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Spatial Process of Green Infrastructure Changes Associated with Rapid Urbanization in Shenzhen, China

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Abstract: Through a case study of Shenzhen City, China, this study focused on a quantitative method for analyzing the spatial processes involved in green infrastructure changes associated with rapid urbanization. Based on RS, GIS and SPSS statistics software, the approach includes selection of the square analysis units and representative landscape metrics, quantification of the change types of landscape metrics in all analysis units through two indices and hierarchical cluster analysis of the above analysis units with different landscape metric change types (i.e. spatial attributes). The analyses verify that there is a significant sequence of continuous changes in green infrastructure in Shenzhen. They are the perforation, the segmentation, the fragmentation, the evanescence and the filling-in processes, which have a good spatio-temporal correspondence with urbanization and reflect the synthetic influence of urban planning, government policies and landforms. Compared with other studies on quantifying the spatial pattern, this study provides an alternative probe into linking the spatial pattern to spatial processes and the corresponding ecological processes in the future. These spatio-temporal processes offer many opportunities for identifying, protecting and restoring key elements in an urban green infrastructure network for areas in the early stages of urbanization or for non-urbanized areas.

Keywords: spatial process; landscape metrics; dynamic change; green infrastructure; urbanization

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1 Introduction

Green infrastructure has been introduced to upgrade urban green spaces as a coherent network system comprising all natural, semi-natural and artificial green spaces within, around and between urban areas (Tzoulas *et al*., 2007). As a natural life-support system, it performs various important ecosystem services, such as food, material and biodiversity supplies, pollutant removal, climate regulation and soil erosion prevention, and it provides other socio-economic benefits (Bolund and Hunhammar, 1999; Gill *et al*., 2005; Xie *et al*., 2010; Peng *et al*., 2011), all of which contribute to the health and quality of life for communities and human beings (Benedict and McMahon, 2000; Tzoulas *et al*., 2007). A whole green infrastructure network can be used to inform conservation-related land use and development decisions, if it is proactively identified, maintained and planned before development (Benedict and McMahon, 2000; Tzoulas *et al*., 2007; Wickham *et al*., 2010), especially in cities where urban growth has widely altered or even reduced the quality and quantity of green spaces (Li F *et al*., 2005). A significant area of green infrastructure research is related to identification and map-

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ping of ecological networks (Noss and Harris, 1986; Benedict and McMahon, 2000; Song and Zheng, 2002; Marulli and Mallarach, 2005; Wickham *et al*., 2010). However, whatever actions urban planners intend to perform on green infrastructures inevitably are based on dynamic systems, which possess both spatial and temporal complexity and chaotic behavior (Antrop, 1998; Haines-Young, 2000; Li F *et al*., 2005; Wickham *et al*., 2010). During the urbanization of a city, dynamic changes in green infrastructures affect urban ecological processes and have a great impact on the urban environment (Pauleit *et al*., 2005; Yue *et al*., 2007; Xie *et al*., 2009), hindering planners and managers in their attempts to control and direct future urban development. In order to make more targeted feedback regulations on urban spaces, urban decision-makers need efficient tools to quantitatively grasp and evaluate the dynamic sequence of changes in green infrastructures.

As in coupling studies of pattern-process-scale relationships based on the patch mosaic model (Mcgarigal and Cushman, 2002; Fu *et al*., 2011), landscape ecology has provided some prominent guidance in landscape planning, design and management (Forman, 1995a; Lyle, 1999; Li F *et al*., 2005). In landscape ecological studies, landscape metrics are increasingly applied to studying dynamic changes in urban spatial patterns (Xu *et al*., 2001; 2003; Abdullah and Nakagoshi, 2006; Yu and Ng, 2007; Lu *et al*., 2011). Some studies have combined landscape metrics with gradient analysis to quantify the spatial and temporal dynamics of urbanization in metropolitan areas (Wu, 2000; Luck and Wu, 2002; Wu, 2003; Zhang *et al*., 2004; Gong *et al*., 2007; Yu and Ng, 2007; Sun *et al*., 2012). Several studies have analyzed the dynamics of urban wetland landscape patterns and the impacts of urbanization on wetlands (Cao, 2008; Wang Xuelei *et al*., 2008). Kong and Nakagoshi (2006), Sun and Xu (2008) systematically studied spatial and temporal gradient characteristics of urban green spaces by the moving window and transect method, which was innovative in obtaining spatial information on each local area for the entire landscape. However, it is still unclear how to quantify the spatial processes leading to green infrastructure changes with urban expansion. Since there should be a broader sequence of spatial processes in landscape transformation or land conversion (Forman, 1995a), such as landscape fragmentation, it is important to examine the role of these spatial processes in landscape change (Forman, 1995b). Rather than analyzing the spatial and temporal gradient trends along the special transect by digital curve diagrams, this paper focuses on investigating and visualizing the spatial process of urban green infrastructure changes through both the quantitative spatial attributes and the corresponding morphological spatial diagrams based on landscape metrics.

Shenzhen, a large city developed only within the past thirty years (from 1978 up to date) and representative of the rapid urbanization in China, was chosen as the study area. The findings will have reference value for other rapid-developing Chinese cities. In this study, five sets of Landsat TM images were used, and two hundred square grids were selected to analyze the dynamic changes in green infrastructure with urbanization. The following questions were addressed: 1) What are the general spatial characteristics of green infrastructure changes with urban expansion? 2) Do spatial change processes of urban green infrastructures exhibit a broader sequence of landscape transformation? If they do, what is the correspondence between the spatial process of green infrastructures and the stage of urbanization? 3) Are there any differences between the spatial process of urban green infrastructures analyzed in this paper and those proposed by Forman?

2 Data and Methods

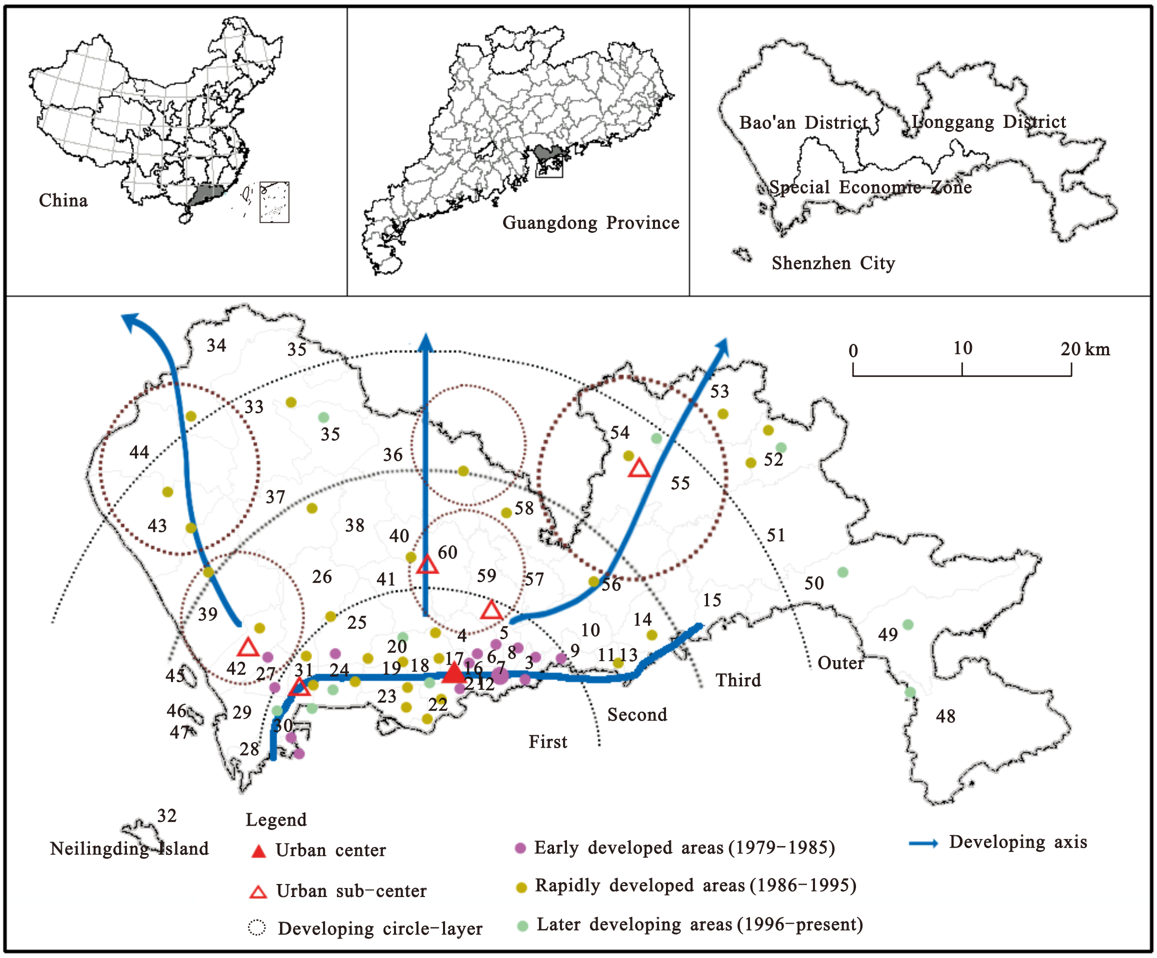
2.1 Study area

Shenzhen (22°26'59''–22°51'49''N, 113°45'44''–114°37'21''E) is located in Guangdong Province in South China (Fig. 1), bordering Hong Kong Special Administrative Region to the south. Its total terrestrial area is 1950 km^2, excluding Neilingding Island and other islands. Shenzhen has various landforms, mostly hilly, with dotted plain patches. Its topography is relatively high in the southeast and low in the northwest. It has a subtropical monsoon climate with an average annual temperature of 22.4°C, annual precipitation of 1948 mm and average annual wind speed of 2.7 m/s.

Shenzhen was established in November 1979 and was given the right of provincial-level economic administration in 1980 (the Special Economic Zone, SEZ). In the past three decades, based on national special preferential policies and foreign industrial power, Shenzhen has become one of the rapidly-growing metropolitan areas in China. Now it comprises three administrative districts:

the SEZ and the Bao′an District and the Longgang District (Fig. 1).

The process of urbanization in Shenzhen is divided into three stages: the early urbanization period of 1979–1985, the accelerated urbanization period of 1986–1995 and the stable urbanization stage. The stable one includes the adjustment period of 1996–2000 (Wang, 2003) and the optimization period from 2001 to the present (Xie *et al*., 2009). Correspondingly, urban spatial expansion in Shenzhen is displayed as a multi-centered, axis and layered pattern (Wang, 2003). As Fig. 1 shows, the early developed areas, from 1979 to 1985 (the purple dots), were concentrated in the SEZ in the southern first layer more than in other layers. The urbanization level index (UI), defined as the urban built-up share in a certain region, was about 2.73% from 1979 to 1985 according to the built-up urban area given in the study of Li W F *et al.* (2005). Then with the increase in building intensity, there was so little usable land for development in the SEZ that urban development extended first to the hilly areas inside SEZ, then to the flat plains and finally to the hilly areas in both the Bao′an District and the Longgang District outside the SEZ. The UI rose to 2.88% and 10.15%, respectively, in the periods 1986–1990 and 1991–1995, so that the rapidly developed areas were distributed over the whole city (the dark yellow dots in Fig. 1), especially in the later accelerated urbanization period of 1991–1995. After entering the stable urbanization stage, the UI decreased to 6.26%, indicating that urban development began to slow down, especially in the early developed areas where the industrial structure transformation and urban renewal had



1.Guiyuan; 2. Nanhu; 3. Huangbei; 4. Qingshuihe; 5.Dongxiao; 6. Sungang; 7. Dongmen; 8. Cuizhu; 9. Liantang; 10. Donghu; 11. Shatoujiao; 12. Meisha Island; 13. Haishan; 14. Yantian; 15. Meisha; 16. Yuanlin; 17. Huafu; 18. Lianhua; 19.Xiangmihu; 20. Meilin; 21. Nanyuan; 22. Futian; 23. Shatou; 24. Shahe; 25. Taoyuan; 26. Xili; 27. Nantou; 28. Zhaoshang; 29. Nanshan; 30. Shekou; 31. Yuehai; 32. Neilingding Island; 33. Gongming; 34.Songgang; 35. Guangming; 36. Guanlan; 37. Shiyan; 38. Dalang; 39. Xixiang; 40. Longhua; 41. Minzhi; 42. Xin′an; 43. Fuyong; 44. Shajing; 45. Xiaochan Island; 46.Dachan Island; 47. Zai Island; 48. Nan′ao; 49. Dapeng; 50. Kuicong; 51. Pinshan; 52. Kenzi; 53. Pindi; 54. Longcheng; 55. Longgang; 56. Henggang; 57. Nanwan; 58. Pinghu; 59. Buji; 60. Bantian

Fig. 1 Location and urban spatial pattern of study area started. However, in the transition between the early and rapidly developed areas, large-scale urban constructions and industries are still being developed rapidly at this stage. Simultaneously, urban development has just begun in the later developing areas (the green dots in Fig. 1).

2.2 Data acquisition and preparation

2.2.1 Creation of green infrastructure database

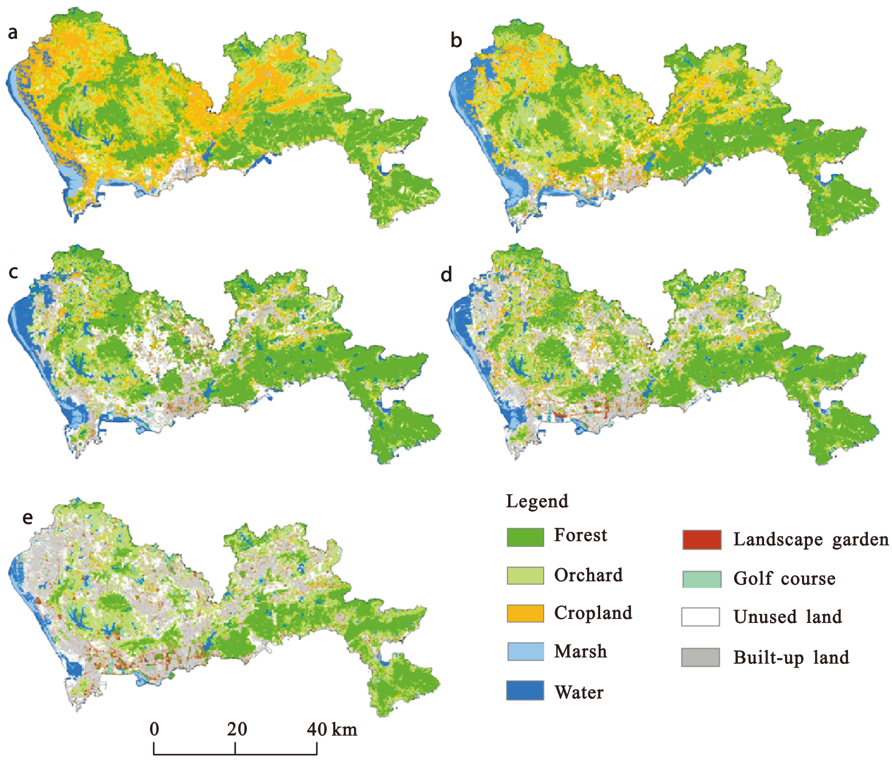
Landsat TM data were adopted (path121/row44, path122/row44), including the Landsat 5 TM images from 1986, 1990, 1995 and 2005, and the Landsat 7 ETM+ images from 2000. Based on the image preprocessing, the basic near-infrared band, the NDVI band and the first principal component in the K-L analysis were selected as the optimal three bands for interpreting green infrastructures. Then according to field surveys and urban green-space-type maps, seven green infrastructure types and two gray infrastructure types (Table 1) were identified (Fig. 2). Finally, we took 210 field-survey sampling points that were kept unchanged from 1986 to 2005 as the test samples, and the test results showed that the whole classification precision was 82.43% and the Kappa coefficient was 0.801. All this data processing was accomplished with the support of the remote-sensing image-processing software and the geographical information system (GIS).

2.2.2 Selection of suitable analysis unit

Selecting the spatial scale is very important for landscape ecological studies. It is generally expressed by the extent and grain. In this study, the grain is a pixel size of

Table 1 Classification system of urban infrastructures in Shenzhen

Classification	Sub-classification	Type
Green infrastructure	Natural	Forest, marsh, water such as river and reservoir
	Semi-natural	Orchard and cropland
	Artificial	Landscape garden such as park, roadside garden
Gray infrastructure		Built-up land, involving residential, industrial, commercial and public facilities land
		Unused land, where all land covers have been cleared for development



a: 1986; b: 1990; c: 1995; d: 2000; e: 2005

Fig. 2 Green infrastructure classification maps of Shenzhen from 1986 to 2005

30 m × 30 m determined by the resolution of the TM image. Thus selecting a suitable extent unit becomes the first step in analyzing the landscape-pattern change of urban green infrastructures. According to the boundary appearance of Shenzhen City, we selected a 21 km × 21 km square region located in the middle-west, which covers around 23% of the terrestrial area of Shenzhen and contains all of the green infrastructure types (Fig. 3a). Next, based on the extent design method of Wu (2000) and Gong and Xia (2007), we shrank the square region along the diagonal direction from the southeast (SE), northwest (NW), southwest (SW) and northeast (NE) corners by a range of 1.5 km. As a result, the square region was divided into four groups, each comprising 14 analysis units of different extent scales (Fig. 3b). Through the resulting 56 units, the green infrastructure map in the square region was cropped into 56 small, square maps. Then we calculated landscape metrics on the landscape level of 56 landscape maps with different spatial extents in FRAGSTATS (Version 3.3), and we chose the patch density (PD), area-weighted mean fractal index distribution (FRAC_AM), contagion index (CONTAG), Shannon′s diversity index (SHDI), interspersion & juxtaposition index (IJI) and aggregation index (AI) to analyze landscape metrics changes with different spatial extents.

As Fig. 4 shows, with an extent of 100 pixels (3 km × 3 km), the curves of PD, IJI, CONTAG and AI in all four directions, as well as the curve of FRAC_AM in the SE-NW direction, have obvious inflection points. With an extent of 150 pixels (4.5 km × 4.5 km), although the above curves have some random points of inflection, they tend to level off, and this is especially so with an extent of 350 pixels (10.5 km × 10.5 km). The curves of FRAC_AM in the other three directions are continuously upward, and there are some random points of inflection in the SW-NE and NE-SW directions. The curve of SHDI with an extent of 250 pixels changes in all four directions, and the change with an extent of 100 pixels (3 km × 3 km) is the greatest. Thus it is revealed that as the extent of the green infrastructure map becomes larger than the 3 km × 3 km square region, a majority of the landscape metrics are not more sensitive to the change of the spatial extents, so a square unit of 3 km × 3 km can be used to analyze the landscape-pattern change of urban green infrastructures in the study area.

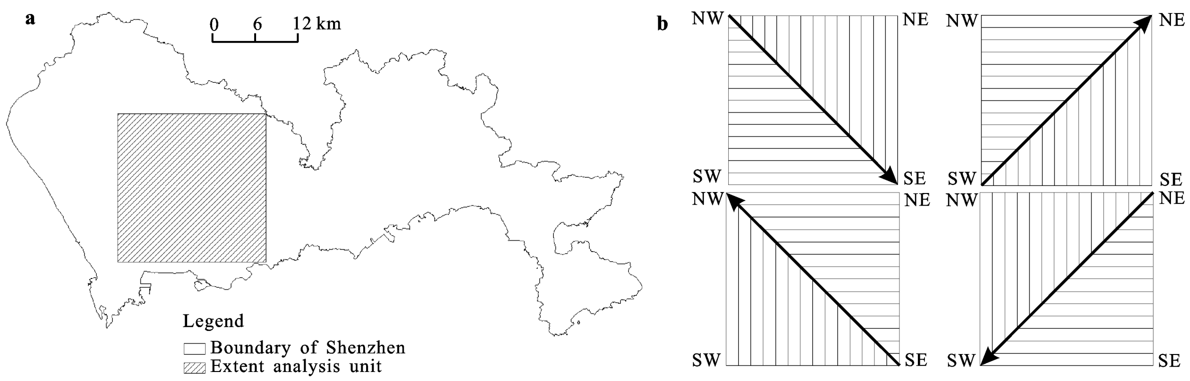
2.2.3 Selection of representative index based on landscape metrics

There are various landscape metrics reflecting different landscape pattern characteristics, so it is necessary to select some representative indices. In this study, we applied a ′moving window′ analysis supported by FRAGSTATS to calculate landscape metrics of the green infrastructure map on the landscape level and to extract the main factors of the landscape pattern. The radius of the window was selected as the 3 km × 3 km square (see section 2.2.2), and 11 landscape metrics were calculated. Then these metrics were analyzed to select the representative ones by Principal Component Analysis in the statistical software IBM SPSS Statistics.

2.3 Quantification of dynamic changes in spatial pattern of green infrastructures

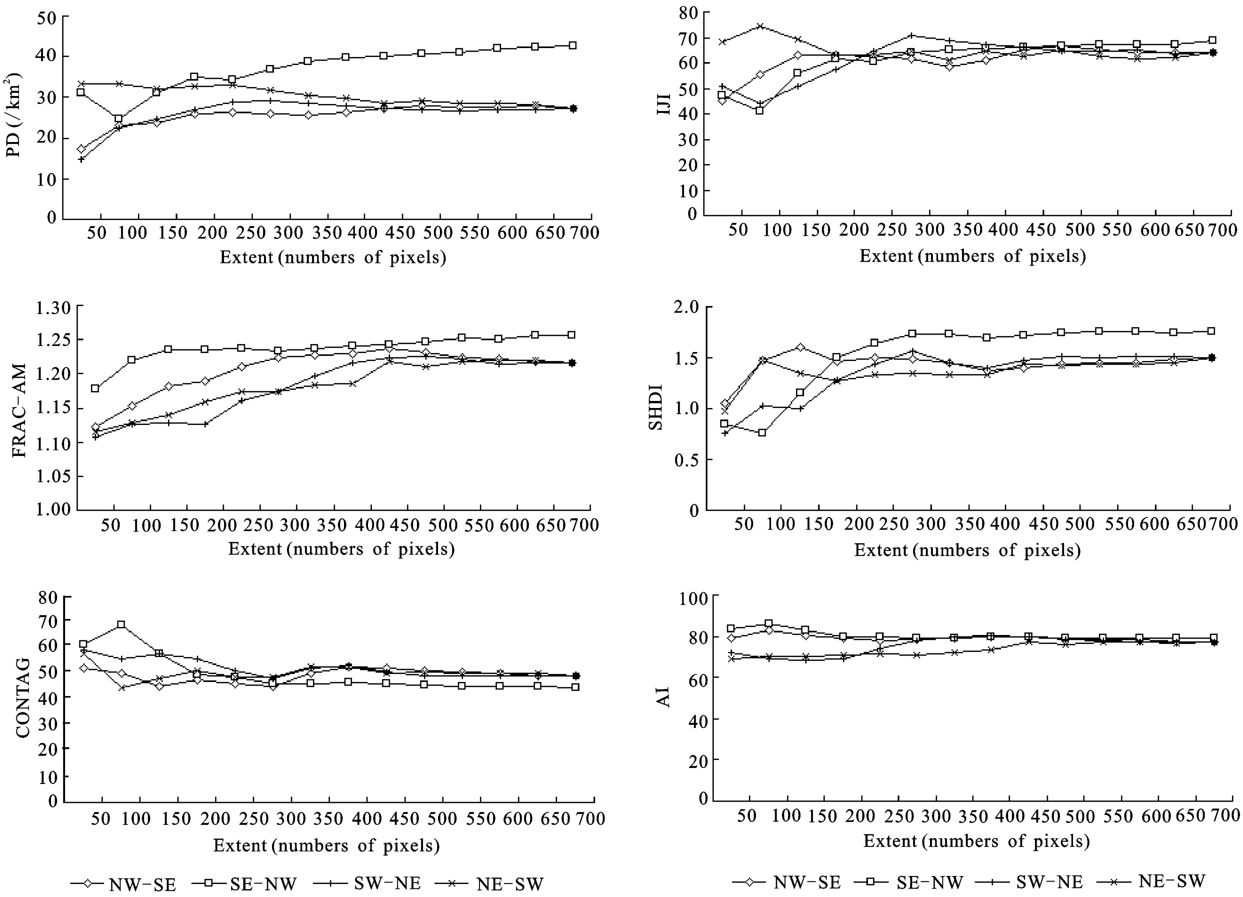
2.3.1 Indices for quantifying change characteristics of landscape metrics

After selecting the square units and representative landscape metrics, we defined two indices to quantify the change characteristics of landscape metrics in each grid



NW: north-west; NE: north-east; SW: south-west; SE: south-east

Fig. 3 Diagram for selecting study extent scale



PD: patch density; FRCA_AM: area-weighted mean fractal index distribution; CONTAG: contagion index; IJI: the interspersion & juxtaposition index; SHDI: Shannon′s diversity index; AI: aggregation index

Fig. 4 Curves of landscape metrics of green infrastructures with different spatial extents (2005)

unit. One is the Slope of Landscape metrics (S_{LM}), and the other is the Slope of Changes in the Landscape metrics (S_{LMC}). The slope index of a certain value can be calculated in the two-dimensional coordinate system composed of the value itself as the vertical axis and the corresponding time-point as the abscissa (Wang X C *et al.*, 2008).

The index of S_{LM} in each square unit is the slope value of a landscape metric index from 1986 to 2005 in an analyzing unit. It reflects the change in direction of landscape metrics and is calculated as follows:

$$S_{LM} = \frac{n\sum(LM \cdot t) - \left(\sum LM\right)\left(\sum t\right)}{n\sum t^2 - \left(\sum t\right)^2}$$

where t is the study year code, which equals 1, 2, 3, 4 and 5, respectively, in 1986, 1990, 1995, 2000, and 2005; LM is the landscape metric value in one square unit in the corresponding year; and n is the number of study years, which equals 5. A value of S_{LM} larger than zero indicates that the landscape metric index is increasing and a value smaller than zero indicates that it is decreasing. If S_{LM} equals zero, then the landscape metric index remains stable. The S_{LM} value of landscape metrics has different ecological meanings as landscape metrics vary. For example, the S_{LM} values of SHDI and PD are larger than zero. The former reveals that the landscape has been more diverse, but the latter indicates that it has been more fragmented.

The index of S_{LMC} in each square unit is the slope value of changes in a landscape metric index between two adjacent study years. It shows the acceleration of landscape metric changes. We calculated S_{LMC} as follows:

$$S_{LMC} = \frac{N\sum(LMC \cdot T) - \left(\sum LMC\right)\left(\sum T\right)}{N\sum T^2 - \left(\sum T\right)^2}$$

$$LMC = LM_{t+1} - LM_t$$

where T is the study interval code, which equals 1, 2, 3 and 4, respectively, in the intervals 1986–1990, 1990–1995, 1995–2000, and 2000–2005; LMC is the change in value of a landscape metric index in one square unit in the corresponding interval, and N equaling 4 is the number of the study interval. If the value of S_{LMC} is larger than zero, the landscape metric changes (either increase or decrease) faster and faster. If S_{LMC} is equal to zero or smaller than zero, the landscape metric change (either increase or decrease) has stabilized or has become slower and slower.

2.3.2 Definition for landscape metric change types

For actual landscape changes, the condition that S_{LM} equals zero rarely occurs. So in this study, we hypothesized that the landscape metric change in one square unit should level off, as its own S_{LM} value was between –0.5 and 0.5 times the standard deviation of S_{LM} values in all units. So based on the standard deviation value of S_{LM}, all analysis units were classified into three categories, the rise, the fall and the stable type (Table 2). Then according to the S_{LMC} value, units with the rise and fall types were classified into increasing and decreasing subclasses, respectively, and each change type was given a certain number code, as listed in Table 2. In this way, the change-type codes of the landscape metrics in each square unit were acquired. Then with the support of GIS, these code numbers were input to the attribute database of 242 square units.

2.3.3 Hierarchical cluster analysis of all analysis units

Hierarchical cluster analysis is a multi-statistical method that classifies samples by the similarities and differences in clustering indices. In this study, taking all square analysis units as samples, we used the change type codes of the landscape metrics in Table 2 as indices for hierarchical clustering in SPSS (selecting Ward′s Method) to classify the dynamic process of green infrastructure changes in the study area.

3 Results

3.1 Representative landscape metrics

It is shown that the cumulative eigenvalue of the top three components reaches 81.594% of all landscape metrics (Table 3). This reveals that the top three components have reflected the main landscape characteristics involving the patch shape, complexity and domination of the spatial configuration. So we chose five landscape metrics (the black bold ones with underlining in Table 3) as spatial pattern indices: the three metrics with the highest coefficients in the first principal component (PD, CONTAG and SHDI) and those with the highest coefficients in the second and third principal components (SHAPE-AM and TA).

3.2 Synoptic spatial pattern changes of urban green infrastructures

The statistical matrix from 1986 to 2005 shows significant changes in landscape metrics and types of green infrastructures in Shenzhen (Table 4). The five landscape metrics, with the exception of TA, showed non-monotonic variations. TA deceased steadily over the study period. PD increased rapidly from 1986 (16.23) to 1990 (20.33) and 1995 (23.86), increased slightly in 2000 (24.73) and then by 2005 began to decrease significantly (21.70). The changes of SHAPE-AM were the opposite, that is, it decreased from 1986 (19.07) to 2000 (7.23) and increased slightly by 2005 (8.66). CONTAG generally decreased before 1995 and then increased from 1995 to 2005. SHDI decreased also from 1986 until 1995, and then it began to increase. The changes in TA, PD and CONTAG indicate that from 1986 the fragmentation of green infrastructures increased but then improved slowly (1995 to 2005). However, at the same time, between 1986 and 1995, the diversity of green infrastructures declined significantly and then until 2000 began to increase.

Table 2 Indices for defining landscape metric change types based on S_{LM} and S_{LMC}

Classes (Abbreviation)		Subclasses (Abbreviation)		Description	Code
Name	Index	Name	Index		
Rise type (R)	S_{LM} >0.5S.D.	Increasing rise type (R_1)	S_{LMC} >0	Landscape metric values increase faster and faster	1
		Decreasing rise type (R_2)	$S_{LMC} \le 0$	Landscape metric values increase more slowly	2
Stable type (S)	$-0.5S.D. \le S_{LM} \le 0.5S.D.$			Landscape metric values change scarcely, and the increasing or decreasing value remains within a very small range	3
Fall type (F)	S_{LM} <–0.5S.D.	Increasing fall type (F_1)	S_{LMC} >0	Landscape metric values decline faster and faster	4
		Decreasing fall type (F_2)	$S_{LMC} \le 0$	Landscape metric values decline more slowly	5

Table 3 Rotated-component matrix of landscape metrics by Principal Component Analysis in SPSS

Landscape metric (Abbreviation)	Component coefficients		
	1	2	3
Mean patch size (MPS)	–0.564	–0.059	0.296
Patch density (PD)	**0.767**	0.355	–0.095
Interspersion & Juxtaposition index (IJI)	0.337	–0.739	0.020
Area-weighted mean fractal index distribution (FRAC-AM)	0.284	0.898	0.087
Largest patch index (LPI)	–0.473	0.189	0.792
Landscape shape index (LSI)	0.493	0.734	0.377
Area-weighted mean shape index distribution (SHAPE-AM)	0.149	**0.902**	0.220
Total area (TA)	0.043	0.438	**0.874**
Contagion (CONTAG)	**–0.895**	–0.110	0.287
Percentage of like adjacencies (PLADJ)	–0.488	–0.069	0.810
Shannon′s diversity index (SHDI)	**0.911**	–0.064	–0.073
Total eigenvalues	3.460	3.084	2.431
% of variance	31.452	28.039	22.102
Cumulative %	31.452	59.491	81.594

Table 4 Synoptic change characters of urban green infrastructures from 1985 to 2005

Year	Landscape metrics					Area of landscape elements (km^2)		
	TA (km^2)	PD (/km^2)	SHAPE-AM	CONTAG	SHDI	Natural	Semi-natural	Artificial
1986	1858.08	16.23	19.07	55.83	1.179	872.47	982.24	3.37
1990	1796.05	20.33	11.85	44.32	1.158	1026.99	752.47	16.60
1995	1464.39	23.86	9.84	39.12	1.020	1044.41	354.07	65.91
2000	1412.45	24.73	7.23	42.87	1.111	985.04	432.29	95.13
2005	1190.26	21.70	8.66	44.86	1.171	600.96	487.20	102.10

Notes: TA, total area; PD, patch density; SHAPE-AM, area-weighted mean shape index distribution; CONTAG, contagion index; SHDI, Shannon′s diversity index

At the same time, proportions of the three green infrastructure elements also changed. Natural elements, comprising forests and wetlands, increased by 171.94 km^2 from 1986 to 1995, then decreased rapidly and up to 2005 had decreased by 443.45 km^2. In contrast, the semi-natural elements, such as croplands and agro-forests, decreased significantly from 982.24 km^2 in 1986 to 354.07 km^2 in 1995, but after 1995 increased steadily and reached 487.2 km^2 in 2005, at the same time the natural elements were decreasing. In contrast with the above two elements, the artificial elements, which include urban green spaces and golf courses, significantly and steadily increased over the entire study period (Table 4).

The above analysis reveals the general characteristics of changes in green infrastructures during urbanization, but it does not provide detailed information on the spatial heterogeneity of landscape pattern changes in local areas with different urbanization periods. This subject is taken up in the next section.

3.3 Spatial heterogeneity of landscape metric changes in urban green infrastructures

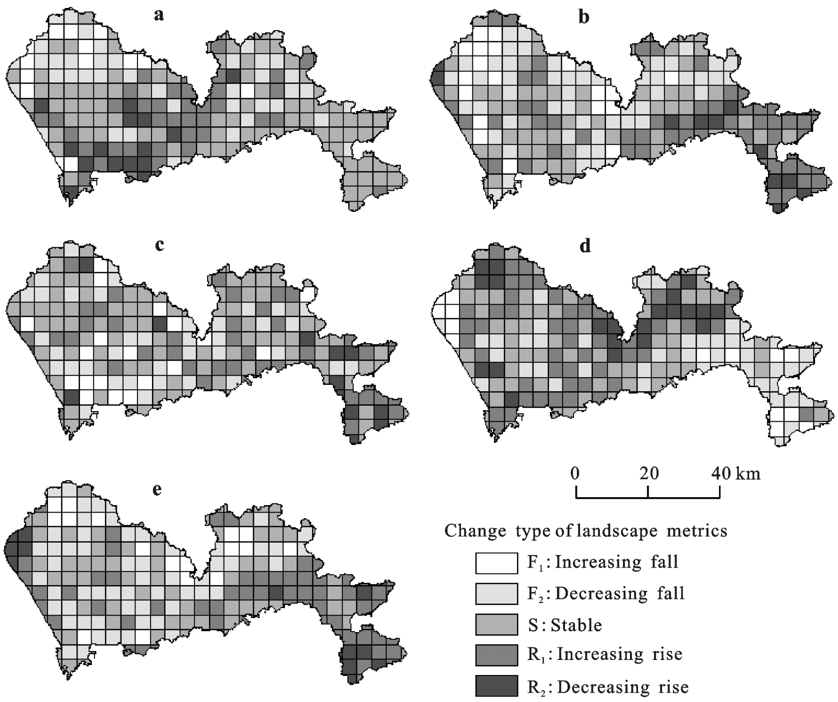
By calculating S_{LM} and S_{LMC} and defining change types of five landscape metrics in each square unit, the spatial heterogeneity of changes in landscape metrics of the urban green infrastructure in Shenzhen could be determined as illustrated in Fig. 5.

Figure 5a shows the result for the total area (TA). It is the most regular of the five metric change patterns in its variation from west to east. Generally, most squares indicating the rise type (involving R_1 and R_2) are in the center, showing that the proportions of green infrastructures in the central areas increased from 1986 to 2005; grids with the fall type (involving F_1 and F_2) and the stable type (S) occurred mainly in the west and east, respectively, indicating that the proportions of green infrastructures kept decreasing or leveled off in these regions. Specifically, squares of the increasing rise type (R_1) are found along three urban development axes drawn in Fig. 1, including Xixiang, Xili, Shahe, Meilin, Yuanling sub-districts along the west axis, Pinghu, Buji, Bantian sub-districts along the north-south central axis and Henggang, Longcheng sub-districts along the east axis. Squares of the decreasing rise type (R_2) are located in the early developed centers, such as the centers of Nantou, Shatou, Futian, Huafu sub-districts in SEZ and the centers of Xin′an, Minzhi, Buji and Longcheng sub-districts outside of SEZ. Grid squares of the increasing fall type (F_1) are scattered in the rapidly developed or developing zones outside of the second circle-layer, including Shajing, Fuyong, Songgang, Guangming and Gongming sub-districts′ centers in the west and Longgang sub-district's center in the east, showing that the total area of green infrastructures in the west fell more frequently than in the east and the center. The decreasing fall types (F_2) generally appear around the periphery of the increasing fall squares. In contrast, most squares with the stable type (S) are concentrated in the eastern outer layer such as those of Dapeng and Nan′ao sub-districts and in the transition between the west and central axis such as those of Shiyan and Xili sub-districts.

The change in the patch density (PD) of green infrastructures in Shenzhen also shows a gradient pattern clearly, from west to east and from inner to outer (Fig. 5b). PD fell increasingly (F_1) mainly in the rapidly developed or developing zones in the second-third layer transition (including Songgang, Gongming, Fuyong and Shajin sub-districts in the west and Pinghu sub-district on the north-south central axis), slightly in the first layer (Huangbei sub-district) and on the east axis (Longcheng sub-district). Squares showing decreasing fall (F_2) also occurred around the periphery of those showing an F_1 change type. With the exception of very small areas scattered in the south-east, most squares showing the stable type (S) were distributed in the rapidly developed areas along the west, east and south-north central axes. In contrast, the number of squares showing the rise type was smaller. Most squares with the R_1 and R_2 change type appear in the east, such as Pingshan, Kuicong, Dapeng and Nan′ao sub-districts in the east, but there are a few in the west (Fuyong, Dalang and Guanlan sub-districts) and the south (Nantou, Yuehai and Shahe sub-districts in SEZ).

Compared with the above two landscape metrics, the spatial heterogeneity of changes in the area-weighted mean shape index distribution (SHAPE-AM) is more irregular (Fig. 5c). In general, the number of squares respectively showing the fall, rise and stable types remained nearly equal over the whole area. The increasing-fall squares (F_1) are mostly located in the south first layer (Xili, Shatou and Futian sub-districts in the SEZ), and the rest are scattered in the outer areas of other urban development layers (Shiyan, Fuyong, Guangming, Guanlan and Buji sub-districts in Bao′an district and Kuicong and Kenzi sub-districts in Longgang district. Besides a few existing outside of the second circle-layer (such as the Songgang district in the west and Dapeng, Kenzi sub-districts in the east), most squares showing F_2 occur in Xixiang, Longhua, Meilin, Yuanlin, Yantian sub-districts within the second circle-layer. SHAPE-AM leveled off (S) not only in the transition among Shajing, Guangming and Shiyan sub-districts in the northwest and between Yantian and Longgang districts in the central eastern area, but also on the fringe in the north-east (the Pingdi sub-district) and in the south (Futian, Nanyuan and Nanhu sub-districts). Squares with the rise types occur in the northeast. Among them, the decreasing rise squares (R_2) are fewer than the increasing rise squares (R_1). The former occur in Dapeng, Nan′ao, Gongming and Guanlan sub-districts in the outer layer and Nanshan sub-district in the first circle-layer; the latter appear in the west third circle-layer (such as Shiyan and Guangming subdistricts), as well as along both the east and the north-south central development axis .

The spatial heterogeneity of changes in the contagion index (CONTAG) of green infrastructures is shown in Fig. 5d. CONTAG rose mainly along the development axis, such as in Xixiang, Fuyong, Shajing and Songgang sub-districts in the west, Futian, Buji and Guanlan sub-districts in the center and Henggang, Longgang, Pingdi and Kenzi in the east; however, the rate of rise shows differences among the multi-circle layers, that is, CONTAG rose decreasingly mainly in the outer layer (R_2) and increasingly equally in all layers (R_1). Squares indicating the stable type (S) occur along the development axis and the circle-layer, mostly along the west axis and the east third and outer layer, slightly along the central axis. In contrast, CONTAG fell more sporadic-



a: TA (total area); b: PD (patch density); c: SHAPE-AM (area-weighted mean shape index distribution); d: CONTAG (contagion index); e: SHDI (Shannon′s diversity index)

Fig. 5 Spatial heterogeneity maps for five landscape metric changes of green infrastructures in Shenzhen

ally. It fell increasingly (F_1) only in rapidly developed areas in the west (Fuyong and Shajing sub-districts) and in developing areas in the east (Pingshan, Dapeng and Nan′ao sub-districts); however, it fell decreasingly (F_2) more commonly in in the east outer layer (Kuicong, Dapeng and Nan′ao sub-districts) than in the west.

The whole distribution of the rise and fall types of Shannon′s diversity index (SHDI), shown in Fig. 5e, is in striking contrast to that of CONTAG. The increasing fall rate squares (F_1) mostly occur in the west and east outer layer, and the decreasing fall rate squares (F_2) are mainly distributed along the west, central and east development axis. The decreasing rise rate squares (R_2) only occur in Dapeng, Nan′ao (east), Fuyong and Shajing (west); the increasing rise rate ones are mainly concentrated in the east and are slightly scattered in the west. The squares indicating the stable type (S) occur in the transition between the multi-layer and multi-axis, mostly in the west.

3.4 Dynamic spatial processes of urban green infrastructure with urbanization

Based on the above change-type codes of five landscape metrics in each square unit, the overall units were clustered into five categories of spatial change processes in SPSS, and Fig. 6 was created by GIS. The categories are perforation, segmentation, fragmentation, evanescence and filling-in processes, composing a continuous change sequence. All of them result in a transitional spatial pattern of urban green infrastructures at a certain urbanization stage (Fig. 7).

The perforation-process squares (those with dots in Fig. 6) showed very small changes in patch density, contagion, shape and diversity of green infrastructures, except the total area was gradually reduced (Fig. 5). This process generally occurred in the region that was at the early urbanization stage such as most of Dapeng and Nan′ao sub-districts in the outer layer and Donghu sub-district in the transition, where green infrastructures were distributed contiguously, as can be seen in the matrix in the whole landscape (Fig. 7a), although human development activities had nibbled away at the green infrastructures, especially croplands in the plains.

With the rapid urban development, green infrastructures became more perforated and dissected by the increasing numbers of buildings and roads so that their total areas were markedly reduced, and the patch density began to increase. However, the changes in contagion and shape remained small, and the diversity of green landscapes increased slightly because of the appearance of urban green spaces. This marked the occurrence of the segmentation process (the squares with bias in Fig. 6), mainly in the eastern central towns of the outer layer (Dapeng and Nan′ao sub-districts) and the transition among the west, north-south central and east axes and among the SEZ and the outer zones, such as Xili, Donghu and Yantian sub-districts. This process causes green infrastructures to appear in a landscape as many large islands with inner perforations and outer linear edges (Fig. 7b).

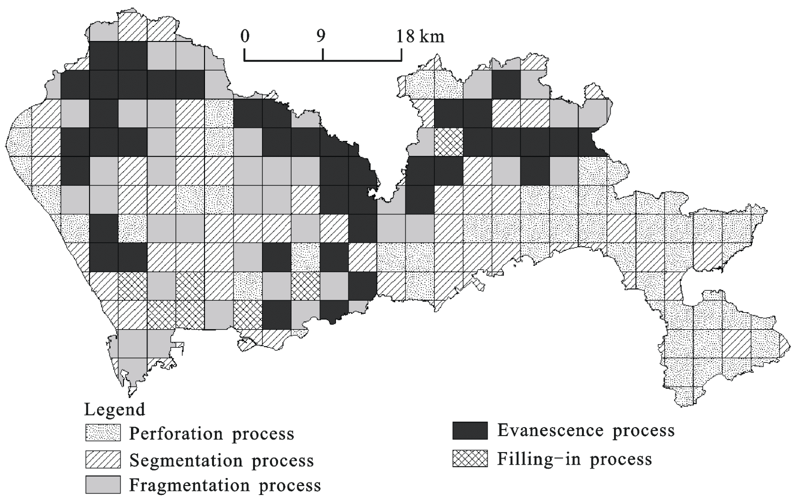


Fig. 6 Green landscape pattern dynamic process map for Shenzhen

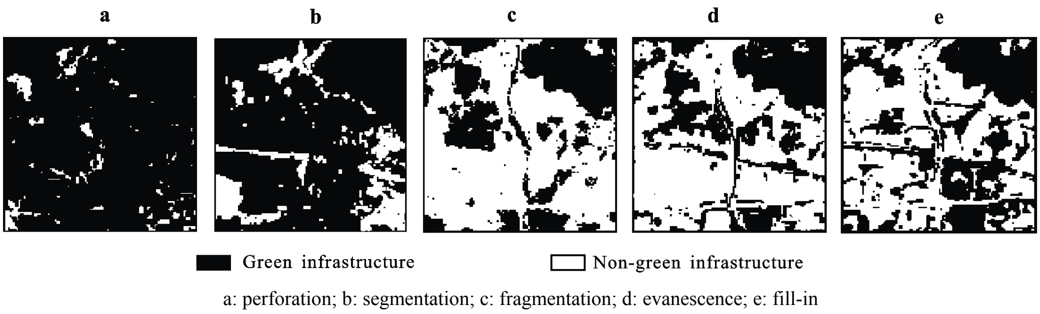


Fig. 7 Diagram for urban green infrastructure patterns resulting from spatial dynamic processes

The fragmentation process is usually a continuous one of increasing segmentation. In the regions where industry has existed for a long time, the total area of green infrastructures was significantly reduced, the diversity began to decrease with the disappearance of natural or semi-natural elements, and the patch shape changed distinctly; however, the patch density increased slowly and even began to level off in some squares (Fig. 5). So green infrastructure patches only gathered at certain sites with high altitudes, and the whole green infrastructure pattern is pictured as a few large islands with many islets (Fig. 7c). The squares representing this process (the gray squares in Fig. 6) mostly exist in the outer towns of the rapidly-developed zones such as Xixiang, Shajing, Shiyan, Songgang and Gongming sub-districts in the west and Guanlan, Longhua and Dalang sub-districts in the central north and in Nanshan, Shekou, Zhaoshang and Xili sub-districts in the south.

Following the fragmentation process, the evanescence process occurs where industry has been developed, such as the central towns in the second and third layers (Songgang and Shajing sub-districts in the west, Pinghu, Buji and Henggang sub-districts in the center, Longgang, Pingshan and Kenzi sub-districts in the east) and in Futian and Dongmen sub-districts of the SEZ in the south. With this process (the black squares in Fig. 6), the total area and diversity of green infrastructures continued to decrease, and large numbers of green patches constantly shrank so that the patch density decreased rapidly. However, the contagion of green patches appeared more obvious than other processes, contributing to the appearance of linear green belts. Consequently, green infrastructures are not the matrix in the urban landscape any longer, and there seem to be some sporadic islands or linear patches in the concrete matrix (Fig. 7d).

The filling-in process generally occurs at the later stable urbanization stage. During this process, civil construction has been less and less, but more patches of artificial green spaces are planned and built in the concrete matrix in order to meet the increasing open-space demand of residents. So during the filling-in process (the squares with grids in Fig. 6, such as Xi′an, Shahe, Huafu and Guiyuan sub-districts in the south first layer), the total area and the patch contagion of green infrastructures have risen slightly, and the diversity and the shape index declined, indicating that the type becomes simpler and the shape becomes more regular (Fig.7e).

4 Discussion and Conclusions

The above analyses have shown that there were significant continuous changes in the spatial pattern of green infrastructures during the urbanization in Shenzhen. These dynamic change processes had a good correspondence both with the stage of urbanization and with the corresponding urban expansion pattern. This correspondence could reflect the synthetical influence of urban planning, government policies and landforms, and it in turn contributed to the decision making about urban spatial development and urban green infrastructure planning.

4.1 General metric behavior of green infrastructure changes with urbanization

Based on the synoptic analyses in Section 3.1, the overall change characteristic of green infrastructures in Shenzhen can be represented by the schematic illustration in Fig. 8, which shows a visual history of urban green infrastructure changes with urbanization. As mentioned above, urban sprawl accelerated in Shenzhen starting in 1986, and the expanding development of new factories, houses, highways and townships increasingly encroached on green infrastructures, as reflected in landscape metric changes such as the total area, diversity and contagion decreases and the distinct patch density increase. With the coming of the adjustment stage of urbanization in 2000, the large-scale construction activities became fewer, and especially with the influence of urban smart growth, green infrastructures were given more attention and restoration. These changes were accompanied by slight decreases in the total area and patch density and a slow increase in the diversity, indicating that the fragmentation of green infrastructure is improving.

The urbanization process is also reflected in green infrastructure composition changes. The proportion of artificial elements increased continuously throughout the whole study period, but semi-natural and natural ones significantly decreased respectively before 1995 and after 1995. These results indicate that green infrastructures were losing their natural characteristics with the development of urbanization; furthermore, green infrastructures that were encroached upon by construction of buildings were the semi-natural ones before the stable urbanization stage, but then became the natural ones. Accordingly, the dominance of natural elements in Shenzhen at the stable stage became distinctly lower than at the early urbanization stage.

4.2 Spatial processes of green infrastructure changes through urbanization

The noticeable spatial heterogeneity of green infrastructures was demonstrated in Section 3.2 through the change types of five representative landscape metrics in 242 square units. Changes of all the landscape metrics appear as gradients along the axis and circle-layer as shown in Fig. 5, but with mutations in particular locations, especially for the shape index (Fig. 5c). By combining the spatial heterogeneity of changes in the total area with that of the patch density, shape, contagion and diversity in all squares, a continuous spatial sequence of changing green infrastructures was depicted as five clustering categories (Fig. 6). They are the perforation, segmentation, fragmentation, evanescence and filling-in processes, all of which have different trends in spatial attribute changes. For example, in squares with the perforation process, the total area of green infrastructures changed little, but the patch density and diversity tended to rise increasingly, and the contagion tended to fall increasingly (Fig. 5). However, in squares with the filling-in process, the total area, contagion and diversity of green infrastructures increased distinctly, but the patch density changes were not obvious and the patch shape became regular (Fig. 5).

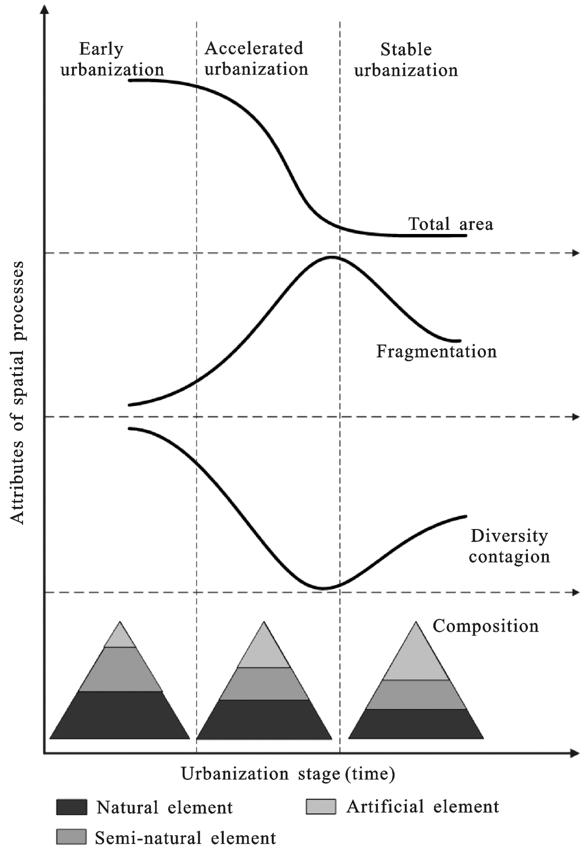


Fig. 8 Diagram for metrics behaviors of urban green infrastructures through urbanization in Shenzhen City

Shenzhen is a typical planned and hilly city in China; its urban spatial extension is clearly constrained by landforms and is also guided by urban planning and policy decisions. The urban development is shown as a multi-centered, circle-layered and axial pattern (Fig. 1). Regions along the west and central axes developed faster than those along the east axis, those in the south first layer developed faster than those in the north out layers (Wang, 2003). These patterns of expansion have in turn been reflected by the dynamic processes of spatial pattern changes in green infrastructures. Based on the locations and spatial processes of 242 square units (Fig. 6), five spatial processes of green infrastructure changes can overlap through the urbanization as depicted in Fig. 9. The perforation process generally occurs in the east outer layer, where the altitude is high and where urban development is slower (with little urban build-up area). The process of segmentation appears in the transition among the west, central and east axes and between the SEZ and the outer layers, where urban development with new industries and construction is being extended steadily, but it is also constrained by the landform at middle altitudes. The fragmentation process takes place in the peripheral towns of developed centers, where large-scale urban build-up is rapidly spreading without strict limitation by the landform. The evanescence process comes about both in the central towns in the plains of the outer layers along three axes and in several renewal parts of the SEZ, where large-scale urban build-up appears as a contiguous pattern with few green patches and where economic transformation has just started. Finally, the filling-in process occurs in some parts of the SEZ where artificial green spaces have been built to provide a close-to-nature environment for the resident.

4.3 Testing conceptual principle of spatial process in landscape changes

Through the combined five spatial processes of green infrastructures (Fig. 6) and their overlapping sequence through the period of urbanization in Shenzhen (Fig. 9), the conceptual principle of spatial processes of land transformation has been tested in this paper. Forman (1995a; 1995b) proposed that land is transformed by several spatial processes, such as perforation, dissection, fragmentation, shrinkage and attrition, and that they are measured by several landscape metrics, including patch number, average patch size and connectivity across an area. Moreover the processes are usually ordered by relative importance, beginning with perforation and dissection and ending with attrition (Fig. 10). The results of this study confirmed that similar spatial processes actually occurred during urban green infrastructure changes and could be quantified by clustering the square units with the spatial attributes of landscape metric changes.

However, it is worth noting that there were some differences between the spatial processes identified in this study and theoretical principles that are shown in Fig. 10. Firstly, although the sequence of urban green infrastructure changes began with perforation, the dissection process identified in the theoretical principle was not obvious in the urban green infrastructure changes and generally occurred with further perforation of the green infrastructures, so in this paper it was defined as the segmentation process. Secondly, the shrinkage and attrition processes in the theoretical principle also occurred simultaneously in the urban green infrastructures. Furthermore, they were occasionally followed by the occurrence of some new types, such as green belts along roads. These kinds of green infrastructure change were reclassified as the evanescence process. Lastly, the spatial process of urban green infrastructure changes did not end with the attrition but with the filling-in process, which is attributed to the increasing artificial green spaces such as the community park, the roadside green space and even the roof garden.

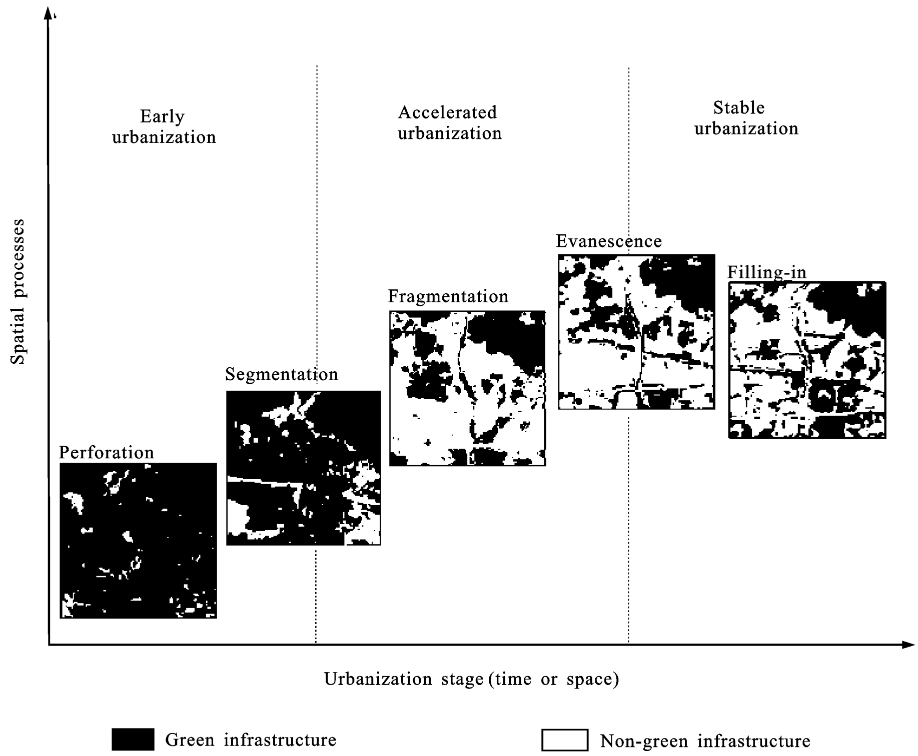


Fig. 9 Spatial process sequence of green infrastructures through urbanization in Shenzhen City

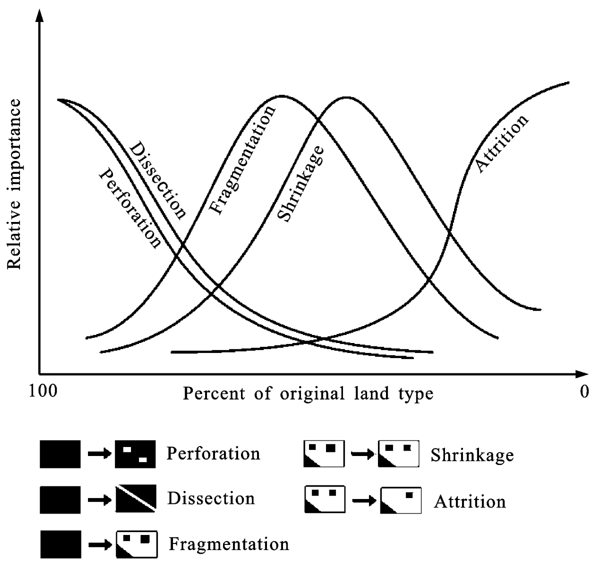


Fig. 10 General principle of spatial processes changing with land transformation predicted by Forman in 1995

4.4 Importance of spatial process analysis of urban green infrastructure changes

Landscape metrics together with gradient analysis has provided a well-known means for understanding how urban landscape patterns evolve and change over time (Herold *et al*., 2003). This kind of method is always based on the organism-centered assumption (Mcgarigal and Cushman, 2002), so landscape changes in the study years can be detected by examining landscape metrics that usually vary along one or two transects from the urban fringes, through the suburbs and to the city center (Luck and Wu, 2002; Zhang *et al*., 2004; Kong and Nakagoshi, 2006; Yu and Ng, 2007). However, it is difficult to analyze how a landscape changes continuously during a study period, and the information about the spatial process of urban landscape changes is then lost. This paper has advanced a square-based clustering method based on the varying functions of landscape metrics to quantify the spatial processes of urban green infrastructure changes, a method that is especially suitable for multi-centered cities such as Shenzhen. The results provide assurance that there is an overlapping spatial variation sequence of green infrastructures through the urbanization of Shenzhen and demonstrate a continuous landscape pattern trajectory from perforation, to segmentation, to fragmentation, to evanescence and fill-in. These results can tell urban planners and management how to avoid excessive occupation of green infrastructures during the urban expansion of other rapidly-developing cities in China.

In addition, because urban green infrastructure transformation may affect ecological processes in cities, either among elements within green infrastructures or between green and gray infrastructures, the spatial process analysis developed in this paper also provides an alternative probe for future studies of urban landscape changes and the corresponding ecological effects.

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