhang, Q.; He, G.; Zhang, L.; Lu, Y. Delineating pollution threat intensity from onshore industries to coastal wetlands in the Bohai Rim, the Yangtze River Delta, and the Pearl River Delta, China. *J. Clean. Prod.* **2021**, *320*, 128880. [CrossRef]
58. NOAA National Centers for Environmental Information. 2022: ETOPO 2022 15 Arc-Second Global Relief Model. NOAA National Centers for Environmental Information. Available online: https://data.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM//iso/xml/etopo_2022.xml&view=getDataView&header=none (accessed on 25 February 2023).
59. *GB/T 21010-2017*; Classification of Land Use Status. China National Standardization Administration: Beijing, China, 2017.
60. Peng, L.; Dong, B.; Wang, P.; Sheng, S.; Sun, L.; Fang, L.; Li, H.; Liu, L. Research on ecological risk assessment in land use model of Shengjin Lake in Anhui province, China. *Environ. Geochem. Health* **2019**, *41*, 2665–2679. [CrossRef] [PubMed]
61. Foody, G.M. Status of land cover classification accuracy assessment. *Remote Sens. Environ.* **2002**, *80*, 185–201. [CrossRef]
62. Dong, Y.; Xu, L. Aggregate risk of reactive nitrogen under anthropogenic disturbance in the Pearl River Delta urban agglomeration. *J. Clean. Prod.* **2019**, *211*, 490–502. [CrossRef]
63. Zhu, H.Y.; Li, X.B. Discussion on the index method of regional land use change. *Acta Geogr. Sin.* **2003**, *3*, 643–650.
64. Lu, C.M.; Qi, L.G.; Sang, C.J. Analysis on mathematic model of land use changes. *Resour. Dev. Mark.* **2007**, *7*, 25–27.
65. Liu, J.Y.; Zhang, Z.X.; Zhuang, D.F.; Wang, Y.M.; Zhou, W.C.; Zhang, S.W.; Li, R.D.; Jiang, N.; Wu, S.X. A study on the spatial-temporal dynamic changes of land-use and driving forces analyses of China in the 1990s. *Geogr. Res.* **2003**, *22*, 1–12.
66. Li, Y.F.; Liu, G.H.; Huang, C. Dynamic changes analysis and hotspots detection of land use in the central core functional area of Jing-Jin-Ji from 2000 to 2015 based on remote sensing data. *Math. Probl. Eng.* **2017**, *2017*, 2183585. [CrossRef]
67. He, P.; Zhang, H.R. Study on factor analysis and selection of common on landscape metrics. *For. Res. Beijing* **2009**, *22*, 470–474.
68. McGarigal, K.; Marks, B.J. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*; General Technical Report PNW-GTR-351; Pacific Northwest Research Station, U.S. Department of Agriculture, Forest Service: Portland, OR, USA, 1995.
69. Cabral, A.I.; Costa, F.L. Land cover changes and landscape pattern dynamics in Senegal and Guinea Bissau borderland. *Appl. Geogr.* **2017**, *82*, 115–128. [CrossRef]
70. Schindler, S.; Wehrden, H.V.; Poirazidis, K.; Hochachka, W.M.; Wrbka, T.; Kati, V. Performance of methods to select landscape metrics for modeling species richness. *Ecol. Model.* **2015**, *295*, 107–112. [CrossRef]
71. Kuwil, F.H.; Atila, Ü.; Abu-Issa, R.; Murtagh, F. A novel data clustering algorithm based on gravity center methodology. *Expert Syst. Appl.* **2020**, *156*, 113435. [CrossRef]
72. Zhang, W.L. The application of Principal Component Analysis (PCA) in SPSS. *Mark. Res.* **2005**, *12*, 31–34.
73. Hu, R.M.; Du, S.; Li, P.F.; Yao, Y.Z.; Wang, R.Z.; Teng, K.Y. Analysis of landscape fragmentation and driing forces in semiarideco-logically fragile regions based on the moving window method. *J. Agric. Resour. Econ.* **2021**, *38*, 502–511.
74. Xian, S.; Li, L.; Qi, Z. Toward a sustainable urban expansion: A case study of Zhuhai, China. *J. Clean. Prod.* **2019**, *230*, 276–285. [CrossRef]
75. Liu, T.; Liu, H.; Qi, Y. Construction land expansion and cultivated land protection in urbanizing China: Insights from national land surveys, 1996–2006. *Habitat Int.* **2015**, *46*, 13–22. [CrossRef]
76. Seto, K.C.; Güneralp, B.; Hutyra, L.R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 16083–16088. [CrossRef]
77. Bren d'Amour, C.; Eitelberg, D.A.; Verburg, P.H. A global analysis of land take in cropland areas and production displacement from urbanization. *Glob. Environ. Chang.* **2017**, *43*, 107–115.
78. Tang, Y.; Fang, Z.; Zhang, Z.; Zhong, Y.; Chen, K.; Liu, B.; Fan, J.; Xiong, T.; Lu, X. Ecological indicators showing the succession of macrofauna communities in Sonneratia apetala artificial mangrove wetlands on Qi'ao Island at Zhuhai, South China. *Acta Oceanol. Sin.* **2014**, *33*, 62–72. [CrossRef]
79. Yu, J.; Zhou, K.; Yang, S. Land use efficiency and influencing factors of urban agglomerations in China. *Land Use Policy* **2019**, *88*, 104143. [CrossRef]
80. Fu, F.; Deng, S.; Wu, D.; Liu, W.; Bai, Z. Research on the spatiotemporal evolution of land use landscape pattern in a county area based on CA-Markov model. *Sustain. Cities Soc.* **2022**, *80*, 103760. [CrossRef]
81. Briassoulis, H. Factors influencing land-use and land-cover change. *Land Cover Land Use Glob. Chang. Encycl. Life Supp. Syst. (EOLSS)* **2009**, *1*, 126–146.
82. Sterling, S.M.; Ducharne, A.; Polcher, J. The impact of global land-cover Change on the terrestrial water cycle. *Nat. Clim. Chang.* **2013**, *3*, 385–390. [CrossRef]
83. Amuti, T.; Luo, G. Analysis of land cover change and its driving forces in a desert oasis landscape of Xinjiang, northwest China. *Solid Earth* **2014**, *5*, 1071–1085. [CrossRef]

84. Liu, Y.; Liu, S.; Sun, Y.; Wang, F.; Li, M. Driving forces of cultivated land evolution in agropastoral areas on the Qinghai-Tibet Plateau based on ecological niche theory. *J. Clean. Prod.* **2021**, *313*, 127899. [CrossRef]
85. Hamidov, A.; Helming, K.; Balla, D. Impact of agricultural land use in Central Asia: A review. *Agron. Sustain. Dev.* **2016**, *36*, 6. [CrossRef]
86. Mborah, C.; Bansah, K.J.; Boateng, M.K. Evaluating alternate post-mining land-uses: A review. *Environ. Pollut.* **2016**, *5*, 14–22. [CrossRef]
87. Dai, E.; Wu, Z.; Du, X. A gradient analysis on urban sprawl and urban landscape pattern between 1985 and 2000 in the Pearl River Delta, China. *Front. Earth Sci.* **2018**, *12*, 791–807. [CrossRef]
88. Hu, X.H.; David, H.K. The emergence of affluence in Beijing: Residential social stratification in China's capital city. *Urban Geogr.* **2001**, *22*, 54–77. [CrossRef]
89. Tendaupenyu, P.; Magadza, C.H.D.; Murwira, A. Changes in land-use/landcover patterns and human population growth in the Lake Chivero catchment, Zimbabwe. *Geocarto Int.* **2017**, *32*, 797–811. [CrossRef]
90. Jia, L.; Ma, Q.; Du, C.; Hu, G.; Shang, C. Rapid urbanization in a mountainous landscape: Patterns, drivers, and planning implications. *Landsc. Ecol.* **2020**, *35*, 2449–2469. [CrossRef]
91. Ye, C.; Hu, L.; Li, M. Urban green space accessibility changes in a high-density city: A case study of Macau from 2010 to 2015. *J. Transp. Geogr.* **2018**, *66*, 106–115. [CrossRef]
92. Zhang, X.; Kloosterman, R.C. Connecting the 'workshop of the world': Intra and extra-service networks of the Pearl River Delta city-region. *Reg. Stud.* **2016**, *50*, 1069–1081. [CrossRef]
93. McGrane, S.J. Impacts of urbanization on hydrological and water quality dynamics, and urban water management: A review. *Hydrol. Sci.* **2016**, *61*, 2295–2311. [CrossRef]
94. Omurakunova, G.; Bao, A.; Xu, W.; Duulatov, E.; Jiang, L.; Cai, P.; Abdullaev, F.; Nzabarinda, V.; Durdiev, K.; Baiseitova, M. Expansion of impervious surfaces and their driving forces in highly urbanized cities in Kyrgyzstan. *Int. J. Environ. Res. Public Health* **2020**, *17*, 362. [CrossRef] [PubMed]
95. Yu, L.; Dang, X.H.; Ji, C. Wetland Landscape Pattern Evolution and Its Driving Force Analysis in Zhuhai City. *Geospat. Inf.* **2021**, *19*, 48–53+7.
96. Bey, A.; Sánchez-Paus Díaz, A.; Maniatis, D.; Marchi, G.; Mollicone, D.; Ricci, S.; Bastin, J.F.; Morre, R.; Federici, S.; Rezende, M.; et al. Collect earth: Land use and land cover assessment through augmented visual interpretation. *Remote Sens.* **2016**, *8*, 807. [CrossRef]
97. Silberstein, J.; Maser, C. *Land-Use Planning for Sustainable Development*; CRC Press: Boca Raton, FL, USA, 2013.