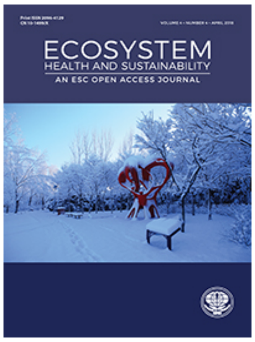


Taylor & Francis
Taylor & Francis Group

Ecosystem Health and Sustainability

ISSN: 2096-4129 (Print) 2332-8878 (Online) Journal homepage: https://www.tandfonline.com/loi/tehs20

# A comparative study of spatiotemporal patterns of urban expansion in six major cities of the Yangtze River Delta from 1980 to 2015

Chenyu Fang & Shuqing Zhao

**To cite this article:** Chenyu Fang & Shuqing Zhao (2018) A comparative study of spatiotemporal patterns of urban expansion in six major cities of the Yangtze River Delta from 1980 to 2015, Ecosystem Health and Sustainability, 4:4, 95-114, DOI: 10.1080/20964129.2018.1469960

**To link to this article:** https://doi.org/10.1080/20964129.2018.1469960



Published online: 09 May 2018.

ECOSYSTEM HEALTH AND SUSTAINABILITY, 2018
VOL. 4, NO. 4, 95–114
https://doi.org/10.1080/20964129.2018.1469960

Taylor & Francis
Taylor & Francis Group

ARTICLE

OPEN ACCESS Check for updates

# A comparative study of spatiotemporal patterns of urban expansion in six major cities of the Yangtze River Delta from 1980 to 2015

Chenyu Fang and Shuqing Zhao

College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China

**ABSTRACT**

**Introduction:** China has been experiencing dramatic urbanization in parallel with its economic boom over the past three to four decades. The Yangtze River Delta (YRD), as the most important engine in the Chinese economy, has pioneered in the rapid urbanization road of China since the late 1970s. We quantified and compared the spatiotemporal patterns of urban expansion in six major cities in the YRD urban agglomeration between 1980 and 2015.
**Outcomes:** We found that Shanghai, Nanjing, Hangzhou, Wuxi, Suzhou and Ningbo expanded by an annual rate of 5.4%, 5.9%, 9.6%, 7.4%, 6.3% and 8.1% from 1980 to 2015, suggesting larger cities generally possess lower growth rates. Spatiotemporal patterns of urban expansion are defined by multiple forces including physical conditions and urban planning and policy. The urbanization processes in Shanghai, Nanjing and Hangzhou generally conformed with the diffusion-coalescence theory as the number of patches (NP) and patch density (PD) of urbanized land peaked and the proportion of leapfrogging urban growth type began to decrease around 2005, which separating their urbanization processes into diffusion phase before and coalescence phase after. In contrast, Suzhou, Wuxi and Ningbo is either in the diffusion or in the transition phase from diffusion to coalescence, not showing temporal dynamics of diffusion-coalescence phase across the study period, which might be related to the fact that the urban areas in these three cities were more dispersive in space than that of other cities.
**Conclusions:** These spatially explicit findings are the fundamental cornerstone to understand the characteristics, drivers and consequences of urban expansion in the urban agglomerations, and then detect the feasibility of general urbanization theories and further advance in-depth theoretical understanding to support a sustainable urban future.

**ARTICLE HISTORY**
Received 27 November 2017
Revised 12 April 2018
Accepted 22 April 2018

**KEYWORDS**
Urban growth type; landscape metrics; remote sensing; buffer analysis; directional variability; urban agglomeration

## Introduction

We are now living in a rapidly urbanizing world. The proportion of global urban population has increased from 29.4% in 1950 to 54% in 2014, increasing at a rate of 4% per decade (United Nations 2015). Alongside the unprecedented global population growth and demographic shift from rural to urbanized areas, the need for living space and jobs results in a simultaneous growth of urban areas. Although urban land only occupies less than 1% of the Earth's land surface (Schneider, Friedl, and Potere 2009), it contributes about 78% of global greenhouse gas emissions and consumes 60% of global freshwater resources and 76% of wood resources (IPCC 2014). The rapid urban expansion, as an important component of global land transformation, has caused a wide range of environmental problems, which will directly affect human health and quality of life, such as heat island and heat wave effects (Meehl et al. 2004; Zhao et al. 2015a), haze pollution (Gao 2015; Gao et al. 2015), degraded water quality (Hobbie et al. 2014; Yan et al. 2017) and noise pollution (Roefs et al. 2017). Urban expansion can also lead to socioeconomic issues like congestion, urban unemployment and lack of public services (Bloom, Canning, and Fink 2008). More importantly, the impacts of urban expansion transcend far beyond the city boundary and the time when it occurs. Therefore, how and where urban expands will have profound implications for the long-term outlook of human societies.

Remote sensing (RS) technology enhances the availability of spatially explicit and temporally consistent land use and land cover change information (Herold, Scepan, and Clarke 2002; Michishita, Jiang, and Xu 2012) and Geographical Information Systems (GIS) facilitates the data progressing, which combine together to help characterize complex urbanization process (Luo and Wei 2009; Mashagbah and Atef 2016). Urban growth typologies and landscape metrics are widely used to quantify the dynamics of urban land composition and configuration, which enable conceptualizing the processes of urbanization and further the understanding of its underlying

**CONTACT** Shuqing Zhao sqzhao@urban.pku.edu.cn College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China.

organization and mechanism (Herold 2005; Zhu et al. 2006; Yu and Ng 2007; Fragkias et al. 2009). Sociologists and Geographers have long explored the urban form, morphology and functions, and many theories have been developed, such as the concentric zone model (Burgess et al. 2008), the cellular automata, the self-organization theory (Juval et al. 2000) and the diffusion-coalescence hypothesis (Dietzel et al. 2005a; Dietzel et al. 2005b). The diffusion-coalescence hypothesis has been examined based particularly on spatiotemporal patterns of urban expansion (Dietzel et al. 2005b). However, the generality of the theory is still under debate (Schneider, Seto, and Webster 2008; Jenerette and Potere 2010; Liu et al. 2010; Martellozzo and Clarke 2011), more work across various cities with different history, developing level, location and social economic and institutional contexts is needed.

Since the implementation of the reform and opening-up policy, China has undergone a remarkable economic growth and became the world's second-largest economy in 2014. Along with this fast economic growth, China has urbanized on a scale unprecedented in human history. The proportion of China's urban population increased from 17.4% to 54.8% between 1975 and 2014, and it is expected to increase to 60% by 2030 (State Statistical Bureau (SSB) 2015; United Nations, Department of Economic, and Social Affairs, Population Division 2016). Simultaneously, the number of cities grew three times and urban areas expanded more than six times (State Statistical Bureau (SSB) 2015). China's urbanization has attracted wide scholarly attention as its path is distinct either from other developing countries or developed ones. Cities have been considered as urban systems rather isolated areas since Gottmann (1957) put forward the concept of a megalopolis. In a megalopolis, cities benefit from mutual proximity and become increasingly integrated with each other (Tian et al. 2011). The Yangtze River Delta (YRD), one of the world's six largest urban agglomerations and the largest one in China, has pioneered in the rapid urbanization road of China since the late 1970s (Yue, Liu, and Fan 2013). The YRD has been studied extensively in terms of patterns, driving forces and effects upon the environment of urban expansion (e.g., Liu, Zhan, and Deng 2005; Zhang et al. 2011; Alqurashi, Kumar, and Alghamdi 2016; Jun et al. 2017). However, most of them provided an overall look at urban expansion of the urban agglomerations (Zhang et al. 2011; Chen et al. 2015; Gao et al. 2015) or focused on a single city of the urban agglomerations (Luo and Wei 2009; Yue et al. 2014; Chen et al. 2016d). There is a dearth of cross-city spatially explicit comparative study on the magnitude, form and spatial structure of urban expansion for the major cities of the YRD urban agglomeration across a relatively long timeframe. Using the spatially explicit and temporally continuous data to characterize and compare the dynamics of urbanization patterns across multiple cities will not only help understand the form, speed and scale of urban development, but also support optimal urban planning and management strategies toward a more sustainable urban future.

In this study, we quantified and compared the spatiotemporal patterns of urban expansion in Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo in the YRD urban agglomeration between 1980 and 2015 with relatively high temporal frequencies (i.e., 1980, 1990, 1995, 2000, 2005, 2010 and 2015) using Landsat RS data, integrated with landscape metrics and urban growth type analysis. Shanghai, as one of four municipalities of China, is the nucleus city of the YRD. Nanjing and Hangzhou are the capital city of Jiangsu province and Zhejiang province, respectively. Suzhou, Wuxi and Ningbo are chosen because they were defined as the main centers by the Development planning of the YRD urban agglomeration issued by State Council issued in 2010. The YRD, with long and advanced urbanization history, is an ideal place for a comprehensive understanding of the evolution of urban development in China's urban agglomeration.

The aims of this study were to: (1) dynamically map the extent of urban or built-up land; (2) quantify patterns and dynamics of urban growth; (3) compare the similarity and differences in speed, scale and form of urban expansion across cities, and in temporal dynamics of landscape metrics along different directions and at different distances from the city center within each city; and (4) test the applicability of diffusion-coalescence theory on the evolution of urban development for six major cities in the YRD urban agglomeration.

## Data and methods

### *Study area*

The YRD, located in the eastern coastal area of China, together with the Jing-Jin-Ji megalopolitan region (JJJ) in the north and the Pearl River Delta megalopolitan region (PRD) in the south, are the most important regions of Chinese trade, commerce, manufacture and industry (Wang, Liu, and Dadao 2011). The YRD (Figure 1) is composed by Shanghai, Zhejiang province and Jiangsu province possessing the high level of urbanization and economic development of China. As one of the most active economic area in China, the YRD is regarded as an important engine of China's economic development, contributing to more than a quarter of the country's economic output and

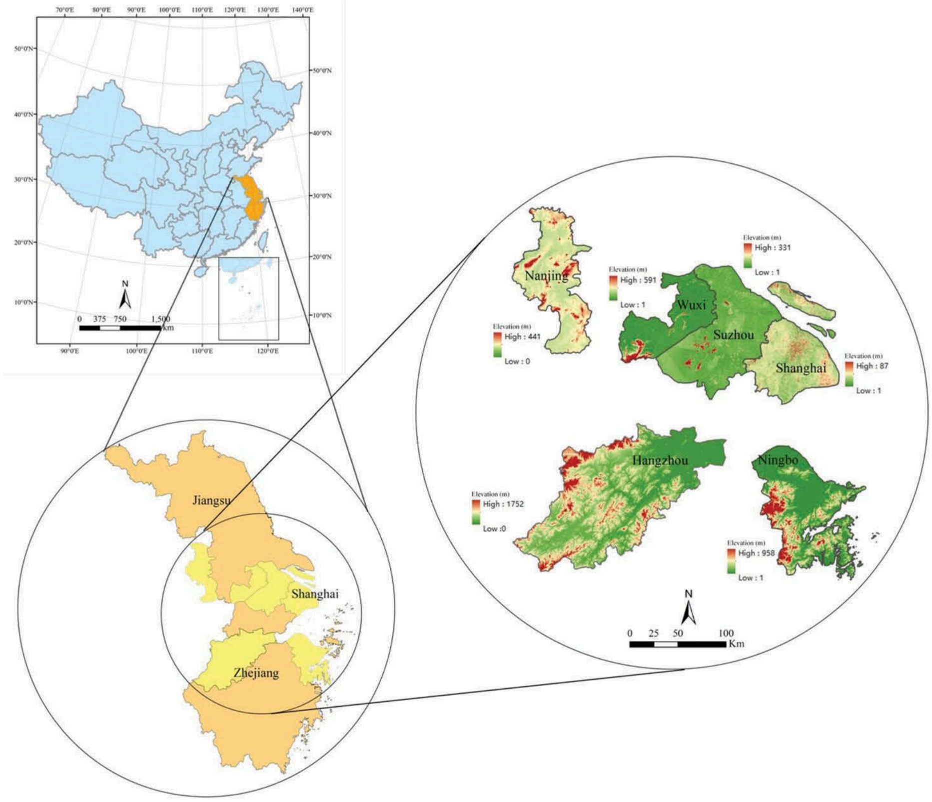


Figure 1. The location and administrative division of the study area. The background map of the six cities shows the elevation information.

industrial added value in only 2.2% of the country's land area (Zhang et al. 2011).

Our study area included six major cities in the YRD (Figure 1). Shanghai is a municipality under direct administration of the Central Government, which is adjacent to Jiangsu and Zhejiang Provinces. Located in the northwest of East China Sea, Shanghai is the economic center of the whole country. It is also a national historical and cultural city with a profound modern urban culture and many historical monuments. Nanjing, Suzhou and Wuxi all belong to Jiangsu Province whose GDP reached over 7,600 billion in 2016 only lagging behind Zhejiang Province across the country. Nanjing, as the political, economic and cultural center of Jiangsu province, is the provincial capital and has become an important gateway to the YRD radiation to drive the development of central and western regions. Suzhou, nearest to Shanghai among these six cities (within 100 km to the northwest of Shanghai), is an important national cultural industry base and national high-tech industrial base. The innovative city Wuxi, located between Nanjing and Suzhou, is the advanced manufacturing base and one of networking application centers. Hangzhou and Ningbo are both in the north of Zhejiang Province. Hangzhou, the provincial capital of Zhejiang Province, is the political, economic, cultural, scientific, educational, transportation, media, communications and financial center of the province. Ningbo, the south estuary of the Grand Canal in China and the original eastern port of "Marine Silk Road," is called the fourth largest port city of the world. It also enjoys the status of the economic center of Zhejiang Province. The basic conditions of the six major cities in YRD are listed in Table 1.

### *Remote sensing data and data processing*

Seven consecutive series of RS images were selected to acquire long-term land cover information of the study area: circa 1980, 1990, 1995, 2000, 2005, 2010 and 2015. Cloud-free Multispectral Scanner (MSS) images (before 1985, bands 1–4, resolution 60 m), Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) satellite images (bands 1–5 and 7, resolution 30 m,) were obtained from USGS website (http://www.usgs.gov/, accessed 5 April 2016). The detailed information of the images are shown in Table 2.

A series of data progressing, including band combination, image mosaic, reprojection, classification and classification accuracy assessment were conducted using ERDAS Imagine version 9.2 and ArcGIS version 10.1. To keep consistent with the TM/ETM+ images, we resampled the MSS images to a resolution of 30 m × 30 m. The maximum likelihood method was used to classify the images into five types: cropland, forest,

Table 1. The basic conditions of the six major cities in Yangtze River Delta.

| Metropolitan areas | Shanghai | Nanjing | Suzhou | Wuxi | Hangzhou | Ningbo |
|---|---|---|---|---|---|---|
| Geographic position | 30∘ 40′ to 31∘ 53′ N and 120∘ 52′ to 122∘12′ E | 31∘ 14′ to 32∘ 37′ N and 118∘22′ to 119∘14′E | 31∘19′N and 120∘ 37′ E | 31∘07′ to 32∘02′N and 119∘31′ to 120∘ 36′ E | 29∘11′ to 30∘33′N and 118∘21′ to 120∘ 30′ E | 28∘ 51′ to 30∘ 33′ N and 120∘ 55′ to 122∘16′ E |
| Area ($km^2$) | 6340 | 6597 | 8488 | 4627 | 16,596 | 9816 |
| Climate | Subtropical monsoon climate, with annual mean temperature of 16∘ C and an annual precipitation of 1173.4 mm | Subtropical and humid, with annual mean temperature of 15.4∘C and an annual precipitation of 1200 mm | A temperate zone and a subtropical monsoon marine climate,with annual mean temperature of 15.7∘C and an annual precipitation of 1100 mm | Subtropical monsoon marine climate with an annual mean temperature of 16.2∘C and an annual precipitation of 1121 mm | Subtropical monsoon climate, with an annual mean temperature of 17.8∘C and an annual precipitation of 1454 mm | Subtropical monsoon climate, with an annual mean temperature of 16.4∘C and an annual precipitation of 1480 mm |
| Population in 2015 ($10^4$) | 2415 | 824 | 1064 | 651 | 902 | 783 |
| GDP in 2015 ($10^8$) | 24,965 | 9721 | 14,500 | 8518 | 10,054 | 8012 |

Table 2. Information on remotely sensed data used in this study.

| Cities | Path/Row (MSS) | Path/Row (WRS2) | Date 1980 | 1990 | 1995 | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|---|---|---|---|---|
| Shanghai | 127/38 | 118/38 | 1979/8/4 | 1989/8/11 | 1995/10/31 | 2000/9/2 | 2005/8/15 | 2009/7/17 | 2015/8/3 |
| | 127/39 | 118/39 | 1979/8/4 | 1989/8/11 | 1995/10/31 | 2000/9/2 | 2005/8/15 | 2009/7/17 | 2015/8/3 |
| Nanjing | 129/37 | 120/37 | 1979/9/11 | 1985/4/24 | 1989/3/10 | 1995/4/20 | 2000/9/16 | 2010/10/30 | 2016/2/25 |
| | 129/38 | 120/38 | 1979/9/11 | 1985/4/24 | 1989/3/10 | 1995/4/20 | 2000/9/16 | 2010/4/5 | 2016/2/25 |
| Hangzhou | 128/39 | 119/39 | 1981/7/16 | 1991/7/23 | 1995/9/4 | 2000/10/11 | 2005/10/17 | 2010/8/20 | 2016/2/26 |
| | 128/40 | 119/40 | 1981/7/16 | 1992/10/29 | 1995/9/4 | 2000/10/11 | 2005/10/17 | 2010/3/21 | 2015/5/12 |
| | 129/39 | 120/39 | 1981/7/17 | 1990/10/15 | 1995/5/6 | 2000/9/16 | 2006/5/20 | 2009/6/5 | 2015/5/13 |
| | | 120/40 | | 1992/10/20 | 1995/5/6 | 2000/9/16 | 2006/5/20 | 2009/6/5 | 2015/5/14 |
| Suzhou | 127/38 | 118/38 | 1981/7/15 | 1990/4/24 | 1995/10/31 | 2000/9/18 | 2005/11/27 | 2009/7/17 | 2015/6/5 |
| | 128/38 | 119/38 | 1981/10/23 | 1990/2/26 | 1995/8/3 | 2000/9/17 | 2005/10/17 | 2010/5/24 | 2015/7/14 |
| | 128/39 | 119/39 | 1980/5/1 | 1990/10/8 | 1995/12/9 | 2000/9/17 | 2005/10/17 | 2010/5/24 | 2015/7/14 |
| Wuxi | 128/38 | 119/38 | 1981/10/23 | 1990/2/26 | 1995/8/3 | 2000/9/17 | 2005/10/17 | 2010/5/24 | 2015/7/14 |
| | 128/39 | 119/39 | 1980/5/1 | 1990/10/8 | 1995/12/9 | 2000/9/17 | 2005/10/17 | 2010/5/24 | 2015/7/14 |
| | 129/38 | 120/38 | 1981/7/17 | 1990/10/15 | 1995/10/13 | 2000/9/16 | 2005/10/24 | 2010/8/19 | 2015/7/14 |
| Ningbo | 127/39 | 118/39 | 1981/7/15 | 1990/6/11 | 1995/8/12 | 2000/9/18 | 2005/11/27 | 2009/7/17 | 2015/3/12 |
| | 127/40 | 118/40 | 1981/7/16 | 1990/6/11 | 1995/8/12 | 2000/9/18 | 2005/11/27 | 2009/7/17 | 2015/3/12 |

bareland, urban or built-up land and water body. The built-up land is defined as all non-vegetative areas dominated by human-made surfaces (e.g., roads and buildings), including residential, commercial, industrial and transportation space in both urban and rural settlements within the administrative boundary. Water body includes the reservoirs, ponds and rivers. Cropland includes paddy field, irrigated and dry farmland. Forest includes all forested areas having a predominance of trees. Bareland is generally an area of thin soil, sand, or rocks with almost no vegetation or other cover. As our main focus was on the built-up land, the other four types of land covers were further classified into non built-up land. Due to the resolution limitation of RS images, it is difficult to distinguish small isolated urban pixels from non-urban patches, which may lead to some biases of the classification results. To reduce this effect, a 1 km×1 km moving window was used to generate built-up land intensity, defined as the percentage of built-up land pixels at 30 m × 30 m resolution within each 1 km×1 km grid. The urban pixels with built-up land intensity less than 5% in a 1 km×1 km moving window were then excluded from built-up land category. The urban dynamic data sets of these six cities were extracted from the classified urban and non-built-up lands during the periods 1980–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2015. The classification accuracy was assessed using the stratified random sampling combined with Google Earth to calculate the kappa coefficient which represented the overall accuracy (Zhou et al. 2011). And the overall Kappa coefficients in the results (Table 3) met the accuracy requirement of land cover change evaluation (Foody 2002). Detailed procedures of data processing can be seen from our previous work (Zhao et al. 2015a, b).

### Landscape metrics

The landscape patterns, characterized by interactions among patches, can be summarized using Landscape Metrics. Eight metrics, which have been proven to be suitable for examining the temporal dynamics of urban characteristics (McGarigal and Marks 1995), were chosen for this study to evaluate the spatiotemporal patterns of built-up land changes: percentage of Landscape (PLAND), Largest Patch Index (LPI), the number of patches (NP), Patch Density (PD), Mean Patch Size (MPS), Landscape Shape Index (LSI), the Clumpiness index (CLUMPY), and the contagion index (CONTAG) (Table 4). The first seven metrics were class-level metrics focusing on characterizing the landscape dynamic changes during the urban expansion while the CONTAG is a landscape-level metric quantifying overall dispersion. These eight metrics were calculated by FRAGSTAS version 4.2 (McGarigal et al. 2002). We further examined the detailed spatial patterns of the landscape at different distance from the city center and in different directions within each city. The place of the municipal government was assumed as the city center. We generated a series of buffer rings with a distance of 5 km from the centers to the edges of each city and used a division at 45 degrees across the city center to divide these cities into eight sectors. Landscape metrics along urban–rural distances and in different directions within each city were then calculated. To avoid redundancy, we only chose PD and PLAND to represent detailed landscape characteristics within the city.

**Table 3.** Summary of accuracy assessment for the classified products using Kappa coefficients.

| | Shanghai | Nanjing | Hangzhou | Suzhou | Wuxi | Ningbo |
|---|---|---|---|---|---|---|
| Prior 2015 | 0.88 | 0.87 | 0.83 | 0.84 | 0.87 | 0.85 |
| 2015 | 0.82 | 0.83 | 0.8 | 0.82 | 0.84 | 0.81 |

### Annual rate of urban growth

Annual increase (AI) and annual growth rate (AGR) of built-up land were calculated to quantify the magnitude of urban expansion. The annual increase is effective to compare the expansion in the same city among different years while the AGR can contribute to compare the different city's expansion. We calculated the two indexes by the following formula:

$$\mathrm{AI} = \frac{A_{end} - A_{start}}{d} \tag{1}$$

$$\mathrm{AGR} = 100\% \times \left( \sqrt[d]{\frac{U_{end}}{U_{start}}} - 1 \right) \tag{2}$$

where AI ($km^2$ per year) and AGR (%) are the annual growth amount and the AGR of built-up land

**Table 4.** The landscape metrics used in this study.

| . | Acronym | Name of landscape metric (units) | Description |
|---|---|---|---|
| Area metrics | PLAND | Percentage of landscape (%) | The percentage of landscape comprised of corresponding land cover type |
| | LPI | Largest patch index (%) | The proportion of total area occupied by the largest patch of a patch type |
| Density metrics | NP | Number of patches | Density metrics |
| Shape metrics | PD | Patch density (Number/100 ha) | Total number of patches for each individual class |
| | MPS | Mean patch size (ha) | The number of patches of per 100 ha |
| | LSI | Landscape shape index | Shape metrics |
| Landscape Dispersibility | CLUMPY | Clumpiness index | Normalized index depicting the deviation from a random distribution; i.e., distinguishing distributions more uniform than random and more aggregated (or clumped) than random |
| | CONTAG | Contagion index (%) | The degree of agglomeration or extension of different patch types |

respectively, $A_{start}$ and $A_{end}$ are the extent of the urban area at the start and end of the period, respectively, and $d$ is the time span of the period in years.

### Analysis of urban growth type

The urban growth types can be divided into infilling, edge-expansion and leapfrogging (Xu et al. 2007; Zhao et al. 2015b). The infilling type is that the newly developed urban patch is surrounded by the existing urban patch or patches. Edge-expansion indicates the newly urban patch expanding from the fringe of the existing patches. Leapfrogging growth type can be described as the newly urban patch spread out isolating from the existing patches. Three urban growth type can be distinguished using the following formula:

$$E = \frac{Lc}{P} \tag{3}$$

Where $Lc$ represents the common border between the existing patches and the newly developed urban patch, $P$ represents the perimeter of a newly developed urban patch. $E = 0$ indicates that no common border between the newly patches and existing urban patches, denoting leapfrogging type of urban expansion. The urban growth type is defined as edge-expansion when $0 < E \leq 0.5$ and infilling when $0.5 < E \leq 1$.

## Results

### Spatiotemporal dynamics of urban extent

All six cities have experienced a rapid urban expansion since the initialization of the reform and opening-up policy in the late 1970s (Figure 2). Specifically, the urban area monotonically increased from 312.44 $km^2$ to 2053.75 $km^2$ for Shanghai, 200.82 $km^2$ to 1673.28 $km^2$ for Nanjing, 72.93 $km^2$ to 1622.33 $km^2$ for Hangzhou, 181.93 $km^2$ to 2193.16 $km^2$ for Suzhou, 147.44 $km^2$ to 1258.59 $km^2$ for Wuxi and 99.14 $km^2$ to 1493.2 $km^2$ for Ningbo, respectively. By 2015, the urban areas of Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo are 6.57, 8.33, 22.24, 12.05, 8.54 and 15.06 times of those in 1980, respectively.

It can be seen from Figures 2 and 3 that Shanghai has shown a full range of urban development, although its initial development focused on the center of the city. During the period 1980–1990, the scope of the center of Shanghai has been significantly expanded. From 1990 to 2000, Shanghai continued to expand rapidly in the suburbs. At the same time, new expansion spots occurred in the eastern of Shanghai. After 2000, a widespread urban expansion was observed in Chongming Island. By 2015, Shanghai, as one of the most important cities in China, possesses a high level of urbanization and the urban construction area basically covers most of the land. Urban development in Nanjing between 1980 and 1995 was mainly concentrated in the old city located in the southern Yangtze River, and an additional amount of urban expansion is mainly concentrated in Jiangning Development Zone and high-tech zones. From 1995 to 2005, Jiangning District began to develop rapidly, and the urban development center gradually moved southward. Rapid urban development appeared in Jiangbei District as well. Since 2005, further urban expansion in Nanjing was generally out of the main urban area. Hangzhou, due to the limitations of the Tianmu mountain and Siming mountain in the south, the city's development mainly concentrated in the northeast of the city. Binjiang District, the old city center in the southeastern Riverside area, began to sprout in 1990, and the development of this old city center has significantly accelerated in 1995–2000, which was eventually connected with the mainly developed urban areas in the north by 2015. Ningbo's urban expansion was constrained by the mountains, showing a strip development pattern. The most rapid development happened during the period 2000–2005, and a lot of the infrastructure and housing construction with multiple growth centers were established since Yinxian was upgraded to be district during 2005–2010. In 1980, township enterprises flourish and terrain restrictions in the southern Jiangsu where Suzhou and Wuxi are located provided an opportunity to develop the city center and the satellite cities simultaneously. Between 1990 and 2000, the city center was developed and the city satellite city developed more rapidly for Suzhou and Wuxi. Between 2005 and 2015, the core and sub-cores developed closely to each other. Consequently, Suzhou and Wuxi showed a multi-core development pattern.

### Spatiotemporal patterns of urban growth

Table 5 lists the annual urban increase amount (AI: $km^2$) and normalized annual urban growth rate (AGR: %) among six neighboring periods between 1980 and 2015 for six cities. For all cities, the AI were the smallest in the early stages of urbanization, while the largest AI occurred after 2000. Specifically, the largest AI for Shanghai, Nanjing, and Hangzhou is in 2005–2010, for Suzhou and Ningbo is in 2000–2005, and for Wuxi is 2010–2015. As the size of city is different, we used the average AGR to eliminate the effect of the city size. The AGR between 1980 and 2015 for Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo is 5.4%, 5.9%, 9.6%, 7.4%, 6.3% and 8.1%, respectively. Hangzhou, with the least initial urbanized land, had the highest AGR for all neighboring periods except 2000–2005. The larger cities were generally associated with lower AGR. However, since 2005, the large cities, such as

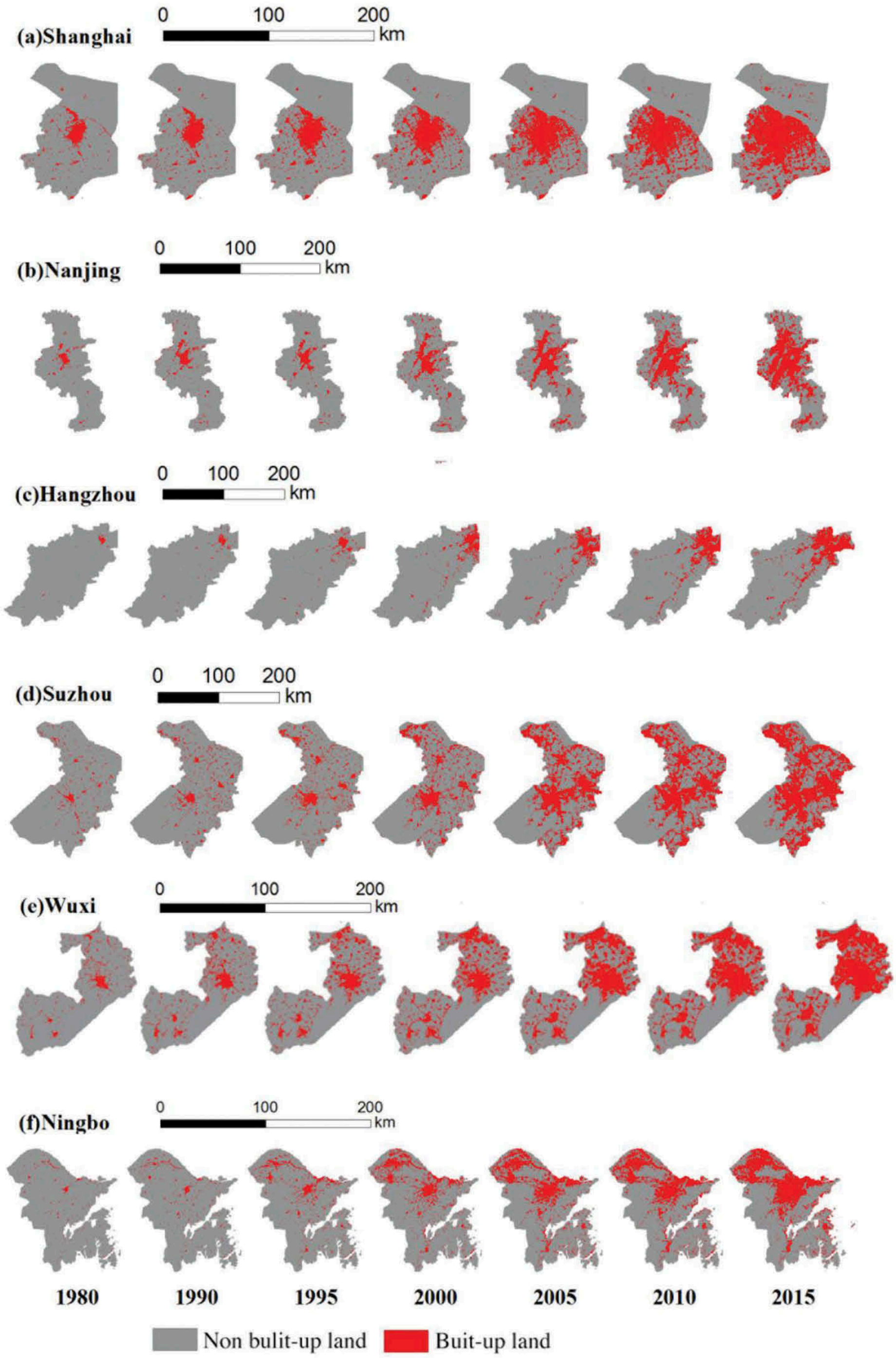


Figure 2. Spatial extent of built-up land for Shanghai (a), Nanjing (b), Hangzhou (c), Suzhou (d), Wuxi (e) and Ningbo (f) from 1980 to 2015.

Shanghai and Nanjing started to have higher AGR than other smaller cities.

Spatial distribution of the three types of urban expansion (infilling, edge-expansion and leapfrogging) were displayed in Figure 4. In Shanghai, leapfrogging growth mainly occurred in the periphery of the center instead of outskirts and edge-expansion growth occurred in the outer ring of the existing urban area for all six periods. The distribution of infilling urban growth varied over time. It infilled the gaps surrounding existing urban patch or patches around the city center in 1995–2000 but filled such gaps in the outer ring of the existing built-up lands or the periphery of the center in 2010–2015. As for Nanjing, the leapfrogging urban growth widely distributed across the city before 2000. The edge-expansion urban growth mainly developed on the outskirts of Nanjing, similar to Shanghai. Since 2000, the edge-expansion and infilling urban growth, as the main expansion types, gathered along the Yangtze River. For Hangzhou, edge-expansion urban growth was the dominant expansion type during all the six periods while the infilling urban growth was sparsely distributed.

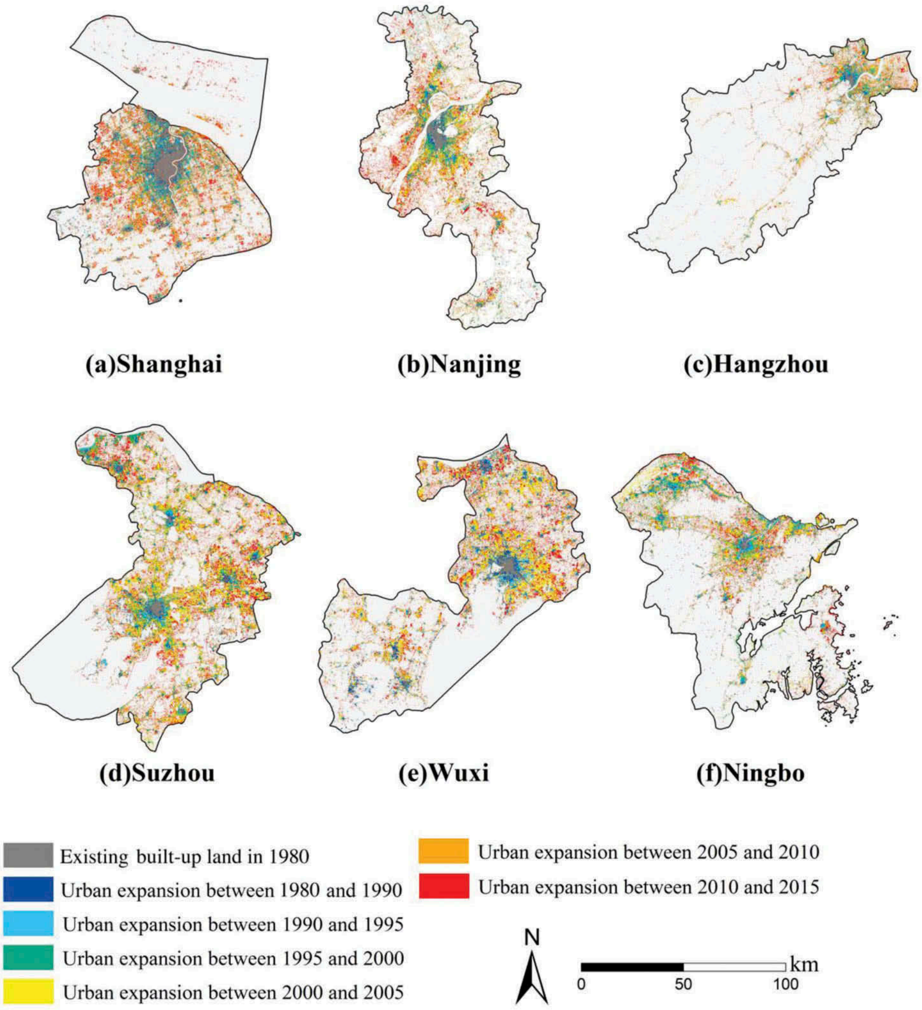


**Figure 3.** Expansion of built-up land in Shanghai (a), Nanjing (b), Hangzhou (c), Suzhou (d), Wuxi (e), and Ningbo (f) from 1980 to 2015.

**Table 5.** Annual increase (AI) in urban area ($km^2$) and normalized annual urban growth rate (AGR) (%) for six cities in YRD among six neighboring periods from 1980 to 2015.

| | City | 1980–1990 | 1990–1995 | 1995–2000 | 2000–2005 | 2005–2010 | 2010–2015 |
|---|---|---|---|---|---|---|---|
| AI ($km^2$) | Shanghai | 16.0 | 41.8 | 54.5 | 80.4 | 118.6 | 36.61 |
| | Nanjing | 5.6 | 9.5 | 25.8 | 11.0 | 73.2 | 46.62 |
| | Hangzhou | 10.3 | 36.3 | 67.2 | 38.1 | 117.3 | 37.78 |
| | Suzhou | 29.65 | 39.76 | 59.72 | 115.29 | 58.46 | 99.37 |
| | Wuxi | 33.26 | 24.42 | 36.47 | 47.93 | 31.47 | 48.67 |
| | Ningbo | 16.01 | 42.92 | 57.58 | 67.09 | 30.65 | 64.58 |
| AGR (%) | Shanghai | 4.22 | 7.36 | 6.61 | 7.02 | 7.59 | 5.53 |
| | Nanjing | 6.97 | 6.11 | 7.39 | 3.13 | 10.62 | 6.24 |
| | Hangzhou | 9.32 | 16.36 | 15.47 | 5.23 | 11.12 | 9.27 |
| | Suzhou | 6.14 | 9.88 | 9.36 | 11.15 | 3.85 | 5.27 |
| | Wuxi | 7.84 | 6.79 | 7.24 | 6.77 | 3.43 | 4.39 |
| | Ningbo | 6.10 | 17.05 | 11.60 | 8.33 | 2.85 | 4.99 |

Spatial distribution of three urban growth types for Suzhou, Wuxi and Ningbo, which all experienced dispersed urban development, presented evident temporal variability with a turning point around 2000. For Suzhou and Wuxi, infilling growth occurred in Township close to the city core and satellite city while edge-expansion and leapfrogging growth reached as far as the whole city and spread throughout the whole city due to the rapid growth of small towns under the impact of Southern Jiangsu developing pattern before 2000. Infilling growth and leapfrogging growth mainly occurred in the corridor between the city core and satellite city to strengthen the link between them afterwards. In contrast, the edge-expansion growth mainly occurred around the city core and satellite city in Ningbo before 2000, and its distribution of edge-expansion and infilling growth had been more extensive, occurring far away from the city core and formed a T-shaped expansion pattern by 2015.

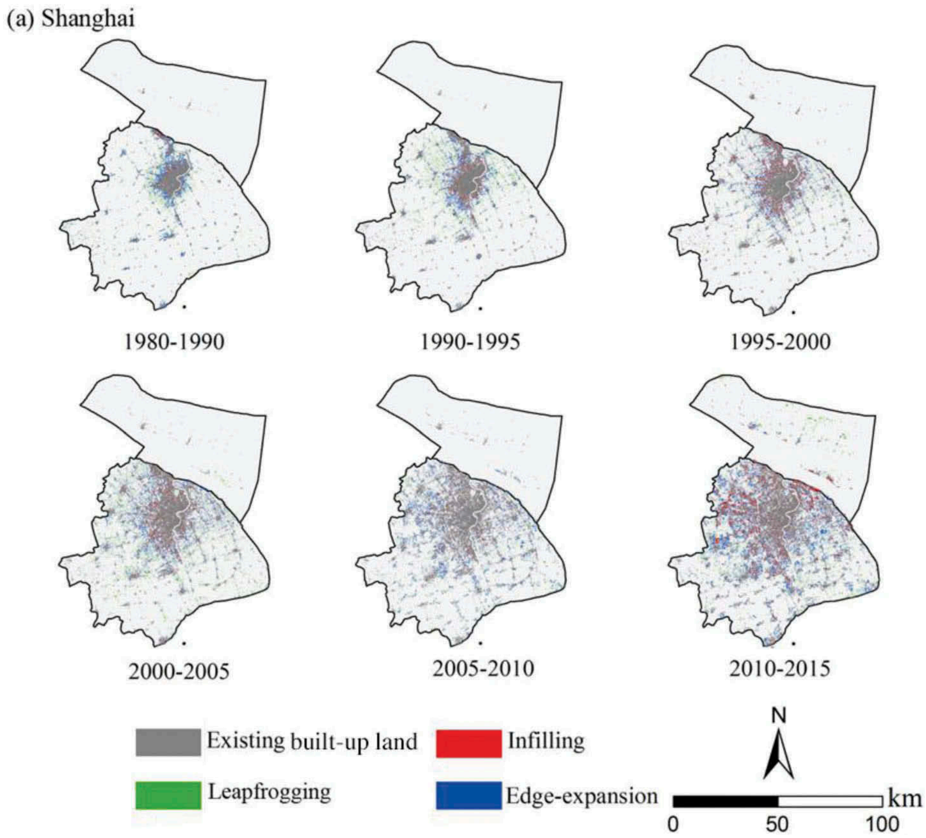


Figure 4. Spatial distributions of three urban expansion types for Shanghai (a), Nanjing (b), Hangzhou (c), Suzhou (d), Wuxi (e) and Ningbo (f) among six neighboring periods from 1980 to 2015.

In addition, these three growth types in Ningbo occurred sparsely in the southern area due to the topographic limitations from southern mountains.

The composition (%) of three urban expansion types varied with city and over time (Figure 5). In terms of area for the newly developed urban patches (Figure 5 (a)), the contribution of edge-expansion was the most for Shanghai, Hangzhou, Suzhou and Ningbo across the entire study period, accounting for 40–70% except the period 1980–1990 for Hangzhou and Ningbo when the leapfrogging type was the main growth type. For Nanjing and Wuxi, leapfrogging contributed the most till 2005, then there was not obvious dominance among three growth types. In terms of the NP (Figure 5(b)), leapfrogging was the most important urban growth types in Nanjing over 35 years and the contribution ceased over time. While edge-expansion contributed most among three growth types across the entire period for Suzhou, and its specific contribution fluctuated over time. For Hangzhou and Ningbo, leapfrogging contributed the most from 1980–1990 to 2000–2005 then the composition of three growth types became relatively stable. Leapfrogging was the most contributor in the early periods and edge-expansion became the most contributor in the late periods for both Shanghai and Wuxi, and the transition time is 2000–2005 and 1995–2000 for Shanghai and Wuxi, respectively.

### *Temporal and spatial changes of landscape metrics*

Figure 6 demonstrates the trends of built-up landscape change for these six cities over the past 35 years. As urbanization proceeded, PLAND and LPI showed a rapid increase among six cities. PLAND in Wuxi, Suzhou and Nanjing had grown more than 20% from 1980 to 2015, while Shanghai, Ningbo and Hangzhou experienced a slight increase. Particularly, the growth of PLAND after 2000 for Suzhou, Wuxi and Nanjing continued to accelerate while the growth trends of Shanghai and Hangzhou were flat. The LSI of all cities increased while the CONTAG decreased and the most dramatic decline was in the city of Suzhou. MPS for these six cities decreased first and increased then, and rebounded afterwards showing a U-shaped curve. PD in Hangzhou and Ningbo are much lower than those of other cities due mainly to the limitation of terrain, which makes the expansion area of the city mainly concentrated in the urban area. While PD declined between 2005 and 2010 for both Shanghai and Nanjing, which may be attributed to the migration of the city’s factories. NP show a consistent trend with PD for above-mentioned four cities. A continuous rise of PLAND, NP and PD was observed in

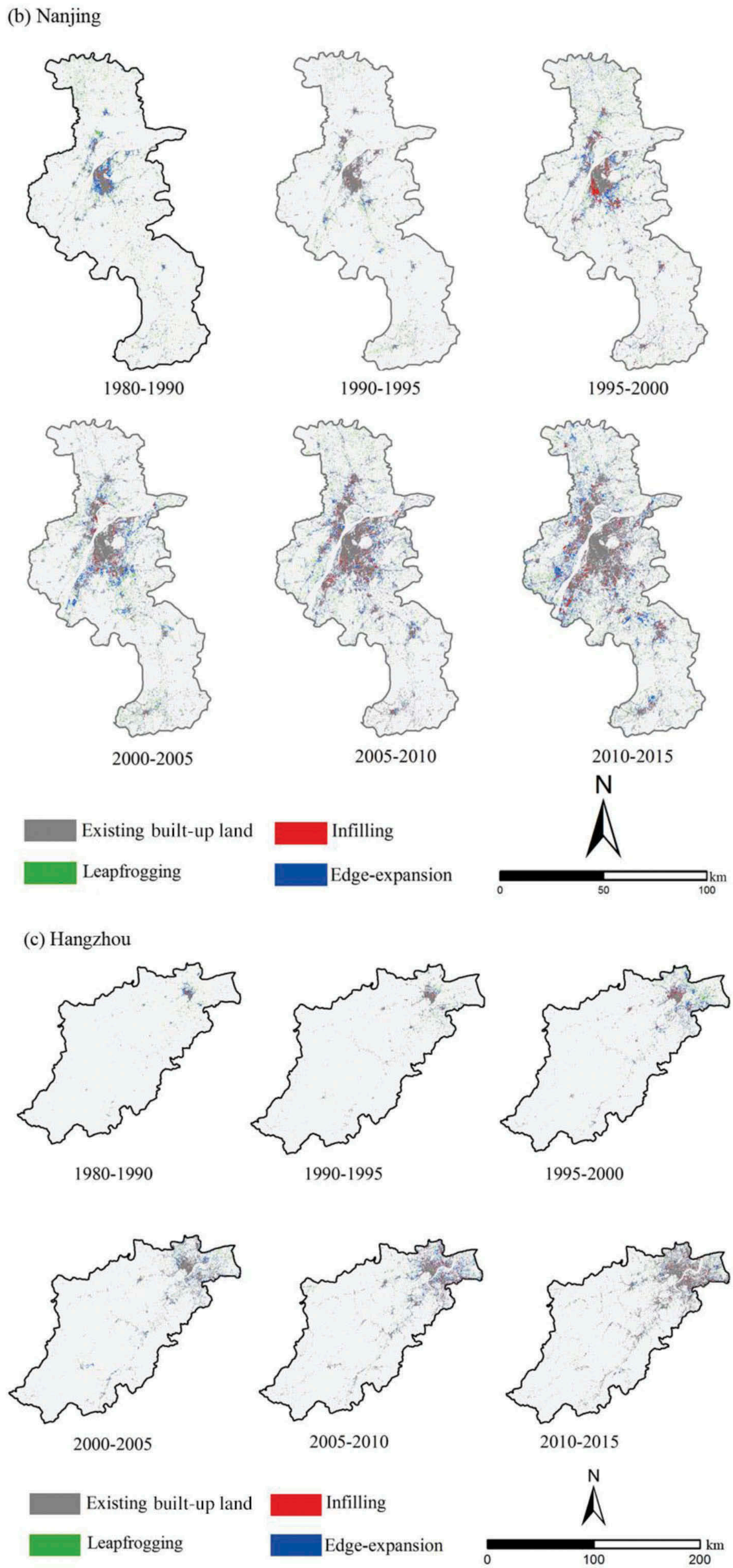


Figure 4. Continued.

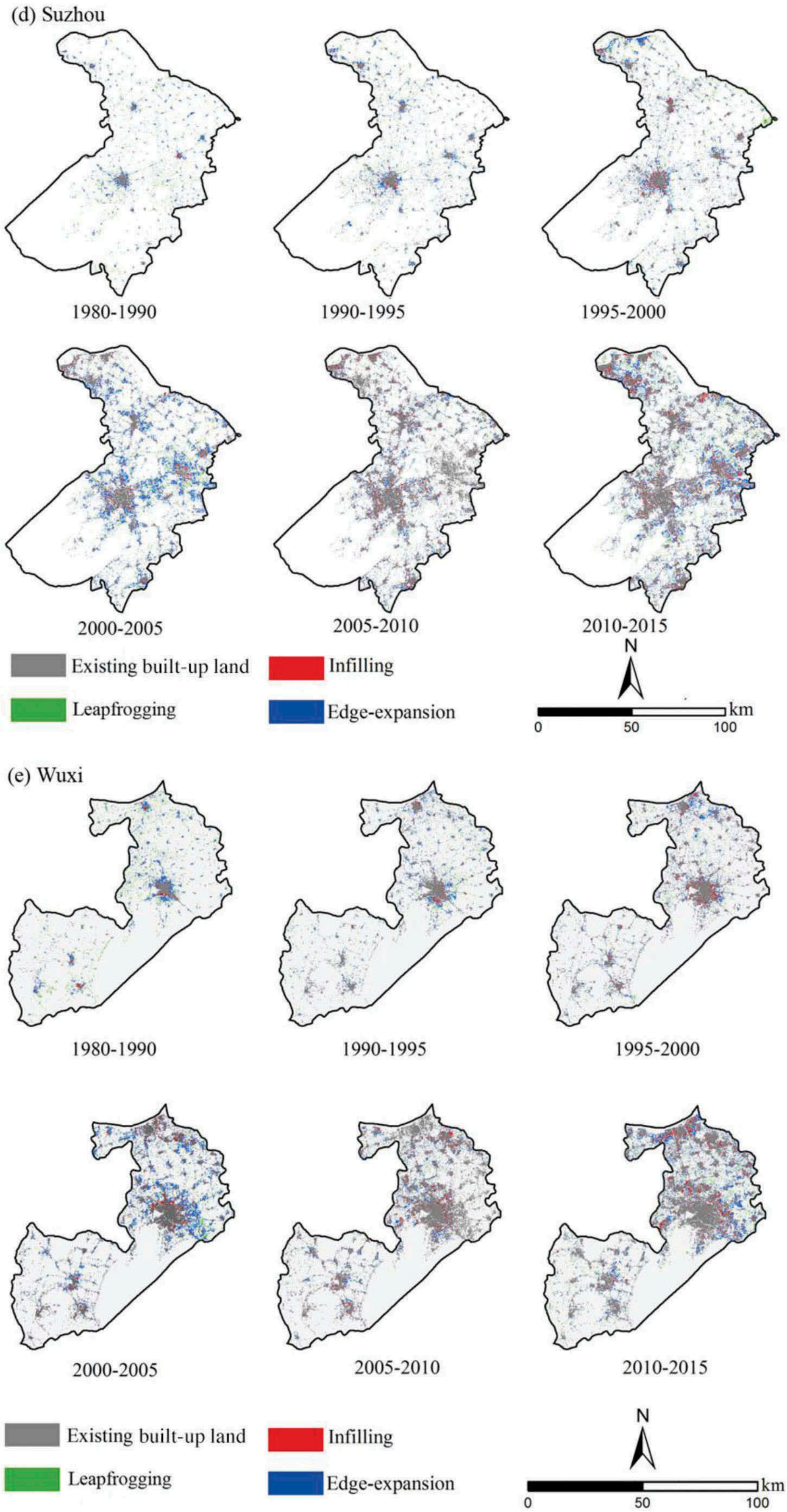


**Figure 4.** Continued.

Suzhou and Wuxi due to the development of satellite towns.

Detailed spatial patterns of built-up landscape can be found within the city (Figures 7 and 8). The location and pattern of city development can be

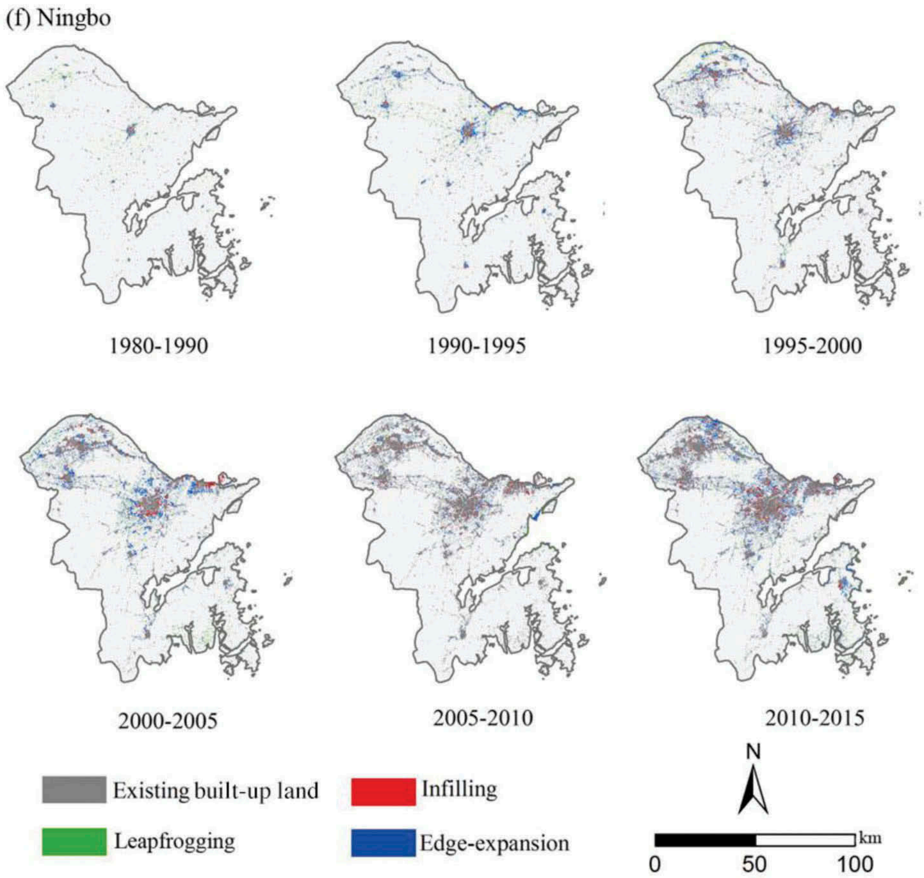


Figure 4. Continued.

tracked by examining the dynamics of PLAND and PD at different distance of the city center (Figure 7). PLAND and PD generally increased over time and the peak location of PD spread to the periphery of the city for six cities. There existed two or more PLAND peaks along the urban–rural transect in Suzhou and Wuxi, presenting dual or multiple cores urban development model. The sub-centers of Suzhou are located at 40 km and 75 km distance from the center, respectively and the sub-center of Wuxi is located at 45 km away from the city center. PLAND in all directions of all six cities increased over time although the magnitude of increase varied with direction. Shanghai was under good development in all directions except the northern direction. Nanjing, located in the plains, had a good performance in all directions. Hangzhou and Ningbo, limited by the existence of the mountains, had a low value of PLAND in the southwest and south. Constrained by Taihu Lake, PLAND of Suzhou and Wuxi in the southwest kept a very low value. As for PD, it showed a pattern similar to PLAND in the directions when PD was relatively small because of less urbanized land in these directions. While the directions in which PD peaks are not consistent with PLAND. The PD changes in all directions were more like concentric rings because of the effect of infilling urban expansion, which increases the area of built-up land but does not change the number of urban patches.

## Discussion

### *Comparison of urban expansion among six cities*

Along with China's rapid economic development and population urbanization, all the six major cities in the YRD urban agglomeration have undergone rapid urbanization since the implementation of the reform and opening-up policy. However, the magnitude, rate and spatiotemporal patterns of urban expansion varied among cities. Shanghai, Nanjing, Hangzhou, Wuxi, Suzhou and Ningbo expanded by 6.6, 8.3, 8.5, 12.1, 15.1 and 22.2 times from 1980 to 2015, respectively. The overall speed of urban expansion for Shanghai and Nanjing, as the most developed cities in the YRD urban agglomeration, was much smaller than that of Hangzhou and Ningbo because the areas of these two cities were 312.4 km$^2$ and 200.8 km$^2$ in 1980, which were much larger than that of Hangzhou (72.9 km$^2$) and Ningbo (99.2 km$^2$). This result conforms to the generally inverse relationship between urban growth rate and city size (i.e., larger cities have lower growth rates) observed from 32 major cities in China over the past three decades (Zhao et al. 2015a).

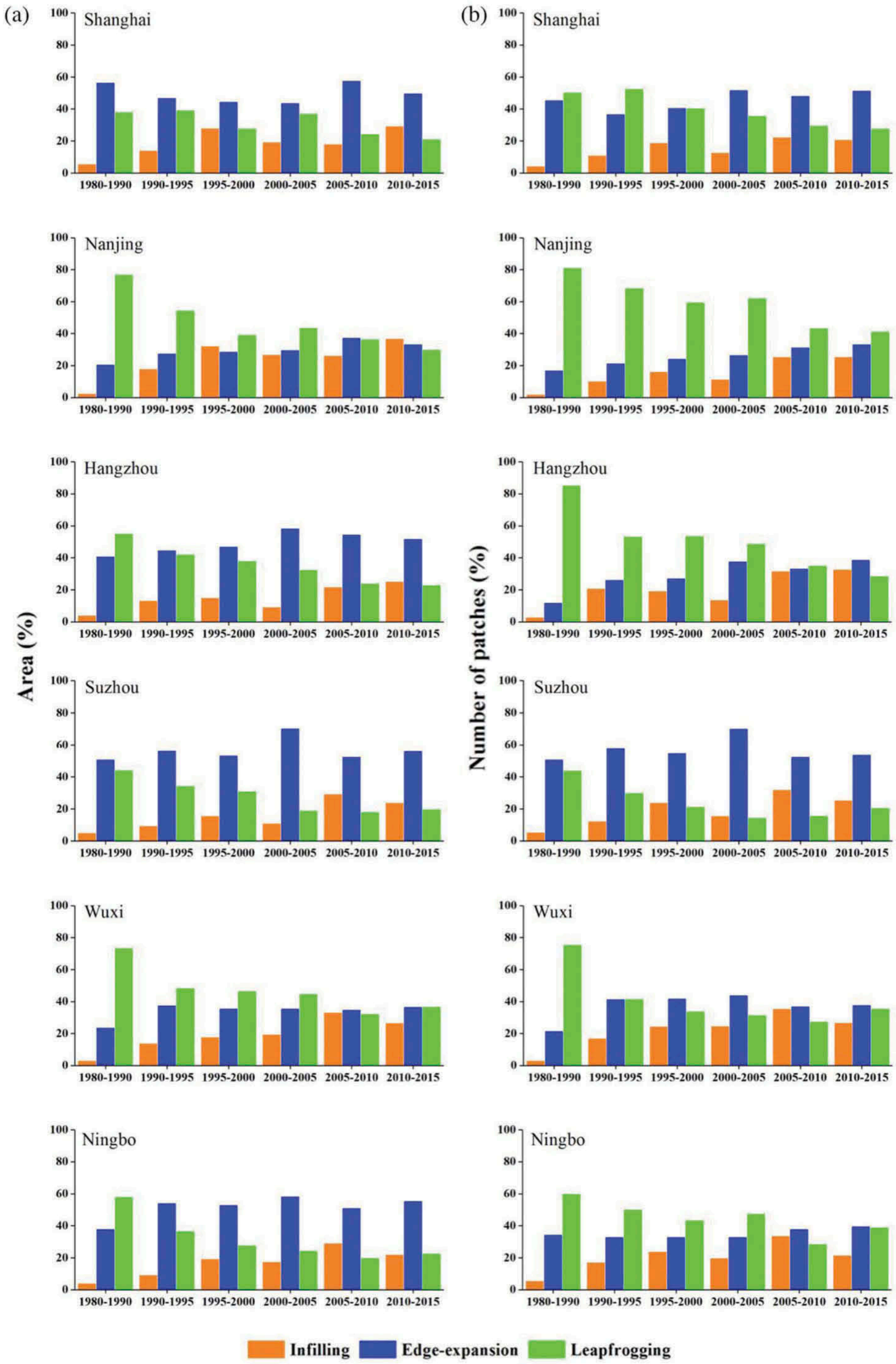


Figure 5. The composition (%) of three urban expansion types for the number of patches (a) and area (b) of newly developed built-up land in Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo among six neighboring periods from 1980 to 2015.

It should be noted that the presented results of expanding areas of the cities usually vary from one report to another due primarily to the discrepancies in the definition of urban area, data sources and methods. Our study area for each city is its administrative boundary, which includes both urban and rural built environment within the boundary, therefore, the area of built-up land in our study is larger than the previous studies that usually focus on the central/main urban area of the city (e.g., Yang, Zha, and Gao 2001; Xu et al. 2007; Chen, Gao, and Yuan 2016a; Chen Gao, Yuan and Wei 2016b) but comparable with the results with the same city boundary definition (Chen, Gao, and Chen 2016c). The distribution of the three urban expansion types is broadly consistent spatially with the results from existing studies covering certain overlapping period with this study (Tian et al. 2011; Gao et al. 2015).

Topography has a significant influence on urban expansion as urban settlements are easier to be built on flat lands (Bengston, Fletcher, and Nelson 2004; Yue, Liu, and Fan 2013; Sun et al. 2013). And water

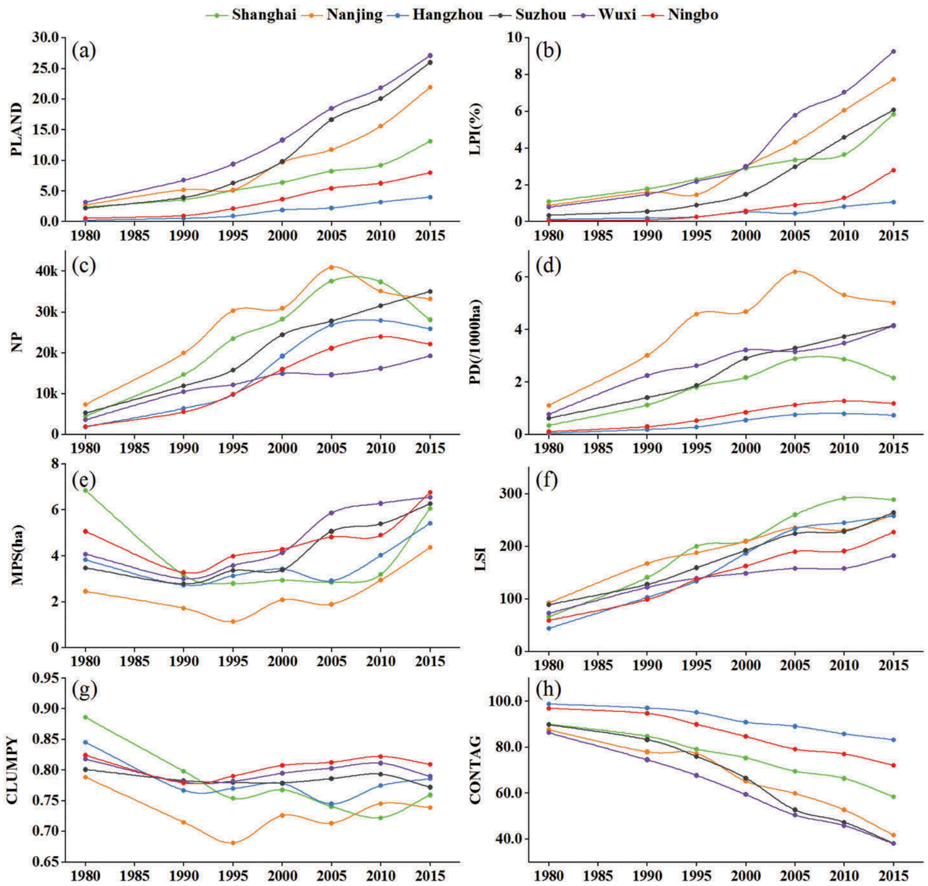


Figure 6. Temporal changes of landscape metrics for the built-up land in Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo from 1980 to 2015: (a) PLAND (%), (b) LPI (%), (c) NP, (d) PD (per 100 ha), (e) MPS (ha), (f) LSI, (g) CLUMPY and (h) CONTAG.

supply and the land provisions, which can be limited by topography at the city level (Li, Zhou, and Ouyang 2013), are the basic conditions for urban development. The expansion of these six cities displayed clear footprints of topographic constraints in the directions and the modes (Figures 2 and 3). Shanghai expanded in all directions because it is located in the Middle and Lower Yangtze Valley Plain. As for Nanjing, the main urban expansion took place on both sides of the Yangtze River, presenting a strip development pattern. Urban expansion developed slowly in the north and south of Nanjing where the city center is far away from. Hangzhou's expansion mainly concentrated in the northeast and formed a strip development along the mountains owing to the limitations of the southwestern mountains and Qiantang River. Urban expansion in Ningbo primarily distributed in the north as a result of the constraints from the southern mountains. The development of urban space in Suzhou and Wuxi was constrained by the existence of Taihu Lake. The number of small cities and towns in Suzhou and Wuxi was much larger than that of other cities due to the rampant development of towns in the Southern Jiangsu, namely the Southern Jiangsu model (Li, and Sun 2013). Under such model, when the expansion of central city tends to saturate, the secondary center and even the third center began to expand rapidly, leading to the built-up land of Suzhou reached 2193.2 $km^2$ in 2015, which is comparable to that of Shanghai.

Urban planning and policy plays a vital role in driving the growth of the urban for all six cities during our study period because it would drive the flow of capital and population into the region and has consequently stimulated urban expansion, similar to the findings from urban expansion studies in Los Angeles (Aguayo et al. 2007), the JJJ urban agglomeration (Wu et al. 2015), and the Treasure Valley of Idaho in USA (Dahal, Benner, and Lindquist 2017). Infilling growth occurred mainly around the main center of city in Shanghai before 1995 because the government began construction of residential villages in the city center and the central city fringe to ease the crowds of public housing and to speed up the transformation of old houses in 1980–1990. The State Council proposed the strategy of "Developing the Pudong" in 1990 and the Pudong New Area was established in 1992. The large-scale centralized industrial park and functional area began to appear in

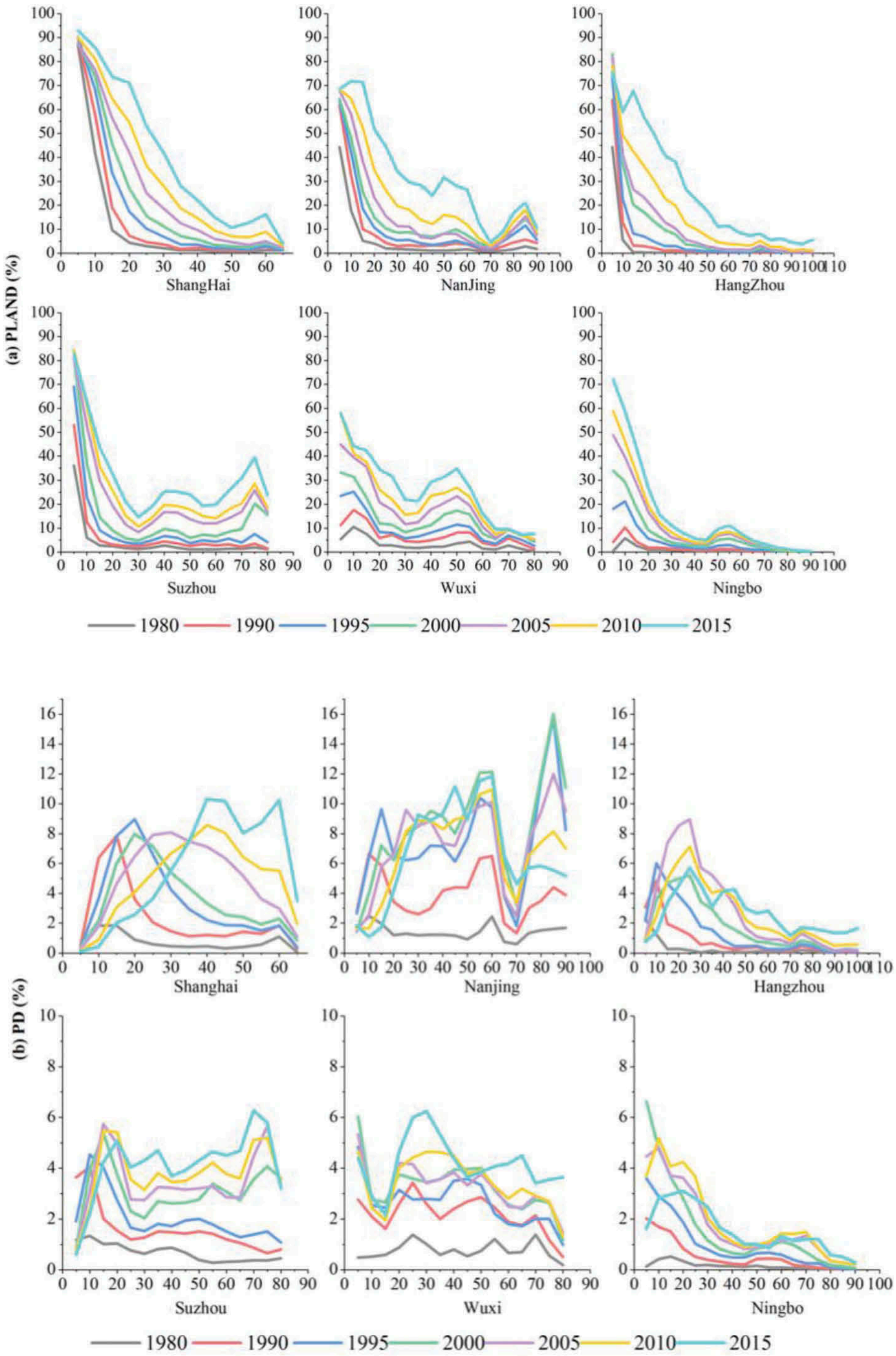


**Figure 7.** Landscape metrics for the built-up land of Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo at different distances (km) from the city center between 1980 and 2015: (a) PLAND (per 100 ha) and (b) PD (%).

Pudong around 1990. It is worth mentioning that the leapfrogging growth occurred in Chongming Island was related to the implementation of the police "Establishment of Chongming District with Revocation of Counties" in 2016. Urban Master Plan of Nanjing (1991–2010) envisioned the strips along the both sides of the Yangtze River as the main development axes, and the south of city center along the traffic trunk as a secondary development axis. Matching with the Urban Master Plan, the expansion of Nanjing mainly concentrated in the both sides of the Yangtze River and the southern part of the main city during 1990–2010. Urban expansion of Hangzhou spread along the Qiantang River but rather limited in the vicinity of the main center located in the north side of Qiantang River, which can be attributed to the adjustment of the direction of urban development proposed by Urban Master Plan of Hangzhou (2001–2010). The distribution of the three urban growth types of Hangzhou can be divided into two stages due to the change of urban planning. Infilling growth and edge-expansion growth mainly concentrated in the northern bank of Qiantang River during 1980–1995, while leapfrogging

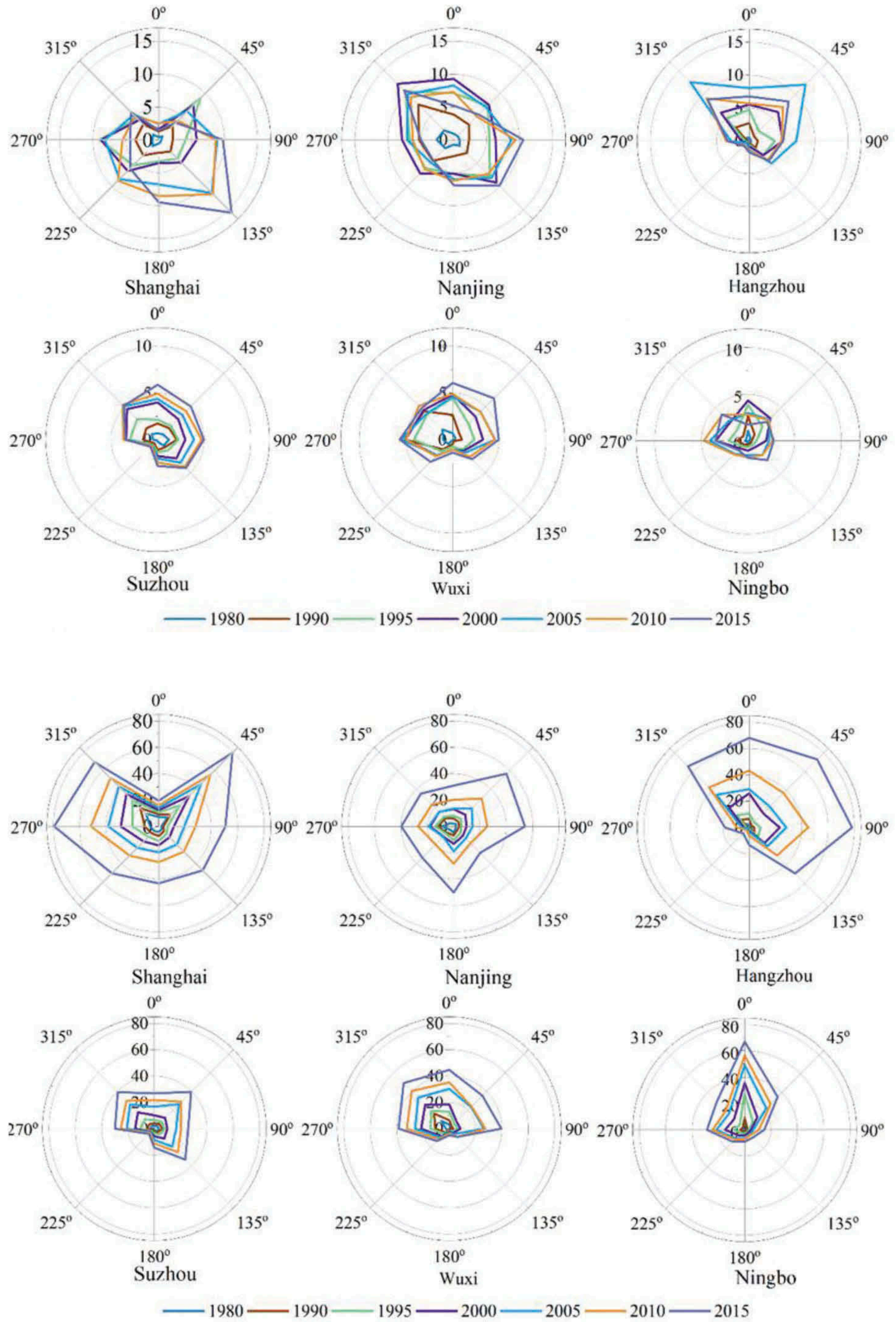


**Figure 8.** Landscape metrics for the built-up land of Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo in different directions between 1980 and 2015: (a) PLAND (per 100 ha) and (b) PD (%).

growth was more extensive, occurring in the Sandun, Changhe, and Economic and Technological Development Zones away from the center (Yue, Liu, and Fan 2013). In the later stage, infilling growth and edge-expansion growth appeared in the south bank of Qiantang River from 1995 to 2000, which can be attributed to the constructions of a large number of infrastructure, housing and factories. During 2000–2015, infilling growth and edge-expansion growth appeared in the whole city, and leapfrogging growth and edge-expansion growth formed a zonal distribution along the mountains in the southwestern area. Urban Master Plan of Suzhou (2004–2020) and Ningbo (2006–2020) emphasized the importance of the links between the old city center and new cores, leading to a shift of urban expansion direction and traffic constructions like highways and rail traffic. As a result, a T-shaped urban expansion pattern was formed since 2010 for both cities. Urban Master Plan of Wuxi (2001–2010) proposed the strategy of "spanning to the south" to promote the development of Lake City and strengthen the contact with Jiangyin, resulting in a wide range of edge-expansion growth in the north of main city. In summary, topography constrained the location and type of urban expansion while the policy drove the direction of urban expansion and affected the pattern of urban expansion. Their specific effects varied with city and time.

### Test of the urban growth theory

The diffusion-coalescence urban growth theory proposed that urbanization process starts with the expansion of an urban core. As the urban core grows, more urban seeds will disperse to new growth centers. While urban development furthers, the process will be along with growth from the fringe of the existing urban areas and infilling of the gaps within them. Therefore, urbanization process is generally characterized as a temporal oscillation between two alternate phases of diffusion and coalescence (Dietzel et al. 2005a; Dietzel et al. 2005b). This theory can be tested by temporal dynamics of landscape metrics and urban growth type. The first stage (dispersed) described the phenomenon that the built-up areas spread to new development centers associated with an increase in both NP and PD, and the leapfrogging accounted for the most in the composition of three urban growth types (i.e., infilling, edge-expansion and leapfrogging). While the latter stage (compact) with the opposite phenomenon was believed to create smaller ecological footprint due to economic use of land and a series of energy conservation (Wu et al. 2015).

The performance of the cities in this study was not all consistent and there existed some discrepancies with this theory. NP and PD of Shanghai, Nanjing and Hangzhou peaked near 2005 when the proportion of leapfrogging urban growth type began to decrease, which separating their urbanization processes into diffusion phase before and coalescence phase after, roughly consistent with this theory. The existing studies on urban expansion in Nanjing roughly supported the diffusion-coalescence urban growth theory as well (Xu et al. 2007; Zhao, Zhu, and Zhao 2014). We have not observed an arrival of coalescence stage for Suzhou and Wuxi as NP and PD continued to increase across the entire study period. As for Ningbo, there was neither a typical diffusion phase nor a coalescence phase after 1990, which might indicate that its urbanization process stayed in the transition phase from diffusion to coalescence.

Following reasons might explain the differences among these cities in testing for the presence the urban growth diffusion-coalescence theory. First, the discrepancies might be attributed to the difference in the form of urban development. The diffusion-coalescence theory was more suitable for highly spatial compact city because the dispersed and isolated area, such as the scattered towns in the exurb would weaken the influence of infilling growth, which would affect the process of coalescence (Sun et al. 2013; Zhao, Zhu, and Zhao 2014). We found that the urban areas in Shanghai, Nanjing and Hangzhou were more agglomerated in space than that of Suzhou, Wuxi and Ningbo which have more than a single development core, as a result, the urbanization processes in Shanghai, Nanjing and Hangzhou generally followed the diffusion-coalescence theory. Second, topography factors, such as mountains and lakes tend to facilitate discrete urban expansion and thus constrained the development of coalescence phase, which could explain why there were no evidences showing the arrival of coalescence phase in Suzhou and Wuxi. Third, the time span may play an important role in the process of urban development. The entire study period for this study was only 35 years, which might not be long enough to reflect the whole diffusion-coalescence process. Suzhou, Wuxi and Ningbo is either in the phase of diffusion or in the transition phase from diffusion to coalescence and would finally develop into the coalescence phase.

## Conclusions

China has been experiencing dramatic urbanization in parallel with its economic boom over the past three to four decades. The YRD, as the most important engine in the Chinese economy, has pioneered in the rapid urbanization road of China since the late 1970s. However, cross-city spatially explicit comparative studies on the magnitude, form and spatial structure of urban expansion for the major cities of the YRD urban agglomeration across a relatively long timeframe is still lacking.

In this study, we quantified and compared the spatiotemporal patterns of urban expansion in Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo in the YRD urban agglomeration over the past 35 years. Results showed that all six major cities in the YRD urban agglomeration have experienced rapid urbanization between 1980 and 2015. Nevertheless, the magnitude, rate, and spatiotemporal patterns of urban expansion varied among cities. The area of built-up land monotonically increased, with an AGR of 5.4%, 5.9%, 9.6%, 7.4%, 6.3% and 8.1% from 1980 to 2015 for Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi and Ningbo, respectively. The composition of urban growth types (infilling, edge-expansion and leapfrogging) and trajectories of urban expansion reflected the constraints from topography, and the effects of urban planning and policy, which varied across cities and over time. The urbanization process in Shanghai, Nanjing and Hangzhou with compact development model generally supported the diffusion-coalescence urban growth theory whereas there did not exist a temporal oscillation phases of diffusion and coalescence across the entire study period for Suzhou, Wuxi and Nanning, which possessed a more dispersive development model, suggesting the diffusion-coalescence theory might be more suitable for the relatively compact cities. More work across multiple cities and regions with different history, different developing level and various physical, social, economic and institutional contexts is needed to test the applicability of the theory, and then contribute to advance the general urbanization theories that can be adopted to support a sustainable urban future.

## Acknowledgments

This study was supported by the National Natural Science Foundation of China Grants 41771093, 41571079, and 41590843. We acknowledge Dr. Yan Sun for her comments and suggestions on an earlier version of the manuscript.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This study was supported by the National Natural Science Foundation of China Grants 41771093, 41571079, and 41590843.

## References

Aguayo, M. I., T. Wiegand, G. D. Azócar, K. Wiegand, and C. E. Vega. 2007. "Revealing the Driving Forces of Mid-Cities Urban Growth Patterns Using Spatial Modeling: A Case Study of Los Ángeles, Chile." *Ecology & Society* 12: 181–194. doi:10.5751/ES-01970-120113.

Alqurashi, A., L. Kumar, and K. Alghamdi. 2016. "Spatiotemporal Modeling of Urban Growth Predictions Based on Driving Force Factors in Five Saudi Arabian Cities." *ISPRS International Journal of Geo-Information* 5: 139. doi:10.3390/ijgi5080139.

Bengston, D. N., J. O. Fletcher, and K. C. Nelson. 2004. "Public Policies for Managing Urban Growth and Protecting Open Space: Policy Instruments and Lessons Learned in the United States." *Landscape & Urban Planning* 69: 271–286. doi:10.1016/j.landurbplan.2003.08.007.

Bloom, D. E., D. Canning, and G. Fink. 2008. "Urbanization and the Wealth of Nations." *Science* 319: 772. doi:10.1126/science.1153057.

Burgess, E. W. 2008. "The Growth of the City: An Introduction to a Research Project." *Urban Ecology* 18: 71–78.

Chen, J., J. Gao, and W. Chen. 2016c. "Urban Land Expansion and the Transitional Mechanisms in Nanjing, China." *Habitat International* 53: 274–283. doi:10.1016/j.habitatint.2015.11.040.

Chen, J., J. Gao, and F. Yuan. 2016a. "Growth Type and Functional Trajectories: An Empirical Study of Urban Expansion in Nanjing, China." *Plos One* 11: e0148389. doi:10.1371/journal.pone.0148389.

Chen, J., J. Gao, F. Yuan, and Y. D. Wei. 2016b. "Spatial Determinants of Urban Land Expansion in Globalizing Nanjing, China." *Sustainability* 8: 868. doi:10.3390/su8090868.

Chen, S. S., Y. Yan, Q. Gao, and D. Liu. 2015. "Quantifying Circular Urban Expansion Patterns of Compact Chinese Cities: The Case of Yangtze River Delta, China." *Environment & Planning B Planning & Design* 42: 279–299. doi:10.1068/b120004p.

Chen, Y., X. Li, X. Liu, B. Ai, and S. Li. 2016d. "Capturing the Varying Effects of Driving Forces over Time for the Simulation of Urban Growth by Using Survival Analysis and Cellular Automata." *Landscape & Urban Planning* 152: 59–71. doi:10.1016/j.landurbplan.2016.03.011.

Dahal, K. R., S. Benner, and E. Lindquist. 2017. "Urban Hypotheses and Spatiotemporal Characterization of Urban Growth in the Treasure Valley of Idaho, USA." *Applied Geography* 79: 11–25. doi:10.1016/j.apgeog.2016.12.002.

Dietzel, C., M. Herold, J. J. Hemphill, and K. Clarke. 2005a. "Spatio-Temporal Dynamics in California's Central Valley: Empirical Links to Urban Theory." *International Journal of Geographical Information Science* 19: 175–195. doi:10.1080/13658810410001713407.

Dietzel, C., H. Oguz, J. J. Hemphill, K. Clarke, and N. Gazulis. 2005b. "Diffusion and Coalescence of the Houston Metropolitan Area: Evidence Supporting a New Urban Theory." *Environment and Planning B: Planning and Design* 32: 231–246. doi:10.1068/b31148.

Foody, G. M. 2002. "Status of Land Cover Classification Accuracy Assessment." *Remote Sensing of Environment* 80: 185–201. doi:10.1016/S0034-4257(01)00295-4.

Fragkias, M., and K. C. Seto. 2009. "Evolving Rank-Size Distributions of Intra-Metropolitan Urban Clusters in South China." *Computers Environment & Urban Systems* 33: 189–199. doi:10.1016/j.compenvurbsys.2008.08.005.

Gao, J. 2015. "Urban Land Expansion and Structural Change in the Yangtze River Delta, China." *Sustainability* 7: 10281–10307. doi:10.3390/su70810281.

Gao, J., H. Tian, K. Cheng, L. Lu, M. Zheng, S. Wang, J. Hao, K. Wang, S. Hua, and C. Zhu. 2015. "The Variation of Chemical Characteristics of PM 2.5 And PM 10 and Formation Causes during Two Haze Pollution Events in Urban Beijing, China." *Atmospheric Environment* 107: 1–8. doi:10.1016/j.atmosenv.2015.02.022.

Gottmann, J. 1957. "Megalopolis or the Urbanization of the Northeastern Seaboard." *Economic Geography* 33: 189–200. doi:10.2307/142307.

Herold, M. 2005. "Spatio-Temporal Dynamics in California's Central Valley: Empirical Links to Urban Theory." *International Journal of Geographical Information Science* 19: 175–195. doi:10.1080/13658810410001713407.

Herold, M., J. Scepan, and K. Clarke. 2002. "The Use of Remote Sensing and Landscape Metrics to Describe Structures and Changes in Urban Land Uses." *Environment and Planning A* 34: 1443–1458. doi:10.1068/a3496.

Hobbie, S. E., L. A. Baker, C. Buyarski, D. Nidzgorski, and J. C. Finlay. 2014. "Decomposition of Tree Leaf Litter on Pavement: Implications for Urban Water Quality." *Urban Ecosystems* 17: 369–385. doi:10.1007/s11252-013-0329-9.

IPCC. 2014. "Climate Change 2014: Mitigation of Climate Change." In *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jenerette, G. D., and D. Potere. 2010. "Global Analysis and Simulation of Land-Use Change Associated with Urbanization." *Landscape Ecology* 25: 657–670. doi:10.1007/s10980-010-9457-2.

Jun, L. I., M. A. Teng, M. Chen, Z. Y. Zhang, and H. Liu. 2017. "The Urban Expansion and Its Driving Forces Based on Remote Sensing Imagery of Wuhan City from 2003 to 2015." *Geomatics & Spatial Information Technology* 40 (4): 7–11.

Juval, P. P. D. 2000. *Self-Organization and the City*. 5 (2): 495–510.

Li, P., and W. Sun. 2013. "Pattern and Driving Mechanisms of Urban Expansion of Southern Jiangsu Province since Reform and Opening Up." *Resources & Environment in the Yangtze Basin* 22: 1529–1536.

Li, X., W. Zhou, and Z. Ouyang. 2013. "Forty Years of Urban Expansion in Beijing: What Is the Relative Importance of Physical, Socioeconomic." *And Neighborhood Factors? Applied Geography* 38: 1–10. doi:10.1016/j.apgeog.2012.11.004.

Liu, J., J. Zhan, and X. Deng. 2005. "Spatio-Temporal Patterns and Driving Forces of Urban Land Expansion in China during the Economic Reform Era." *AMBIO: A Journal of the Human Environment* 34: 450–455. doi:10.1579/0044-7447-34.6.450.

Liu, X. P., L. Xia, Y. M. Chen, Z. Z. Tan, S. Y. Li, and B. Ai. 2010. "A New Landscape Index for Quantifying Urban Expansion Using Multi-Temporal Remotely Sensed Data." *Landscape Ecology* 25: 671–682. doi:10.1007/s10980-010-9454-5.

Luo, J., and Y. H. D. Wei. 2009. "Modeling Spatial Variations of Urban Growth Patterns in Chinese Cities: The Case of Nanjing." *Landscape & Urban Planning* 91: 51–64. doi:10.1016/j.landurbplan.2008.11.010.

Martellozzo, F., and K. C. Clarke. 2011. "Measuring Urban Sprawl, Coalescence, and Dispersal: A Case Study of Pordenone, Italy." *Environment and Planning B: Planning and Design* 38: 1085–1104. doi:10.1068/b36090.

Mashagbah, A., and F. Atef. 2016. "The Use of GIS, Remote Sensing and Shannon's Entropy Statistical Techniques to Analyze and Monitor the Spatial and Temporal Patterns of Urbanization and Sprawl in Zarqa City, Jordan." *Journal of Geographic Information System* 8: 293–300. doi:10.4236/jgis.2016.82025.

McGarigal, K., and B. J. Marks. 1995. "FRAGSTATS—Spatial Pattern Analysis Program for Quantifying Landscape Structure." *U. S. Forest Service General Technical Report Pnw 351(1995).*

McGarigal, K. S., S. Cushman, M. Neel, and E. Ene. 2002. *FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps*. Computer software program produced by the authors at the University of Massachusetts, Amherst. Accessed 30 Mar 2009.

Meehl, G. A., and C. Tebaldi. 2004. "More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century." *Science* 305: 994. doi:10.1126/science.1098704.

Michishita, R., Z. Jiang, and B. Xu. 2012. "Monitoring Two Decades of Urbanization in the Poyang Lake Area, China through Spectral Unmixing." *Remote Sensing of Environment* 117: 3–18. doi:10.1016/j.rse.2011.06.021.

Roefs, I., B. Meulman, J. H. Vreeburg, and M. Spiller. 2017. "Centralised, Decentralised or Hybrid Sanitation Systems? Economic Evaluation under Urban Development Uncertainty and Phased Expansion." *Water Research* 109: 274–286. doi:10.1016/j.watres.2016.11.051.

Schneider, A., M. Friedl, and D. Potere. 2009. "A New Map of Global Urban Extent from MODIS Satellite Data." *Environmental Research Letters* 4: 044003. doi:10.1088/1748-9326/4/4/044003.

Schneider, A., K. C. Seto, and D. R. Webster. 2008. "Urban Growth in Chengdu, Western China: Application of Remote Sensing to Assess Planning and Policy Outcomes." *Environment & Planning B Planning & Design* 32: 323–345. doi:10.1068/b31142.

State Statistical Bureau (SSB). 2015. *China City Statistical Yearbook*. Beijing: China Statistics Press. in Chinese.

Sun, C., Z. F. Wu, Z. Q. Lv, N. Yao, and J. B. Wei. 2013. "Quantifying Different Types of Urban Growth and the Change Dynamic in Guangzhou Using Multi-Temporal Remote Sensing Data." *International Journal of Applied Earth Observation & Geoinformation* 21: 409–417. doi:10.1016/j.jag.2011.12.012.

Tian, G., J. Jiang, Z. Yang, and Y. Zhang. 2011. "The Urban Growth, Size Distribution and Spatio-Temporal Dynamic Pattern of the Yangtze River Delta Megalopolitan Region, China." *Ecological Modelling* 222: 865–878. doi:10.1016/j.ecolmodel.2010.09.036.

United Nations, Department of Economic, and Social Affairs, Population Division. 2016. *World Urbanization Prospects: The 2015 Revision*. New York: United Nations.

Wang, B., W. Liu, and L. U. Dadao. 2011. "Allocation Efficiency of Science and Technology Resources in Jing-Jin-Ji,Yangtze River Delta and Pearl River Delta Regions." *Progress in Geography* 30: 1233–1239.

Wu, W., S. Zhao, C. Zhu, and J. Jiang. 2015. "A Comparative Study of Urban Expansion in Beijing, Tianjin and Shijiazhuang over the past Three Decades." *Landscape and Urban Planning* 134: 93–106. doi:10.1016/j.landurbplan.2014.10.010.

Xu, C., M. Liu, C. Zhang, S. An, W. Yu, and J. M. Chen. 2007. "The Spatiotemporal Dynamics of Rapid Urban Growth in the Nanjing Metropolitan Region of China." *Landscape Ecology* 22: 925–937. doi:10.1007/s10980-007-9079-5.

Yan, Y., X. Jia, S. Peng, and W. U. Gang. 2017. "Water Environmental Impact Assessment of Urban Development Based on Water Degradation Footprint: A Case Study of Beijing." *Acta Scientiae Circumstantiae* 37: 779–785.

Yang, S., Y. Zha, and J. Gao. 2001. "Applications of Remote Sensing and GIS to Monitoring of Urban Sprawl: A Case Study in Wuxi City, China." *Geographic Information Sciences* 7: 137–141.

Yu, X. J., and C. N. Ng. 2007. "Spatial and Temporal Dynamics of Urban Sprawl along Two Urban–Rural Transects: A Case Study of Guangzhou, China." *Landscape & Urban Planning* 79: 96–109. doi:10.1016/j.landurbplan.2006.03.008.

Yue, W., P. Fan, Y. D. Wei, and J. Qi. 2014. "Economic Development, Urban Expansion, and Sustainable Development in Shanghai." *Stochastic Environmental Research and Risk Assessment* 28: 783–799. doi:10.1007/s00477-012-0623-8.

Yue, W., Y. Liu, and P. Fan. 2013. "Measuring Urban Sprawl and Its Drivers in Large Chinese Cities: The

Case of Hangzhou." *Land Use Policy* 31: 358–370. doi:10.1016/j.landusepol.2012.07.018.

Zhang, H., M. Uwasu, K. Hara, and H. Yabar. 2011. "Sustainable Urban Development and Land Use Change—A Case Study of the Yangtze River Delta in China." *Sustainability* 3: 1074–1089. doi:10.3390/su2071074.

Zhao, J., C. Zhu, and S. Zhao. 2014. "Comparing the Spatiotemporal Dynamics of Urbanization in Moderately Developed Chinese Cities over the past Three Decades: Case of Nanjing and Xi'an." *Journal of Urban Planning and Development*. doi:10.1061/(ASCE).

Zhao, S., D. Zhou, C. Zhu, W. Qu, J. Zhao, Y. Sun, D. Huang, W. Wu, and S. Liu. 2015a. "Rates and Patterns of Urban Expansion in China's 32 Major Cities over the past Three Decades." *Landscape Ecology* 30: 1541–1559. doi:10.1007/s10980-015-0211-7.

Zhao, S., D. Zhou, C. Zhu, Y. Sun, W. Wu, and S. Liu. 2015b. "Spatial and Temporal Dimensions of Urban Expansion in China." *Environmental Science & Technology* 49: 9600–9609. doi:10.1021/acs.est.5b00065.

Zhou, Q., M. Wang, Q. Zhang, and R. Wang. 2011. "[Ecological Effects of Land-Use Changes in a Small Town of Zhejiang Province, China]." *Chinese Journal of Soil Science* 16: 651.

Zhu, M., J. Xu, N. Jiang, J. Li, and Y. Fan. 2006. "Impacts of Road Corridors on Urban Landscape Pattern: A Gradient Analysis with Changing Grain Size in Shanghai, China." *Landscape Ecology* 21: 723–734. doi:10.1007/s10980-005-5323-z.