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Article

A Spatiotemporal Pattern Analysis of High-Frequency Land-Use Changes in the Guangdong–Hong Kong–Macao Greater Bay Area, from 1990 to 2018

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Abstract: With continuous rises in GDP, land cover in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) has undergone a drastic change over the period 1990–2018. In this study, land use in the GBA was divided into six types: farmland, forestland, grassland, wetland, construction land, and unused land. We analyzed changes in spatiotemporal patterns according to region and type by using statistical analysis, spatial clustering, and hotspot analysis, focusing on the spatial characteristics of areas where land-use types changed with high frequency. The high-frequency land use in the GBA has strategic guidance for further urban planning and management. With discussions on urban planning, the natural environment, and social and economic development, we found the following: (1) Urban construction land in the GBA showed a unipolar growth mode, increasing from 5.63% to 14.34% from 1990 to 2018. Accordingly, the degree of urban concentration and contiguity rose continuously. (2) Hotspots with frequent land-use changes were concentrated mainly in areas with economic intensity. (3) Plots with high-frequency land-use changes (Flc > 2) were concentrated primarily in the waters and rivers of the GBA within 10 km of the administrative boundaries of prefecture-level cities. (4) Nearly 80% of the land has been or will be transformed into ecological land over the period 1990–2018. On the basis of these findings, we suggest further improving land-use efficiency, and ecological land damage and the over-occupation of sea space should be avoided while maintaining economic growth. Thus, linking increases and decreases in construction land is an excellent land-consolidation mechanism to transform inefficient urban land into ecological land.

Keywords: Guangdong–Hong Kong–Macao Greater Bay Area; land-use change; transition matrix; high-frequency region; land arrangement

Citation: Lv, C.; Lian, A.; Wang, Z.; Jia, T.; Sun, X.; Dong, R. A Spatiotemporal Pattern Analysis of High-Frequency Land-Use Changes in the Guangdong–Hong Kong–Macao Greater Bay Area, from 1990 to 2018. *Land* **2023**, *12*, 102. https://doi.org/10.3390/land12010102

Academic Editor: Le Yu

Received: 2 December 2022
Revised: 21 December 2022
Accepted: 23 December 2022
Published: 28 December 2022

1. Introduction

Land is regarded as a vital resource and material guarantee for humans. Land resources are at the basic position in the complex system of population–resource–environment–development (PRED). Land use reflects the closest and most direct interaction between humans and nature [1]. Thus, humans generate economic development and material wealth as the result of land use and affect natural resources from the perspectives of their structure, ecology, and environment [2]. In recent decades, China has experienced rapid economic development and unprecedented urbanization. Consequently, China is facing various sustainable problems related to land use, which cover population growth, resource depletion, and ecological and environmental deterioration. The urgency and the value of research on land use are determined by the polygenesis and structural complexity of land use [3]. From 1990 to 2018, the proportion of the population in urban areas increased from 26.41% to 59.58% [4]. With this accelerated urbanization, land-use patterns have changed dramatically, and the contradiction between human activity and the land has become increasingly prominent. Economic development and environmental protection have a complicated history in China, arising from the competing needs to boost rural economies and conserve natural resources. More recently, China has shifted from a "grow first, clean up later" approach toward an "ecological civilization" orientation, in which development respects environmental carrying capacity [5]. Relatedly, cities are typical complex socioeconomic ecosystems [6], and land-use changes result from multiple factors. Urbanization was inevitably accelerated in the GBA. In addition to the boost in the economy, the population clustering and change in the ecosystem also led to problems. The significance of land-use change is worth discussing.

The environmental effect of land-use/-cover change (LUCC) is an important research topic [7]. Previous studies have used change detection to understand LUCC patterns and processes [8]. Jin et al. started with the physical characteristics of LUCC and built a diffusion equation to stimulate and predict urban LUCC [9]. In contrast, Gibas and Majorek took a further step to create an evaluation method on LUCC under the background of sustainable development, which evaluates LUCC in Europe on the scales of society, economy, and environment. The evaluation method created by Gibas and Majorek helps balance the reasonable usage of natural resources and sustainable development in urban land use [10]. The spatial patterns of urban change in two Chinese urban megaregions, Beijing–Tianjin–Hebei and the Yangtze River Delta, have been examined in the context of national urbanization policies and the associated modes of economic growth. Davis [11] summarized the amount of deforestation, reforestation, and persistent forestation for different time intervals (1938–1956, 1956–1975, 1975–1997, and 1997–2009) and then compared the trends by using a time interval capturing only the first and last periods. Studying the Beijing–Tianjin–Hebei and Yangtze River Delta urban megaregions, Yu et al. comparatively quantified urban expansion and change on the basis of developed land on both the regional and city scales during 1984–2010 [12]. Yang (2021), meanwhile, found that changes in the thermal environment were closely related to variations in the urban form in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) [13].

After China's reform and opening-up, rapid socioeconomic development occurred in the coastal areas, the urbanization rate continuously increased, and land-use types considerably changed [14]. Many studies have investigated the spatial patterns of land-use change and changes in ecosystem service value in the GBA [15–18]. Few, however, have conducted hotspot analyses of land-use changes in the GBA using long time series. The land-use-change trajectory model is widely used in research on the spatiotemporal evolution of land-use changes [19]. Also, the similarity/turnover/diversity indicators represent the similarity, change times, and diversity of the evolution process of each spatial land unit during the study period. The comprehensive dynamic degree of land use is also used as an analysis index of land-use-change hotspots [20,21]. Liu et al. used the number of land-use changes during the study period as an index to identify global land-use transformation patterns and hotspots [22]. Watson et al. used the frequency of land-use change as an indicator to study the effect of land-use change on biological communities [23]. Generally, depicting the characteristics of regional land-use changes and hotspots is vital for land-resource governance and ecosystem construction.

China initiated a land-consolidation project in the late 1990s that was implemented primarily after 2008. It was a far-reaching land-use-change project that had profound effects on ecosystems. Land consolidation has become essential to China's landscape ecology practices [24].

Along with the New York, San Francisco, and Tokyo Bay areas, the GBA is one of the four largest bay areas in the world [25]. The GBA urban agglomeration has a high degree of openness and economic vitality, and its development has been an essential part of China's strategic planning. The strategic position of the GBA places higher requirements on the GBA for top-level design, industrial complementarity, market integration, and resource allocation [26]. The GBA's advanced stage of development in terms of industrialization, urbanization, socioeconomic level, social systems, and market mechanisms has essential effects on land space. Therefore, the GBA is a suitable "experimental field" for studying land-space evolution. Urban construction in the GBA has occupied a great deal of forestland, farmland, and wetland in recent decades. As a result, the functioning of land and sea ecosystems, the retention rate of natural coastline, and biodiversity have all been significantly reduced, and environmental problems have become increasingly prominent [27–30]. Analyzing the spatial land structure and its evolution characteristics can therefore provide important scientific support for land use and spatial planning. The mentioned previous studies provide insightful methods to discuss the transformation on ecological patterns [18,31], LUCC efficiency [32], and ecological system service [33,34] in the GBA, but these studies lack in covering LUCC frequency for spatiotemporal characteristics.

This study aimed to explore the spatial characteristics of LUCC in the GBA. Our research questions were as follows:

1. What are the spatiotemporal characteristics of construction land expansion in the GBA?
2. Which plots have a higher change rate than other areas?
3. Why was almost all this high-frequency change region finally transformed into ecological lands, such as forests, wetlands, and grassland?
4. To maintain land stability and reach sustainable development on future land use, what methods can reduce change frequency and disturbance?

To answer these questions, we quantified the spatiotemporal characteristics of urban expansion on the basis of thematic land-use and land-cover (LULC) maps. Then, we calculated the land-use-change transfer matrix of the study area for the period 1990–2018 to reveal the transformation relationships of each category. Finally, we further analyzed spatial clustering by using a hotspot analysis.

2. Materials and Methods

2.1. Study Area

The GBA is located between 21°33′–24°23′ N and 111°21′–115°25′ E. It includes the Hong Kong and Macao Special Administrative Regions, Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing in Guangdong Province. Its total area is about 55,000 km^2 (Figure 1). The GBA is in the coastal impact plain of the Dongjiang River, Xijiang River, and Beijiang River in the Pearl River Basin. It has a tropical and subtropical monsoon climate. The average annual temperature is 22.3 °C, and the average annual precipitation is 1300–2500 mm. Since China's reform and opening-up, especially after the handover of Hong Kong and Macao, the GBA has been continuously integrated, and its economic strength and overall influence have been enhanced. It has obvious geographical advantages, good economic strength, an aggregation of innovative elements, and conditions conducive to building a first-class international bay area and world-class urban agglomeration [35].

2.2. Extracting Land-Use-Change Information

2.2.1. Determining a Land-Classification System

Defining a standard land-use classification system is crucial to analyzing land-cover changes. Our classification system included six types to match historical data resources and facilitate comparative analysis: farmland, forestland, grassland, wetland, construction land, and unused land. See Table 1 for the corresponding secondary classification system. This classification system was settled by Lambin et al. to gain a common understanding of the cause of LUCC, which provides succinct categories on different land types [36].

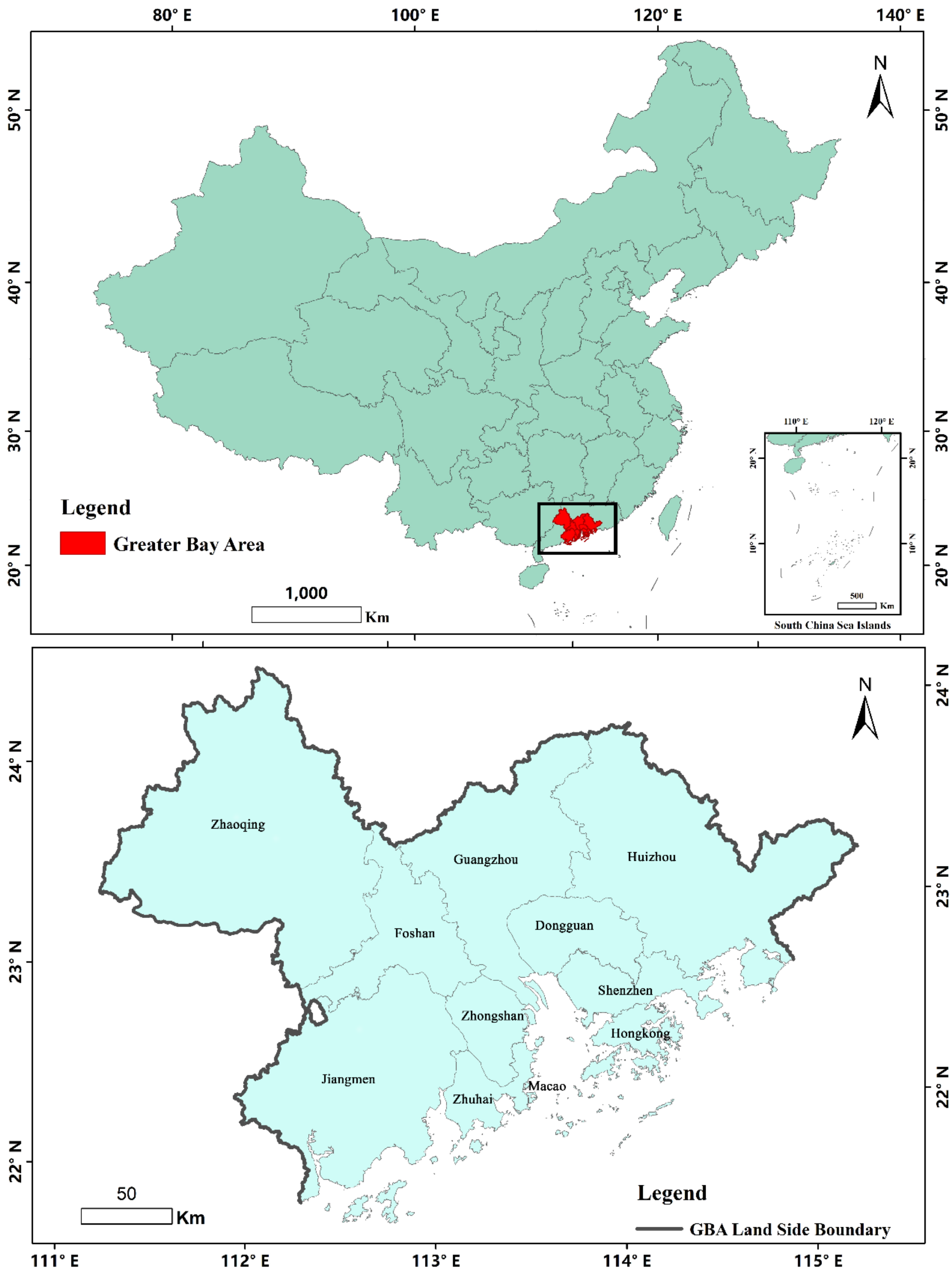


Figure 1. Location of the study area.

Table 1. Land-use classification system for the Guangdong–Hong Kong–Macao Greater Bay Area (GBA).

Primary Classification	Secondary Classification
Farmland	Paddy field, dry land
Forestland	Forested land, shrubland, open woodland, and other woodlands
Grassland	High-coverage grassland, medium-coverage grassland, and low-coverage grassland
Wetland	Canal, lake, reservoir pit, tidal flat, and beach land
Construction land	Town, rural residential area, and industrial and mining land
Unused land	Sand, marshland, bare land, and other

2.2.2. Remote-Sensing Data Selection and Processing

In this study, we used multisensory remote-sensing data from Landsat, which was used as a progressive technique scanner; then, a massive amount of data can be enhanced for further analysis. The data were preprocessed and derived from the distributed database. On the basis of the "China Five–Year Interval Terrestrial Ecosystem Spatial Distribution Data Set (1990–2010)" [37], we selected 1990, 1995, 2000, 2005, and 2010 as our five periods of spatial data. Further, 2018 land-use data for the GBA were obtained from the cloud platform of China's geographical situation monitoring. There were six phases of data in total; these data were dominantly collected from each period of Landsat TM/ETM remote sensing, all of which were resampled to the same spatial coordinate system and exact spatial resolution (100 m). We took 2018 land-use data as the final attribution after years of land-use transformation.

The statistics focused on the period from 1990 to 2018 in the GBA, each administrative region and assigned land-use area, and the spatial distribution of different land types. In the analysis of the spatial change of land use, we assigned different values to the two adjacent land-use data, where the former data were assigned with 0, -1, -2, -3, -4, and -5 and the latter data with 1, 7, 13, 19, 25, and 31. After subducting the latter on the former data, we can obtain a spatial distribution map of land-use types with the value from 1 to 36, which reflects the 36 types of transformation on different land use about the two adjacent land-use data.

2.2.3. Transformed Flow-Direction Analysis

The software that we selected to process results was ArcMap 10.2 (ArcGIS), a powerful type of software to process complex calculations of target geographic data. We used the Grid Calculation Tool in ArcMap 10.2 to calculate the land-use-change transfer matrix of the study area from 1990 to 2018, which revealed the transformation relationships of each category over time, and thus to understand the structural characteristics of each category before and after different times. The time periods were represented by T_0 (1990–2018), T_1 (1990–1995), T_2 (1995–2000), T_3 (2000–2005), T_4 (2005–2010), and T_5 (2010–2018).

2.2.4. Plot Analysis of High-Frequency Change

We used the overlay analysis tool in ArcMap 10.2 to implement our analysis. Analyzing changes involves measuring differences during the study period, including spatiotemporal patterns and the magnitude and rate of variations. Depending on whether the land-use type of the same image element had changed in two adjacent data periods, the number of land-use changes during the six periods was calculated and defined as the land-use-change frequency F_{lc}. The F_{lc} in the six periods was 5, 4, 3, 2, 1, and 0. Land-use-change frequency was classified into low, slightly low, neutral, slightly high, high, and extremely high, according to the number of changes.

F_{lc} was used to characterize the intensity of land-use change. The higher the frequency of land-use change, the more drastic the land-use change and the higher the environmental management pressure, and vice versa. If the last phase of evolution was an ecological land type, such as forestland, wetland, or grassland, it was considered that after some changes, the land was finally classified as ecological land that exerts an ecosystem service.

Six phases of land-use-classification data were imported into ArcGIS 10.2 for overlay analysis, to obtain the spatial distribution of land-use-change frequency. Then, a statistical analysis was performed by using prefecture-level cities as the unit to obtain the area of land-use-change frequency in each city.

2.2.5. Analysis of High-Frequency Areas of Change

The spatial distribution characteristics of F_{lc} were further analyzed by using mathematical statistics, spatial clustering, and hotspot analysis in ArcMap 10.2. A spatial analysis was conducted using shoreline and river vector data to explore the correlation between the changing land mass and those two elements. The river data used in this study came from the national 1:250,000 three-level River Basin dataset from the National Cryosphere Desert Science Data Center. Coastline data were obtained by vectorizing the land boundary of the GBA.

2.3. Land-Management Process Data

Using public data from the Department of Natural Resources of Guangdong Province (http://nr.gd.gov.cn/, accessed on 17 May 2022), we examined the data inventory of the Linking of the Increase and Decrease of Urban and Rural Construction Land in Guangdong Province. Meanwhile, we analyzed the land-use situation, the comprehensive land remediation situation of farmland construction, and "Grain-for-Green" for nine cities in Guangdong Province in the GBA to understand the causes of regional land-use changes.

3. Results

3.1. Spatiotemporal Characteristics of Land-Use Change, 1990–2018

3.1.1. Overall Growth Trend in Construction Land

By analyzing the statistics of various land-use areas and spatial distributions in the GBA's different administrative regions from 1990 to 2018, we can see a pronounced expansion of construction land. The statistics showed an increase in this period, starting at 3090.43 km^2 in 1990, accounting for 5.63% of the construction land, and increasing to 7870.24 km^2 in 2018, accounting for 14.34%. The unchanged construction took up an area of 2593.53 km^2. The newly added construction land was converted from farmland, forestland, wetland, grassland, and unused land in 1990, contributing 39.58%, 16.77%, 8.75%, 1.48%, and 0.47%, respectively. The data show that farmland was the most critical land source for urban construction expansion in the GBA, followed by forestland and wetland; grassland and unused land were less occupied (Table 2.)

This phenomenon corresponded to a gradual reduction of forestland, grassland, wetland, and farmland between cities. In the GBA, the conversion of farmland to construction amounted to 3115.24 km^2 by 2018, accounting for 19.62% of the farmland area in 1990. Furthermore, 1319.67 km^2 of forestland was converted into construction land, accounting for 4.28% of the forestland in 1990, whereas 116.47 km^2 of grassland was converted into construction land, accounting for 9.26% of the grassland in 1990. Meanwhile, an area of 688.65 km^2 of wetland was converted into construction land, accounting for 18.70% of the wetland in 1990. Lastly, 27.59% of unused land was converted into construction land, which reached 36.68 km^2. The proportion of land use in the GBA can be listed in descending order: forestland > farmland > construction land > wetland > grassland > unused land (excluding sea area).

Table 2. Land-use transfer matrix of the GBA, 1990–2018 (unit: /km^2).

1990	2018						
	Farmland	**Forestland**	**Grassland**	**Wetland**	**Construction Land**	**Unused Land**	**Total**
Farmland	10,415.87 65.57%	1022.08 6.43%	57.53 0.36%	1263.01 7.95%	3115.24 19.61%	1.62 0.01%	15,875.35
Forestland	950.62 3.08%	28,010.41 90.62%	320.22 1.04%	225.72 0.73%	1319.67 4.27%	1.56 0.01%	30,828.20
Grassland	62.20 4.91%	214.60 16.95%	841.58 66.47%	22.45 1.77%	116.47 9.20%	0.20 0.02%	1257.50
Wetland	579.93 15.67%	174.59 4.72%	19.71 0.53%	2217.98 59.94%	688.65 18.61%	1.27 0.03%	3682.13
Construction land	267.88 8.64%	142.49 4.60%	7.96 0.26%	78.35 2.53%	2593.53 83.65%	0.22 0.01%	3090.43
Unused land	23.94 15.87%	29.72 19.70%	3.35 2.22%	31.93 21.17%	36.68 24.32%	7.34 4.87%	132.96
Total	12,300.44	29,593.89	1250.35	3839.44	7870.24	12.21	54,866.57

There was also an apparent trend of concentrated and contiguous built-up areas, and the scale of urban clusters was gradually taking shape. In 1990, urban construction land in the GBA was centered mainly on Shenzhen and Guangzhou. Subsequently, the gradual expansion trend of each prefecture-level city radioactively manifested around the city center (e.g., the outward expansion in Guangzhou, Shenzhen, Foshan, Dongguan, and other urban areas). Both sides of the Pearl River show the characteristics of the coast-to-the-interior expanding trend at different speeds. Finally, a contiguous area of construction land, mainly in Guangzhou, Shenzhen, Dongguan, and Foshan, had initially formed before 2018, and this area had also undergone some complex changes.

Overall, the conversion rate of farmland and forestland into construction land during the study period accounted for 5.68% and 2.41% of the total area of the GBA, respectively. These figures indicate that disturbances to the farmland and forest ecosystems were insignificant. However, the trend of increased construction could be ongoing in these regions as a result of urbanization. It could be forecasted that the disturbance in the local ecosystem cannot be eliminated, the current condition of the ecosystem could be accepted on the basis of our results, but the ecosystem will eventually deteriorate if the trend of conversion keeps on growing.

3.1.2. Proportion and Variation Characteristics of Non-Construction Land Types

In the Sankey diagram (Figure 2), the proportion of land use in the GBA is in descending order: forestland > farmland > construction land > wetland > grassland > unused land (excluding sea area). The most direct consequence of construction land expansion was the reduction in the area of farmland, forestland, and wetland, which perform environmental functions. In 2018, the proportion of farmland area gradually decreased, from 28.88% in 1990 to 22.40%, and the forestland area also decreased, from 56.19% in 1990 to 53.89%. However, the area of grassland experienced fluctuation and did not show an obvious overall change, which increased between 1990 and 1995, gradually decreased between 1995 and 2010, and finally increased again in 2018. The wetland area continuously increased between 1990 and 2000, with the proportion increasing from 6.73% to 7.67% and dropping to 7.01% in 2018. Thus, the wetland area increased slightly during the study period. Overall, there was no significant change in the area of unused land during the study period.

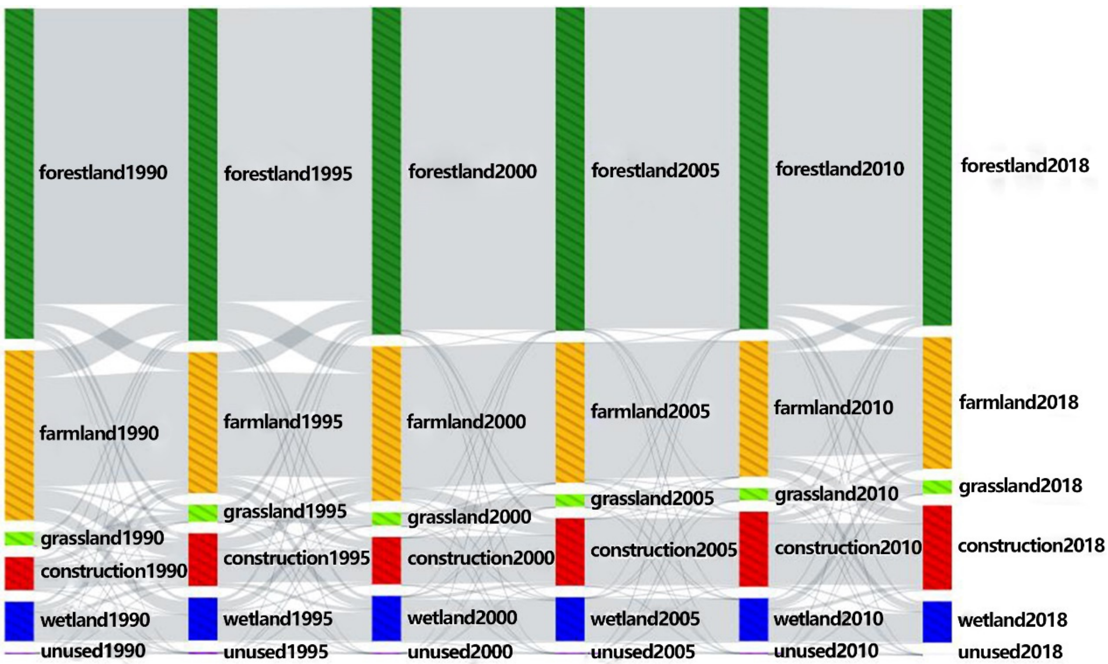


Figure 2. Sankey diagram of land-use change in the GBA.

3.1.3. Distinctiveness of the Type and Rate of Change

Farmland areas in Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Zhongshan, and Hong Kong significantly decreased from 1990 to 2018, whereas construction land areas significantly increased. The forestland area in Shenzhen and Dongguan also significantly decreased and was occupied by construction land. Macao had 0.62 km^2 of farmland before 1995, but that farmland disappeared after 2000. In addition, the wetland area decreased from 4.39 km^2 to 0.77 km^2, and the proportion fell from 20.17% to 3.37%. Meanwhile, the construction land area increased from 7.98 km^2 to 13.60 km^2, and the proportion increased from 36.66% to 59.54%. Huizhou, Jiangmen, and Zhaoqing showed more minor changes in the area and proportion of each category compared with other cities (Figure 3) [38].

The rate of land-type conversion in the GBA was more drastic during 1990–1995 and 1995–2000, reflected mainly in the conversion of farmland to forestland, forestland to farmland, farmland to construction land, and forestland to construction land. The rate of the interconversion of land types decreased during 2000–2005 and 2005–2010, and the primary forms of land-type conversion were the conversion of farmland, forestland, and wetland into construction land. The rate of land-type conversion increased again during 2010–2018 but not as drastically as during 1990–2000. The main forms of land-type conversion in this period were interconversion between farmland and forestland and the conversion of farmland into construction land. The change in farmland was the main line of change in each period.

A special case to be noted is that Macao, which lacks land for development, achieved growth in construction land through reclamation, mainly in the "Cotai Reclamation," at the cost of occupying many coastal wetlands adjacent to the Pearl River Estuary [27]. The increased construction land and forestland through reclamation was also evident in other coastal areas. Increases in demand related to industry, agriculture, production, and living gave rise to land reclamation and sea enclosures for farming. This condition transforms the original natural shorelines, including sandy, silty, and biological ones, into artificial ones.

Table 3 shows the top five types of land-use change in the GBA in each period. The change in farmland was the main line of change in each period. The conversion of farmland into construction land occupied the first place in both T_3 and T_4, while it gradually tended to slow down in T_5.

3.2. Analysis of High-Frequency Land-Use Change by Region

3.2.1. Spatial Patterns of Zones with Different Frequencies of Land-Use Change

Land use in the GBA was characterized by dynamic change and interconversion. Exploring the frequency of change can reveal the extent of the reuse of land resources as a whole. Figure 4 shows the spatial distribution of land-use-change frequency. Table 4 shows the proportion of area in areas with different frequencies of land-use change.

In Figure 4, most peripheral areas of the GBA are green (no change), and the intensity (frequency) of land-use change gradually increases from the peripheral areas to the central areas. A total of 66.11% of the areas were unchanged. The change means that two-thirds of total land use remained unchanged during the study period, thus playing an essential role in the stability of regional land resources. The area of land-use-change frequency in each city was obtained by taking prefecture-level cities as the unit for statistical analysis (Figure 5). For low land-use-change frequency, we found that Zhaoqing, Huizhou, and Jiangmen occupied the most significant area, accounting for 31.96%, 23.53%, and 16.76%, respectively. These three cities are farther away from the core areas of Guangzhou and Shenzhen, and their development and construction activities are relatively slow, leaving a certain amount of ecological land for future development.

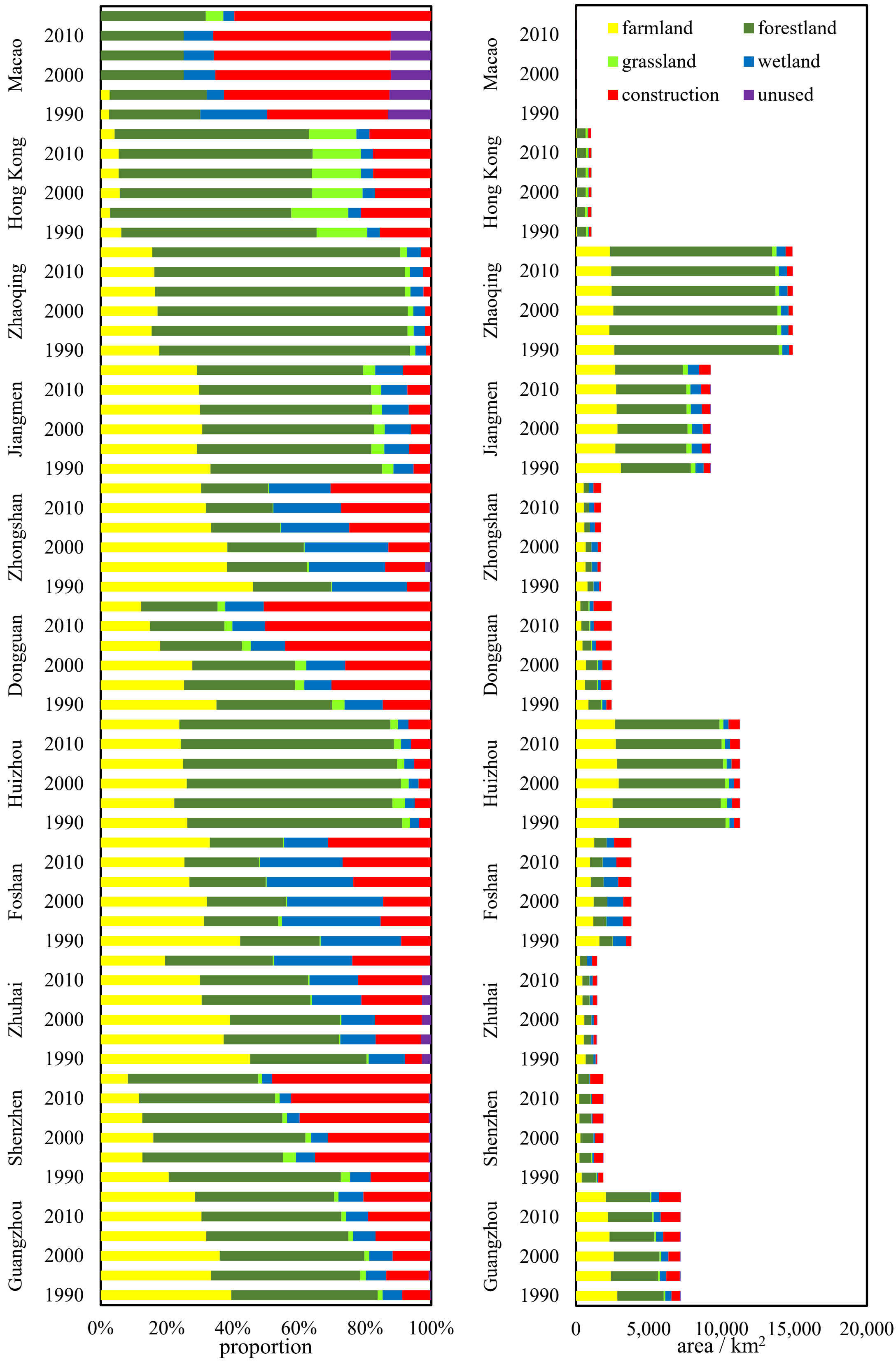


Figure 3. Proportion of land-use change and area of cities in the GBA in each period.

Table 3. The top-five types of land-use change in the GBA in each period. The change in farmland was the main line of change in each period. The conversion of farmland into construction land occupied the first place in both T_3 and T_4, while it gradually tended to slow down in T_5.

Sort	Type	1990–2018 (T_0) Area (hm^2)	Proportion (%)	Type	1990–1995 (T_1) Area (hm^2)	Proportion (%)	Type	1995–2000 (T_2) Area (hm^2)	Proportion (%)
1	Farmland–construction land	311,524	5.68	Farmland–forestland	252,090	4.59	Forestland–farmland	255,260	4.65
2	Forestland–construction land	131,967	2.41	Forestland–farmland	173,489	3.16	Farmland–forestland	181,790	3.31
3	Farmland–wetland	126,301	2.30	Farmland–construction land	163,132	2.97	Construction land–farmland	105,681	1.92
4	Farmland–forestland	102,208	1.86	Farmland–wetland	120,079	2.19	Farmland–wetland	76,173	1.39
5	Forestland–farmland	95,062	1.73	Forestland–construction land	63,635	1.16	Wetland–farmland	75,319	1.37
Sort	**Type**	**2000–2005 (T_3) Area (hm^2)**	**Proportion (%)**	**Type**	**2005–2010 (T_4) Area (hm^2)**	**Proportion (%)**	**Type**	**2010–2018 (T_5) Area (hm^2)**	**Proportion (%)**
1	Farmland–construction land	107,079	1.95	Farmland–construction land	36,673	0.67	Forestland–farmland	139,717	2.55
2	Forestland–construction land	45,310	0.82	Forestland–construction land	21,755	0.40	Farmland–forestland	135,368	2.47
3	Wetland–construction land	32,316	0.59	Wetland–construction land	11,821	0.21	Farmland–construction land	115,595	2.11
4	Farmland–wetland	18,279	0.33	Farmland–forestland	4379	0.08	Wetland–farmland	82,692	1.51
5	Farmland–forestland	5825	0.11	Farmland–wetland	2743	0.05	Farmland–wetland	79,747	1.45

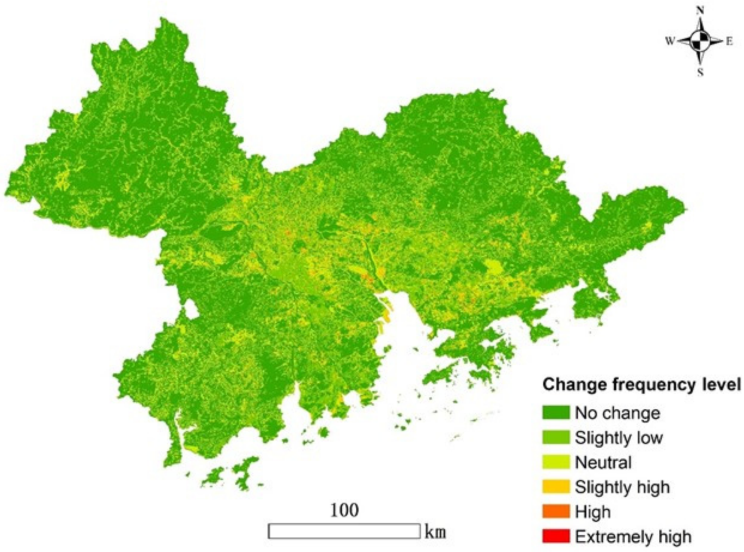


Figure 4. Spatial distribution of land-use-change frequency.

Table 4. Proportion of area in areas with different frequencies of land-use change.

Type	Area (km^2)	Rate (%)
No change ($F_{lc} = 0$)	36,205.39	66.113
Slightly low ($F_{lc} = 1$)	6887.75	12.577
Neutral ($F_{lc} = 2$)	8966.43	16.373
Slightly high ($F_{lc} = 3$)	2562.15	4.679
High ($F_{lc} = 4$)	138.96	0.254
Extremely high ($F_{lc} = 5$)	2.61	0.005

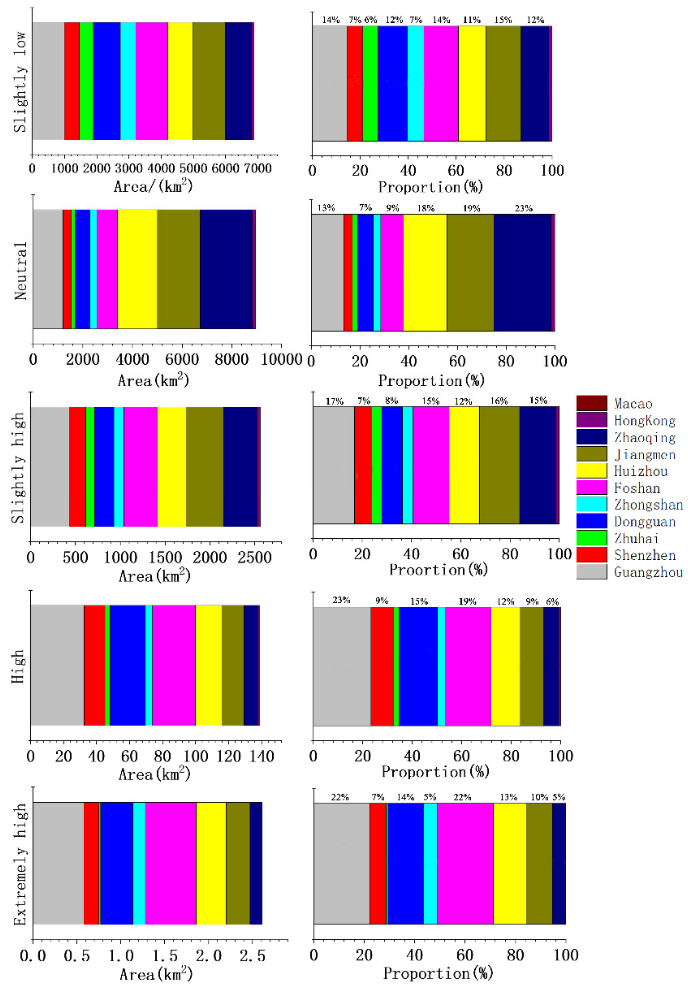


Figure 5. Statistical diagram of the classification of land-use-change frequency.

The extremely high areas might have been related to errors in the classification of remote-sensing images; their proportion was relatively low.

In the slightly low group, except for Hong Kong and Macao, the area of the other nine cities exceeded 440 km^2, among which Jiangmen, Guangzhou, and Foshan accounted for the largest area, accounting for 14.64%, 14.44%, and 14.40% of the slightly low category, respectively. In the neutral group, Zhaoqing, Jiangmen, Huizhou, and Guangzhou accounted for the largest area, accounting for 23.47%, 19.18%, 17.86%, and 13.36% of the neutral category, respectively. In the slightly high group, except for Hong Kong and Macao, the area of the other nine cities was relatively uniform, all exceeding 100 km^2. In the high-land-use-change frequency group, Guangzhou, Foshan, and Dongguan had the largest area, accounting for 23.35%, 18.70%, and 15.45% of the high category, respectively. The size of the area occupied by the high group is negligible. The extremely high areas might have been related to errors in the classification of remote-sensing images; their proportion was relatively low.

3.2.2. Spatial Distribution Characteristics of Areas with a High Frequency of Land-Use Changes

Buffers were established for coastline and rivers in the GBA in 1 km steps by using the buffer analysis tool in ArcGIS, which can explore the relationship between the spatial characteristics of F_{lc} and of coastline and rivers. The proportion of change-frequency area among each class in the buffer was counted to the total area of change frequency (Figure 6). Within 5 km of the river, the area of neutral, slightly high, and high land-use-change frequencies exceeded 60%. Within 10 km of the river, the area of neutral, slightly high, and high land-use-change frequencies exceeded 80%, indicating that more than 80% of the area of drastic land-use change in the GBA was located within 10 km of the river. Within 10 km of the coastline, the area of neutral, slightly high, and high-frequency land-use change accounted for 17.83%, 22.19%, and 28.39%, respectively, indicating that areas with drastic land-use changes in the GBA were not concentrated within 10 km of the coastline.

In general, the area of intense land-use change was strongly correlated with the distribution of the river network. Pressure on the river ecosystem in the GBA is high. Meanwhile, the frequency of extremely high land-use change was negligible because the area was too small.

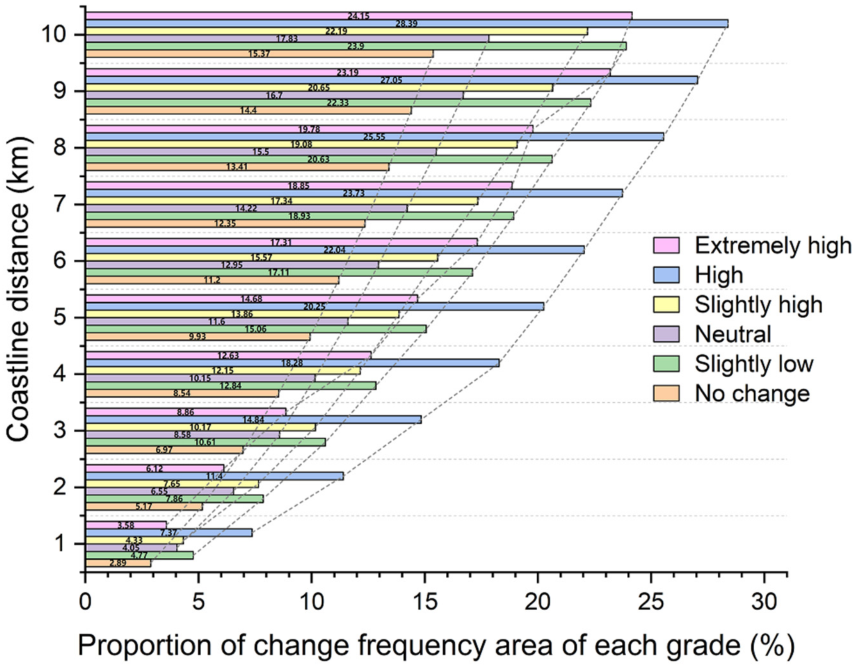
In this study, the frequencies of land-use change that were neutral and above (Flc $\geq$ 2) were considered high. We determined the area of the final land-use type of high-frequency land-use-change plots in each city and its proportion to the total area of high-frequency land-use-change plots in each city (Figure 7)The total proportion of farmland, forestland, grassland, and wetland in each city was ranked from largest to smallest: Zhaoqing > Huizhou > Jiangmen > Hong Kong > Guangzhou > Zhuhai > Zhongshan > Foshan > Macao > Dongguan > Shenzhen.

Ranked from largest to smallest, the percentage of each land type with high-frequency land-use change in the GBA was as follows: farmland > forestland > construction land > wetland > grassland > unused land. The total percentage of farmland, forestland, wetland, and grassland was 78.49%, indicating that nearly 80% of land plots with high-frequency land-use change in the GBA were eventually transformed into ecological land. The transformation could suggest the effectiveness of environmental protection policies in the GBA.

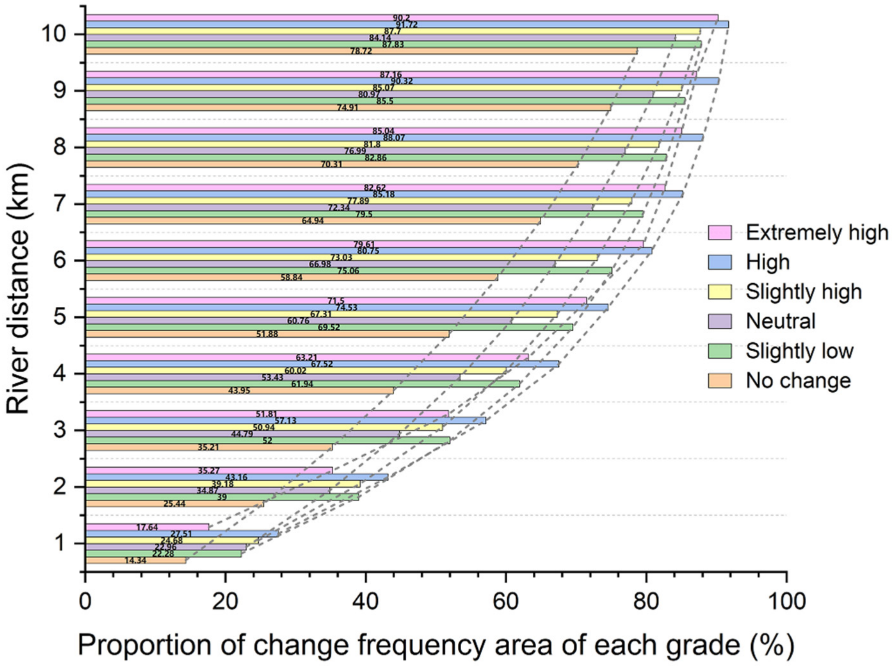
A 10 km buffer zone was established for the administrative boundary of prefecture-level cities toward the inner city, and the area of high-frequency land-use change in the buffer zone was determined (Table 5). Guangzhou and Zhaoqing had the largest area of high-frequency land-use change in the 10 km buffer zone, both over 1000 km^2, while Macau had the smallest area, only 3.89 km^2. The ratio of high-frequency land-use-change area in the 10 km buffer zone to high-frequency land-use-change area in the city ranked from largest to smallest was as follows: Hong Kong = Macao > Zhuhai > Shenzhen > Dongguan > Foshan > Zhongshan > Guangzhou > Huizhou > Zhaoqing > Jiangmen. Among them, Macao and Hong Kong both accounted for 100% because the two cities are small and are fully covered by the buffer zone. Zhuhai and Shenzhen both accounted for more than 90%, Foshan and Dongguan accounted for more than 80%, and the rest accounted for less than 80%—the lowest being Jiangmen, at 42.71%. The higher the frequency of land-use change, the more frequent the land-type change and the more easily the surrounding environment was affected. More than 80% of the plots with high-frequency land-use change in six cities, namely Macao, Hong Kong, Zhuhai, Shenzhen, Dongguan, and Foshan, were within 10 km of the administrative boundary, indicating that the government had tended to impose the environmental effects generated by land-type change on the surrounding municipalities when carrying out territorial spatial planning.

3.2.3. Clustering of High-Frequency Areas of Land-Use Change and Hot–Cold Spot Analysis

We counted the average level (mean value) of land-use-change frequency in township administrative districts. The results for the spatial clustering of land-use-change frequency and the distribution of hot–cold areas in land-use-change frequency were respectively obtained by using the clustering and outlier analysis tool and hotspot analysis tool in ArcGIS (Figure 8). The high-frequency land-use-change, high clustering areas, and hotspot areas were found to be concentrated in the more economically developed regional townships of Guangzhou, Shenzhen, Foshan, and Dongguan. In 2018, the GDP of Guangzhou, Shenzhen, Foshan, and Dongguan accounted for 60% of the GDP of the GBA. Rapid economic development led to the rapid growth of construction land, and the implementation of environmental protection and restoration policies accelerated the tradeoffs and interconversions between land-use types, leading to the aggregation of high values of land-use-change frequency.



(**a**)



(**b**)

Figure 6. Area proportion of land-use-change frequency for each class within a 10 km buffer zone of the coastline (**a**) and the river (**b**).

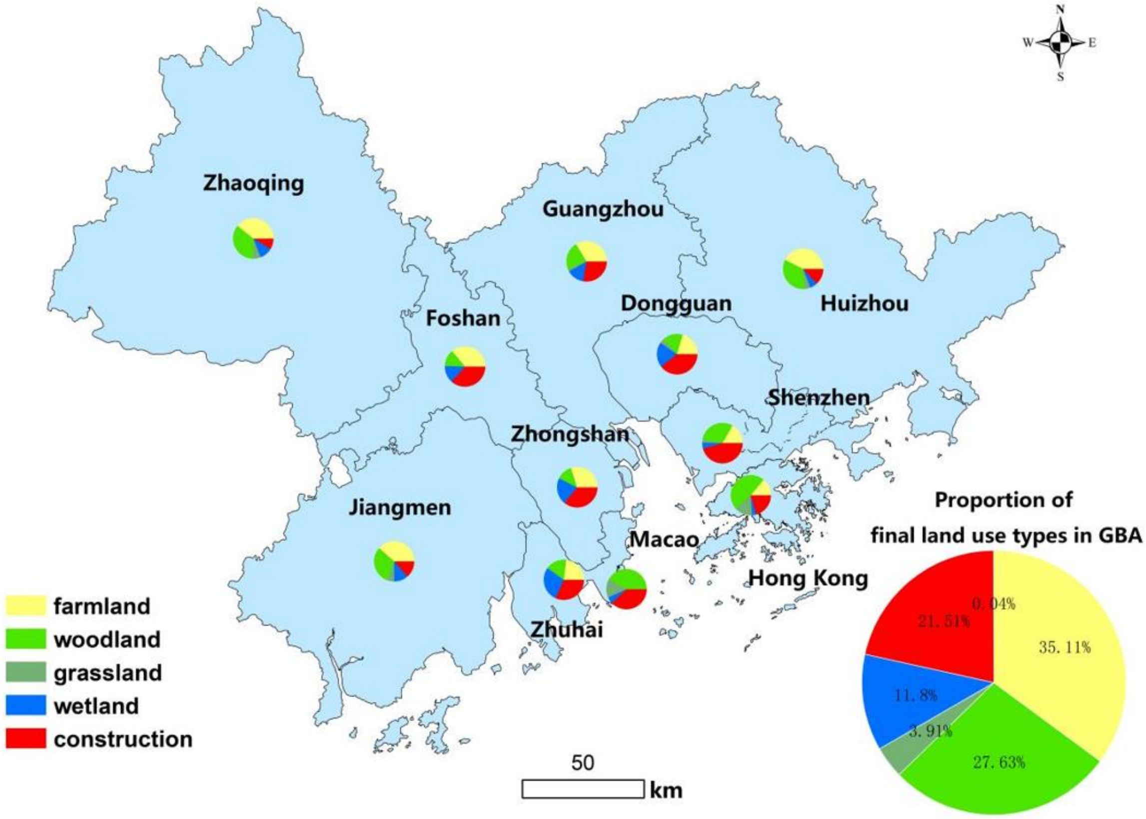


Figure 7. Area and percentage of frequency of land-use change within a 10 km buffer zone of prefecture-level municipal administrative districts.

Table 5. Area and proportion of land-use-change frequency within a 10 km buffer zone of prefecture-level municipal administrative districts.

City	Area of High-Frequency Land-Use Change within 10 km Buffer Zone (km^2)	Citywide High-Frequency Land-Use Change Area (km^2)	Proportion (%)
Macao	3.89	3.89	100.00
Hong Kong	173.52	173.52	100.00
Zhuhai	284.43	284.99	99.80
Shenzhen	490.81	514.85	95.33
Dongguan	660.55	821.30	80.43
Foshan	997.86	1241.08	80.40
Zhongshan	299.83	393.07	76.28
Guangzhou	1074.40	1662.59	64.62
Huizhou	965.34	1935.82	49.87
Zhaoqing	1132.11	2490.76	45.45
Jiangmen	919.19	2152.14	42.71

After 2011, Guangdong Province encouraged the reclamation of plots of land unsuitable for upgrading and transforming into farmland. These freed-up targets were used to construct industrial cities in areas suitable for transformation, while trading was used to marketize land-resource allocation and improve land-use efficiency. This policy optimized the structure of agricultural land and increased the amount of high-quality farmland through environmental restoration, farmland's structure optimization, high-standard field improvement, and other measures. Those that could not be restored to agricultural land could be "regreened" in conjunction with environmental restoration projects to enhance the outlook of urban and rural development.

Duan [39] found that 86% of Chinese cropland could be consolidated to establish a large-scale farming regime with an average field size greater than 16 ha.

We analyzed the 19-period data with recorded indicator flows in reclamation transaction announcements from the Guangdong Provincial Department of Natural Resources. According to the result (Table 6), Guangzhou, Shenzhen, Foshan, and Dongguan were the leading forces in bidding for demolition and reclamation indicators, as shown in Table 6. These four economically developed cities won bids for 57.71% of the demolition and reclamation indicators, the bid price reaching 12.105 billion yuan. The transaction result shows that cities with faster economic development have a greater demand for construction land, and governments are more inclined to purchase indicators to expand the scale of construction land. The booming economic development is considered to be connected with the increase in construction; larger construction land can accommodate more population, which brings sufficient consumption ability and a high employment rate.

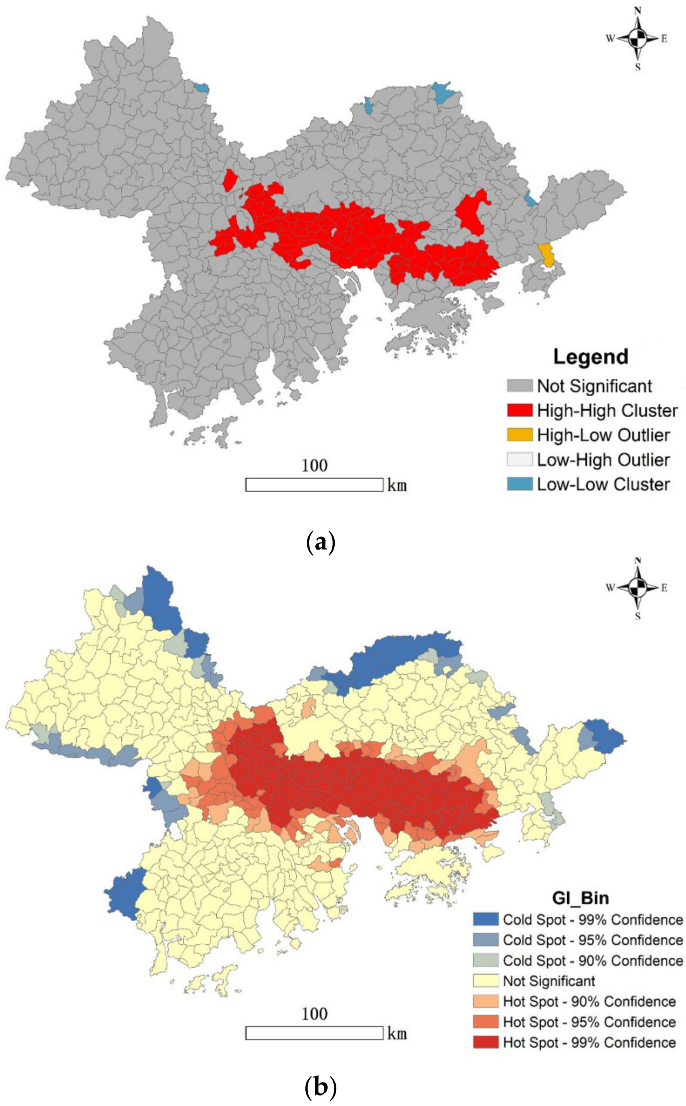


Figure 8. Map of spatial clustering (**a**) and hot–cold regions of land-use-change frequency (**b**).

Table 6. Area for sale and purchase of demolition and reclamation targets for prefecture-level administrative districts.

City	Purchase Indicators		Purchase Amount	
	Area (acre)	Proportion (%)	Amount (billion yuan)	Proportion (%)
Foshan	8609.80	25.06	53.11	25.08
Zhuhai	5203.53	15.15	34.80	16.43
Guangzhou	4730.68	13.77	27.46	12.97
Dongguan	4552.34	13.25	27.95	13.20
Huizhou	3520.85	10.25	19.36	9.14
Zhongshan	3000.00	8.73	20.09	9.48
Jiangmen	2377.17	6.92	14.17	6.68
Shenzhen	1930.07	5.63	12.53	5.92
Zhaoqing	427.24	1.24	2.33	1.10
Total	34,351.68	100	211.8	100

4. Discussion

According to the result of the previous section, it can be seen that there is an inevitable trend of land-use changes in the GBA. This trend is attributed to the development of urbanization. Meanwhile, this trend resulted in the expansion of the urban area. Because the foundation of LUCC was set in the past decades, population clustering and GDP gross were generated from LUCC but reversely promoted the further development of LUCC. Moreover, accompanying the LUCC, the local ecosystem suffered from detrition. Our research places extra emphasis on the functional impacts on the urban areas, nature, society, and economy from the expansion of urban land use. The following part will discuss the LUCC from three perspectives: urban planning, natural environment, and social and economic development.

4.1. Urban Planning

The change in land use was occurring with the development of cities. Under the context of LUCC, the research on the motivation mechanism of land use change in urban agglomeration is considered a hotspot direction in the field of urban agglomeration. According to the results of this paper, fast-growing cities such as Guangzhou, Shenzhen, Dongguan, and Foshan all created a massive rise in GDP. Meanwhile, the transformation of land types is also regarded as a hallmark of the GBA. The appearance of this growth represents the procession of urbanization growing in the GBA. From the urban planning perspective, this result was caused by the implementation and guidance of the government's policy. The GBA has been in the strategic position of the reform and opening-up of China for decades. The requirement of urbanization and GDP increase has been the overarching goal in the GBA since the 20th century, leading to land-type conversions. However, an unbalance in the portion among different land types occurred. The unbalanced allocations were reflected in the urban patterns and the land-use transformations. The original surrounding area of the GBA was dominated by farmland, forestland, and wetland, but most of these land types were utilized as and transformed into construction land. The phenomenon has occurred since the 1990s, with urbanization in Guangzhou, Shenzhen, Dongguan, and Foshan, whereas this pace has decelerated since entering the 21st century. Areas with high-frequency changes in land use were all concentrated in the urban clusters centered in Guangzhou, Shenzhen, Foshan, and Dongguan, which was caused mainly by the faster urbanization in these areas. This phenomenon accelerated the mutual transformation between land-use types and led to the gathering of high-frequency land-use change. The unbalance in land-use types among cities in GBA still exists, but the suggested reason is the difference in urban development.

4.2. Natural Environment

During the research period, the various land types in the GBA experienced different levels of transformation, which resulted in the distinct expansion of construction lands. The portion of non-construction land types suffered from reduction, mainly farmland and forestland. Compared with the portion of non-construction land types between 1990 and 2018, the transformation rate is reasonable, which avoids disturbances to the local ecosystem. However, the land types in the GBA were frequently converted during the study period. The conversion of land types is not conducive to environmental conservation [40]. The resilience of the ecosystem is limited; thus, the function of the ecosystem should be maintained while proceeding with land transformation. The land-use change could reduce the ability of soil water conservation and soil water–holding capacity [41]. The lack of soil water conservation could lead to soil erosion and land degradation, and the following chain effect can directly increase pressure on the marine system [42]. The sea space should not be overcrowded in land–sea coordination, to maintain the functional completeness of the marine system. In January 2021, the government of Guangdong Province issued the Three Lines and One List environmental zoning control program, which requires the strict implementation of the environmental protection red line, environmental quality bottom line, resource utilization upper boundary, and environmental access list [43]. The result also indicates that nearly 80% of the plots in the high-frequency land-use-change area eventually transformed into ecological land, which reflects that the GBA's environmental protection policies had reached specific achievements.

4.3. Social and Economic Development

From 1990 to 2018, the GBA benefited from rapid economic growth, and the pace of urbanization was forced to accelerate. It is estimated that over 10 trillion boosts to the GDP generated during this period, which indicates an astonishing 22 times growth, from 0.48 trillion in 1990 to 10.87 trillion in 2018 [44,45]. The GDP increase stimulates GBA urbanization and accelerates the requirement for construction land. The construction land expansion reversely attracts the population's clustering in Guangzhou, Shenzhen, Foshan, Dongguan. The dense population in the GBA brings abundant labor resources, which are crucial to increasing GDP and inducing high-frequency land-use changes. It can be seen that a loop was established in the GBA, including the GDP gross, population clustering, and LUCC. These three elements are generated from each other and can also reversely motivate each other.

4.4. Limitations

This study was limited by the spatial resolution of the land-use data and the quality of the data. Thus, we explored only terrestrial land-use changes, with low precision in the coastal zone area and limited ability to identify the status of coastal reclamation during the study period. Future research should strengthen the analysis of land-use changes by including the GBA's coastal zones, especially in coastal reclamation. In addition, the related change patterns were not entirely accurate, owing to the limited accuracy of the classification of remote-sensing images in different periods. Thus, only the overall trend of changes was discussed in this paper.

5. Conclusions

The paper explored and analyzed the high-frequency land-use changes in the GBA from 1990 to 2018. The land types in the GBA were dominantly transformed into construction land, which satisfied the economic growth requirement and urbanization development. Specifically, Guangzhou was the city with the most increased construction land area, followed by Dongguan and Foshan. The significant increase in construction land area in these three cities synchronously occurred around 2005. Nevertheless, LUCC often occurred in the cities with a solid economic increase, such as Guangzhou, Shenzhen, Foshan, and Dongguan. We can see the strong connection between economic development and land-use transformation. This phenomenon caused an unbalance in the distribution of land types and cities: the cities with less economic development tended to see less-frequent land-use changes, and the unipolar increase in construction lands also caused functional degradation in the ecosystem. Although nearly 80% of the land was finally transformed into ecological land under relative policy and regulation, the switch between land types still led to disability in ecosystem functions. Therefore, we recommend that land-use efficiency be improved more actively in the GBA to maintain ecological stability and reach sustainable development for land functions in the future. The comprehensive management of land is required in the GBA, which includes the control unit from the township scale. A stricter inspection process for territorial development plans needs to be implemented. In addition, the utilization rate of existing construction land should be in a rational range to avoid wasting land resources. A relevant increase in investing in consolidation is encouraged for the GBA [46].

Moreover, the consolidation of the environmental zoning control program should focus on protecting ecological land while maintaining economic growth. Identifying low-utility urban land as the object of stock space tapping, quality improvement, and efficiency enhancement is also necessary. The land consolidation and ecological restoration projects should proceed under the conditions of ecological protection, restoration, and biodiversity conservation. In addition, the principles of whole-area planning, overall design, and comprehensive management are crucial in this process; the law of nature cannot be obeyed during land transformation and development [46]. The linkage between increases and decreases in urban and rural construction land in Guangdong Province is also a favorable land-consolidation mechanism. This linkage can strengthen village planning and rural living environment governance while providing land for urban construction, especially for key construction projects. It is also conducive to accelerating the process of rural urbanization and modernization while protecting soil resources and implementing land-use planning. The arrangement of land consolidation and ecological restoration projects in rural areas can promote employment and then stabilize the land-change situation. The terrestrial ecosystem protection and integration of land–sea management should be considered. From the perspective of planning and management, we need to continue to improve the management system of reclamation and incorporate reclamation into overall land-use planning. Farmland should be strictly protected. Once the development has been related to permanent farmland, the quantity and quality of cultivated land should be guaranteed to maintain the ecology of farmland. The following indicators must be used to control the stability of farmland development [46]:

(1) The area of newly added farmland shall not be less than 5% of the original area of farmland.
(2) If the adjustment involves permanent farmland, the area of newly added permanent farmland shall not be less than 5% of the adjusted area.

Meanwhile, the exploration of the value realization mechanism of ecological products cannot be separated from the realization of the ecological value conversion [47]; this can be described as "Clear waters and green mountains are as good as mountains of gold and silver" [48]. The availability has been proved by the success of the construction of ecological corridors on both sides of the Dongjiang River, Beijiang River, and Xijiang River. It is also necessary to consider the mobility and complexity of marine ecosystems, which differ from terrestrial ecosystems [49]. Further, we need to take the connection of marine functional zoning and the marine environmental protection red line with terrestrial functional zoning and the terrestrial environmental protection red line as the starting point [50] to incorporate ecosystem services into coastal and offshore spatial planning. This way, we can achieve the overall goal of "one map for land and sea" for ecosystem management and environmental protection.

This study was limited by the spatial resolution of the land-use data and the quality of the data. Thus, we explored only terrestrial land-use changes, with low precision in the coastal zone area and a limited ability to identify the status of coastal reclamation during the study period. Future research should strengthen the analysis of land-use changes by including the GBA's coastal zone, especially in coastal reclamation. In addition, the related change patterns were not entirely accurate, owing to the limited accuracy of the classification of remote-sensing images in different periods. Thus, only the overall trend of changes was discussed in this paper.

Author Contributions: Writing—original draft, C.L.; methodology, A.L.; formal analysis, Z.W.; validation, X.S.; data curation, T.J.; writing—review & editing, R.D.; project administration, R.D. All authors have read and agreed to the published version of the manuscript.

Funding: Strategic Priority Research Program of the Chinese Academy of Sciences: XDA23030403; The National Key Research and Development Program of China: 2022YFC3802903; The Open-end Fund of State Key Laboratory of Urban and Regional Ecology: SKLURE2022-2-5.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: We thank the referees for their insightful advice on this manuscript.

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

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