Land Use Policy 97 (2020) 104753

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Comparing the spatial and temporal dynamics of urban expansion in Guangzhou and Shenzhen from 1975 to 2015: A case study of pioneer cities in China's rapid urbanization

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ARTICLE INFO

Keywords:
Urbanization
Intercity comparison
Landscape metrics
Urban growth types
Land use policy

ABSTRACT

The distinct urbanization process of China has attracted worldwide attention because of its impressive speed, massive scale, and policy intervention. However, the interrelationship between urban expansion and government policies is still not well understood. The Pearl River Delta Urban Agglomeration of China is the first national pioneering urbanization area since the implementation of the policy "Reform and Opening-up" in the late 1970s. Here we compared the spatial and temporal patterns of urbanization in two leading cities of the Pearl River Delta (i.e., Guangzhou and Shenzhen, the provincial capital and the first Special Economic Zone of China, respectively) from 1975 to 2015, using Landsat data integrated with urban growth and landscape metrics analysis, and examined possible footprints of major economic and urbanization policies. Our results illustrated that urban land areas in both Guangzhou and Shenzhen have experienced magnificent annual growth rates at 8.1% and 11%, respectively between 1975 and 2015. On average, Shenzhen witnessed substantially higher urban growth rate than Guangzhou during the past four decades, particularly in the initial period (1978–1990) when the Reform and Opening-up policy was launched and Shenzhen was designated as the first Special Economic Zone in China in the late 1970s. However, the speed of urban expansion in Shenzhen became considerably lower than Guangzhou from 2005 to 2015, subject to physical conditions and a series of urban land use policies. Both cities showed a generally similar dynamics of urban growth forms with leapfrogging as the predominant type of urban growth at first and then edge-expansion while the contribution of infilling in Shenzhen was higher than that in Guangzhou, especially since 2005. The urbanization processes characterized by landscape and urban growth metrics revealed that a diffusion-coalescence-diffusion-coalescence process was identified for Guangzhou, while Shenzhen was generally consistent with the diffusion-coalescence urban growth hypothesis.

1. Introduction

The proportion of the world's urban population is predicted to increase to 68% by 2050, and China, India and Nigeria are expected to account for 35% of the increase (United Nations, 2018). The rapid urban expansion in developing countries not only has impacts on economic development but also exerts considerable challenges on the sustainable development of natural and urban ecosystems such as development imbalances and food security (Cohen, 2006; Qian et al., 2016). Since the implementation of the landmark Reform and Opening-up policy in the late 1970s, urbanization process in China has accelerated and the level of urbanization as measured by urban population increased from 17.9% in 1978 to 54.8% in 2014. A recent study showed that, the urban land areas of Beijing, Tianjin and Shijiazhuang have experienced rapid increase (i.e., 3.7%, 4.7% and 3.2% annual growth rate, respectively) from 1978 to 2010 (Wu et al., 2015). Besides mega cities, low-tier cities such as Nanjing and Xi'an also went through rapid urban land growth (i.e., 6.5% and 7.0%, respectively) from 1980 to 2010 (Zhao et al., 2015). However, China has entered a transformation period of "new normal" when profound social, economic and ecological changes will occur (Liu et al., 2018). The goal of building harmonious society makes a compelling call for healthy and sustainable urbanization (Liu, 2018). The distinct urbanization process of China has attracted worldwide attentions, given the critical role of government intervention, compared with western countries (Zhang, 2000; Gu et al., 2012; Li et al., 2014; Sun and Zhao, 2018). Urban planning, land use policy and financial policy in China could combine to significantly influence the process of urbanization (Yu and Ng, 2007; Qian et al.,

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https://doi.org/10.1016/j.landusepol.2020.104753
Received 25 June 2019; Received in revised form 18 March 2020; Accepted 9 May 2020
Available online 20 May 2020
0264-8377/

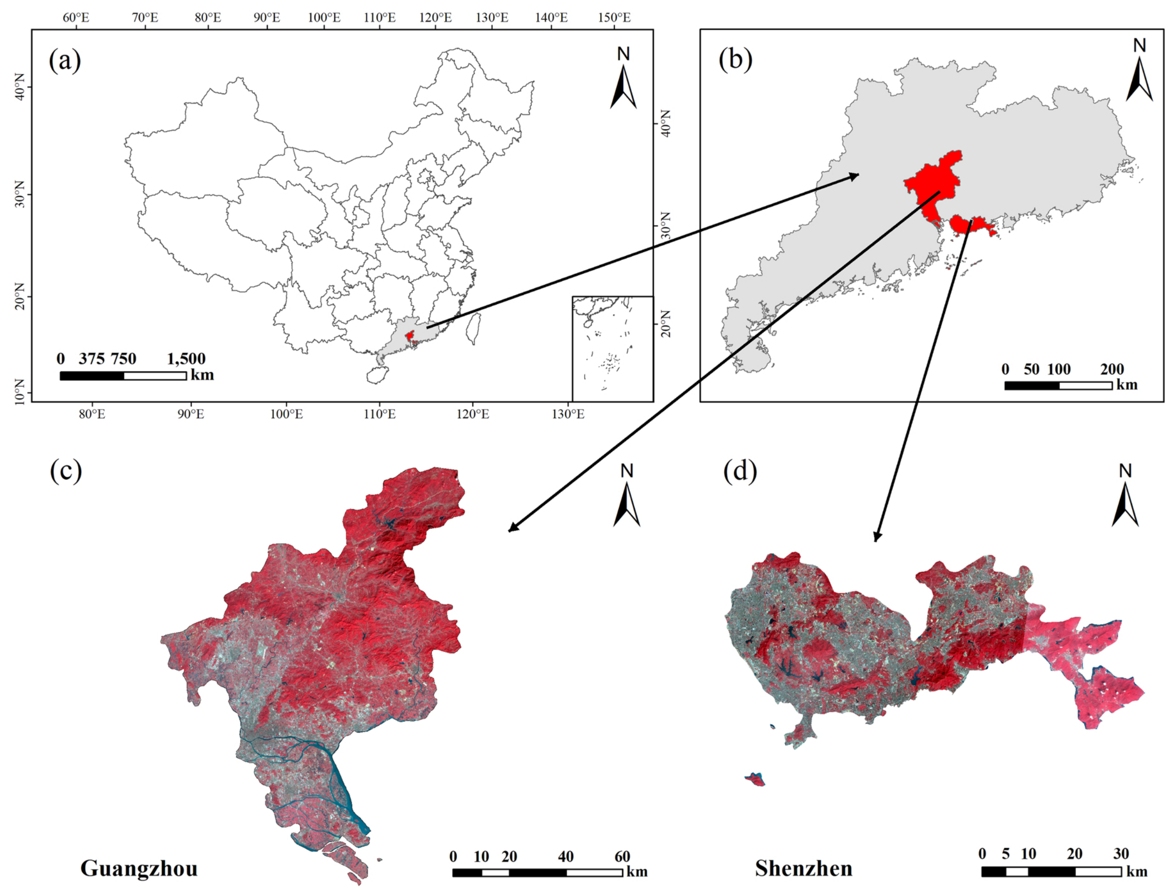

Fig. 1. The study area and the administrative division. (a) The location of the study area in China, (b) the location of Guangzhou and Shenzhen in Guangdong province, (c) and (d) the surface features of Guangzhou and Shenzhen illustrated by false color images from Landsat 8.

2016). Systematic research on key areas or typical case cities will be of great theoretical value and practical significance for land use sustainability under the economic transformation (Liu, 2018). Since the implementation of Reform and Opening-up policy, the Pearl River Delta has been the first national pioneering urbanization area of China (Tian et al., 2014; Fang and Yu, 2016). Particularly, Guangzhou and Shenzhen have attracted increasing attention as the polarization of regional urbanization process (Seto and Fragkias, 2005; Chen et al., 2014). The magnificent urban growth in these two cities since the late 1970s offered a snapshot of the constant experiments of land use market reform and implementation of new urban land use policy, especially for Shenzhen, which is the first Economic Special Zone of China established in 1979 (Tian et al., 2014). Therefore, Guangzhou and Shenzhen are the ideal and typical cities for comparative studies to unfold the complex impacts of land use policy on urban growth (Xu, 2001; Tian et al., 2014). Characterizing the spatial and temporal patterns of rapid expanding cities with different degree of development priority in large urban agglomerations in China will improve our comprehensive understanding of the past rapid urbanization and will formulate adaptation strategies to China's socio-economic development transformation (Liu, 2018). There have been numerous studies implying the negative impacts of urbanization on the environment in China, such as the heavy smog pollution, especially in those fast-growing large cities (Shi et al., 2016; Liu and Li, 2017). Therefore, apart from the characteristics of physical urban expansion, it is indispensable to investigate the corresponding environmental changes driven by the rapid urban expansion in Guangzhou and Shenzhen, in order to achieve sustainable urban development (Li et al., 2010; Qian et al., 2016).

Integrated research from multidisciplinary approach is indispensable to lay out scientific basis for the complicated land use systems. With the improved spatial and temporal resolution of remote sensing data, satellite images could provide long-term and reliable urban land information. Landscape metrics could quantitatively characterize the dynamics of urban land distribution and urban growth type well (Luck and Wu, 2002). Besides, urban development theory of diffuse-coalescence oscillation (Dietzel et al., 2005) has been tested in different cities, but it needs more to verify, especially cities in developing countries. A study comparing Shenzhen with Dongguan, a prefectural-level city of Guangdong Province found that Shenzhen had benefited from a series of favorable policies and achieved higher level of urbanization (Chen et al., 2014). Tian and Wu (2015) compared the urbanization pattern of Guangzhou in China with Phoenix in USA and underscored the profound impacts of physical conditions and land use policies. However, research contrasting the spatiotemporal patterns between Guangzhou and Shenzhen during the past several decades is still lacking. Characterizing spatiotemporal patterns of urban land expansion will provide information to understand urbanization itself, underlying processes, diverse consequences of urbanization, and thus help coordinate urban-rural development under new type of urbanization in China (Yang et al., 2018). Guangzhou and Shenzhen are facing resource shortage of construction land and other ecological problems such as air pollution, rapid loss of cropland and landscape fragmentation (Yu et al., 2007; Qian et al., 2016). Therefore, there is an urgent need for a comparative research emphasizing the long-term and spatially explicit urbanization processes of Guangzhou and Shenzhen, especially after 2000 when both cities entered the rapid development stage, to unravel the interactions between urban land growth and government intervention.

Thus, in this present study, we quantified and compared the magnitude, rates, and spatial patterns of urban expansion in Guangzhou and Shenzhen from 1975 to 2015 using Landsat satellite remote sensing images acquired around seven years (i.e., circa 1975, 1990, 1995, 2000, 2005, 2010 and 2015). The objectives of this study are to (1) analyze the spatial and temporal patterns of urban land expansion in Guangzhou and Shenzhen from 1975 to 2015; (2) compare the dynamic composition features of three urban growth types (i.e., edge-expansion, infilling and leapfrogging), as well as the environmental impacts by urbanization in Guangzhou and Shenzhen; (3) examine the validity of the diffuse-coalescence oscillation theory of urban development in two cities; (4) suggest options to improve land use sustainability under new era of urbanization in China.

2. Data and methods

2.1. Study areas

Our study areas are two pioneer cities (i.e., Guangzhou and Shenzhen) of the Pearl River Delta (Fig. 1c). The Pearl River Delta is in South China, close to Hong Kong and Macao, and consists of nine cities including one provincial capital city (i.e., Guangzhou), one deputy-provincial level city (i.e., Shenzhen), and seven prefectural level cities (i.e., Dongguan, Foshan, Huizhou, Jiangmen, Zhaoqing, Zhongshan, and Zhuhai). Guangzhou is the capital of Guangdong province, recognized as the political, economic, and technological center of Guangdong province and Southern China, with a long development history of more than 2000 years. The elevation ranges from 0 to 1210 m above sea level with mountains in the north. The annual average temperature is 21 °C, and the annual rainfall is 1720 mm. The total area of Guangzhou is 7436 km^2, consisting of eleven districts including Baiyun, Conghua, Haizhu, Huadu, Huangpu, Liwan, Nansa, Panyu, Tianhe, Yuexiu, and Zengcheng. The population was 13.5 million, and the GDP was 1810 billion RMB in 2016.

Also belonging to Guangdong province, Shenzhen was designated as the first Special Economic Zone in China in 1979 and has gradually grown into an international city benefited from the Reform and Opening-up policy. With convenient position of being adjacent to Hong Kong, Shenzhen owns many high-tech industry companies, acting as an Information Communications Technology (ICT) hub (Chen et al., 2014). Shenzhen has an area of 1996.8 km^2, and the coastline of the city is 229.96 km. The elevation is from 70 to 944 m, characterized by open plains, rolling hills, and mountains. The annual temperature is 22 °C, and the annual rainfall is 1933.3 mm. Shenzhen includes 10 districts of Baoan, Dapeng, Futian, Guangming, Longgang, Longhua, Luohu, Nanshan, Pingshan, and Yantian. The GDP of Shenzhen increased from 0.2 billion RMB in 1979 to 1750.3 billion RMB in 2016, and the population of Shenzhen was 11.38 million in 2016 (Li et al., 2010). However, the fast urban development has brought serious problems, especially unsustainable urban land expansion and environmental issues (The Shenzhen Government Work Report, 2005). Table 1 lists the geographic background and socioeconomic conditions of Guangzhou and Shenzhen. This study used the data from the National Bureau of Statistics of China (NBSC) (2016) and the environment quality reports from the government websites of Guangzhou (http://www.gzepb.gov.cn/gzepb/) and Shenzhen (http://www.sz.gov.cn/szsrjhjw/xxgk/tjsj/ndhjzkgb/) to investigate the annual dynamics of air pollutants including NO_x, PM_{10}, SO_2, and acid rain frequency.

Table 1
The geographic background and socioeconomic conditions of Guangzhou and Shenzhen.

	Guangzhou	Shenzhen
Latitude (N)	22°26′–23°56′	22°27′–22°52′
Longitude (E)	112°57′–114°03′	113°46′–114°37′
Elevation (m)	0–1210	0–944
Area (km^2)	7436	1997
Population (Million)[a]	13.5	11.4
GDP (Billion RMB)[a]	1810.0	1750.3

[a] data in 2016.

2.2. Methodology

2.2.1. Land use data

Multispectral Scanner sensor (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+), three categories of Landsat satellite remote sensing data from USGS website (http://www.usgs.gov/), were used to derive land use and land cover maps of Guangzhou and Shenzhen. To explore the land cover changes, we selected cloud-free images with seven times periods at a five-year interval (circa 1975, 1990, 1995, 2000, 2005, 2010, and 2015). Details of the selected Landsat images are shown in the supporting information.

Processing of the satellite images (e.g., band combination, re-projection, supervised classification) was conducted using ERDAS Imagine version 9.2. To derive land use data from the MSS images, we resampled them into a resolution of 30 m to be consistent with the resolution of TM and ETM+. We applied the maximum likelihood method to perform land cover classification and classified the land cover types of two cities into five types: cropland, urban land, water body, woodland, and other land cover (Zhao et al., 2015). Since the land cover type of urban land was the focus of this study, other types of land covers were treated as non-urban area afterwards. The definition of urban land is all non-vegetative area, which includes transportation, industrial, residential, and commercial space (Zhao et al., 2015). Accuracy assessment for the classified products were conducted using Kappa coefficients with reference to the method proposed by Zhou et al. (2012). Acquired images in 2015 from Google Earth Pro® (GE) with high resolution were selected to evaluate the classification products of 2015 and before 2015 in the areas only where the land covers remained unchanged since 1975. Two sets of 300 points each were generated as sample points of the classification result of 2015 and the unchanged area from 1975 to 2015. Accuracy analysis results demonstrated that for the land cover of urban land, the Kappa coefficients were more than 0.80 for both Guangzhou and Shenzhen, which met the accuracy assessment requirement (Foody, 2002).

2.2.2. Annual rate of growth

To measure annual urban expansion, we chose and calculated two indexes–Annual Increase (AI) and Annual Growth Rate (AGR) of urban land (Wu et al., 2015; Fei and Zhao, 2019). Annual increase (AI) is efficient to compare the expansion rates for the same city among different periods, while annual growth rate (AGR) is more suitable for comparison among different cities (Wu et al., 2015). Indexes used to quantify the urban growth rates are defined here:

$$AI = \frac{A_{end} - A_{start}}{d}$$

$$AGR = 100\% \times \left[\left(\frac{A_{end}}{A_{start}} \right)^{1/d} - 1 \right]$$

where A_{start} and A_{end} are the areas of urban land at the initial and end time, respectively, and d (in years) is defined as the time span of study period.

2.2.3. Analysis of urban growth types

Urban growth types of edge-expansion, infilling and leapfrogging types of urban growth were identified (Xu et al., 2007; Zhao et al., 2015). Infilling type means that the non-urban land surrounded by the existing urban patches was converted to urban land between two periods. The way of expanding from the edge of the existing patches of urban land is defined as edge-expansion. The leapfrogging type refers to the new urban land spreading out in isolation from existing urban land patches. To quantitatively recognize these three types of urban growth, the type index (E) was calculated according to Xu et al. (2007):

Table 2
The definition of six landscape metrics from McGarigal (2014).

Acronym	Name of landscape metric (units)	Description
Area metrics		
PLAND	Percentage of landscape (%)	The proportion of the landscape comprised of the corresponding patch type
LPI	Largest patch index (%)	The percentage of occupation by the largest patch
Shape metrics		
LSI	Landscape shape index	0.25 times of the landscape boundary and total edge divided by the square root of the total area.
Density metrics		
NP	Number of patches	Total number of patches for single class type
PD	Patch density (100 ha^{-1})	The number of patches in the landscape
MPS	Mean patch size (ha)	Average patch size for single class

$$E=\frac{L_{com}}{P_{new}}$$

where L_{com} represents the common border length between existing urban patch or patches and a new urban patch, and P_{new} stands for the perimeter of this new urban patch. Index (E) ranges from 0 to 1. The three types of urban growth are defined using specific E value that when $E = 0$, the type is leapfrogging, when $0 < E \leq 0.5$, it is edge-expansion, and when $E > 0.5$ the type is infilling.

2.2.4. Landscape metrics

Six metrics were selected to identify spatiotemporal impact of urban land change on landscape, which are relevant to urban expansion and able to show results effectively (Riitters et al., 1995): Mean Patch Size (MPS), Number of Patches (NP), Largest Patch Index (LPI), Shape Index (LSI), Percentage of Landscape (PLAND), Patch Density (PD) (Table 2). These class-level metrics refer to the spatial distribution of urban land patches (McGarial and Marks, 1995). LSI, NP, PD, and MPS demonstrate key aspects of landscape: edge, quantity, density, and size metrics. LSI measures the irregularity of the landscape (Lausch and Herzog, 2002). When urban land patches increase and the landscape become fragmented, LSI will increase, while LSI may decrease when urban land patches begin to merge. NP is a measure of number of urban patches and PD reflects the density of patches (Deng et al., 2009), both describe the fragmentation of landscape. PD is low but NP is high when urban landscape is dispersed. MPS is a measure of the average patch area at the urban class-level, related to NP and the total area of urban land. PLAND is the proportion of urban land area in the total city land area (Lausch and Herzog, 2002). LPI stands for the percentage of occupied by the largest patch, which measures the degree of urban polarization. Mathematically, we used FRAGSTATS version 4.2 to calculate these metrics according to the method of McGarigal (2014).

3. Results

3.1. Magnitude and rates of urban expansion

Table 3 lists the temporal changes of the annual growth rate of urban land areas for Guangzhou and Shenzhen by period. Both Guangzhou and Shenzhen have experienced magnificent urban expansion, but their magnitudes are different. In 1975, as the capital city of Guangdong province, Guangzhou with an urban land area of 70.0 km^2 was more than four times that of Shenzhen (16.0 km^2), and after four decades of urbanization, the total areas of urban land areas in Guangzhou and Shenzhen expanded to 1558.5 km^2 and 850.2 km^2, respectively. Specifically, the AI of Guangzhou kept increasing from 1975 to 2010 with a decline in 2015, while Shenzhen fluctuated between 12.5 and 34.4 km^2 with the largest AI in the period of 2000 – 2005 and the smallest AI in 1975 – 1990. It is noticeable that there was a substantial decrease of AI in Shenzhen after 2005. After removing the effect of city size, the annual expansion rate (AGR) of Shenzhen was 11.0%, and the AGR of Guangzhou was substantially lower (8.1%). For both cities, the AGR was the highest during 1975 – 1990 over the past four decades. Since 2005, the urban expansion rate of Guangzhou kept higher than that of Shenzhen. During 2010 – 2015, both cities reached their lowest expansion rate over the past four decades, and the AGR of Shenzhen was less than half of the AGR of Guangzhou.

3.2. Spatial patterns of urban land expansion

The characteristics of the spatial patterns of urban growth from 1975 to 2015 for Guangzhou and Shenzhen were illustrated in Fig. 2. Generally, Guangzhou was characterized by a mononucleus expanding from its urban core, and two secondary nuclei rapidly expanded after 2000, forming a tri-core urbanization pattern. It is noticeable that newly developed urban land patches after 2005 were mainly distributed in the northern rural region of Guangzhou (Fig. 3a). Shenzhen has witnessed its multicore expansion as new urban growth points scattered across the entire city even in the initial period of urbanization (1975 – 1990) (Fig. 3b). Specifically, the urban expansion of Shenzhen concentrated mainly in the southwest, which was the original Shenzhen Special Economic Zone and then extended to the northern inland region after 2000.

Fig. 4 demonstrated the spatial distributions of edge-expansion, infilling, and leapfrogging types of urban growth for those newly developed urban land patches, and Fig. 5 summarized the variations of the relative fractions of these three types of urban growth during two adjacent periods in terms of number and area for Guangzhou and Shenzhen from 1975 to 2015. The weight of extremely high proportion of infilling in terms of patch number and patch area showed similar sharp decreasing trend for both cities since 1975, especially during the

Table 3
Annual increase (AI) in urban area (km^2) and normalized annual urban growth rate (AGR,%) for Guangzhou and Shenzhen across six neighboring periods from 1975 to 2015.

	1975 – 1990	1990 – 1995	1995 – 2000	2000 – 2005	2005 – 2010	2010 – 2015	Average
AI (km^2)							
Guangzhou	15.13	25.75	34.2	45.6	83.6	65.31	37.2
Shenzhen	12.5	31.0	24.0	34.4	34.0	16.19	22.0
AGR (%)							
Guangzhou	9.79	7.39	7.14	6.79	8.64	4.81	8.1
Shenzhen	19.38	13.32	6.88	7.24	5.25	2.04	11.0

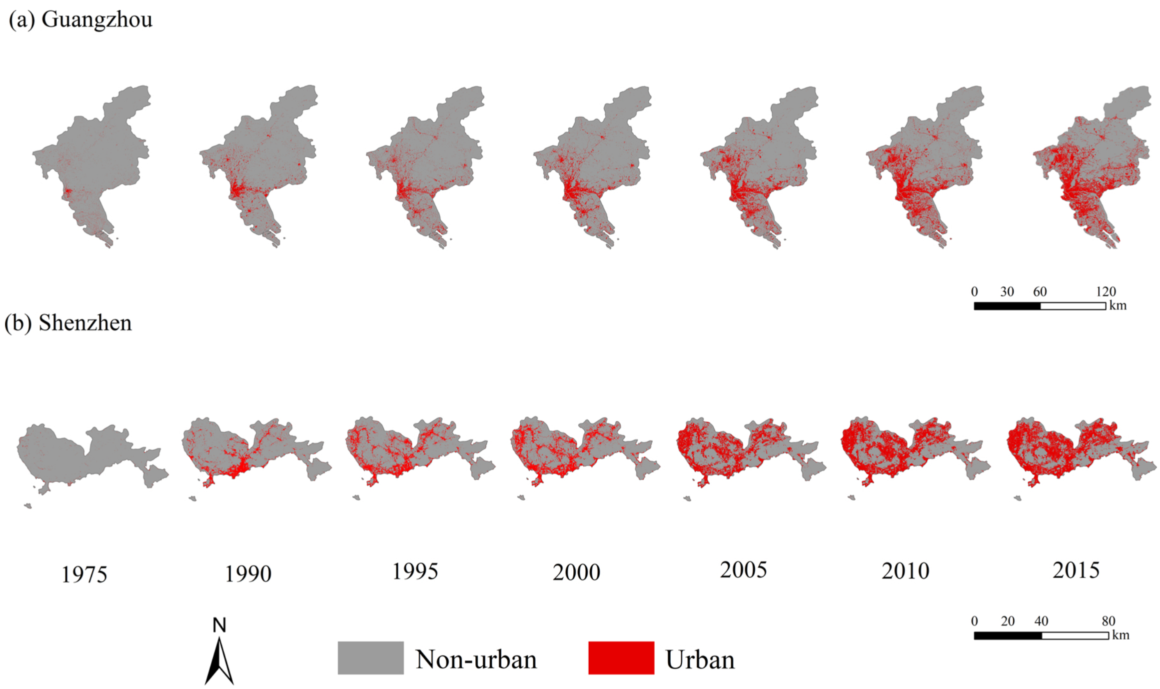

Fig. 2. The spatial urban expansion of urban area in Guangzhou (a) and Shenzhen (b) from 1975 to 2015.

early period. In the meantime, the proportion of edge-expansion and infilling types of urban growth increased. In respect of patch number, leapfrogging was the initial dominant growth type for both cities, however, leapfrogging was overtaken by infilling and edge-expansion in 1995 for Guangzhou and Shenzhen, respectively (Fig. 5). However, the two cities exhibited different variation patterns in the composition of edge-expansion, infilling, and leapfrogging. Specifically, regarding patch number, the type of infilling growth (Fig. 5a and b), in Guangzhou increased first, reaching the highest in 2000 and then edge-expansion contributed to the largest proportion of urban expansion. In contrast, infilling type of urban growth for Shenzhen increased consistently over the past four decades and occupied a comparable proportion to edge-expansion. As for the percentage of area of newly developed urban patches, edge-expansion was the largest (>40%) growth type (Fig. 5c and d) for both Guangzhou and Shenzhen over the entire study period. Between 1975 and 1990, the fraction of leapfrogging in terms of area exceeded 50%, slightly higher than edge-expansion for Guangzhou and Shenzhen. Leapfrogging was the dominant type of urban growth for Guangzhou and Shenzhen from 1990 to 1995 in terms of patch number, which was different from the composition in terms of patch number due to the relative smaller area of leapfrogging patches than edge-expansion. After 1995, the composition of three urban growth types reflected a generally consistent trend with regard to patch number as well as area.

Furthermore, the explicit exploration of the growth types of those newly developed urban patches revealed the urban expansion process among six neighboring periods (Fig. 4). For both cities, urban patches in the form of leapfrogging growth type could be found across the city.

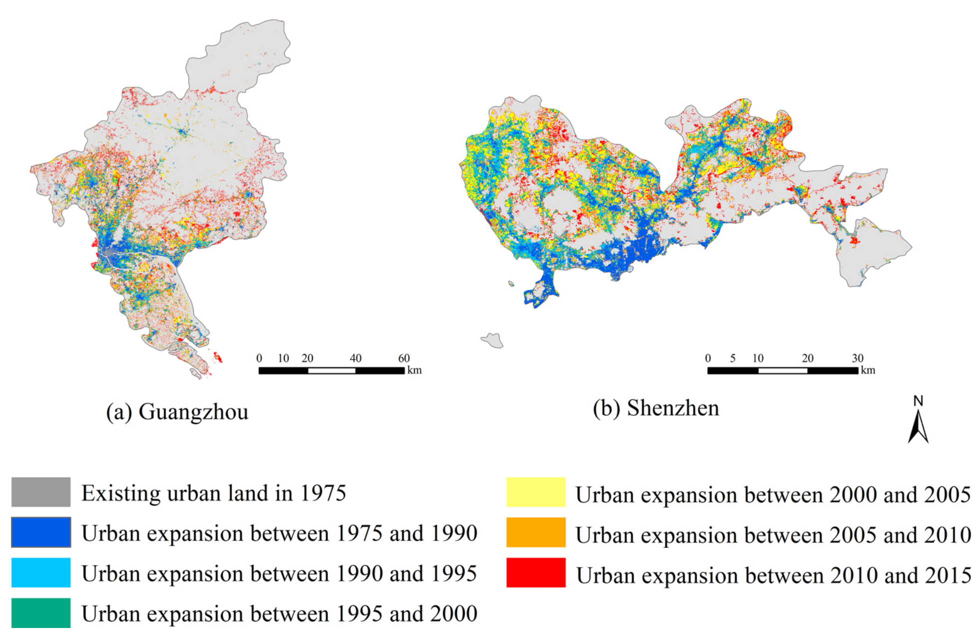

Fig. 3. Existing urban land in 1975 and newly developed urban land between six neighboring periods for Guangzhou (a) and Shenzhen (b) from 1975 to 2015.

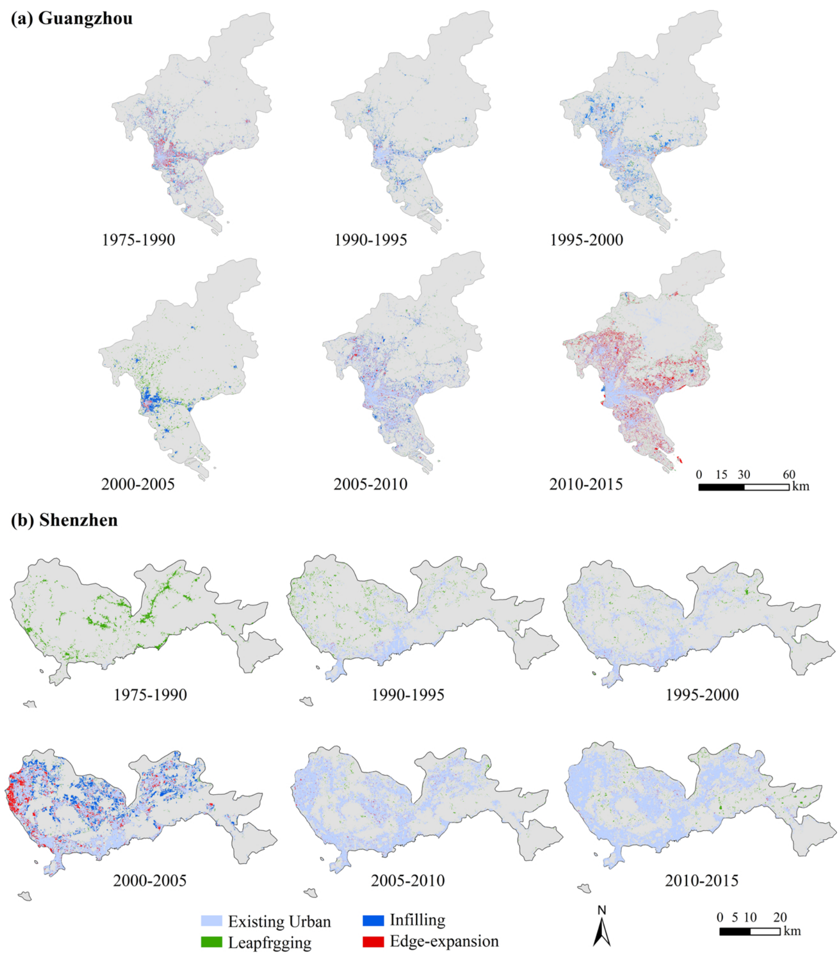

Fig. 4. Existing urban land and the spatial distribution of three urban expansion types (edge-expansion, infilling and leapfrogging) for newly developed urban area in Guangzhou (a) and Shenzhen (b) between six neighboring periods.

The infilling type of urban growth mostly occurred in the municipal districts and/or the centers (Fig. 4). Specifically, leapfrogging happened in the north during the period 1975–2000 and south after 2000 in Guangzhou. Moreover, edge-expansion and infilling types of urban patches were largely within the core of the city over the study period. On the contrary, in Shenzhen, all three growth types spread all over the city, especially in 1975 − 1990 and 2000 − 2005. However, the development directions of three growth types were different. Leapfrogging distributed mainly in the northern and southeastern region of Shenzhen. In contrast, infilling and edge-expansion mostly scattered around the coast and then spread towards the interior in the north.

3.3. Landscape pattern changes during the rapid urbanization process

Fig. 6 illustrates landscape metrics of urban land and the dynamics of landscape pattern in Guangzhou and Shenzhen from 1975 to 2015. During the rapid urban expansion process, the NP, LSI and PD of urban land in two cities displayed dramatic fluctuation pattern. There was a steep increasing trend during 1975–1995, and then declined in 1995 − 2000 for both cities. However, after 2000, Guangzhou and Shenzhen differentiated in the respect of NP, LSI and PD. Guangzhou experienced another increase-decline process, which was similar to the period of 1975–2000 and for Shenzhen, urban land patch numbers, density and shape complexity continued decreasing. The value of MPS for both cities have shown an upward trend over the study period and Shenzhen showed a much steeper increasing trend than that of Guangzhou. The LPI of Shenzhen sharply grew since 1990 and was considerably larger than that of Guangzhou, emphasizing the increase of urban land in the urban core of Shenzhen. After the 40 years of urban expansion, the urban area percentage (i.e., PLAND) increased from 1.5–21.0% for Guangzhou and 0.6–42.6% for Shenzhen, respectively. In 2015, the total proportion of urban land of Shenzhen became twice of Guangzhou.

3.4. Air quality changes during the rapid urbanization process

Available air quality data obtained from national environmental statistics yearbook and local government's environmental quality report showed that along with the rapid urbanization process, the concentrations of NO_x, PM_{10}, SO_2, and acid rain frequency varied considerably in both Guangzhou and Shenzhen (Fig. 7). The air pollutants of NO_x and PM_{10} showed a similar general trend of an initial slight increase and abrupt decrease in the 1990s (Fig. 7a and b). It is noticeable that both NO_x and PM_{10} concentrations of Shenzhen were lower than those in Guangzhou, and its turning point of air pollution decline was earlier than that in Guangzhou. During 2000 − 2005 when the AI of Guangzhou and Shenzhen increased substantially, both cities experienced increasing concentrations of NO_x and PM_{10} after a considerable decline in the 1990s. Nevertheless, after 2005, both of the concentrations of NO_x and PM_{10} showed a gradual decreasing pattern. The concentrations of SO_2 for both Guangzhou and Shenzhen showed large fluctuation during the rapid urban expansion, followed by a steady decrease since 2005 (Fig. 7c). The SO_2 concentrations of Shenzhen kept lower than those in Guangzhou. However, the available acid rain data demonstrated an extremely high frequency for two cities during the urbanization process, and Shenzhen experienced larger increase than

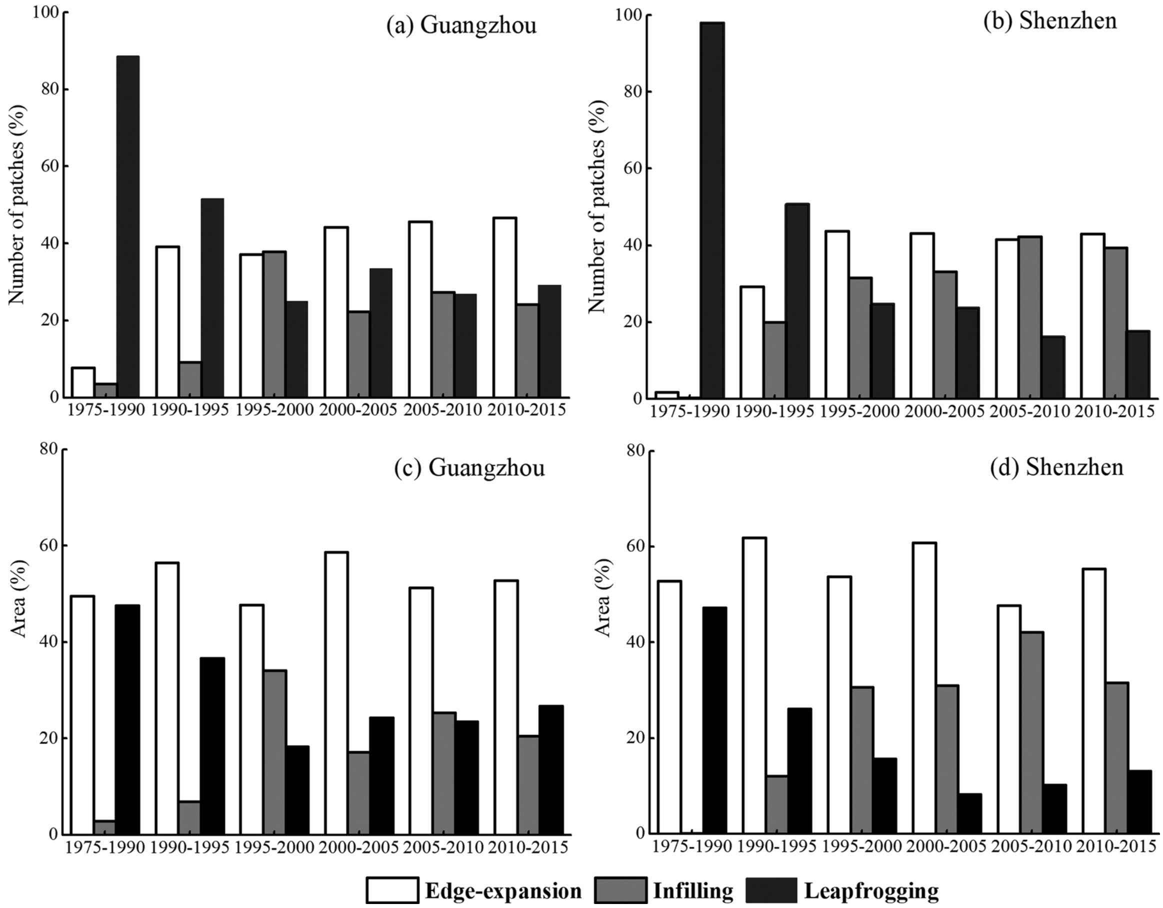

Fig. 5. The composition of edge-expansion, infilling and leapfrogging types of urban growth in number of patches in Guangzhou (a) and Shenzhen (b), and in number of areas for Guangzhou (c) and Shenzhen (d), respectively, across six neighboring periods between 1975 and 2015.

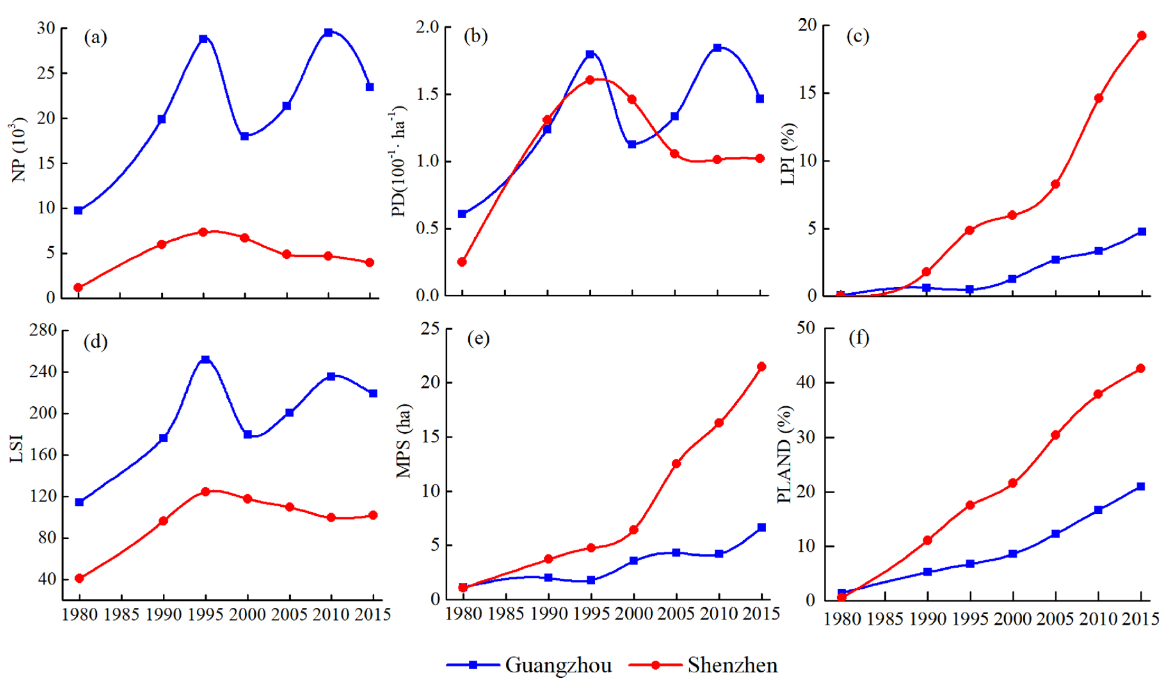

Fig. 6. Dynamics of the landscape metrics for the class of urban land of Guangzhou and Shenzhen from 1975 to 2015: (a) NP, (b) PD (per 100 ha), (c) LPI (%), (d) LSI, (e) MPS (ha), (f) PLAND (%).

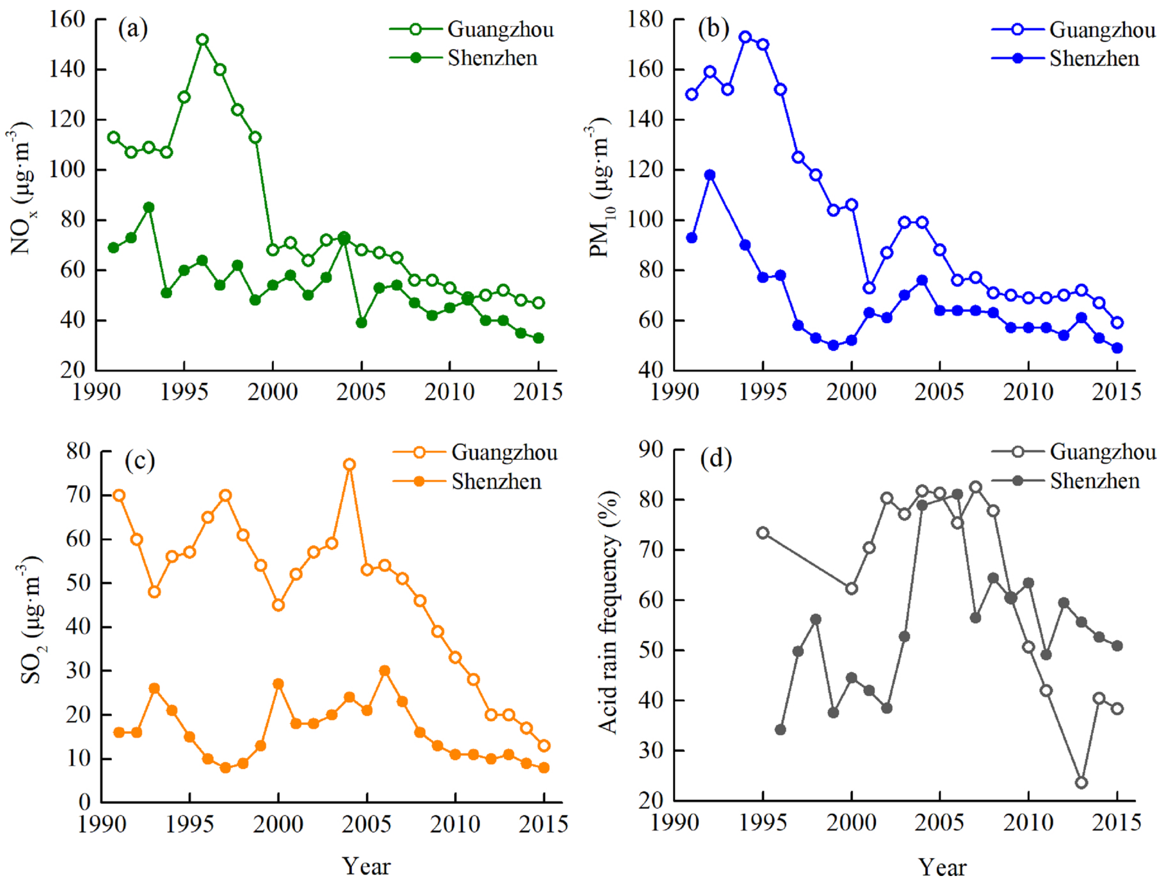

Fig. 7. Changes in major components of air quality between 1991 and 2015 in Guangzhou and Shenzhen: (a) nitrogen oxides (NO_x), (b) particulate matter with particle size between 2.5 and 10 in diameter (PM_{10}), (c) sulfur dioxide (SO_2), and (d) acid rain frequency.

Guangzhou in the 2000s (Fig. 7d). Although the extreme high frequency of acid rain for Guangzhou showed a decreasing trend in the late 2000s, it jumped back in the last several years. It is noteworthy that although the overall air pollutants (NO_x, PM_{10}, SO_2) for Shenzhen were lower than Guangzhou, the acid rain frequency for Shenzhen experienced a transformation from being initially lower than Guangzhou to staying relatively higher in the last decade.

4. Discussion

4.1. Comparison on the magnitude and rates of urban expansion between Guangzhou and Shenzhen

With the enhanced economic development and population increase, urban land areas in both Guangzhou and Shenzhen showed magnificent growth over the past four decades, which is generally consistent with published literature (Ma and Xu, 2010; Chen et al., 2014). The urban land areas of Guangzhou and Shenzhen have extended by 21.2 and 52.1 times, respectively, from 1975 to 2015. The remarkable policy of Reform and Opening-up brought about unprecedented opportunities for investment, industry development as well as infrastructure construction, and consequently, the highest AGR for both Guangzhou and Shenzhen occurred in the initial implementation of the Reform and Opening-up policy stage (1978–1990). The higher initial AGR of Shenzhen (19.38%) than that of Guangzhou (9.79%) might result from two reasons. One is that the initial urban land area of Shenzhen was only 16.0 km^2, smaller than that of Guangzhou (70.0 km^2), which would have higher AGR given similar urban expansions in area. The other reason is that the designation of Shenzhen as the first Special Economic Zone (SEZ) in China in 1979 (Fig. 8b) propelled its distinct pioneering development with permitted foreign funding firstly pouring into this city and investing on its industry construction. And a particular emphasis was laid on the potential value of local land and thus rapid urban expansion happened in not only the city center but also the suburban region of Shenzhen in the initial period of the economic reform in 1978 (Wu and Yeh, 1997). Under the umbrella of the mentioned priority and effective land reform, Shenzhen was the first city to successfully carrying out land leasing and land-use fee charging as early as the 1980s (Zhu, 1994; Fei and Zhao, 2019). In contrast, the local government of Guangzhou still carried out relatively more conservative urban planning policy with land use intervention and constraints (Xu, 2001; Tian et al., 2014). Shenzhen had kept extremely high AGR for 15 years since 1975. In the late 1980s, the special land administration policy that land use right can be freely transferred among users, targeted for the whole region of SEZ, further facilitated its rapid urbanization until 1990.

Entering the 21st century, both Guangzhou and Shenzhen experienced a period of increasing urban expansion. The largest AI happened in Shenzhen from 2000 to 2005, but for Guangzhou, its AI was the highest since 2005. The government of Guangzhou has made great efforts since 2000 to accelerate urbanization, and an important adjustment of administrative divisions happened in 2000. Panyu and Huadu Districts were elevated from their previous county-level status, which aimed to optimize the urban-rural spatial structure through effective planning decisions. Although the highest value of AI for Shenzhen happened in 2000 – 2005, it sharply decreased from 34.0 $km^2\ yr^{-1}$ to 16.19 $km^2\ yr^{-1}$ between 2010 and 2015. Given that the available land in Shenzhen for urban growth became increasingly limited, the Shenzhen government implemented a series of policies to enhance land use sustainability. First, Shenzhen government put limitation on the quantity of development land and reduced the rural-to-urban land conversion intensity. Second, the local government set up an

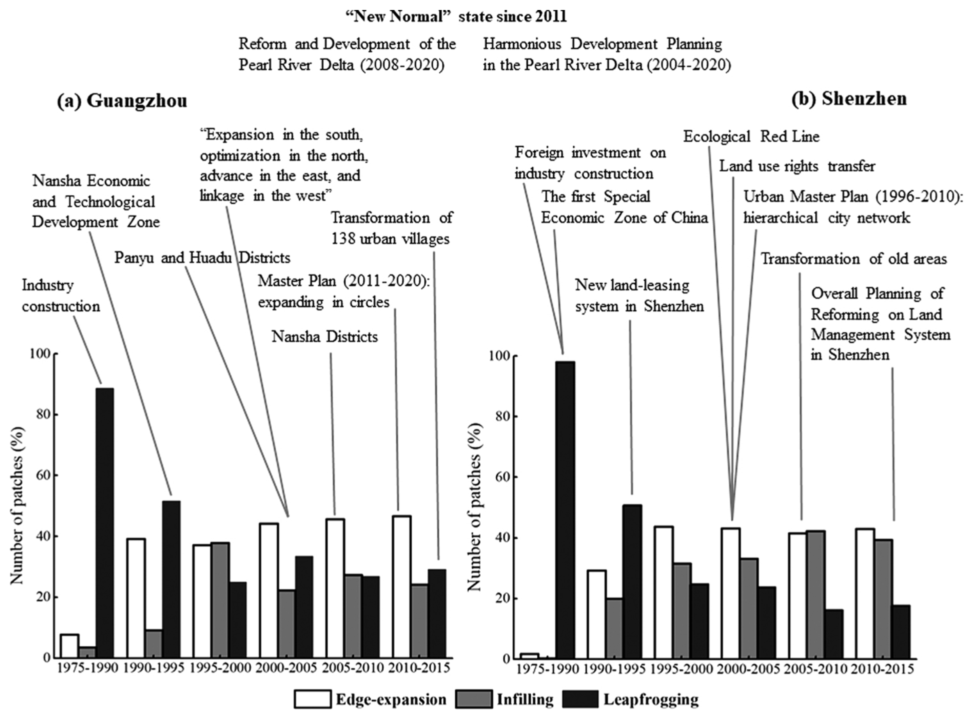

Fig. 8. Main events with the dynamics of urban growth in Guangzhou and Shenzhen from 1975 to 2015.

"Ecological Red Line" to protect green space and arable land (Fig. 8b). Finally, in this period, the urban redevelopment in Shenzhen emphasized on rebuilding its old districts and other inefficiently developed urban areas, consequently facilitated the harmonious people-land relationships (Qian et al., 2016; Liu, 2018).

4.2. Comparison of urban expansion between Guangzhou and Shenzhen

Physical conditions (e.g., elevation and slope) were also important factors that influenced the direction of urban expansion for both cities. Guangzhou and Shenzhen were subject to the constraints of the mountains in the northeast and east, respectively. For Guangzhou, Dajianfeng and Xiaojianfeng Mountains are located in Conghua district in the northeast, and for Shenzhen, Wutong Mountain and Qiniang Mountain are located in Longgang district and Luohu district in the south, respectively. The relatively higher elevation and larger slope contributed to the lower urban expansion process of those regions.

However, despite the typical physical constrains, both Guangzhou and Shenzhen made strategic adjustment of land use policy that contributed to optimize their spatial organization and break the barriers that hinder rural development. Besides physical conditions, both Guangzhou and Shenzhen demonstrated similar urban growth pattern, which was multicenter and "hierarchical city network" pattern (Huang and Xie, 2012). The urban expansion of Guangzhou mainly focused in the southwest of the city accompanied by growing sub-centers and Shenzhen demonstrated an eastward expansion with increasing decentralized pattern of urban land, forming a complicated network of urban growth. In 1993, Guangzhou established Nansha Economic and Technological Development Zone, which made the southern part of Guangzhou a new center of urban expansion after 2000 (Tian and Wu, 2015). Between 2000 and 2005, the spatial patterns of newly developed urban land patches of Guangzhou (Fig. 3) showed that the center of urban expansion shifted from Panyu to Huadu and Zengcheng, mainly extending to the south, north and east, probably stimulated by the "expansion in the south, optimization in the north, advance in the east, and linkage in the west" policy (Fan et al., 2007). For Shenzhen, the strong pioneering effect of the Special Economic Zone on urban land growth lasted until 1990s (Tian et al., 2014). Afterwards, the Urban Master Plan of Shenzhen (1996–2010) promoted the urban construction land increase of the whole city and formed the western, central and eastern axes to build a "hierarchical city network" (Huang and Xie, 2012).

4.3. Testing the urban development hypothesis

Dietzel et al. (2005) found that the process of urban growth generally follows an alternative phase of coalescence and diffusion. The temporal evolution of the composition of three urban growth types (edge-expansion, infilling and leapfrogging) and landscape metrics could combine to test the urban development hypothesis mentioned above. For example, at the diffusion phase, NP, LSI and PD generally increased with high percentage of leapfrogging urban growth while the characteristics of the coalescence phase were opposite (Xu et al., 2007; Tian et al., 2011). This research found different spatiotemporal urbanization pattern of Guangzhou and Shenzhen using area, shape and density categories of urban land class-level metrics. Different processes of urban growth resulted from distinct urban planning policy of the two cities. For Guangzhou, the turning point for the two diffusion-coalescence processes was in 2000. A study on the urbanization process of Guangzhou during 1900–2000 also found the coalescence phase in 1990–2000 (Tian and Wu, 2015). As for Shenzhen, the diffusion phase was in 1975–1995, and entered the coalescence process after 1995. It is noticeable that before 2000, the urban growth of Guangzhou and Shenzhen were similar, while after that Guangzhou began a new round diffusion phase again, corresponding to the dramatic increase of urban land areas (Table 3). Scattered distribution of newly developed urban land as leapfrogging might have intensified the land use inefficiency in the recent decades and the new normal state of China requires more practical countermeasures in land consolidation (Liu et al., 2018). In contrast, after 2000 the number of patches and area of infilling in Shenzhen experienced a rapid increase and the MPS of Shenzhen began to increase from six to 21 ha, which was larger than Guangzhou. The coalescence process was related to the Shenzhen urban land policy and planning. Due to the relatively lower degree of government intervention, the promotion of urban redevelopment in Shenzhen was more effective than Guangzhou, implied by the different composition dynamics of infilling growth in two cities. In order to solve the problem of urban villages, which are characterized as incomplete construction and poor development, the Shenzhen government designated a creative three-party mechanism to coordinate city development among the government, developers and owners. The mechanism encouraged the developers to lead the negotiation work and the government only formulated rules and served the parties. Although Guangzhou almost began to redevelop urban land area to solve the same problem, the Guangzhou government was the main leader in the negotiation rather than the developers. Guangzhou established the Guangzhou Urban Renewal Bureau which was the first administrative institution in China to deal with the update and alteration of the city in 2015. Furthermore, Guangzhou Master Plan (2011–2020) put forward a policy encouraging urban expansion in circles. Therefore, it is possible that edge-expansion and infilling will increase substantially, leading to the coalescence phase. Given that Guangzhou might experience the coalescence phase (Gong et al., 2018) in the near future with similar "urban village" problem, it is urgent for Guangzhou to learn from the experience of urban renewal in Shenzhen.

The similarities and differences presented in this paper are reflective of the physical conditions, urban planning policy, and land market in Guangzhou and Shenzhen. First, the available land areas in Guangzhou for urban construction are larger than Shenzhen. Second, the local government of Guangzhou made effective administrative interventions (e.g., changing Panyu and Huadu into urban districts and establishing Nansha New District) which resulted in higher percentage of leapfrogging than Shenzhen in 2000 – 2015. Finally, the land use policy of Shenzhen was more flexible and the urban development was more depended on market than Guangzhou, and thus Shenzhen completed the urban development and renewal faster, which was consistent with the market-oriented urban expansion mode (Zhu, 1999).

4.4. Environmental impacts of the rapid urban expansion in Guangzhou and Shenzhen

In China, the acid rain problems have been especially notable in the southern region (over 70% of cities) of China (Ministry of Environmental Protection of China, 2009). Guangzhou and Shenzhen are among the highest in Guangdong Province in terms of the pH value and frequency (Zhang et al., 2008; Cao et al., 2009; Huang et al., 2010). The temporal variation of air quality for Guangzhou and Shenzhen (Fig. 7) showed that although the concentrations of NO_x, PM_{10}, SO_2 generally declined in the study period due to the great efforts made by the local governments, prevention and control of acid rain remains an urgent task of urban environmental protection (Huang et al., 2010). A recent research in Shenzhen has found that anthropogenic activities and rapid urbanization process have significant impacts on the chemical characteristics of precipitation, resulting in the temporal variation of rain acidification (Zhou et al., 2019). Integrating environmental issues into urban land use planning and management is pressing to address local environmental problems (Liu and Li, 2017). In addition, urban expansion has brought about landscape fragmentation in both Guangzhou and Shenzhen, evidenced by the increasing value of LSI across the study period. The continuing urban expansion process might encroach valuable ecological land such as wetlands and natural coastal areas near the Pearl River (Haas and Ban, 2014). Intensive land cover changes could significantly alter urban biodiversity as the change of landscape composition played the dominant role in shaping the urban species profile in Guangzhou (Jim and Chen, 2009). Rapid increase of plant species and their homogenization were found in the municipal parks of Shenzhen, which might also be attributed to the rapid urbanization process (Ye et al., 2012). Moreover, rapid urbanization could aggravate other environmental problems such as urban heat island and urban flood runoff (Xiong et al., 2012; Du et al., 2015; Guo et al., 2016). Therefore, it is imperative to enhance land use sustainability of cities under new type urbanization.

5. Conclusions

Using long-term and spatially explicit remote sensing data, we investigated the dynamics of urban expansion in Guangzhou and Shenzhen from 1975 to 2015. Results demonstrated the difference and similarities between Guangzhou and Shenzhen in rates of urban expansion, landscape pattern and urban growth types. Guangzhou and Shenzhen have expanded annually at 8.1% and 11.0%, respectively. The dominant urban growth form of leapfrogging in the early period (1975 – 1990) resulted in the substantial urban land growth for both cities. In the recent decade, the annual expansion rate of Shenzhen was lower than Guangzhou, and the contribution of infilling in Shenzhen was higher than Guangzhou, which revealed a trend of compact urban growth form in Shenzhen. Over the four decades of rapid urbanization, the urban development mode for Guangzhou was diffusion-coalescence-diffusion-coalescence pattern, and Shenzhen demonstrated a typical diffusion-coalescence pattern. As the representative mega cities of China, Guangzhou and Shenzhen shared generally similar urban expansion dynamics and patterns, considerably influenced by policy and physical condition. However, the land use policy of Shenzhen was more flexible and the urban development was more depended on market forces than that of Guangzhou, thus Shenzhen completed the urban development and renewal phase faster. Ecological consequences of rapid urban expansion including fragmented landscape structure, varied acid rain frequency as well as flora diversity in urban districts should arouse attention from the social and scientific communities. Similarities and differences of the spatiotemporal patterns of urbanization for Guangzhou and Shenzhen could provide basis for land use policy formulation to achieve sustainable urbanization, especially for mega cities of China.

Acknowledgments

This study was supported by the National Key R&D plan of China Grant (2018YFA0606104), the National Natural Science Foundation of China Grant (41771093) and undergraduate student research training program of the Ministry of Education. We acknowledge all members in Shuqing Zhao's Lab for their assistance with data processing.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104753.

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