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RESEARCH ARTICLE

A gradient analysis on urban sprawl and urban landscape pattern between 1985 and 2000 in the Pearl River Delta, China

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Abstract Urbanization is an irreversible trend worldwide, especially in rapidly developing China. Accelerated urbanization has resulted in rapid urban sprawl and urban landscape pattern changes. Quantifying the spatiotemporal dynamics of urban land use and landscape pattern not only can reveal the characteristics of social transfer and economic development, but also can provide insights into the driving mechanisms of land use changes. In this study, we integrated remote sensing (RS), geographic information system (GIS), landscape metrics, and gradient analysis to quantitatively compare the spatiotemporal dynamics of land use, urban sprawl, and landscape pattern for nine cities in the Pearl River Delta from 1985–2000. For the whole study region, urbanization was obvious. The results show an increase in urban buildup land and shrinkage of cropland in the Pearl River Delta. However, the nine cities differed greatly in terms of the process and magnitude of urban sprawl for both the spatial and temporal dimensions. This was most evident for the cities of Guangzhou and Shenzhen. Gradient analysis on urban landscape changes could deepen understanding of the stages of urban development and provide a scientific foundation for future urban planning and land management strategies in China.

Keywords urbanization, urban sprawl, landscape pattern, gradient analysis, Pearl River Delta in China

1 Introduction

In the last several decades, unprecedented rapid urbanization has been evident worldwide, characterized by demographic concentration and urban area sprawl (Sato and Yamamoto, 2005). Globally, the proportion of the urban population has increased from 30% in 1950 to 54% in 2014, and is projected to reach 66% by 2050 (United Nations, 2014). The continuously increasing population and anthropogenic activities have led to simultaneous land use and cover changes from global to regional scales, resulting in irreversible urbanization (Angel et al., 2011; Seto et al., 2011). Urban sprawl also leads to environmental change and affects ecosystem services, including diminishing cropland, air pollution, biodiversity loss, and climate change from the global scale to regional and local scales (Johnson, 2001; Grimm et al., 2008; Seto et al., 2012; Han et al., 2015). At the same time, urbanization is closely linked to the economy, policies, and culture, which profoundly alter the pattern and structure of landscapes and even lead to exacerbated landscape spatial heterogeneity and fragmentation (Zhang, 2000; Liu et al., 2005; Irwin and Bockstael, 2007). Therefore, to deepen understanding of the spatiotemporal dynamics and driving forces of urban sprawl, it is important to quantify land use and landscape pattern changes.

Advances in remote sensing (RS) and geographic information systems (GIS) techniques provide frequent and consistent spatiotemporal data and help to detect and quantify land use and cover changes (Hammer et al., 2004; Fichera et al., 2012). Landscape pattern metrics can also help quantify pattern features of land use and land cover (Liu and Weng, 2013). Combining remote sensing data and landscape metrics provides a method for detecting urban

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sprawl processes (Deng et al., 2009), of which gradient analysis on landscape pattern metrics can reflect the ecological effects of urbanization (Luck and Wu, 2002; McDonnell and Hahs, 2008; Ramachandra et al., 2015). Ji et al. (2006) used long-term remote imagery data and landscape metrics to characterize urban sprawl at multiple levels in Kansas, USA, suggesting that landscape metrics can identify different stages of urbanization. Irwin and Bockstael (2007) found that the land use fragmentation process was closely associated with the evolution of urban sprawl in the state of Maryland. At the forefront of the rapid spread of urbanization worldwide over the last 20 years, much attention has focused on the urban expansion process in China, especially in metropolises and agglomeration regions. These regions fuel economic development and population aggregation, such as the Beijing-Tianjin-Hebei (abbreviation as Jing-Jin-Ji) (Xiao et al., 2006; Tian et al., 2010; Wu et al., 2015), Yangtze River Delta region (Long et al., 2009; Li et al., 2013; Haas and Ban, 2014; Qin et al., 2015), and the Pearl River Delta region (Seto and Kaufmann, 2003; Du et al., 2014; Fan and Fan, 2014). The Pearl River Delta region has pioneered the nation in economic development and urbanization process, and has also attracted the attention of more and more scholars. For example, some studies focused on spatial restructuring and spatial pattern changes in this region. Seto and Fragkias (2005) made a quantitative analysis of spatial and temporal patterns of urban land use change for four cities in the Pearl River Delta. They found that the cities exhibited common patterns which suggested a convergence toward a standard urban form. Lv et al. (2012) also studied the urban sprawl and landscape pattern in this rapidly developing region. They identified three urban sprawl types, including edge-expansion, infilling, and outlying to analyze the evaluation of urban pattern. Lin (2001) focused on spatial restructuring of the metropolitan and agricultural land use. They thought that the rapid expansion of the extended metropolitan zone was driven primarily by forces of rural industrialization prior to 2000. Other studies focused more on the driving forces of land use change and the relationship between urban sprawl and farmland loss in this region. Yeh and Li (1999) and Du et al. (2014) both assessed economic development and farmland dynamics in the Pearl River Delta region. They paid more attention to their relationships and drew a conclusion that the accelerated urbanization and farmland loss were driven by many factors. Several studies summarized and reviewed the urbanization in the Pearl River Delta region in recent decades (Xu and Li, 2009; Xu et al., 2015). They found that terrain conditions, transportation development, policy making, population, and economic growth are the important factors in the process of urbanization. Despite many works having been done in this region, there has not been much focus on a comparative inter- and intra-city analysis at the regional scale using remote sensing data and landscape metrics.

As one of the fastest urbanizing developing countries, China has witnessed rapid growth in both population and economic development (Chen et al., 2013). In the past 35 years, from 1980 to 2015, China's urbanization increased from 19.4% to 56.1% (National Bureau of Statistics of China, 2016). The most notable evidence associated with urbanization is dramatic urban land use expanding in both the qualitative and spatial dimensions, which is driven by demographic concentration and national political reformation (Liu et al., 2005). The Reform and Opening policy is a milestone in China's urbanization process. The Pearl River Delta, as the most significantly influenced region and the experimental area, has incurred breathtaking change. However, accelerated urbanization in this rapidly developing area has led to a severe labor shortage in rural communities and hastened significant transition in agricultural practices, resulting in agricultural land loss (Yeh and Li, 1999; Yang, 2013). This unreasonable land use is attributed to the lack of prospective planning and effective implementation when the Reform and Opening policy was initiated (Xu and Li, 2009). Studying profit-oriented urban development patterns in the Pearl River Delta during a relatively rapid development period (1985–2000) is an important response to the economic and population boom in China.

In this study, we used remote sensing data in the Pearl River Delta region to quantitatively analyze spatiotemporal dynamic changes in land use and urban sprawl. Regarding methodology, we integrated landscape metrics and a gradient analysis to characterize landscape pattern changes from 1985–2000. The objectives were to: (i) obtain land use data from the remote sensing images and detect land use changes in 1985, 1995, and 2000; (ii) quantify and visualize urban sprawl for nine typical cities using different buffer distances for each study period; (iii) characterize landscape pattern changes by using landscape metrics and gradient analysis; and (iv) explore the driving forces of urbanization and provide a scientific foundation for future urban planning and land management strategies.

2 Materials and methods

2.1 Study area

Our study area, the Pearl River Delta, is located in the south-central region of the Guangdong Province (111°59′–115°25.3′E, 21°17.6′–23°55.9′N) (Fig. 1). The region covers approximately 54,754 km^2, accounting for 30.5% of the total area of Guangdong Province (Statistics Bureau of Guangdong Province, 2014). The average elevation of the region is less than 200 m, with a flat alluvial plain topography. Characterized by a subtropical monsoon climate, the mean annual temperature is about 22°C and mean annual precipitation is 1500 mm. The soil is fertile and water resources are plentiful.

Fig. 1 Location of cities in the Pearl River Delta (Guangdong), South China.

With the implementation of the Reform and Opening policy in the 1980s, the Pearl River Delta experienced rapid economic development, ranking first in terms of economic development in Guangdong Province and the country. The population grew from 23.69 million in 1990 to 42.89 million in 2000, an increase of 81% in 10 years. The GDP increased 8.36 times from 1006.88 billion CNY in 1990 to 8422.24 billion CNY in 2000 (Statistics Bureau of Guangdong Province, 2014). Excessively rapid economic development also induced rapid urbanization and dramatic changes in land use over the last three decades, especially during 1985–2000. The Pearl River Delta comprises nine cities, namely Dongguan, Zhongshan, Foshan, Guangzhou, Huizhou, Jiangmen, Shenzhen, Zhuhai, and Zhaoqing (Fig. 1). Although the average level of urbanization in the Pearl River Delta region is the greatest in Guangdong Province and in China overall, there is disequilibrium between the province's cities. In the general urban and land management strategy for the whole Pearl River Delta region, different strategies need to be adopted for different cities to harmonize development and urbanization objectives and realize sustainable development for both the region and each city. Therefore, this paper conducts a comparative inter- and intra-city analysis using landscape metrics and gradient analysis of different buffer distances to the geometric centers of each city.

2.2 Data and methods

2.2.1 Land use data processing and classification

We used remote sensing images to generate land use/land cover data for the following urban dynamic analysis. To classify land use and land cover, we used Landsat Thematic Mapper (TM) for 1985 and 1995 and Landsat Enhanced Thematic Mapper (ETM) for 2000. Remote sensing data (Landsat series) was downloaded from the Global Land Cover Facility (http://www.glcf.umd.edu/). The remote sensing images were first rectified and georeferenced to a unified projection coordinate system. Following this, the images were registered to topographic maps based on identified points such as road intersections and stream confluences. Images pertaining to the study area were then sheared to the boundary of the study region. The Landsat TM images for 1985 and 1995 (spatial resolution of 28.5 m × 28.5 m) were resampled to 30 m to maintain consistency of spatial resolution. In terms of land use categories, the human-machine interactive interpretation and unsupervised classification techniques were adopted to extract land use changes. In this study, the land use maps were classified into 8 land use categories which were referenced to the classification system by Liu et al. (2003). In addition, the categories were also revised according to our specific objectives. There are some scientific considerations for this classification. At first, the data sources and handling are relatively consistent in the two studies. We both used the Landsat TM data and visual interpretation to classify the land use landscape. We did not use the category suggested by the land use administration of local government because that classification system may be more focused on the land market management. More detailed categories are needed and the data are mostly derived from the land resource survey. Secondly, the study period by Liu et al. (2003) is in line with our study, which shows the similar policy context. Thirdly, considering our research objectives, some revisions have been made based on the classification system suggested by Liu et al. (2003) to highlight the changes in urban land. Based on the above, we adopted the land use categories as shown in Table 1, including cropland (CL), woodland (WL), orchard land (OL), grassland (GL), water body (WB), aquiculture land (AL), urban buildup land (UBL), and rural residential land (RRL). To evaluate the classification accuracy, a random sample check was conducted by comparing our categories with the land use datasets from the Data Center for Resources and Environmental Sciences, CAS (Chinese Academy of Sciences). Although the datasets from CAS were produced at the national scale (1:100,000-scale), they had been fully tested by field validation (Liu et al., 2014), which had certain reference in our study. The results of the comparison showed that the overall accuracy was 92.5%, 93.1%, and 95.4% in 1985, 1995, and 2000, respectively.

Table 1 Land use classification categories

Land use class	Secondary land use category
Cropland (CL)	Paddy Farmland
Woodland (WL)	Forest Shrub Sparse woodland
Orchard land (OL)	Economic forest
Grassland (GL)	High coverage grassland Moderate coverage grassland Low coverage grassland
Water body (WB)	River and aqueduct Lake Tidal flat and bottomland
Aquiculture land (AL)	Reservoir and pond
Urban buildup land (UBL)	Urban land Other construction land
Rural residential land (RRL)	Rural residential land

2.2.2 Detecting land use changes

We derived land use changes through coupled map algebra with the spatial analysis method using ArcGIS software. To monitor land use changes from 1985–1995 and 1995–2000, the categorized images were overlaid and converted amounts for each category were computed, resulting in a land use transformation matrix for each city. The relatively fast development period of 1985–2000 was broken into two periods, which were based on criterions such as policy, data source, and different stages of regional development. Firstly, the two periods were affected by the change in policies and regulations. In 1995, "The Urban Real Estate Administration Law of the People's Republic of China" began, which brought about major changes in habitation, especially in cities and towns. The same year, "Development Planning of Urban Agglomeration in the Pearl River Delta-Coordination and Sustainable Development (1995–2010)" was implemented. The start of regulations and planning would inevitably affect the urban land and result in urban sprawl and landscape pattern change. This is consistent with the objective of our study. Secondly, we chose these two periods due to the limitation of the data source. We just obtained the remote sensing images of 1985, 1995, and 2000. The selection of these two periods was also made on the basis of the historical stages of urban development. In terms of the Pearl River Delta, this region experienced two obvious stages of urban sprawl, including "Rural Industrialization" (from the Reform and Opening policy to the middle of 1990s) and "Urban Regional Development" (after 1997) (The Pearl River Delta Region Planning, 2014). Therefore, these two periods, 1985–1995 and 1995–2000, were chosen to analyze the urban sprawl and land use change in the Pearl River Delta region. The information for land use for each category can be extracted by the following equation (Shi et al., 2000):

$$\mathrm{C}_{ij} = \mathrm{A}_{ij}^{k} \times 10 + \mathrm{A}_{ij}^{k+1}, \tag{1}$$

where A_{ij}^{k} and A_{ij}^{k+1} are the land use data of two periods and C_{ij} is the code change of land use categories from period k to period $k+1$. Eq. (1) can be applied when the number of land use types is less than 10.

2.2.3 Exploring landscape pattern changes

Landscape metrics can be used to describe and quantify particular aspects of landscape patterns, interactions among patches within a landscape mosaic, and changing patterns and interactions over time (O'Neill et al., 1988; Haas and Ban, 2014). Various landscape metrics have been developed to characterize spatial patterns at the patch, class, and landscape levels (McGarigal and Marks, 1995). In terms of the urban landscape, previous studies characterizing urban landscape patterns focused on size, density, shape, edge, diversity, connectivity, and compactness (Seto and Fragkias, 2005; Schwarz, 2010; Liu and Weng, 2013; Xu and Min, 2013). To quantify the spatial patterns of urbanization in the Pearl River Delta, landscape metrics were selected based on the ecological significance of the metrics and by considering the most commonly used metrics in urbanization studies. Six landscape pattern metrics for three aspects (density, agglomeration, and diversity) at the landscape level were selected in this study, namely the largest patch index (LPI), mean patch area (AREA_MN), contagion index (CONTAG), interspersion and juxtaposition index (IJI), Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). These landscape metrics were calculated using the landscape pattern analysis software FRAGSTATS 3.3 (McGarigal et al., 2002).

2.2.4 Gradient analysis on land use change and landscape characteristics

To identify the characteristics of urban land use and landscape pattern changes, 20 km buffer zones were selected for the gradient analysis on land use change and landscape characteristics. Considering the outermost range of all nine cities in the Pearl River Delta, these buffer zones were divided into three concentric circles with distances of 0–4 km, 4–10 km, and 10–20 km to the geometric centers of the cities. In more detail, we first took the geometric center of the urban buildup area in 1985 as the center of the buffer zones. Then, the maximum radius of urban buildup area was measured for each city during 1985–2000. In 1985, the radius of the 9 urban buildup areas measured from 2.15 km (Zhongshan) to 4.20 km (Shenzhen). In 1995, the radius is measured from 4.3 km (Zhongshan) to 9.5 km (Guangzhou), and in 2000, from 7.5 km (Zhongshan) to 18.2 km (Guangzhou). Based on these measurements, we selected radii of 0–4 km, 4–10 km and 10–20 km to investigate the urbanization progress in the Pearl River Delta. Changes in land use types and landscape metrics were calculated and analyzed for these buffer zones. The gradient analysis method helped to visualize the forms of urban sprawl, monitor buildup density, and identify driving factors using a time series analysis (Ramachandra et al., 2015).

3 Results

3.1 Land use changes in the Pearl River Delta

The results of land use maps in 1985, 1995, and 2000 are shown in Fig. 2. To investigate land use dynamics in the Pearl River Delta, urban land expansion should be considered. Based on the land use data derived from remote sensing images, the configuration of land use in the 9 cities within a 0–20 km buffer zone to the urban center is shown in Fig. 3. The results indicated that the area of urban buildup land increased from 405.3 km^2 (4.69%) to 1211.6 km^2 (14.02%) between 1985 and 2000 for the whole Pearl River Delta region. Expansion rates also increased from 7.2% (1985–1995) to 14.5% (1995–2000), essentially doubling in 10 years. The area for rural residential land increased from 3.44% to 7.41% as the population increased from 1985 to 2000. The area of the aquiculture land showed a small increase during the urbanization process. The areas of cropland, woodland, grassland, and water body decreased over the same period as they were each affected by urban sprawl. The area of cropland decreased the most, by 1082.6 km^2. The area of woodland, orchard land, grassland, and water body showed a reduction of 220.3 km^2, 60.3 km^2, 16.2 km^2, and 99.2 km^2 respectively. Results revealed that a large area of cropland transformed into urban buildup land, orchard land, and aquiculture land. This is an important phenomenon, because of the urbanization process and agricultural structure adjustment in the study region.

3.2 Urban sprawl process

As mentioned above, three buffer zones were identified to analyze the urban sprawl process in the study region, including 0–4 km, 4–10 km, and 10–20 km to the geometric centers of the cities. Figure 4 depicts the urban sprawl process in the three buffer zones of the nine cities of Dongguan, Zhongshan, Foshan, Guangzhou, Huizhou, Jiangmen, Shenzhen, Zhuhai, and Zhaoqing from 1985–2000. Our results showed that the urban development of Dongguan was expanding to the southwest (Fig. 4(a)). The area of urban buildup land increased from 30.0 km^2 to 113.3 km^2 during 1985–2000. The expansion rate of urban buildup land in the period of 1995–2000 was much greater than the previous period (1985–1995). The area of urban buildup land increased by 4.6 times in the 0–4 km zone, 5.8 times in the 4–10 km zone, and 3.1 times in the 10–20 km zone.

The urban sprawl process of Zhongshan was to the south, and a new urban area appeared in the southwest (Fig. 4(b)). The area of urban buildup land increased from 22.6 km^2 to 81.5 km^2 during the period. The area of urban buildup land increased by 3.1 times in the 0–4 km zone, 9.8 times in the 4–10 km zone, and 2.8 times in the10–20 km zone. Foshan expanded to the northeast (Fig. 4(c)). The area of urban buildup land increased from 34.4 km^2 to 159.9 km^2 during that period. The area of urban buildup land increased by 3.5 times in the 0–4 km zone, 6.1 times in the 4–10 km zone, and 4.5 times in the 10–20 km zone. The expansion of Guangzhou was mainly to the eastern region (Fig. 4(d)). The urban buildup land increased by 1.1 times in the 0–4 km zone, 2.6 times in the 4–10 km zone, and 3.1 times in the 10–20 km zone. Urbanization in Huizhou appeared south along the river bank before 1995,

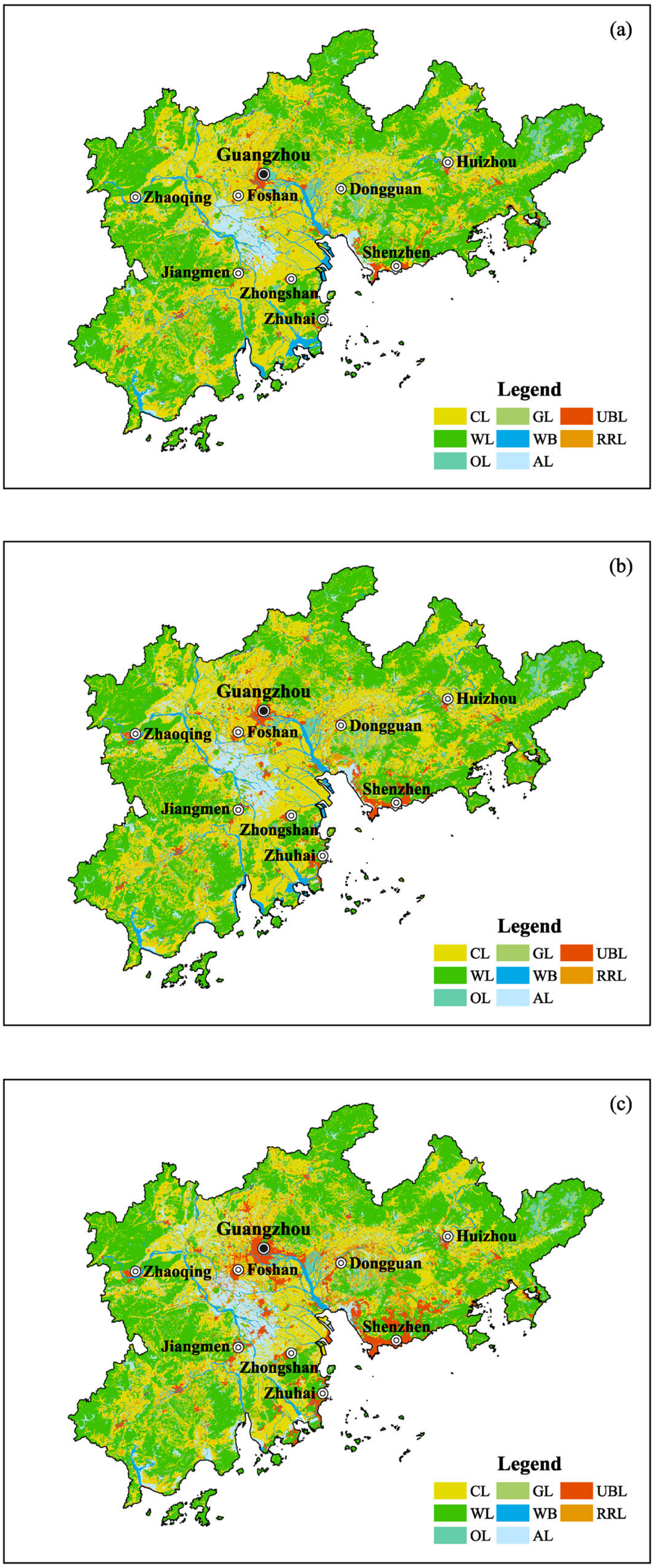

Fig. 2 Land use maps in the Pearl River Delta (Guangdong) in 1985, 1995, and 2000. (a) 1985; (b) 1995; (c) 2000. CL: cropland; WL: woodland; OL: orchard land; GL: grassland; WB: water body; AL: aquiculture land; UBL: urban buildup land; and RRL: rural residential land.

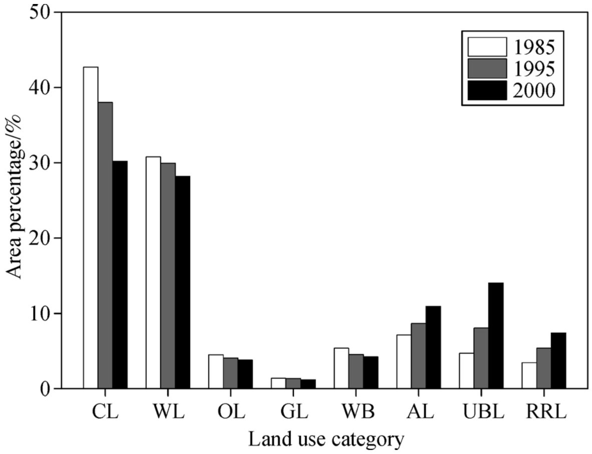

Fig. 3 Land use changes in the 9 cities within a 0–20 km buffer zone in 1985, 1995, and 2000. CL: cropland; WL: woodland; OL: orchard land; GL: grassland; WB: water body; AL: aquiculture land; UBL: urban buildup land; and RRL: rural residential land.

and then rapidly expanded to the northern bank (Fig. 4(e)). The urban buildup land increased by 2.2 times in the 0–4 km zone, 1.9 times in the 4–10 km zone, and 1.3 times in the 10–20 km zone. Jiangmen sprawled mainly along the watershed (Fig. 4(f)). The area of urban buildup land increased from 25.2 km^2 to 76.0 km^2 during 1985–2000. For Shenzhen, the pace of urban sprawl was very fast from the south to the north (Fig. 4(g)). The area of urban buildup land increased from 85.9 km^2 to 275.0 km^2. The urban buildup land increased by 2.0 times in the 0–4 km zone, 6.1 times in the 4–10 km zone, and 3.0 times in the10–20 km zone. Zhuhai expanded along the coastline (Fig. 4(h)). The urban buildup land increased by 2.1 times in the 0–4 km zone, 3.1 times in the 4–10 km zone, and 8.7 times in the 10–20 km zone. Zhaoqing's urban sprawl was mainly north of the river during 1985–1995. In the later period from 1995 to 2000, the expansion rate slowed down (Fig. 4 (i)). The urban buildup land increased by 2.2 times in the 0–4 km zone, 1.9 times in the 4–10 km zone, and 1.3 times in the 10–20 km zone.

Our results also showed differences between the nine cities in different periods of development. For 1985–1995, the area of urban buildup land for Shenzhen, Zhuhai, Foshan, and Guangzhou increased relatively more than the others, increasing by 63.6 km^2, 50.0 km^2, 38.2 km^2, and 38.1 km^2, respectively. For 1995–2000, Shenzhen, Guangzhou, Foshan, and Dongguan increased more, increasing by 125.6 km^2, 114.3 km^2, 87.2 km^2, and 59.1 km^2, respectively. Except for Zhuhai and Zhaoqing, the urban expansion areas for the other cities in the later period was significantly larger than that in the previous period. In terms of different buffer zones for different cities, the relatively faster expansion area for Dongguan, Zhongshan, Foshan, Huizhou, Shenzhen, and Zhaoqing was in the 4–10 km zone. However, the relatively faster expansion areas for Guangzhou, Jiangmen, and Zhuhai was in the 10–20 km buffer zone.

To explore urban change in different buffer zones, we also calculated the percentage of urban buildup land in the three buffer zones for the total area of nine cities (Fig. 5). In the 0–4 km buffer zone (Fig. 5(a)), Zhaoqing had the highest percentage of urban buildup land in 1985, accounting for 69%. This indicates that the urban area of Zhaoqing was concentrated in this buffer zone. Shenzhen and Dongguan had a relative minor proportion of urban buildup land, accounting for 21% and 20%, respectively. The proportion of urban buildup land increased to 44% in Dongguan, showing rapid expansion of urban construction in the 0–4 km zone by 1995. Zhuhai decreased by 11% in 1995, meaning that urban expansion mainly occurred in the outlying areas during this period. In the 4–10 km zone (Fig. 5(b)), the proportion of urban buildup land in Zhuhai, Guangzhou, and Jiangmen in 1985 was similar, accounting for 48%, 47%, and 46% respectively. Our results showed an increase in the proportion of urban buildup land in Dongguan, Zhongshan, Foshan, Huizhou, and Zhaoqing during 1985–1995. From 1995–2000, the proportion decreased in Shenzhen, Zhuhai, and Guangzhou. This result indicates urban expansion at a distance exceeding 10 km from the city center. In 1985, in the 10–20 km zone (Fig. 5(c)), Dongguan and Shenzhen ranked first for the percentage of urban buildup land in the whole Pearl River Delta, accounting for 67% and 65% respectively. This means that the proportion of urbanization decreased for all cities, except Huizhou and Zhuhai, during 1985–1995. For the period 1995–2000, the proportion of urbanization increased in all eight cities except for Huizhou.

3.3 Landscape pattern changes

The six landscape metrics mentioned above were calculated at the landscape level for 0–20 km, 0–4 km, 4–10 km, and 10–20 km buffer zones for each city in 1985, 1995, and 2000. These results are presented in Figs. 6–11.

3.3.1 Largest patch index (LPI)

The LPI equals the percentage of the landscape that the largest patch comprises (McGarigal et al., 2002). This metric can identify the dominant type of landscape. As shown in Fig. 6(a), Shenzhen had its maximum value in the 0–20 km buffer zone and decreased rapidly during 1995–2000. The value decreased for all cities except for Guangzhou and Jiangmen. The values for Dongguan, Foshan, and Zhuhai fluctuated widely during 1985–2000. In the 0–4 km buffer zone (Fig. 6(b)), the value for all cities increased during the study period, with the highest increase in Foshan and Shenzhen. In the 4–10 km buffer zone (Fig. 6(c)), the value for all cities decreased, except for Guangzhou. The rate of decrease during the period 1995–

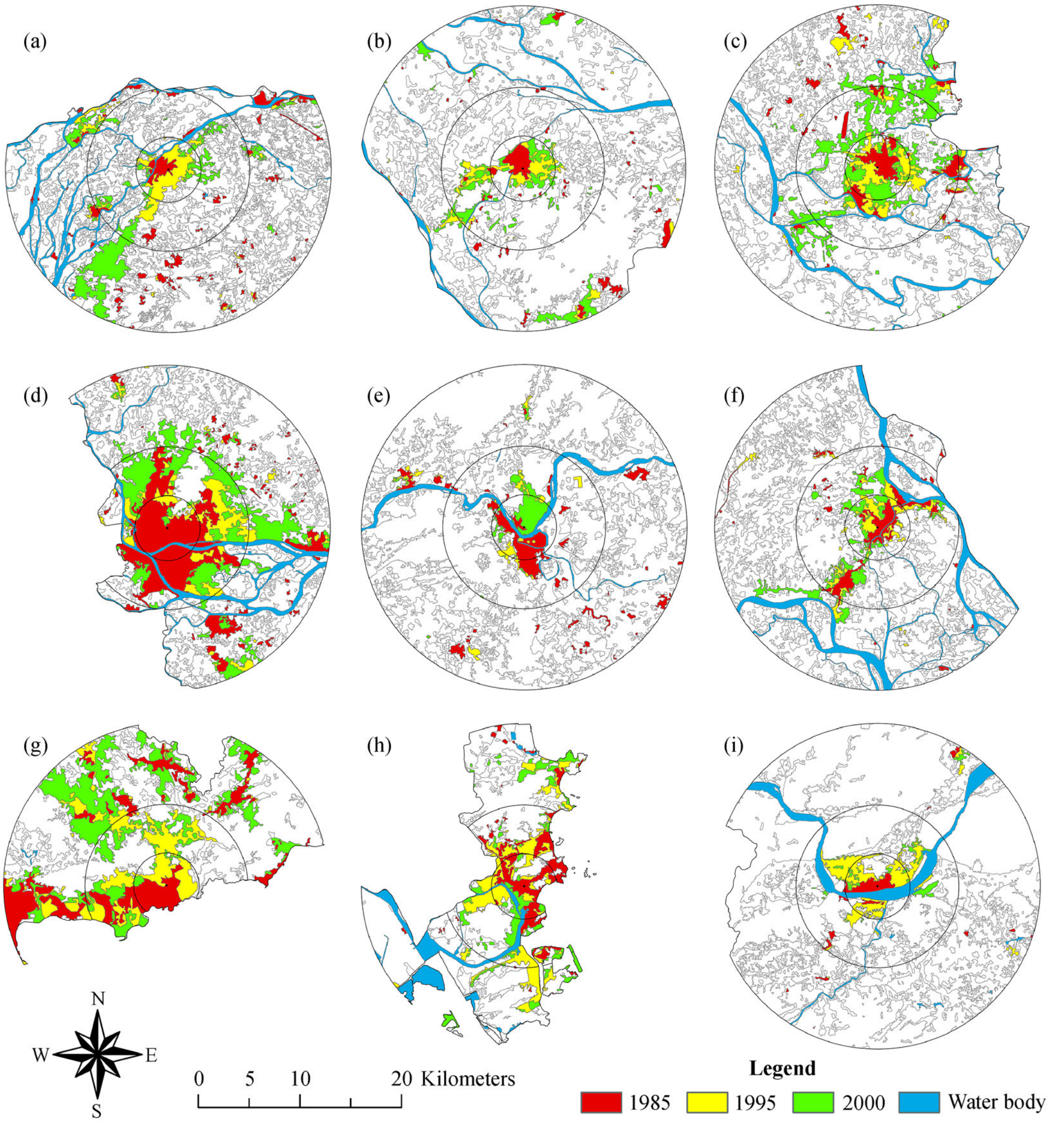

Fig. 4 Urbanization in the buffer zones of cities in the Pearl River Delta during 1985–2000. (a) Dongguan, (b) Zhongshan, (c) Foshan, (d) Guangzhou, (e) Huizhou, (f) Jiangmen, (g) Shenzhen, (h) Zhuhai, (i) Zhaoqing.

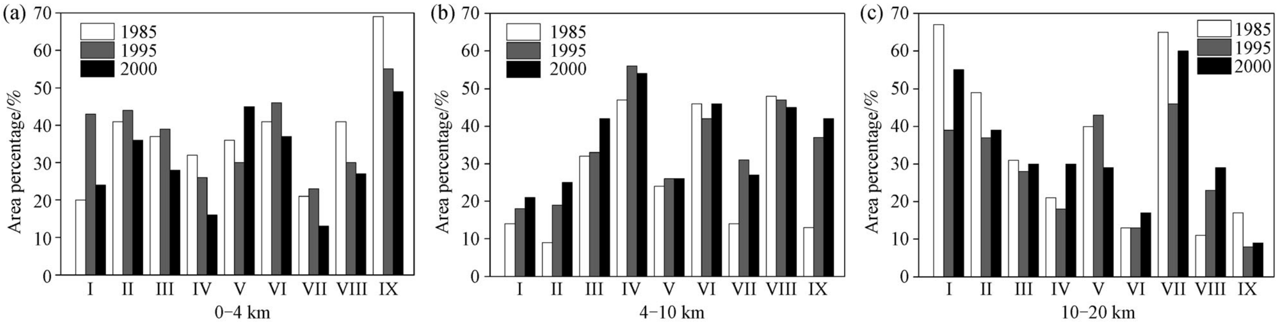

Fig. 5 Percentage of urban buildup land in three buffer zones for the total area of nine cities in the Pearl River Delta during 1985–2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

1985 was faster than that during 1995–2000. In the 10–20 km buffer zone (Fig. 6(d)), the values for Foshan, Guangzhou, and Zhuhai decreased.

3.3.2 Mean patch area (AREA_MN)

AREA_MN indicates the degree of fragmentation of the whole landscape. In the 0–20 km buffer zone, the value decreased for all cities during 1985–2000, except for Shenzhen and Foshan (Fig. 7(a)). The mean patch area for Zhongshan had the greatest decrease. Dongguan had the minimum mean patch area in 2000, indicating a high fragmentation level. In the 0–4 km buffer zone (Fig. 7(b)), Guangzhou had the maximum value for the three periods. Zhongshan and Shenzhen fluctuated greatly during 1985–2000. Huizhou, Zhaoqing, and Jiangmen had no significant changes in this index during the period 1985–2000. In the 4–10 km buffer zone (Fig. 7(c)), the value of Guangzhou declined slightly during 1985–1995 and then increased significantly during 1995–2000. However, the AREA_MN for Dongguan, Zhongshan, and Jiangmen decreased consistently. In the 10–20 km buffer zone (Fig. 7(d)), the value for Zhongshan decreased during 1985–2000. This result suggests dramatic changes in urban land use in this buffer zone during 1985–2000.

3.3.3 Contagion index (CONTAG)

The CONTAG is inversely related to edge density and affected by dispersion and interspersion of patch types (McGarigal et al., 2002). This metric reflects connectivity and fragmentation over the whole landscape. Our results showed that the CONTAG index in the 0–20 km zone decreased for all cities, except for Zhuhai and Shenzhen, during 1985–2000 (Fig. 8(a)). Shenzhen and Zhaoqing had a higher value in 2000, but the dominant patch type was different. The dominant patch type for Shenzhen is urban buildup land, and for Zhaoqing forest land. In the 0–4 km buffer zone (Fig. 8(b)), the value increased for all cities, except for Zhongshan, during 1985–2000, indicating that the connectivity of the dominant patch improved. In the 4–10 km buffer zone (Fig. 8(c)), the index for Zhuhai, Guangzhou, and Shenzhen increased. This increasing trend suggests significant urban sprawl during the study period. In the 10–20 km buffer zone (Fig. 8(d)), the value decreased for all cities, except Shenzhen.

3.3.4 Interspersion and juxtaposition index (IJI)

The IJI measures the degree of patch adjacencies and interspersion. Variation of the IJI is shown in Figs. 9(a)–

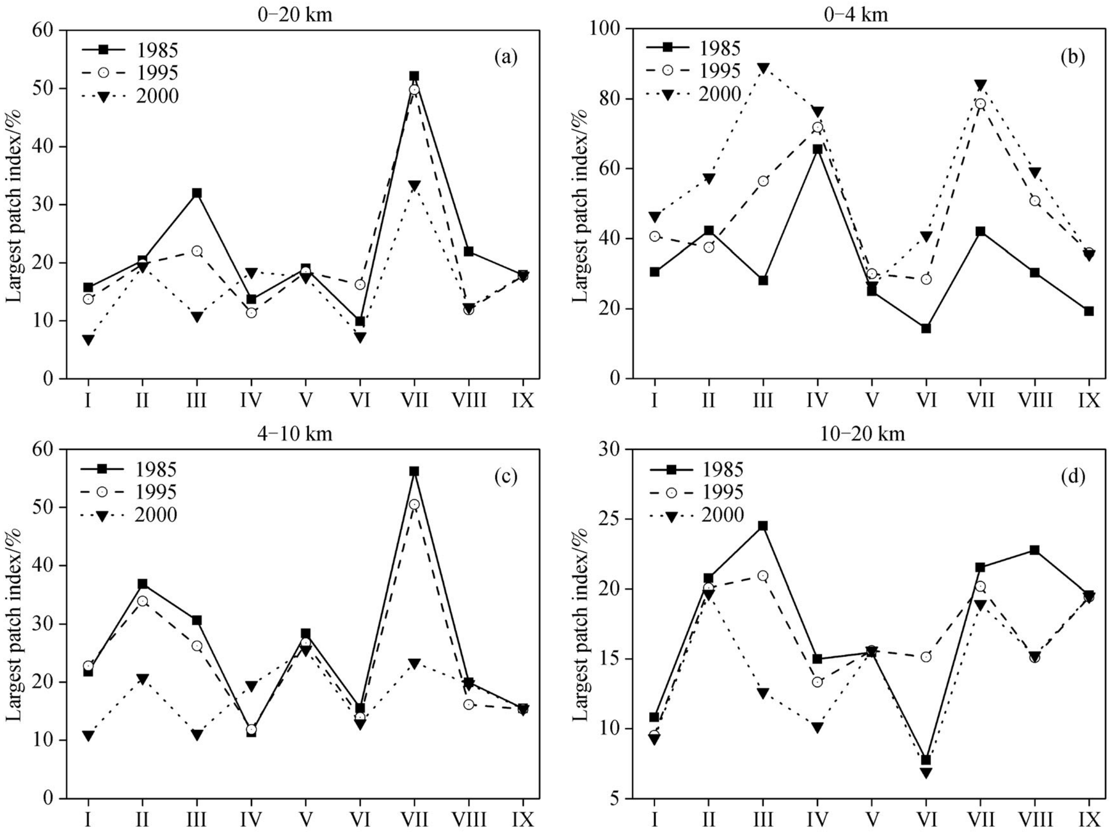

Fig. 6 The largest patch index (LPI) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

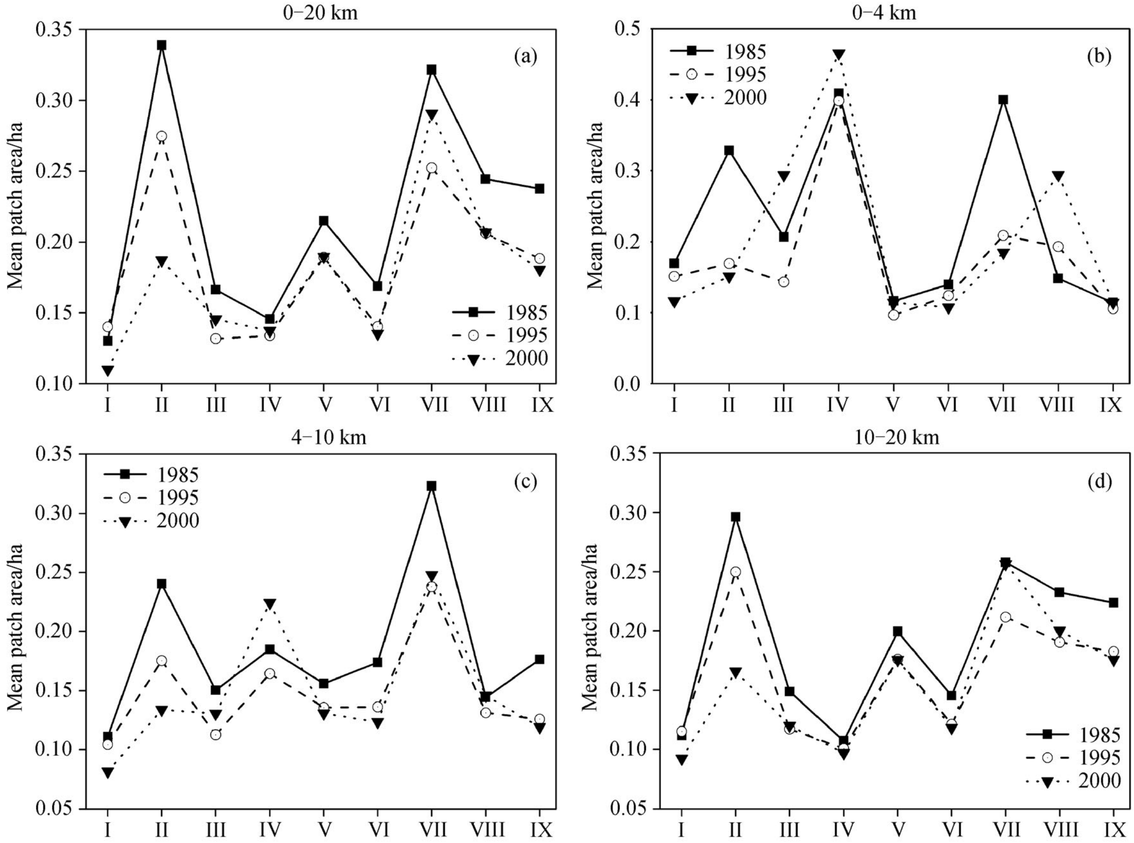

Fig. 7 The mean patch area (AREA_MN) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

9(d). In the 0–20 km buffer zone (Fig. 9(a)), the values for all nine cities increased slightly during 1985–2000, except for Zhuhai and Zhongshan. In the 0–4 km buffer zone (Fig. 9(b)), Foshan decreased rapidly during 1985–2000, reaching the lowest value in 2000. In the 4–10 km buffer zone (Fig. 9(c)), the index for Shenzhen and Zhuhai increased rapidly during 1985–1995, and then decreased significantly during 1995–2000. The value of the IJI in Zhaoqing, Foshan, and Jiangmen demonstrated a continued increase. In the 10–20 km buffer zone (Fig. 9(d)), the value for Shenzhen, Zhuhai, and Zhongshan increased and then decreased during the period 1995–2000. The results also indicated that the value for other cities increased slightly during 1985–2000.

3.3.5 Shannon's diversity index (SHDI)

The SHDI indicates landscape heterogeneity and is sensitive to less-occupied patch types. In the 0–20 km buffer zone (Fig. 10(a)), the value for all cities increased during 1985–2000, except for Shenzhen. In the 0–4 km buffer zone (Fig. 10(b)), the index for Foshan, Guangzhou, and Shenzhen decreased during 1985–2000. In the 4–10 km buffer zone (Fig. 10(c)), great differences for SHDI variation were evident between these cities. SHDI values for Dongguan, Foshan, Zhongshan, and Jiangmen increased significantly, while that for Guangzhou decreased during the period. In the 10–20 km buffer zone (Fig. 10(d)), the value increased for all cities during the study period.

3.3.6 Shannon's evenness index (SHEI)

The Shannon's evenness index is expressed such that an even distribution of areas among patch types results in maximum evenness. As such, evenness is the complement of dominance (McGarigal et al., 2002). We see that except for Zhuhai and Shenzhen, the value of SHEI in the 0–20 km buffer zone of these cities increased (Fig. 11(a)). In the 0–4 km buffer zone (Fig. 11(b)), the value decreased for the whole landscape, but especially for Foshan and Shenzhen. In the 4–10 km buffer zone (Fig. 11(c)), the value of SHEI in Dongguan, Zhongshan, Foshan, Jiangmen, and Zhaoqing increased rapidly. However, for Guangzhou, the index decreased significantly during the period, especially for 1995–2000. In the 10–20 buffer km zone (Fig. 11(d)), the value for all cities increased during 1985–2000, except for Shenzhen.

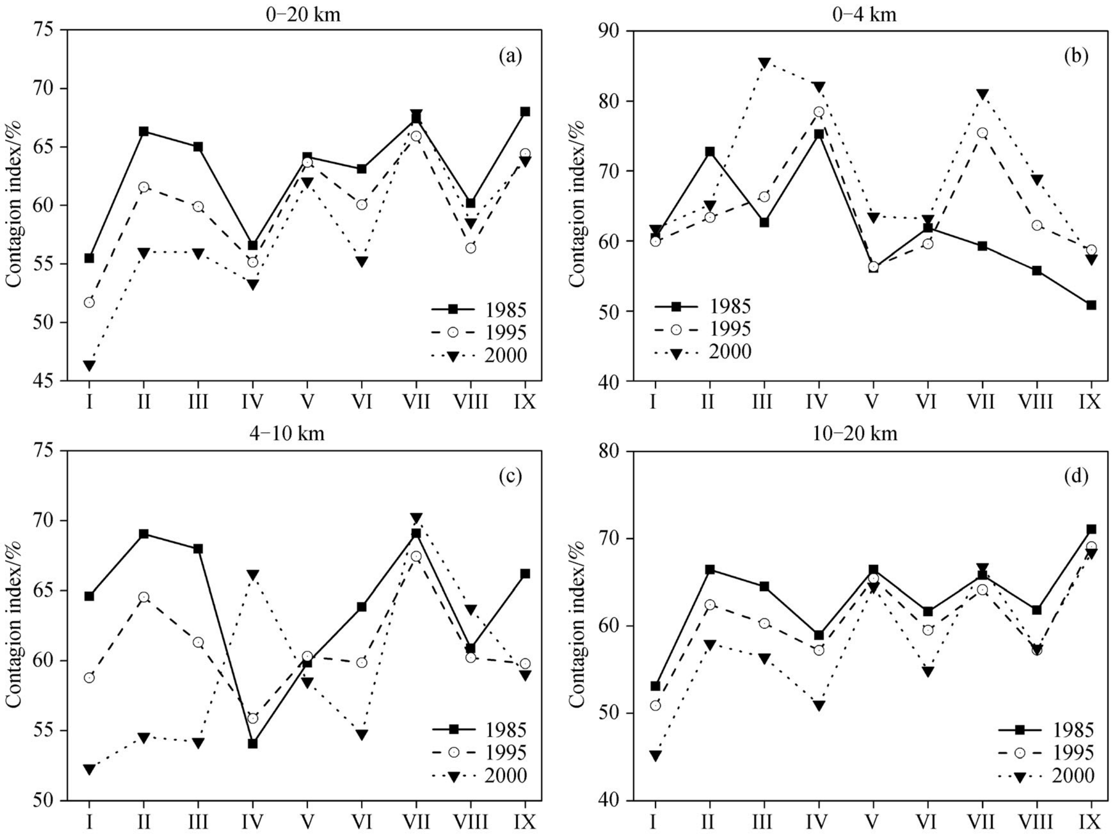

Fig. 8 The contagion index (CONTAG) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

4 Discussion

4.1 Urban sprawl process and driving forces analysis

The results of our study showed a process of accelerated urban sprawl whereby the urban buildup of land in the Pearl River Delta region occurred in a relatively short period of time. From an overall perspective, although rapid urbanization occurred in the whole region, it was believed that the urbanization of the Pearl River Delta was on the way of diversification which was reflected on the spatial and temporal dimension. From the spatial point of view, the urban sprawl process for each city mainly showed differences for different buffer zones. For example, the urban sprawl of Guangzhou and Shenzhen was more intense than that of the other cities; thus, these two cities serve as "dual-nuclei" of economic development and population aggregation in the Pearl River Delta (Lv et al., 2012). It was found that the urban area was concentrated in the 0–10 km buffer zone, and demonstrated the more compact characteristics of urban structure (Fig. 4). As a city with a long history in the Pearl River Delta, Guangzhou's expansion was centered towards the old city during 1985–2000. Shenzhen demonstrated a more comprehensive expansion from a small village under the Reform and Opening policy from 1980s. The urbanization processes of the two cities were mainly affected by the government, showing as the "from top to bottom" development mode. Therefore, the policy has strong orientation with regard to the urban sprawl process.

For Dongguan, the spatial pattern of urban sprawl showed apparent directional extension to Hong Kong and Macao. We thought this development mode was mainly driven by external investment. During 1985–2000, the external investment from the special administrative regions, especially from Hong Kong, accounted for over 65% of the total external investment in the Pearl River Delta (Lin, 2006). For Foshan, Zhongshan, and Huizhou, the urban sprawl experienced a process of distributed sporadically. This is the typical development mode of "from bottom to top". The spatial pattern of urbanization was mostly affected by rural industrialization. Under the economic stimulus, a large number of township enterprises emerged, contributing to the increase of the urban buildup land. In addition, some urban sprawl was limited by physical conditions. For the cities located near to the coastline and the river, urban sprawl was more inclined towards the coastline or river bank such as in Zhuhai and Zhaoqing.

From the temporal point of views, two periods were

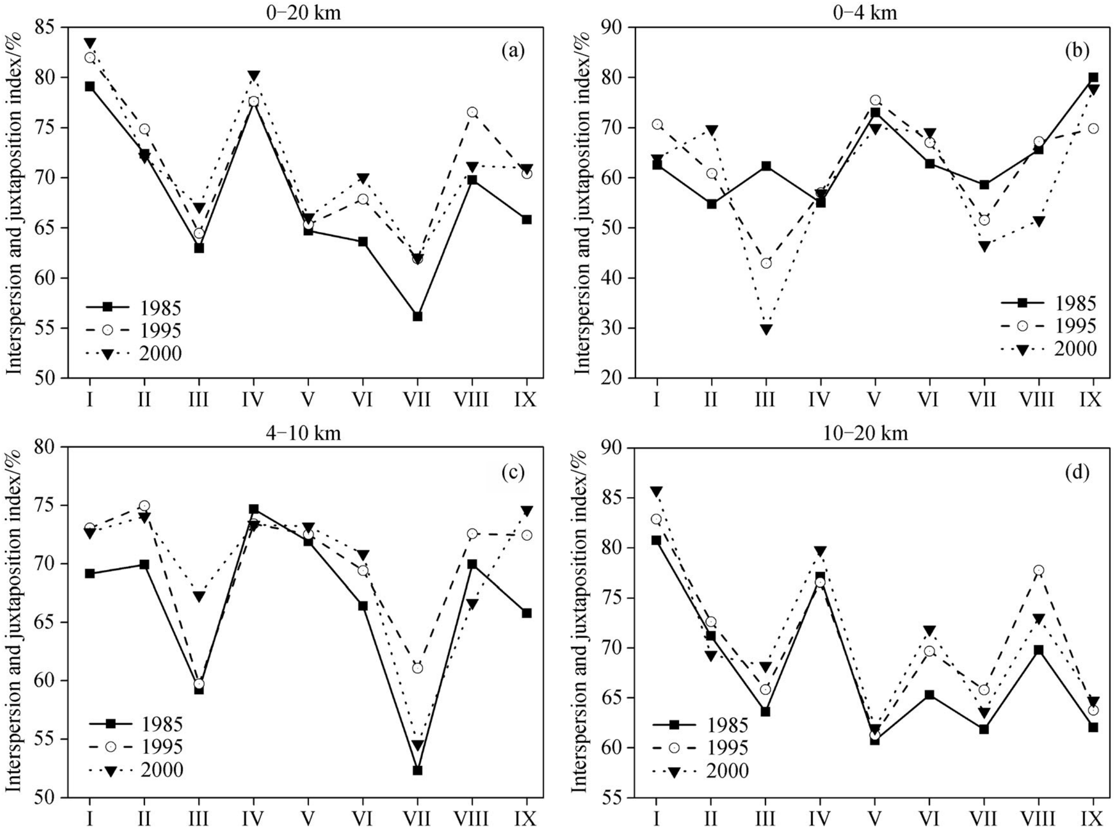

Fig. 9 The interspersion and juxtaposition index (IJI) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

chosen to analyze the urban sprawl in the Pearl River Delta region. The period of 1995–2000 had a faster expansion rate than that in the previous period of 1985–1995 for most cities. The urban sprawl was characterized by obvious stages, resulting from different influential factors.

Based on the above, drastic transformation of land use and the rapid urban sprawl at inter- and intra-city dimensions can be attributed to significant driving factors such as population, economy, policy, and geographical relationship. The population in the Pearl River Delta increased from 23.69 million in 1990 to 42.89 million in 2000, nearly doubling in only 10 years (Statistics Bureau of Guangdong Province, 2014). A large number of immigrants prompted the expansion of urban buildup land and residential land to ensure regular accommodation and living. As one of China's development engines since the Reform and Opening policy of the 1980s, the regional economic boom after 1990 was mostly the result of domestic and foreign investment, especially from the exterior. However, obvious intra-regional disparity also existed because of industry specialization in the region (Seto and Fragkias, 2005). Rapid development in this region was driven by the multi-agents economic mode (Seto and Kaufmann, 2003). On one hand, the local government increasingly exploited land resources to attract more foreign investment, which created competition among these cities (Zhang, 2000). On the other, the government — on multiple scales from provinces, cities, towns, villages, and landowners — negotiated and finally shaped land use patterns through multiple trade-offs while considering their own development objectives. With the implementation of the Reform and Opening policy in China, a series of policies and regulations were issued to improve land use structure, promote land use efficiency, and optimize spatial configuration in the Pearl River Delta. For example, "the Law of Land Administration of the People's Republic of China" was promulgated in 1986 and amended in 1988. In this act, it was stipulated that to promote reform on urban land use rights, legalized private organizations and individuals can obtain land use rights of state-owned land to activate the land market in China (Ding, 2003). In 1992, "the Urban and Rural Planning Law of the People's Republic of China" was implemented in Guangdong Province. Furthermore, in 1995, the "Development Planning of Urban Agglomeration in the Pearl River Delta-Coordination and Sustainable Development (1995–2010)" began to promote regional integration. In addition, to protect eco-land, "the Law on the Protection of Basic Farmland" was issued to realize the dynamic balance of the total arable land (Ding, 2003). Each policy and

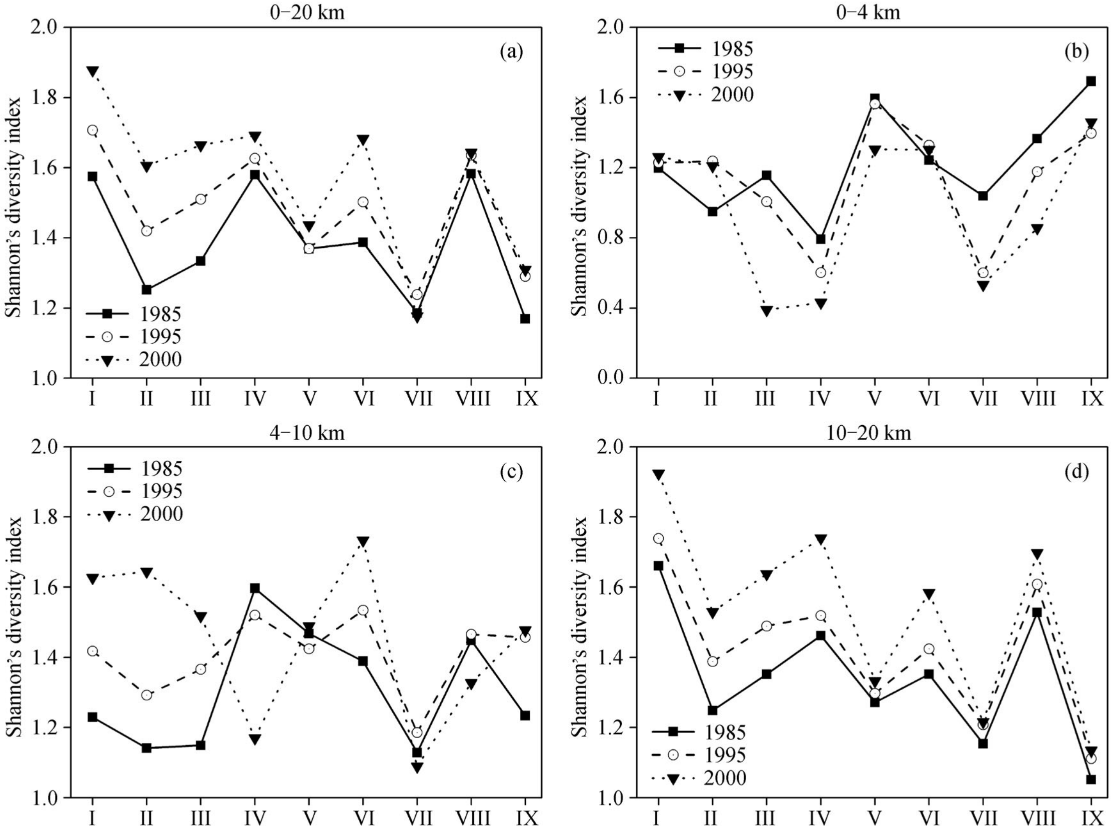

Fig. 10 The Shannon's diversity index (SHDI) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

regulation had enormous influence on the urbanization process for this region, especially for Guangzhou and Shenzhen. In addition, since 1992, the establishment of high-tech industrial development zones, such as the establishment of national high-tech zone in Zhuhai has affected the urban sprawl pattern.

The most particular driving factor of urban sprawl in the Pearl River Delta is the geographical relationship with the special administrative region, Hong Kong and Macao. These two regions had been governed under the formula of "one country, two systems", promoting the coordinated development of economic mode. For example, the Shenzhen and Zhuhai special economic zones located adjacent to Hong Kong and Macao had benefited more from the plentiful external investment (Wang et al., 2009). The labor-intensive industries had been migrating briskly towards this region. In the middle of 1990s, more than 80% of the enterprises from Hong Kong had set up the factories in the Pearl River Delta region, which had formed the model of "Front Shop, Back Factory" (Xu and Li, 2009). After 20 years of the Reform and Opening policy, the investment from Hong Kong had greatly contributed to the urban sprawl and economic development in the Pearl River Delta region.

4.2 Landscape pattern responses to the rapid urbanization

The results of six landscape metrics for different buffer zones and time periods indicate that variation of the metrics is reasonably independent in indicating the landscape responses of land use and urban sprawl. In the Pearl River Delta, the LPI, AREA_MN, and CONTAG demonstrated a decreasing trend, while the IJI, SHDI, and SHEI showed an increasing trend during 1985–2000. The LPI describes the dominance of a particular land use type at the landscape level, and helps understand urbanization transitions (McGarigal and Marks, 1995; Ramachandra et al., 2015). The decrease demonstrated by the LPI means that urban buildup land has become increasingly dominant in the whole region under urbanization. At the same time, dominant patches of cropland and woodland are decreasing, although they still occupy about 70% of the region. AREA_MN and CONTAG are related to the degree of fragmentation at the landscape level, with a lower value indicating greater fragmentation and a higher value reflecting aggregated growth embracing the city center (Ramachandra et al., 2015). In the post-reform period, other studies identified more fragmented urban patterns (Seto and Fragkias, 2005; Yu and Ng, 2007). The IJI is

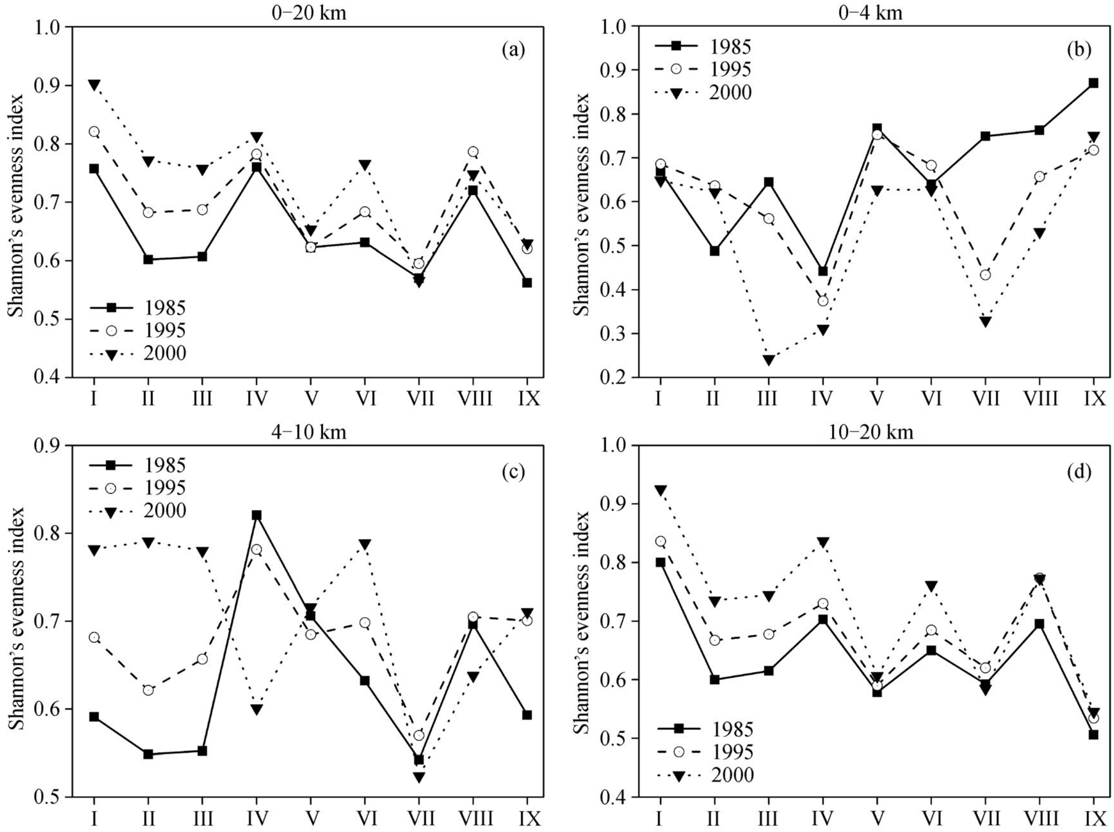

Fig. 11 The Shannon's evenness index (SHEI) for different buffer zones of the nine cities in 1985, 1995, and 2000. I: Dongguan, II: Zhongshan, III: Foshan, IV: Guangzhou, V: Huizhou, VI: Jiangmen, VII: Shenzhen, VIII: Zhuhai, and IX: Zhaoqing.

higher when the types of urban patches are interspersed, whereas lower values characterize landscapes where patches are poorly interspersed (McGarigal and Marks, 1995; McGarigal et al., 2002). An increase in the IJI, SHDI, and SHEI reflect increasing landscape heterogeneity. Our results suggest an increase in the degree of human manipulation of the landscape, which can be explained by the increase in landscape fragmentation, interspersion, and heterogeneity. These phenomena are also revealed in Jing-Jin-Ji and the Yangtze River Delta urban agglomeration in China, as well as in the state of Maryland in the USA (Irwin and Bockstael, 2007; Haas and Ban, 2014).

Landscape pattern and spatial metrics are spatially correlated and scale-dependent (Wu, 2004). The results of landscape pattern responses to land use changes indicate different development routines for cities undergoing rapid urbanization in the region. For example, Shenzhen is ranked first in terms of degree of urbanization, showing lower fragmentation and higher connectivity in the landscape metrics. However, urbanization in Guangzhou, Dongguan, and Zhuhai is relatively lower, but demonstrates higher landscape diversity and fragmentation. These differences in landscape pattern are caused by various factors, such as geographical location, physical condition, geometrical shape, and the spatial scale of the gradient analysis for each city. Among these, our selected buffer zones are important in determining the response of landscape patterns to land use changes. In this study, the selection of buffer zones was based on the measurement of the maximum radius of urban buildup area for each city, which included as much urban buildup information as possible. This is our principle concern in our study area. Our results of landscape pattern metrics suggest that integrating representative metrics can describe landscape responses to urban sprawl, help understand the different stages of urban development, and reflect the ecological implications of specialty urbanization (Liu and Weng, 2013). Moreover, the results can provide significant implications for city planning and land management in other urban agglomerations in China.

4.3 Implications for planning in China

Urbanization will continue worldwide, especially in Asia, where half of the world's urbanization is forecast to occur. Of the Asian countries, China will be at the forefront (Seto et al., 2012). With continued urban sprawl, there will be greater contradiction between the serious shortage of land resources and demand. Though China's urbanization increased from 19.4% to 56.1% between 1980 and 2015, it developed far ahead of the country’s economic growth, and the advantages of urbanization are offset by perennial urban curses including overcrowding, air and water pollution, and environmental degradation (Yang, 2013). Therefore, effective urban design and planning are crucial to control urban sprawl at a reasonable speed and benefit current and future residents. In this study, evaluation of urbanization is associated with the size, scale, and shape of cities, which reflect different development stages. Gradient analysis for landscape metrics reveals hierarchy characteristics of the city center. Different agents closely related to urban management and planning should make a trade-off for urban growth in different buffer zones to maximize resource utilization and eco-services. As the spearhead of economic development, dramatic changes in the Pearl River Delta region were mainly due to policy factors and urban planning. Each city conducted urban planning; however, the government recently proposed a new project to construct a world-class metropolitan area in the Pearl River Delta region, followed by “The Pearl River Delta Region Planning” strategy, which was launched in 2014. Regional planning is integrated with previous urban planning, which not only concentrates on the whole region, but also on local details for each city and each department including regional ecological security protection, regional water resources utilization, regional traffic integration, regional land development control, and core area space optimization. As the population and urban sprawl increase, more national and local urban agglomerations emerge. Our results for the Pearl River Delta region provide recommendations and implications to help complete planning for the Pearl River Delta region, and are important in realizing the high-quantity development of other agglomerations in China.

5 Conclusions

Urban land use changes and urban sprawl shape the cityscape and promote the urbanization process. A deeper understanding of these phenomena reveals characteristics of the economy and reflects the degree of anthropogenic disturbance to the natural landscape. In this study, we integrated the RS, GIS, and landscape ecology methods to quantitatively investigate the spatiotemporal dynamics of land use, urban sprawl, and landscape patterns in the Pearl River Delta region during 1985–2000.

Our results show that urbanization is characterized by the expansion of buildup land, which during the study period was mostly at the expense of cropland in the Pearl River Delta. Although rapid urbanization occurred throughout the region, different cities demonstrating urban expansion and landscape metrics were heterogeneous. There was greater urban sprawl in Guangzhou and Shenzhen than in the other seven cities in this region. The population as well as economic, policy, and geographical relationship factors drive this intra-regional discrepancy. Our results also showed that gradient analysis within specific buffer zones to the geometric city center can reveal the features of urban sprawl, and representative landscape metrics can demonstrate the landscape pattern responses of urban sprawl. The evolution of urban landscape patterns demonstrates transformation from disorder to order and from diffusion to coalescence during periods of rapid development. Finally, our results may provide important implications for urban planning and land resources management in China.

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