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RESEARCH ARTICLE

# The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China

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**Abstract** To better understand the spatio-temporal dynamics of the urban landscape of the Nanjing metropolitan region, China, we conducted a series of spatial analyses using remotely sensed data of 1979, 1988, 1998, 2000 and 2003. The results showed that the urban area as well as the growth rate increased significantly. Three urban growth types were distinguished: infilling, edge-expansion and spontaneous growth. The pattern of urban growth can be described as a 'diffusion–coalescence' phase transition. Although edge-expansion was the most common growth type, the spontaneous growth took a greater proportion in area and patch number than the infilling growth at the early stage, but its dominance decreased as urbanization proceeded from the diffusion phase to the coalescence phase. Hot-zones of urban growth and the distribution pattern of newly urbanized areas in different periods were studied with a buffering analysis. More than 80% of the growth area occurred within a zone of 1.4 km wide outwards from the pre-growth urban fringes. The spatial distribution of newly urbanized areas in each period showed a uniform negative exponential decline relative to the distance from the edge of the urban patches. There existed an outward wave-like shifting of urban growth hot-zones, but the distance-growth area curves varied at different stages of urban growth. While a double-peaked pattern usually occurred in the diffusion phase, a single-peaked pattern was common in the coalescence phase.

**Keywords** Growth type · Growth hot-zone · Landscape pattern · Urbanization

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## Introduction

Urbanization can be defined as the conversion of rural lands to urban or other built-up uses, representing an important type of land transformation (Antrop 2000; Pickett et al. 2001; Bürgi et al. 2004) and a key research topic in landscape ecology (Wu and Hobbs 2002). Although urbanized areas account only for 1% to 6% of the earth's land surface, their influences on the functioning and services of local and global ecosystems are enormous (Grimm et al. 2000; Berling-Wolff and Wu 2004b; Alberti 2005).

The landscape pattern of an urban area reflects the range, intensity and frequency of human intervention and affects the processes of ecological systems in the urbanized area (Redman 1999). Understanding the relationship between the spatial pattern of urbanization and ecological processes has been recognized as a major objective of urban ecology (Breuste et al. 1998; Loucks 1994; Sukopp 1998; Wu and David 2002). Urban pattern and dynamics have been extensively studied during the past century and many urban theories developed, such as the concentric zone theory (Burgess 1925), the sector theory (Hoyt 1939) and the multiple nuclei theory (Harris and Ullman 1945). Although the concepts and ideas of these theories were widely accepted and used to model urban systems, they have for the most part remained hypothetical and are incapable of describing the spatio-temporal details of urban pattern dynamics because the process of urbanization is fairly complex (Batty 2002). Since the 1960s, a variety of new approaches from non-equilibrium and non-linear system perspectives were explored (Luck and Wu 2002) and widely used to analyze, model and forecast the pattern of urban systems. These theories and methods, such as catastrophe theory (Wilson 1976), chaos theory (Wong and Fotheringham 1990), dissipative structure theory (Allen and Sanglier 1979), percolation theory (Franceschetti et al. 2000; Makse et al. 1995), self-organization theory (Portugali 2000), fractals (Batty and Longley 1989; White and Engelen 1993), cellular automata (Batty 1997; Couclelis 1985), agent-based simulation (Batty 2005) and the entropy method (Yeh and Li 2001), have provided a deeper understanding of urban structure and dynamics.

Remote sensing techniques could represent an important source of information for urban analysis with high spatial and temporal accuracy and consistency (Batty and Howes 2001; Jensen and Cowen 1999). The sequential snap-shot allowed quantitative descriptors of the geometry of urban form to be computed and compared over time (Herold et al. 2003). During the past decades, a variety of approaches for urban land use classification and change detection have been developed to facilitate urban analysis (Masek et al. 2000; Ridd and Liu 1998; Sohl 1999; Seto and Liu 2003; Yang and Liu 2005). Among the various sources of remotely sensed data, Landsat (MSS, TM and ETM+) images provide a way to monitor urban growth over three decades. Despite proven advantages, urban remote sensing has widely remained ‘‘blind to pattern and process’’ (Longley, 2002). In more recent studies, Landscape indices were integrated into urban pattern analysis supported by remote sensing (Berling-Wolff and Wu 2004a; Dietzel et al. 2005; Herold et al. 2003; Seto and Fragkias 2005; Xie et al. 2006). Also, the analyses of scale effect and temporal variation can be performed when landscape indices are applied to multi-scale or multi-temporal data sets (Wu et al. 2000; Wu 2004).

The spatial pattern of an urban region is a consequence of the interaction of various kinds of driving forces including natural and socioeconomic factors (Bürgi et al. 2004). Spatial heterogeneity of these factors such as topography, soil characteristics, population and market conditions could influence urban morphology and cause different typologies of urban sprawl. Camagni et al. (2002) distinguished five types of urban growth: infilling, expansion, linear development, sprawl and large-scale projects. Wilson et al. (2002) identified five types of urban growth: infill, expansion, isolated, linear branch and clustered branch. Although the terminology used to define growth typology could differ from author to author, the connotations are similar.

Basically, there are three main types of urban growth documented: infilling, edge-expansion and spontaneous growth (see Berling-Wolff and Wu 2004a). Infilling means the non-urban area surrounded by urban being converted to urban; edge-expansion, also called urban fringe development, refers to the newly developed urban area spreading out from the fringe of existing urban patches; and spontaneous growth means the new urban patches are formed and have no direct spatial connection with the existing urban patches. Forman (1995) calls this type of landscape process ‘perforation’, and defines it as ‘‘the process of making holes in objects such as habitat or land type.’’ Other types of urban growth can be viewed as some combinations of these three types. The geometric attributes as well as spatial distribution vary among the different growth types, and more importantly, development direction and speed may be different. The study of urban growth typology is meaningful for urban theory and modeling (Luck and Wu 2002).

In this paper, we combined multi-temporal remotely sensed data with landscape indices to investigate urban growth patterns of the Nanjing metropolitan region, China, from 1979 to 2003. Furthermore, we proposed a simple method to distinguish urban growth typology and then the quantitative composition and distribution of the growth types were analyzed during the different periods. Afterwards, the distance effect on urban growth pattern from the center and fringe of urban patches was studied using buffering analysis. The purpose of this paper is to address the following questions: (1) How does urban area grow over time? (2) Where is the growth spatially located?

## Methods

### Study area and data preprocessing

The Nanjing metropolitan region is located in the west of the Yangtze Delta, between 31°14′–32°36′N and 118°22′–119°14′E (Fig. 1). The mean annual temperature is 15.7°C and the mean annual precipitation is 1 106.5 mm. Nanjing covers an area of approximately 4,736 km$^2$, and nearly 15% of the total area is occupied by low hills. There are eleven districts within the metropolitan region, with a total population of over 5.3 million.

The Yangtze Delta is one of the most important agricultural and industrial regions and has the highest economic growth rate and population density in China. Being one of the three core cities in the Yangtze Delta, Nanjing has been undergoing a rapid urbanization process since the 1980s. Socioeconomic data from 1979 to 2003 display a significant growth in population and gross domestic product (GDP) in the Nanjing metropolitan region (Fig. 2) (Nanjing Statistical Bureau 2004). We selected the years of 1979, 1988, 1998, 2000 and 2003 to profile the urbanization process during this period. These dates with unequal intervals correspond to the initial stage, the accelerated stage and the steady growth stage of economic growth in China since the Reform and Open policy was initiated (Tang and Yao 1999; Nanjing Statistical Bureau 2004).

Five cloud-free Landsat scenes were selected in this study. The images were acquired on August 16, 1979 (MSS), July 5, 1988 (TM), April 28, 1998 (TM), November 3, 2000 (ETM+) and October 19, 2003 (TM), respectively. Each scene was geometrically corrected using over 30 ground control points (GCPs) evenly distributed. The second-order polynomial transformation and the nearest-neighbor resampling method were used in the geometric correction. The accuracy was improved to less than 0.5 pixel of root mean square error (RMSE). Supervised classification approach was chosen for mapping land cover with the maximum likelihood method. The classification result was revised according to visual interpretation and ground survey. Accuracy assessment was conducted using the ground truth data and the accuracy of each land cover map was above 90%. Raster layers of urban land use derived from every scene were resampled to a uniform resolution (80 m) and the patches less than 3 pixels were filtered. As we focused only on the changes in urban land use, landscape heterogeneity was represented in two classes: urban (including residential, commercial, industrial, park and developing area) and non-urban. Overall changes in urban pattern were analyzed using several landscape indices including number of patches (NP), area-weighted mean patch area (AWMPA), the largest patch index (LPI) and the area-weighted mean Euclidean nearest-neighbor distance (AWMENND) (see McGarigal et al. 2002). As possible ambiguity might be introduced by landscape indices (Li and Wu, 2004; Tischendorf 2001), we only choose those that have explicit meanings in relation to the behavior of urban patches (diffusion or coalescence). The landscape indices were calculated with public domain software FRAGSTATS version 3.3 (McGarigal et al. 2002).

### Typology of urban growth

For the convenience of implementation, a simple quantitative method to distinguish the three

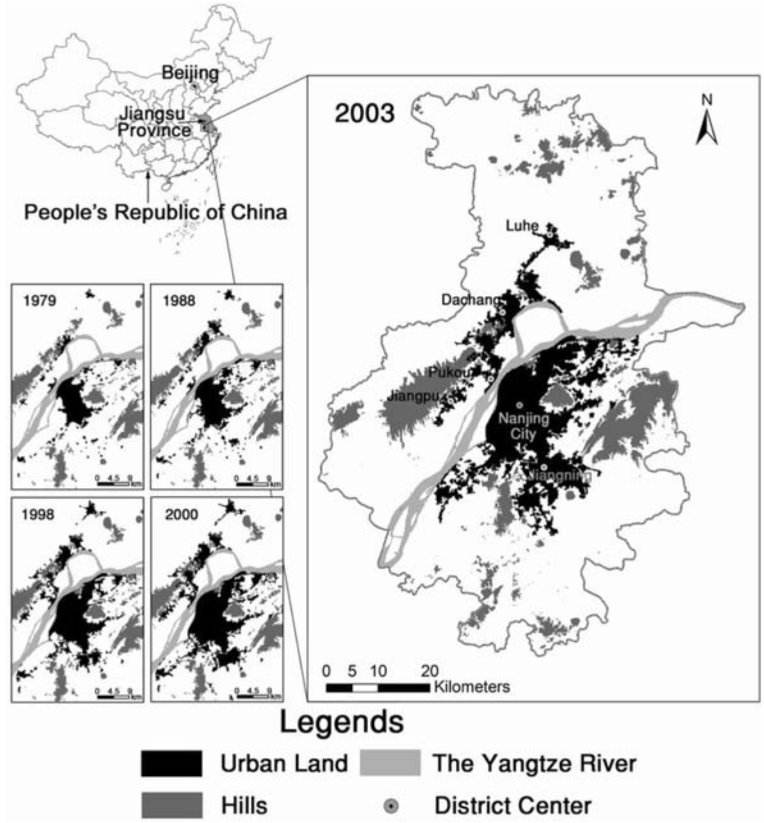


**Fig. 1** The location of the Nanjing metropolitan region and the extent of urban land use from 1979 to 2003

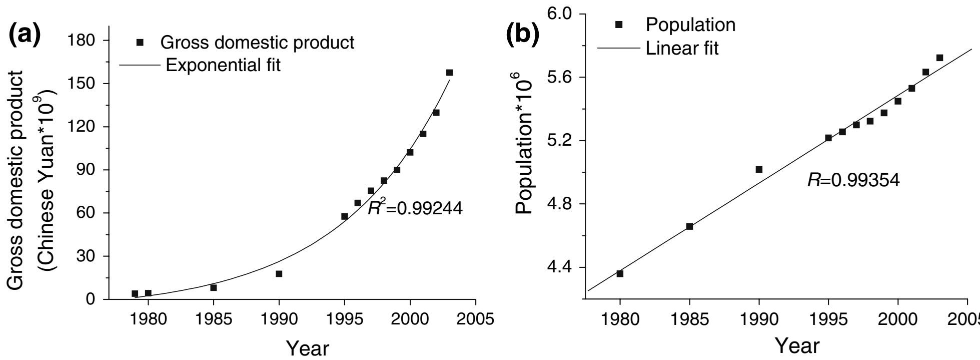


**Fig. 2** Economic and population growth in the Nanjing metropolitan region from 1979 to 2003: (**a**) gross domestic product growth and (**b**) population growth

growth types was proposed using the following equation:

$$S = L_c/P$$

where $L_c$ is the length of the common boundary of a newly grown urban area and the pre-growth urban patches, and $P$ is the perimeter of this newly grown area (Fig. 3). Urban growth type is identified as infilling when $S \geq 0.5$, edge-expansion when $0 < S < 0.5$, and spontaneous growth when $S = 0$ which indicates no common boundary. The three growth types are illustrated in Fig. 4.

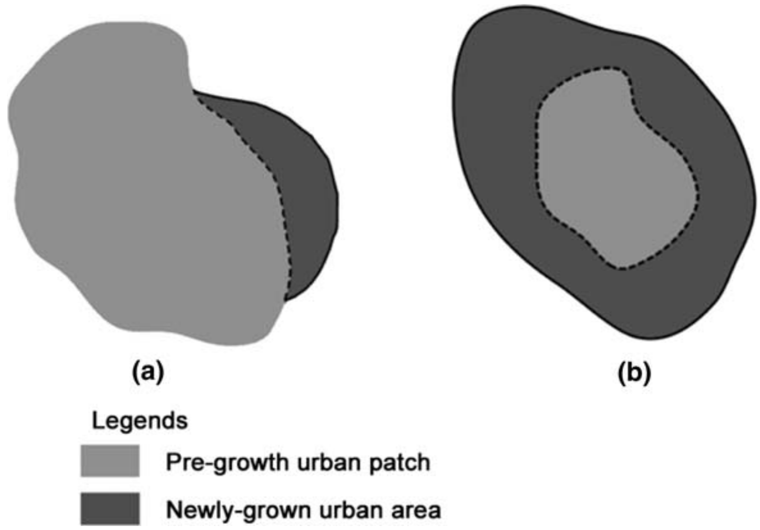


**Fig. 3** Illustration of the criteria for urban growth type. The dashed lines represent the common boundary ($L_c$) of pre-growth urban patches (light grey area) and newly grown area (dark grey area). The length of the perimeter ($P$) of the newly grown urban area is the sum of the length of dashed line and solid line (**a**). When the pre-growth patch is enclosed by the newly grown area, $P$ is calculated as the sum length of the solid and dashed line (**b**)

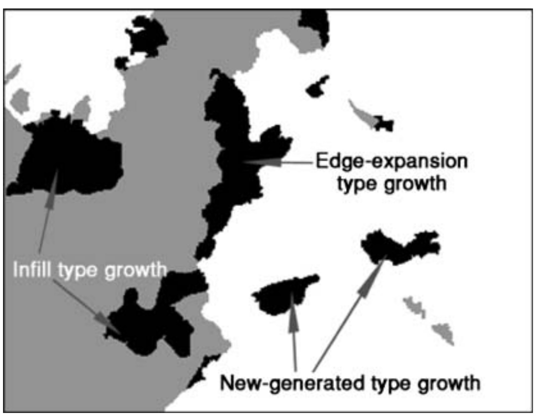


**Fig. 4** Typology of urban growth. The grey area represents the pre-growth urban patches and the dark area represents the newly grown urban patches

The area-weighted mean distance index (AWMDI) reflects the distance effects from the newly grown urban patches of some growth type to the urban center (the geometric center of the main city patch in the whole study area), and is defined as:

$$\text{AWMDI}_j = \sum_i \left( d_{ij} \frac{A_{ij}}{A_j} \right)$$

where $\text{AWMDI}_j$ is the area-weighted mean distance index of growth type $j$, $d_{ij}$ is the Euclidean distance from some newly grown urban patch $i$ of growth type $j$ to the urban center, $A_{ij}$ is the area of the newly grown urban patch $i$ of type $j$, and $A_j$ is the total area of the newly grown urban patches of type $j$. Here we use subscripts in $\text{AWMDI}_\text{i}$, $\text{AWMDI}_\text{e}$, and $\text{AWMDI}_\text{s}$ to represent infilling, edge-expansion and spontaneous growth type, respectively.

Location of hot-zone

Buffers around the pre-growth urban patch polygons at regular intervals of 200 m were created and overlaid with the newly grown urban polygons. Then the area of the newly grown urban land in each buffer ring was extracted. The distribution pattern of the newly developed urban land from the former urban fringe with increasing distance was investigated using this method. The impact of the distance factor from the urban center on the growth area was also estimated using buffering analysis. The newly grown urban area in the buffer rings around the urban center point at regular intervals of 3 km was extracted.

The administrative districts in the Nanjing metropolitan region were connected with each other both spatially and socioeconomically. However, they experienced relative independent development from a local perspective. So it is necessary to study the growth pattern at local scale. The study area was divided into three sub-regions: the main city region (MC), the northern river region (NR, including Luhe, Pukou, Dachang and Jiangpu district) and Jiangning region (JN, including Jiangning district). MC is the old city with little new development space left; JN is the area very close to MC and it experienced a quick growth with relatively sufficient development space; NR is relatively far away from MC and the development has been slower than in the other two sub-regions since it is separated from MC by the Yangtze River. The division was based on not only the geographic locations but also socioeconomic conditions for each district. The relationship between the growth area and the distance from the growth core (using the geometric center of the main urban patch in the sub-region) for each sub-region was analyzed using the same method as the whole study area.

## Results

### Changes in the landscape characteristics in the urbanization process

During the period 1979–2003, the urban area increased continuously and rapidly in the Nanjing metropolitan region. In 1979, the urbanized area was 12,806 ha (2.7% of the study area), while in 2003, the area expanded to 46,084 ha (9.73% of the study area), representing an increase of 360% and could be well fitted with an exponential curve (Fig. 5a). The mean annual growth rates also increased greatly, which were 467, 1,035, 2,054 and 4,869 ha/year for the four periods of 1979–1988, 1988–1998, 1998–2000 and 2000–2003, respectively (Fig. 5b), indicating that the urbanization process of Nanjing has been accelerated over the past 24 years.

The changes in all of the investigated landscape indices are illustrated in Fig. 6. The number of urban patches (NP) was 87 in 1979; this increased to 122 by the year 1988 and later decreased gradually to 57 from 1988 to 2003. The AWMPA continuously increased from 0.6 ha to 2.5 ha. The area-weighted mean Euclidean nearest-neighbor distance (AMENND) had a descending tendency despite a slight ascending in the year 2000. The changes in these indices suggested that many urban patches joined each other as they expanded in the process of urbanization. The largest patch index (LPI) showed a similar pattern to the AWMPA, indicating that the main urban patch (corresponding to the main city) became more dominant in the landscape.

### Typology of urban growth

Three urban patch growth types were identified and the contribution of each in the four periods was illustrated in Fig. 7a. Throughout all of the 24-year period, the edge-expansion was the primary growth type. In the first period (1979–1988), the infilling type growth occupied only 14.7% of the total newly developed urban land, while the edge-expansion type occupied 58.6%. The spontaneous growth accounted for a considerable proportion of 26.6%. Between 1988 and 2000, the percentage of the infilling type growth increased to almost 45% (44.5% for the period of 1988–1998 and 43.9% for 1998–2000), very close

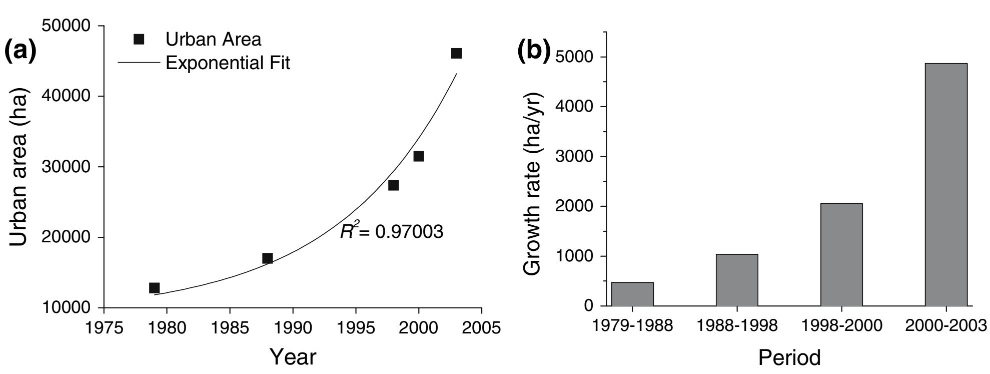


**Fig. 5** Urban area (**a**) and growth rate (**b**) in the different periods from 1979 to 2003

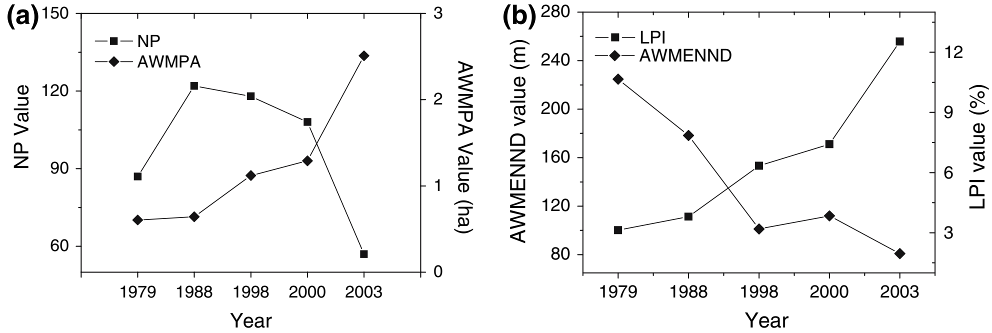


**Fig. 6** Changes in the landscape indices during the period of 1979–2003: (**a**) number of patches (NP) and area-weighted mean patch area (AWMPA) and (**b**) the largest patch indiex (LPI) and area-weighted mean Euclidean nearest-neighbor distance (AWENND)

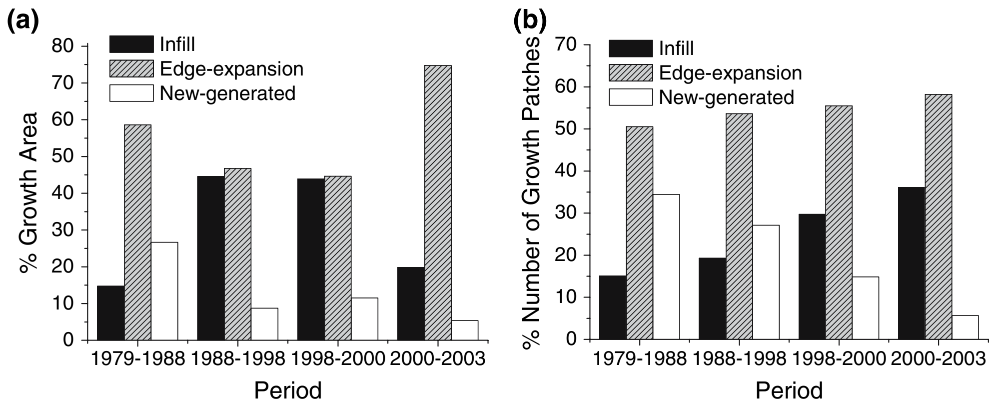


**Fig. 7** The proportion of growth area (**a**) and patch number (**b**) of the three growth types in the different periods

to the edge-expansion type (46.7% for 1988–1998 and 44.6% for 1998–2000). In contrast, the spontaneous growth decreased to about 10% (8.7% for 1988–1998 and 11.5% for 1998–2000). In the period 2000–2003, the proportion of the edge-expansion type growth rose to 74.8% and the infilling type growth dropped back to 19.8%, whereas the spontaneous growth remained a small proportion at 5.4%.

NP proportion of the three growth types exhibited some regularity in the temporal pattern (Fig. 7b). The edge-expansion type growth had the largest percentage in patch number with a small increase from 50.5% to 58.2% in the 24 years, but the infilling and spontaneous growth changed in opposite directions significantly. The infilling type increased from 15.1% to 36.1% while the spontaneous growth decreased from 34.4% to 5.7% and by the end of the 24-year period, the proportion of the infilling type growth had become the smallest one.

The area-weighted mean distance index for the three growth types changed with different patterns in the four periods (Fig. 8). As a whole, $AWMDI_e$ was less than $AWMDI_s$ but greater than $AWMDI_i$. $AWMDI_s$ (18.7 km) was much greater than $AWMDI_i$ (8.1 km) and $AWMDI_e$ (11.3 km) in the first period of 1979–1988 and later the differences among them became smaller.

In 1988–1998, $AWMDI_i$ remained almost unchanged while $AWMDI_e$ increased to 14.6 km and $AWMDI_s$ decreased to 15.4 km. In the period of 1998–2000, $AWMDI_i$ increased to 11.4 km, $AWMDI_s$ increased back to 18.5 km and $AWMDI_e$ showed a slight decrease to 14.3 km. From 2000 to 2003, $AWMDI_e$ (17.3 km) and $AWMDI_i$ (12.8 km) both rose while $AWMDI_s$ (18.3 km) dropped a little.

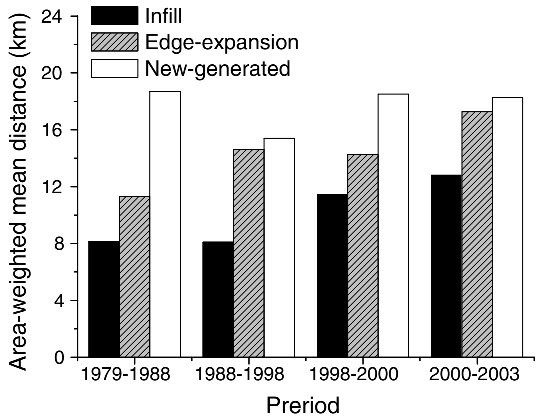


**Fig. 8** Area-weighted mean distance index of the different growth types

Overall, $AWMDI_i$ and $AWMDI_e$ showed an increasing tendency despite some slight decreases, whereas $AWMDI_s$ initially decreased and later increased again.

## Hot-zones of urban growth

Although the total growth area varied in different periods, the distribution patterns of the new growth area related to the pre-growth patches were similar (Fig. 9), and could be well fitted with negative exponential equations ($R^2 > 0.9$). Over 35% and 50% of the total growth took place in the zones within a distance of 200 m to 400 m from the edge of the pre-growth urban patches respectively, and all dropped to below 10% in each 200 m-wide buffer rings when further than 600 m. Over 80% of the total growth area for 1979–1988 and 2000–2003 and over 90% for the other periods took place within a distance of 1.4 km from the former urban fringe. So, the buffer zone from 0 to 1.4 km can be identified as the hot-zone of urban growth in this study.

Investigation of the relationship between the growth area and its distance from the urban center revealed the movement of the hot-zone in the whole study region (Fig. 10a). The distribution of the area as a function of increasing distance was represented as single-peaked curves except in 1979–1988 when the curve was double-peaked. The peaks reflected the hot-zones of urban growth in each period. In 1979–1988, the area–distance curve displayed two peaks: urban growth mostly occurred within 6–9 and 21–24 km distance from the urban center. The peak at the distance of 6–9 km represented the growth at the fringe of the main city patch, and the other peak reflected the development of Dachang industrial region during this period. Afterwards, the curves all exhibited a single peak, which represented the development of the urban fringe. Along with urban growth, the region at the urban fringe moved outwards. In 1998–2000 the peak occurred at 9–12 km while in 2000–2003 the peak had moved to 15–18 km. Overall, a single-peaked curve was the general form of the relationship between urban growth area and distance; this represented the hot-zone of urban growth moving progressively with the moving distance increasing with the acceleration of urbanization in the four periods.

The area–distance relation for the three sub-regions displayed single or double-peaked patterns, which were similar to the whole Nanjing region (Fig. 10b–d). For MC region, the curves exhibited a single peak in each period. The hot-zone was located at 6–9 km distance from the growth center of the sub-region in 1979–1988 and 1988–1998, and then moved to the distance of 9–12 km in 1998–2000. It spread further to 9–15 km distance in 2000–2003. For JN region, the curves all exhibited single peaks in each period. In 1979–1988, 100% of the growth area occurred within 3 km distance from the center. Ninety-six percent of the growth area occurred at the distance of 0–6 km in 1988–1998 and 74% in 1998–2000. By the period of 2000–2003, 97% of the growth area occurred at 3–9 km. The curve for NR region did not show any obvious peak shift over time. However, the moving tendency of the growth hot-zone was still apparent. For NR region, the hot-zone appeared at 6–9 km distance from the growth center in all periods. In 1979–1988 there was a peak occurred at the distance of 0–3 km, representing nearly 30% of the growth area and a peak at the distance of 18–21 km, representing 21% of the growth area in 1998–2000. Compared with the other two regions, no clear peak-movement pattern emerged in NR sub-region.

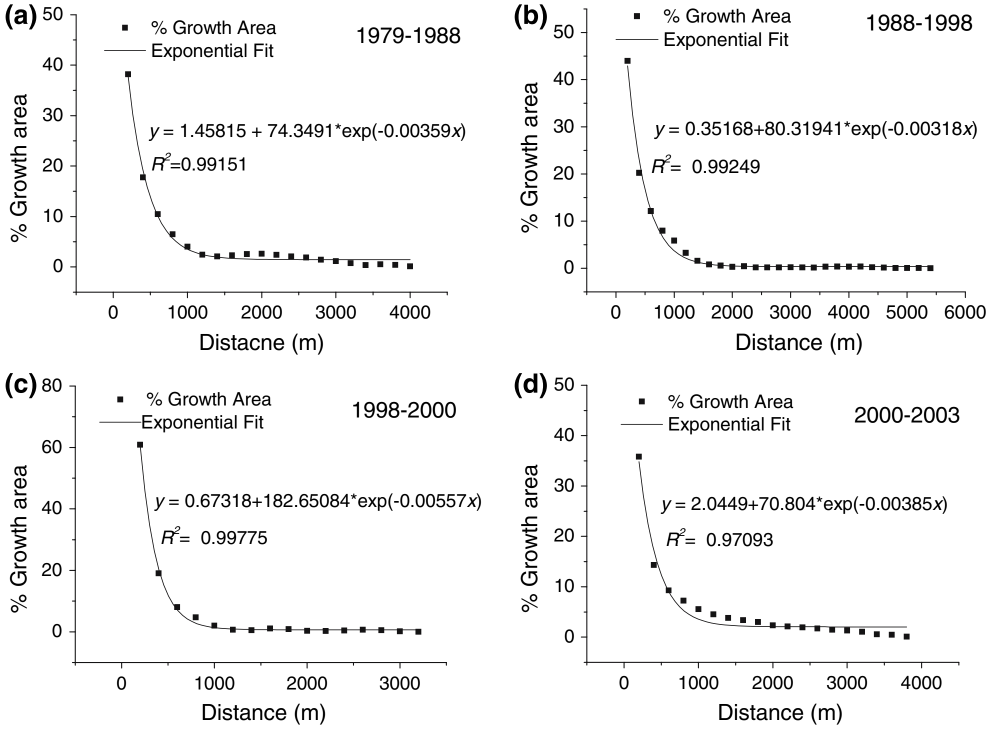


**Fig. 9** The relationship between the area of urban growth and the distance from the fringe of the pre-growth urban patches: (**a**) 1979–1988, (**b**)1988–1998, (**c**)1998–2000, (**d**) 2000–2003

## Discussion

As a city in the progress of rapid urbanization, Nanjing is representative of Eastern China which is undergoing fast economic development (Tang and Yao 1999; Liu et al. 2005). In the Nanjing metropolitan region, the urban area increased exponentially (Fig. 5a) and the growth rate for the four periods (1979–1988, 1988–1998, 1998–2000 and 2000–2003) also exhibited a significant increase (Fig. 5b). The results mentioned above can adequately address the questions defined in the Introduction and provide an advanced comprehension of the character of rapid urban sprawl.

### Phases of diffusion and coalescence in urbanization

The results showed two distinct phases in a rapid urbanization process in the Nanjing Metropolitan region. Dietzel et al. (2005) proposed that the urban growth process could be described as a general temporal oscillation between the phases of diffusion and coalescence based on the idea of alternating phases of urban growth (Cressy 1939; Hoover and Veron 1959; Duncan et al. 1962; Winsborough 1962), which were supported by some recent studies (Seto and Fragkias 2005; Xie et al. 2006). The urbanizing process of Nanjing during the 24-year period just came through this oscillation.

In 1979, urban patches were mostly distributed in the urban cores. Along with the development of urbanization, the mean area of the urban patches increased and numerous new patches formed contemporarily, which can be identified as the diffusion phase. This occurred mainly as a result of the establishment of the industrial regions and the high-tech zones driven by the initiated economic growth. The period of 1979–1988 can be seen as the end of the diffusion phase and the beginning of the coalescence phase which is evidenced by the number of patches (NP). As the growth continued, proximate urban patches became increasingly connected. The reduction of the area-weighted mean Euclidean

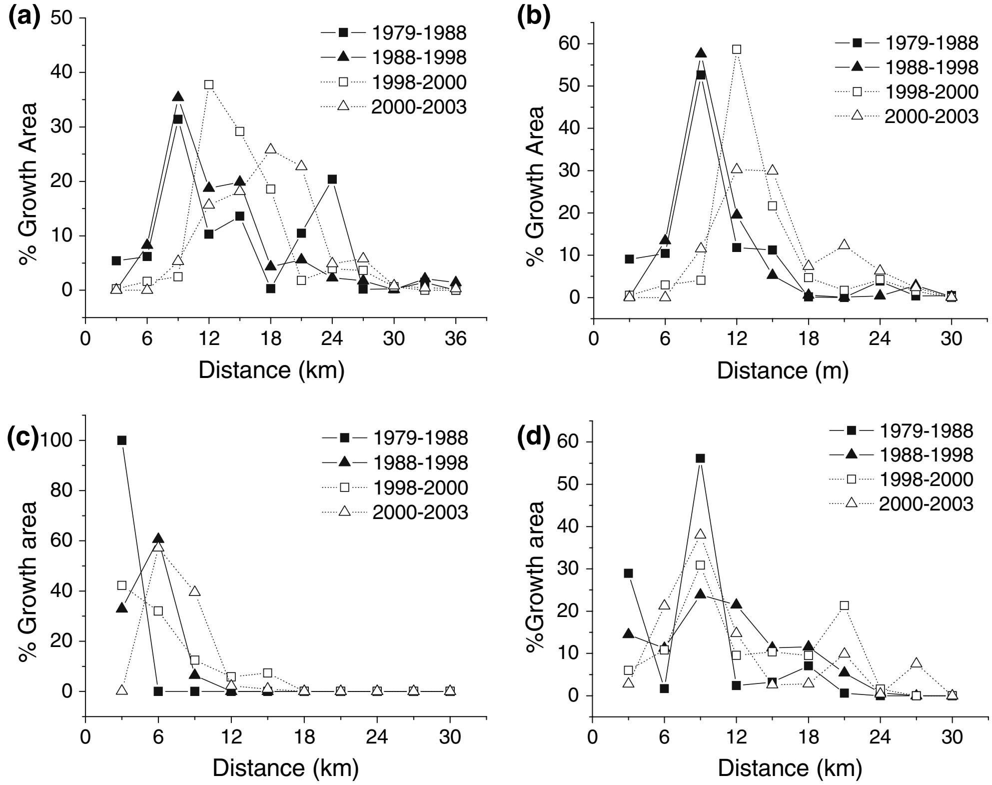


**Fig. 10** The relationship between the area of urban growth and the distance from the center of the pre-growth urban land: (**a**) the whole study area, (**b**) main city region (MC), (**c**) Jiangning region (JN), (**d**) northern river region (NR)

nearest-neighbor distance (AMENND) indicated coalescence became the major characteristic of the changes in urban pattern from 1988 to 2003. In addition, the heterogeneity among the urban patches increased as a consequence of coalescence. The main urban patch grew faster and tended to be more and more dominant as some other diffused urban patches were joined, which was evidenced by the increasing of the largest patch index (LPI).

There occurred a kind of rhythm along with the diffusion and coalescence processes from the perspective of the growth types. In the period of 1979–1988 there was sufficient space for urban development. Edge-expansion growth was the most dominant type and spontaneous growth, corresponding to 'diffusion', occupied a considerable proportion, too. The tendency of decreasing proportion of growth area and patch number for the spontaneous growth indicated the decline of diffusion and the enhancement of coalescence. In the phase of coalescence, the vacant (non-urban) land was mostly occupied by the infilling type growth, changing the urban landscape towards a saturated pattern. Later, as the available growing space was reduced, the infilling type growth dropped back and the edge-expansion type growth became the major form again. The area-weighted mean distance index also showed changing patterns concordant with the diffusion–coalescence phases. The $AWMDI_e$ and $AWMDI_i$ both had an increasing tendency, indicating the enlarging of urban area on the whole. However, the $AWMDI_s$ dropped from 1979 to 1988, indicating the transition phase from diffusion to coalescence, and later went up along with the process of coalescence.

Overall, the results demonstrated the periodicity in the process of urban growth. At first, urban land expands outwards in a great proportion. Afterwards, the growth fills the vacant lots (non-urban land) inwards. Meanwhile, the outward edge-expansion is still ongoing. When the growing space has been compressed and urban form has become more compact, the main direction of urban growth turns outwards again. This finding has some important implications for urban modeling. The rhythm of the growth types needs to be incorporated in the spatial explicit models, such as cellular automata models (Batty 1997).

The link between the ecological processes and the pattern of the growth types is an important issue to be addressed. In general, non-urban land with relatively higher value (for housing, commerce and, etc.) and lower developing cost (the flat land is easier to develop than the mountainous area, for example) tends to be converted to urban land earlier (Nelson 1985). Drivers such as topography, economic conditions, transportation network and planning efforts result in heterogeneity of land use aptness, developing cost and land price (Bürgi et al. 2004). The process of urban growth revealed in this study might be represented as a consequence of such heterogeneity. As the impact of driving factors on urban dynamics was not included in this study, the mechanism of such periodicity of urban growth pattern is expected to be further studied if socioeconomic data with spatial details is combined.

## The shift of growth hot-zone

Understanding the location of the growth hot-zone is essential for urban modeling as well as city design and planning. In the Nanjing metropolitan region, the area of urban growth showed an exponential decline from the urban fringe in each period (Fig. 9). Most of the growth was located in a relatively narrow ring (about 1.4 km) from the edge of the pre-growth urban patches. The proportion of the growth area declined more slowly in the first period because diffusion, represented as the spontaneous growth, is one of the major growth forms at the first stage and the mean distance of this type of growth from the pre-growth urban was longer than for the other types. A similar decreasing rate occurred in 2000–2003 because the total growth area was relatively large and the growth expanded farther when the nearest area from urban fringe area was occupied.

Blumenfeld (1954) proposed the use of a wave analog for describing urban growth, and the concept was spatialized by Boyce (1966). Clark (1951) developed a negative exponential model to describe the profile of urban population density with distance from the city center. Newling (1969) extended Clark's (1951) model by formulating a ''density-profile- classification of urban growth'' similar to the wave approach. According to the wave theory, the wave crest, i.e., the hot-zone of the growth, would move outwards from the city core with a particular periodicity. In this study, the wave-like growth pattern was confirmed at the whole regional scale based on remotely sensed data. The relationship between the growth area and the distance factor displayed single-peaked or double-peaked curves. Generally, the peak area closer to the urban center covered an annular region with a width of over 6 km. As the appearance of a new growth center in the diffusion phase, some hot-spots would occur in a farther area, thus multi-peaked patterns were detected. The outward movement of the peak (growth hot-zone) over time was illustrated clearly in Fig. 10a. For the three sub-regions, the curves showed similar shapes but the changing pattern varied. Clear outward shift of curve peak was displayed in MC region. The moving tendency of the hot-zone also existed in JN region though peak shift apart from the growth center was not as apparent as MC region. In contrast, such pattern was not shown in NR region. As urban systems have great complexity, spatial heterogeneity of various driving factors could cause different growth patterns among the different parts of the same city. The sub-regions in Nanjing experienced relatively independent developing process. In MC and JN, urban land expanded around the core area, while in NR region growth took place in a linear form along the Yangtze River and the main road. There was no obvious growth center in NR region and the growth pattern differed from the other two sub-regions. However, the curve also showed similar shapes as the largest urban patch could 'attract' more growth. Basic urban pattern such as concentric zone, sectors and multi-nuclei in the classic urban theories can be interpreted as 'ideal' conditions or basic structure at local scale, and the real pattern could be viewed as a composition of multiple structures in the urbanization process.

Ultimately, our results from the observation of the Nanjing metropolitan region in a 24-year period could support the 'diffusion–coalescence' phase dynamics. Increasing spatial heterogeneity of urban land formed different growth typologies with different locations and contributions for urban growth. Periodicity in the growing process, and the regularities of the shift of growth hot-zone revealed in this paper could be important implications for urban modeling.

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