Case Study

Comparing the Spatiotemporal Dynamics of Urbanization in Moderately Developed Chinese Cities over the Past Three Decades: Case of Nanjing and Xi'an

Jiajia Zhao[1]; Chao Zhu[2]; and Shuqing Zhao[3]

Abstract: Urbanization has substantially altered the landscape throughout the world, and most previous studies have concentrated in areas with fast urbanization. Urbanization with moderate rates has received relatively less attention. Here, the urban patterns and dynamics in two moderately developed Chinese cities (i.e., Nanjing and Xi'an) are analyzed and compared using multitemporal Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) images of circa 1980, 1985, 1990, 1995, 2000, 2005, and 2010 integrated with landscape metrics and urban growth type analysis. Results showed that both cities experienced a rapid expansion of urban land from 1980 to 2010, with a 7.2 and 8.5 times increase for Nanjing and Xi'an, respectively. The urbanization process of both cities can be divided into two stages (the diffusion phase and the transition period from diffusion to coalescence) that were roughly consistent with the phase oscillation theory of urban development. The first phase was during 1980–1995 for Nanjing and 1980–1990 for Xi'an, characterized by scattered development of new urban areas, an increase of the number of patches (NP), a decrease of mean patch size (MPS) and mean Euclidean nearest-neighbor distance (ENN_MN) for urban land, and high proportion of outlying urban growth type, resulting in increasing landscape fragmentation. The second phase was from 1995 to 2010 for Nanjing and from 1990 to 2010 for Xi'an when the newly developed urban areas became aggregated and compact, NP increased slowly, MPS increased, ENN_MN generally remained stable, and edge-expansion became the dominant urban growth type. The detailed quantitative analysis on the general trends of urbanization and urban growth patterns in Nanjing and Xi'an provide insights for future efforts on a comprehensive understanding of urbanization in China. **DOI: 10.1061/(ASCE)UP.1943-5444.0000251.** *© 2014 American Society of Civil Engineers.*

Author keywords: Urban expansion; Remote sensing; Landscape metrics; Urban growth types; Urban development theory.

Introduction

The proportion of the global urban population, risen from 29.4% in 1950 to 52.1% to 2011, is expected to increase to 67.2% by 2050 (UN 2012). Although the large-scale and rapid urbanization has greatly promoted economic development, it may also bring diverse ecological and social problems and severely affect people's living quality (Darrel Jenerette and Potere 2010; Grimm et al. 2008; Shi and Li 2007; Zhao et al. 2006; Zheng et al. 2012). Moreover, the effects of urban expansion have far transcended city boundaries and the time when urbanization occurred. The complexity of urbanization begs for more comprehensive research on its patterns and consequences (Antrop 2000; Darrel Jenerette and Potere 2010; Murakami et al. 2005; Seto et al. 2010; Wu et al. 2011). Cross-sectional observations at multiple points in time on the evolution course of city forms are critical to characterize the details of urbanization patterns spatially and temporally, which is a prerequisite for testing the adequacy of urbanization theories and finding feasible ways to solve social and ecological problems.

Remote sensing data provide spatially and temporally consistent urban land-use information (Herold et al. 2003; Michishita et al. 2012), and landscape and urban growth metrics are widely used to quantify urban landscape patterns through measuring the heterogeneity and categorizing complex landscapes into simple patterns (Herold et al. 2003; McGarigal and Marks 1995; Sudhira et al. 2004; Turner and Gardner 1991; Turner et al. 2001; Wu and David 2002; Wu et al. 2011). A variety of urbanization theories have been developed including the concentric zone theory (Burgess 1925), the self-organization theory (Portugali 2000), and the diffuse-coalescence oscillation theory of urban development (Dietzel et al. 2005a, b and Fig. 1). The oscillation theory in particular can be tested in light of the dynamic coevolution of multiple landscape and urban growth metrics as these metrics holistically reflect the dynamic processes of city growth. Many previous investigations tested and corroborated part of this hypothesis that the urban development could experience the phase transition from diffusion to coalescence (Darrel Jenerette and Potere 2010; Liu et al. 2010; Martellozzo and Clarke 2011; Schneider et al. 2005; Sun et al. 2012; Tian et al. 2011; Xu et al. 2007). However, to test the generality of the oscillation theory requires more studies across a wide range of scales, locations, urban history, and social and economic contexts.

Since the implementation of the reform and opening-up policy in 1978, China has experienced rapid urbanization. The number of cities grew from 193 to 657 [State Statistical Bureau (SSB) 2012a], and the proportion of urban population increased from 17.4 to

[1]Graduate Student, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking Univ., Beijing 100871, China.

[2]Graduate Student, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking Univ., Beijing 100871, China.

[3]BAIREN Plan Professor, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking Univ., Beijing 100871, China (corresponding author). E-mail: sqzhao@urban.pku.edu.cn

Note. This manuscript was submitted on December 22, 2013; approved on August 26, 2014; published online on November 4, 2014. Discussion period open until April 4, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Urban Planning and Development***, © ASCE, ISSN 0733-9488/05014029(9)/$25.00.

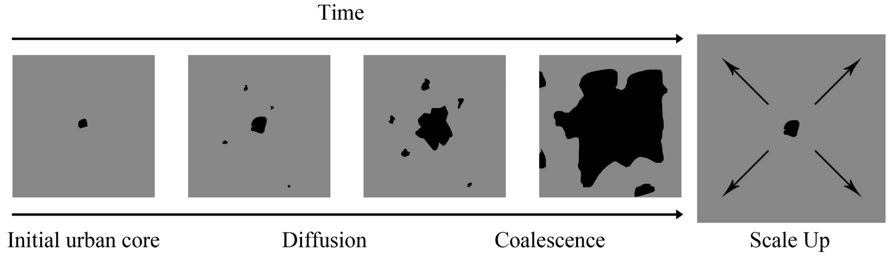

Fig. 1. Hypothetical sequence of the spatial evolution of urban development (adapted from "Spatio-temporal dynamics in California's Central Valley: Empirical links to urban theory", Charles Dietzel, Martin Herold, Jeffrey J. Hemphill, International Journal of Geographical Information Science, 2005 Taylor & Francis, reprinted by permission of the publisher Taylor & Francis Ltd., http://www.tandfonline.com)

51.3% (SSB 2012b) between 1975 and 2011. By 2050, China's population is projected to be 1.3 billion with 77.3% living in cities (UN 2012). With the advantages of the geographic locations and policy preferences, booming cities such as Guangzhou, Shenzhen, and Shanghai have attracted excessive attention economically and ecologically. As a result, extensive studies have been carried out to quantify the urbanization in these economically frantically growing cities (Han et al 2009; Liu et al. 2010; Sun et al. 2012; Wang et al. 2012; Weng 2002; Wu and Yeh 1997; Yeh and Xia 2001), and other cities were rather absent of relevant studies. Given that the research on booming cities provided useful information on the first-tier cities in China (Schneider and Woodcock 2008; Seto and Fragkias 2005; Sun et al. 2012), it is urgently required to obtain complementary information on the economically moderately developed cities to enrich the urbanization researches in China.

In this study, the authors mapped and quantified the urbanization in Nanjing and Xi'an, two moderately developed cities, located in the east and west of China, respectively, using multitemporal Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) images, and landscape and urban growth type analysis techniques. The objectives of this study were to: (1) compare the extent of urban land and dynamic spatial evolution of two cities from 1980 to 2010, (2) compare and analyze the trend of landscape metrics and urban growth types for both cities over the past three decades, and (3) test the adequacy of the theories on the evolution of urban development.

Data and Methods

Study Area

Nanjing and Xi'an, two famous ancient cities located in the east and west areas of China, are the capitals of Jiangsu and Shaanxi Provinces, respectively (Fig. 2). Situated at the lower reaches of the Yangtze River, Nanjing covers an area of 6,587 km^2, including eleven districts and two counties, with 15% of its total area occupied by low mountains. The average annual temperature in Nanjing is 16.2°, and the annual precipitation is about 1,298.4 mm. Xi'an, situated on the Guanzhong Plain at the southern edge of the Loess Plateau, consists of nine districts and four counties covering an area of 9,983 km^2. Almost half of the Xi'an in the south belongs to the Qinling Mountains, difficult if not impossible to inhabit. The mean annual temperature in Xi'an is 14.9°, and the annual precipitation is 525.1 mm, less than half of that in Nanjing.

As the administrative headquarters of their respective provinces, Nanjing and Xi'an have experienced accelerated urbanization over

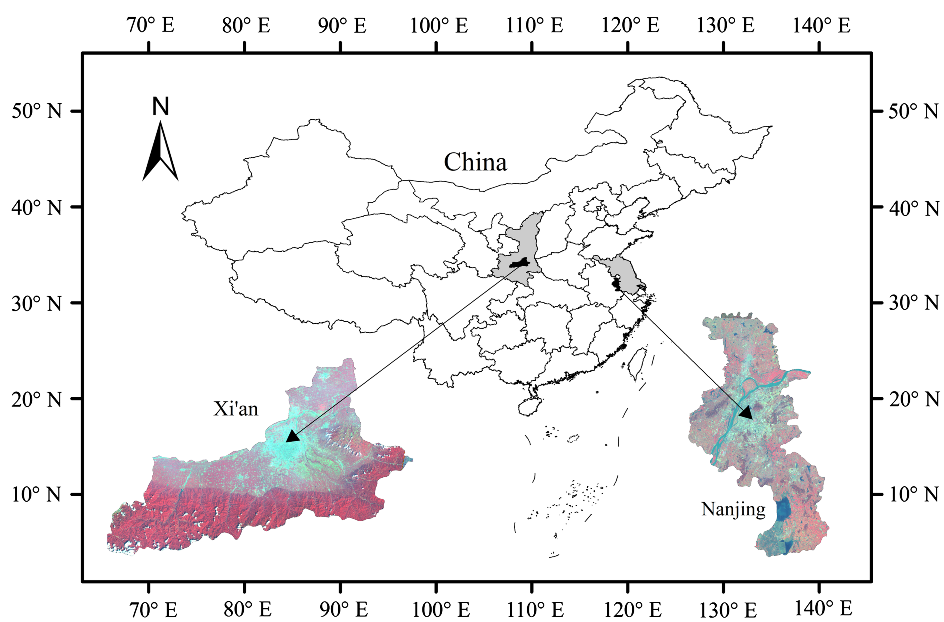

Fig. 2. Locations of Nanjing and Xi'an, China. The background maps of Nanjing and Xi'an are the false color composite satellite images (data from United States Geological Survey 1879)

Table 1. Information on Remotely Sensed Data for Nanjing and Xi'an Used in This Study

		Period (year-mouth-day)						
City	Path/row	1980	1985	1990	1995	2000	2005	2010
Nanjing	129/37	1979-8-6	—	—	—	—	—	—
	129/38	1979-8-6	—	—	—	—	—	—
	120/37	—	1985-4-24	1989-3-10	1995-4-20	2000-9-16	2005-9-10	2010-10-30
	120/38	—	1985-4-24	1989-6-9	1995-4-20	2000-9-16	2005-10-16	2010-10-30
Xi'an	137/36	1979-9-7	—	—	—	—	—	—
	137/37	1978-8-1	—	—	—	—	—	—
	136/36	1978-4-14	—	—	—	—	—	—
	127/36	—	1984-7-27	1988-8-23	1995-5-7	2000-5-12	2004-6-24	2010-8-28
	127/37	—	1984-7-27	1993-6-18	1994-5-4	2000-6-29	2004-6-8	2010-8-28
	126/36	—	1983-8-27	1990-8-22	1995-9-21	2000-5-21	2005-9-8	2010-10-8

the past 30 years. The population has increased from 4.3 to 8 million in Nanjing (Nanjing Statistical Bureau 2011), and from 2.0 to 7.8 million in Xi'an (Xi'an Statistical Bureau 2011). Being one of the three core cities in Yangtze Delta (Shanghai, Nanjing, and Hangzhou) with rapid economic development, Nanjing has undergone an impressive fast development (Tian et al. 2011). As one of the key spots in the national strategy of developing the west, Xi'an also expanded remarkably. Considering economic power, political status, and urban size, Nanjing and Xi'an are both considered as second-tier cities in China.

Satellite Monitoring of Urbanization

Landsat remote sensing data captured long-term (since late 1970s) land cover change information of the study area. Cloud-free Landsat MSS, TM, and ETM+ images for Nanjing and Xi'an were obtained from the United States Geological Survey (USGS) circa 1980, 1985, 1990, 1995, 2000, 2005, and 2010. Detailed information of the selected Landsat images is shown in Table 1.

Data preprocessing was accomplished using ERDAS (Leica Geosystems, Norcross, Georgia) and ArcGIS (ESRI, Redlands, California). The MSS images were resampled to a resolution of 30 m × 30 m to keep consistent with that of TM. As the urban land was the focus of the current study, the land covers were grouped into two types, urban land and nonurban land, using the maximum likelihood method. Accuracy assessment of classified products was performed using stratified random sampling combined with *Google Earth* (Google) at 300 locations for each city. The overall accuracy as represented by the kappa coefficient (Table 2) met the accuracy requirement of land cover change evaluation (Foody 2002).

Table 2. Accuracy Assessment of Classified Urban Land Products for Nanjing and Xi'an

City	Period	Producer's accuracy (%)	User's accuracy (%)	Kappa coefficient
Nanjing	Prior 2010	79.7	93.6	0.86
	2010	75.4	81.1	0.85
Xi'an	Prior 2010	90.6	93.6	0.86
	2010	88.6	78	0.83

Calculation of Landscape Metrics

Four commonly used landscape metrics were selected for this study to quantify land cover changes (Berling-Wolff and Wu 2004; Darrel Jenerette and Potere 2010; Kong et al. 2012; Mcgarigal et al. 2002): the number of patches (NP), mean Euclidean nearest-neighbor distance (ENN_MN), mean patch size (MPS), and the contagion index (Contag) (Table 3). The first three are class-level metrics, usually serving as the indexes of landscape configuration such as fragmentation, while the Contag index is a landscape-level metric measuring overall patch dispersion (Turner et al.1989). These metrics have been proven to be suitable for examining temporal dynamics of urban characteristics (Dietzel et al. 2005a; Xu et al.2007). Their values were calculated using *Fragstats* 3.3 (Mcgarigal et al. 2002).

Analysis of Urban Growth Type

Although the categorizations of urban growth types vary (Camagni et al. 2002; Xu et al. 2007), they follow a similar connotation (Shi 2012). Generally, there are three major types: infilling, edge-expansion, and outlying; other forms are considered to be the hybrids or combinations of the three basic types (Berling-Wolff and Wu 2004; Shi 2012; Sun et al. 2012). As indicated in Fig. 3, infilling refers to the newly developed urban patches surrounded by the existing patches. Edge-expansion can be described as the new urban patches spreading out from the fringe of the existing patches. A new urban patch developing isolated from existing patches indicates the outlying growth type. Mathematically, these three urban growth types can be defined as (Xu et al. 2007)

Table 3. Definition of the Landscape Metrics Used in This Study (Data from McGarigal et al. 1995, 2002)

Landscape metrics	Abbreviation	Description	Unit
Number of patches	NP	The total number of a specified land cover type	None
Mean patch size	MPS	The area of a particular land cover type divided by the number of patches of this land cover type	Hectares
Mean Euclidean nearest-neighbor distance	ENN_MN	Average distance between two patches of the same land cover type	Meters
Contagion index	CONTAG	The extent of the dispersion of different land cover types in the landscape	%

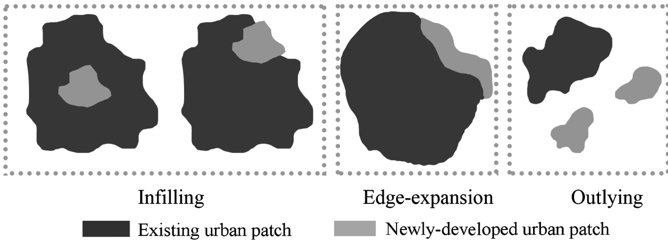

Fig. 3. Illustrations of three urban growth types (adapted from Xu et al. 2007, with kind permission from Springer Science and Business Media)

$$E = Lc/P \tag{1}$$

where Lc = length of common border between existing and newly-developed urban patches; and P = perimeter of newly-developed patch. If $E = 0$, the growth type would be outlying as the newly-developed patch has no common boundary to the existing ones. The urban growth type is considered to be edge-expansion when $0 < E \leq 0.5$ and infilling when $0.5 < E \leq 1$.

Results

Comparison of Urban Land Dynamics from 1980 to 2010

The urban expansion processes of Nanjing and Xi'an over the past three decades are shown in Fig. 4. The urban area of Nanjing has continuously increased from 200.7 km^2 in 1980 to 1,438.2 km^2 in 2010 with an annual growth rate of 6.5%. In contrast, the urban area of Xi'an increased from 135.4 km^2 to 1,142.8 km^2 during the same period with an annual growth rate of 7.0% [Fig. 5(a)]. Accordingly, the percentage of the urban area increased from 3.2 to 21.8% in Nanjing and from 1.4 to 11.2% in Xi'an over the past three decades, respectively.

Temporal changes of landscape metrics for Nanjing and Xi'an over the past three decades are illustrated in Figs. 5(b–e). Along with the dramatic increase of urban areas in Nanjing and Xi'an, the NP of urban land in the two cities experienced rapid increases, and the increasing trend declined approximately since 1995 for Nanjing and 1990 for Xi'an. The MPS for both cities decreased first and then increased, showing a U-shaped curve [Fig. 5(c)], and ENN_MN for both cities decreased first and then became relatively stable [Fig. 5(d)]. The turning points in both MPS and ENN_MN were 1995 for Nanjing and 1990 for Xi'an. The temporal patterns of these three class-level metrics suggest the urban development was more scattered before 1995 for Nanjing and 1990 for Xi'an, and it became relatively compact afterwards. The consistent decrease of the Contag index over time for both cities directly reflected the increase of landscape fragmentation and heterogeneity in both cities under the impact of rapid urbanization [Fig. 5(e)].

Comparison of Urban Growth Types

Fig. 6 indicates the spatial distribution of urban expansion for both cities over the past three decades. Urban expansion in Nanjing spread all over the city, while the expansion in Xi'an was basically concentrated in the north part of the city, constrained by the Qinling Mountains located south of the city. Spatial distributions of urban expansion suggest that Nanjing and Xi'an were monocentric cities,

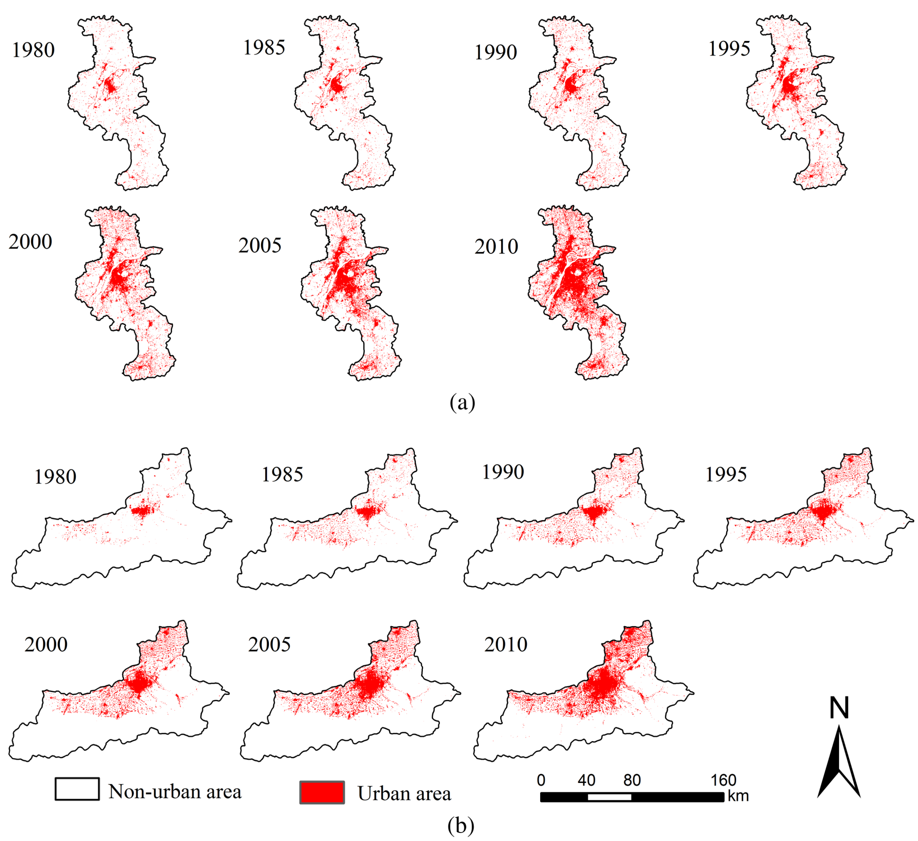

Fig. 4. Spatial distribution of urban land for (a) Nanjing; (b) Xi'an, over the past three decades (data from United States Geological Survey 1879)

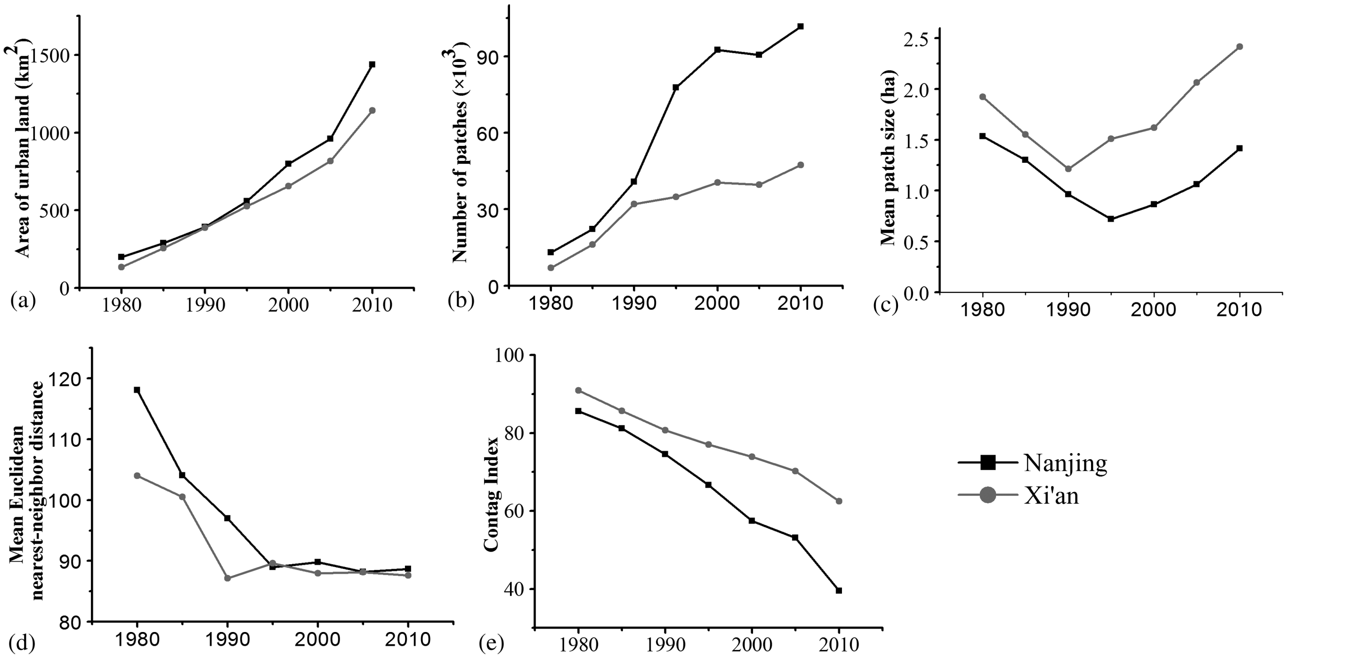

Fig. 5. For Nanjing and Xi'an: (a) temporal changes of urbanized areas; and the landscape metrics at class levels: (b) NP; (c) MPS; (d) ENN_MN; (e) whole landscape level (Contag index)

as urban expansion for both cities occurred mainly around the urban cores (Fig. 6).

The distribution of three urban growth types illustrated the distinct growth patterns of Nanjing and Xi'an for six neighboring periods: 1980–1985, 1985–1990, 1990–1995, 1995–2000, 2000–2005, and 2005–2010 (Figs. 7 and 8). Edge-expansion was the dominant urban growth type for both Nanjing and Xi'an in the 30 years' development except the periods 1985–1990 for Nanjing and 1980–1985 for Xi'an when the outlying type was the main growth type (Fig. 7). For Nanjing, the contribution of infilling was the least among the three types, accounting for 9.6–20.7%. In Xi'an, infilling contributed the least from 1980–1995, and outlying contributed the least in the subsequent period (i.e., 1995–2010).

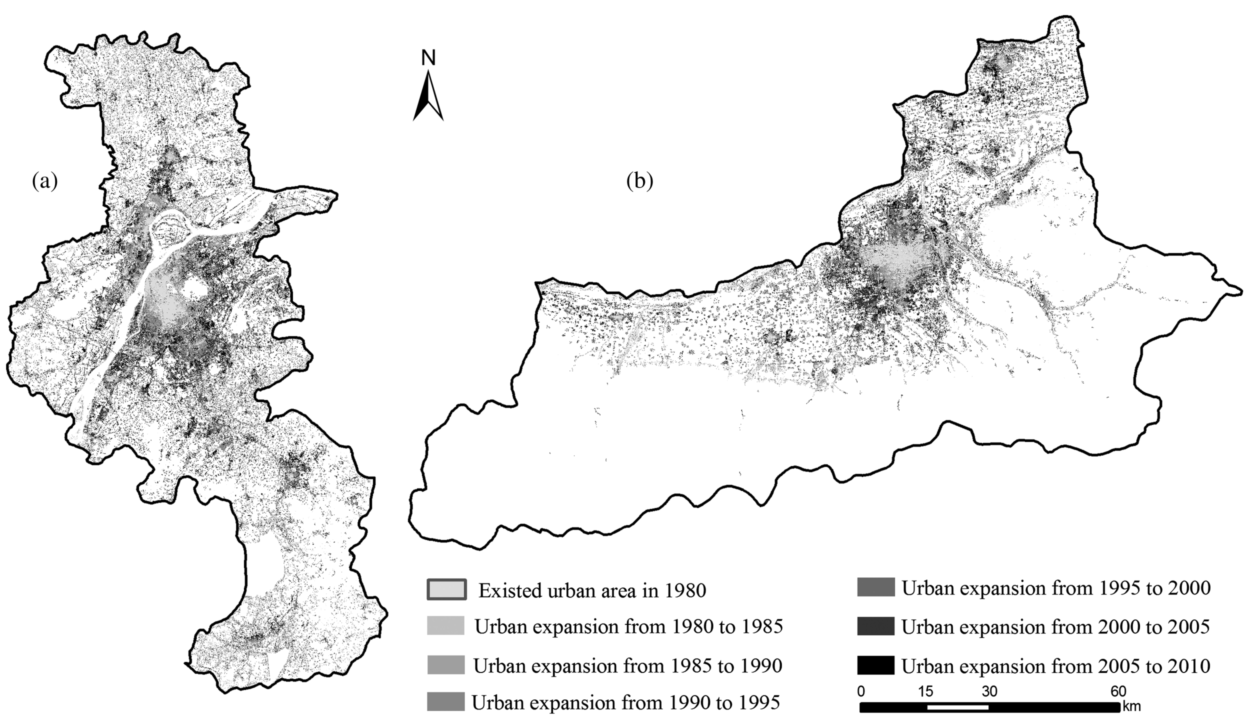

Fig. 6. Spatial distribution of urban expansion for (a) Nanjing; (b) Xi'an, over the past three decades (data from United States Geological Survey 1879)

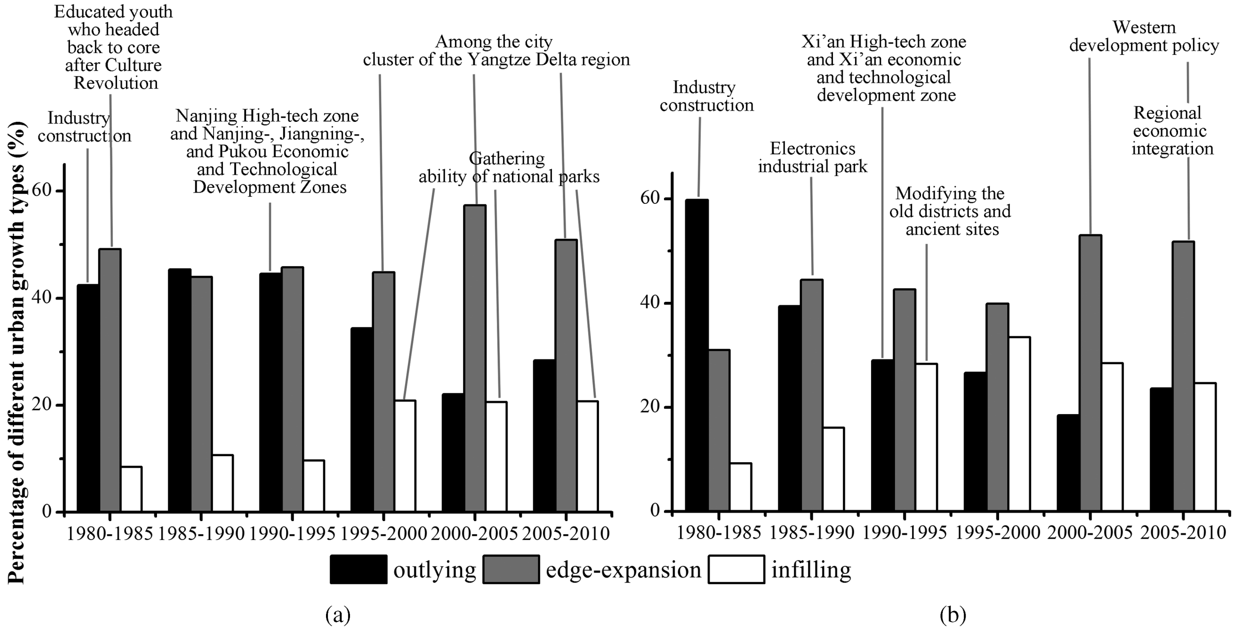

Fig. 7. Percentage of three growth types for (a) Nanjing; (b) Xi'an, among six neighboring periods with main historic events shown

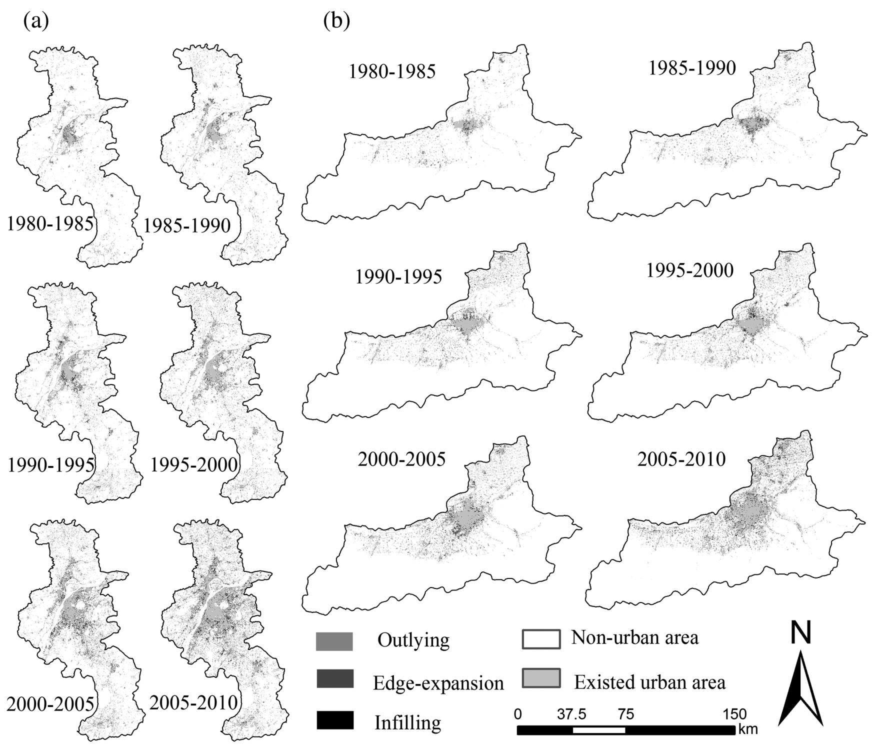

Fig. 8. Spatial distributions of three urban growth types for (a) Nanjing; (b) Xi'an, among six neighboring periods (data from United States Geological Survey 1879)

Spatially, the outlying type scattered all over the city and away from the core, the edge-expansion type mostly developed along the center and transportation network that greatly enlarged the city center, and the infilling type mostly occurred in the city center and/or the capitals of the counties (Fig. 8). Specifically, for Nanjing, both outlying and edge-expansion had proportions higher than 40% during the period 1980–1995 [Fig. 7(a)]; the edge-expansion was mostly found around the main core and the main satellite towns while the outlying occurred mostly in the suburbs and exurbs. Since the period 1995–2000, edge-expansion was found not only along the main center and suburbs but also along the road networks and in the exurbs, which further facilitated the spread of edge-expansion type in Nanjing in the subsequent period 2000–2010 [Fig. 8(a)]. As for Xi'an, the outlying urban areas were distributed dispersedly away from the center, especially on the west and northeast of Xi'an, and the edge-expansion was basically concentrated on the fringe of Xi'an center especially in the north before 1990. Since 1990, the spread of edge-expansion happened primarily in two ways: one surrounding the city core, continued from previous period, and the other around small towns in the northeast of Xi'an [Fig. 8(b)].

Discussions

Spatiotemporal Dynamics of Urbanization in Two Cities

Over the past three decades, both Nanjing and Xi'an have experienced rapid urban expansion. These results showed that the urbanization process of both cities can be divided into two distinct stages separated at 1995 for Nanjing and 1990 for Xi'an. Each stage was characterized by distinct landscape metrics and urban growth types. During the first stage (i.e., the diffusion phase), NP increased, MPS and ENN_MN decreased rapidly, and the proportion of outlying urban growth type was high and that of infilling was low for both cities. These phenomena corresponded well with the development history of these cities. In 1978, China just commenced the reform and opening-up policy, and put great emphasis on the industry construction. Consequently, many scattered and small-scale industrious zones in the outlying towns were frequently established in both cities (Wei and Zhang 2012; Wu and Yeh 1997; Wu and Ren 1999; Xu et al. 2007), especially before the land reform in 1987 when China was inexperienced in industry construction and lack of market regulation (Wu and Ren 1999), which greatly increased the NP and fragmentation and also led to the high outlying urban growth (Dietzel et al. 2005a; Schneider and Woodcock 2008; Irwin and Bockstael 2007). During this stage, Nanjing also had a great percentage of edge-expansion, which can be attributed to the high urban land demand to accommodate the return of the educated youth in Cultural Revolution from the countryside to Nanjing's core, especially in the period 1980–1985 (He and Cui 2000). Though the role of edge-expansion in Xi'an was not as important as in Nanjing, it was still easily detected from the urban expansion on the southwest part along the Xi'an core where an electronics industrial park was constructed in the late 1980s. Compared to Xi'an, Nanjing's diffusion phase extended five more years (i.e., 1980–1995 for Nanjing versus 1980–1990 for Xi'an). This was because many national zones like the Nanjing Hi-Tech Industry Development Zone and the Nanjing, Jiangning, and Pukou Economic and Technological Development Zones (all approved in 1992) were established around the city center and became the new urban growth points in space. These zones benefited from the support from the government, promoted the exploitation of large tracts, and caused the consistent increase of NP, decrease of MPS and ENN_MN, and high outlying urban growth (Seto and Fragkias 2005; Sun et al. 2012). The edge-expansion also maintained at a high proportion as the industrial upgrading drove the large-scale urban center to expand along its edges.

During the second stage, Xi'an also enjoyed the support to construct national zones in the early 1990s, such as Xi'an Hi-Tech Industry Development Zone in the southwestern suburbs (1991) and Xi'an Economic and Technological Development Zone in the northern suburbs (1993) around the core (Wang et al. 2006; Wu et al. 2005). The construction of these zones increased the NP and stimulated more outlying urban growth. However, much emphasis on modifying the old districts and ancient sites had deep influence on city development, which could infill the city center, merged the existing urban patches, and slowed down the increase of NP. As the development zones in both cities became more mature, their gathering ability increased. With the higher cost of housing in the urban center after the implementation of land reform, and more jobs and opportunities provided by the new zones, the development of relevant industries such as new residential sites and corresponding commercial centers around them were greatly promoted, which in turn defined the dominant role of edge-expansion and increased MPS. Moreover, because of the driving role of Nanjing in the city cluster of the Yangtze Delta region, and of Xi'an in western development policy (2002) (Wu et al. 2005; Zhang et al. 2011) and the regional economic integration in Shaanxi provincial Xi'an and Xianyang (Wu et al. 2005), the transport network for both cities was greatly improved to meet the need of the intracity convenience and intercity cooperation to satisfy each cities' development, such as the extensive expressways and highways, which led to dominant position of edge-expansion and also increased the infilling percentage to some extent and reduced fragmentation in the second stage (Antrop 2004; Irwin and Bockstael 2007; Turner et al. 2001).

Testing Hypothesis on Spatiotemporal Patterns of Urbanization

According to Dietzel et al (2005a, b), urban growth could be described as the process of alternative phases between diffusion and coalescence. At the process of diffusion, the built-up areas spread to new development centers dispersedly, while the coalescence is the outward expansion or infilling of existing built-up areas. The diffusion-coalescence theory can be validated using landscape metrics. The increase of NP and the decrease of MPS and ENN_MN generally indicate the diffusion phase while the opposite trends of the metrics suggest the coalescence stage. In addition, the contagion index can be used as a landscape metric to test the theory as well, but it needs a much longer timeframe than the metrics mentioned above. In a longer time scale, contagion is expected to decrease in the diffusion phase, and its increase shows the transformation of the diffusion phase to the coalescence phase. Correspondingly, outlying growth generally characterizes the diffusion phase, and infilling and edge-expansion are observed more often in the coalescence phase (Tian et al. 2011; Xu et al. 2007).

While the results of this study were roughly consistent with this theory, there still existed some differences. The changing trends in landscape metrics and urban growth types for Nanjing during 1980–1995 and Xi'an during 1980–1990 signified a diffusion phase according to the theory proposed by Dietzel et al (2005a, b). The periods of 1995–2010 for Nanjing and 1990–2010 for Xi'an were not perfectly accordant with the theory, neither a typical diffusion phase nor a coalescence phase, and might be in the transition phase from diffusion to coalescence.

The discrepancies might be related to the following three reasons. First, the temporal scale or urbanization process might be different. Compared to the case of California (Dietzel et al. 2005a) over a hundred-year time span, the 30 years' study time might not be long enough to examine the whole diffusion-coalescence process of urban development. While this study time was close to the 29-year period of the Houston case (Dietzel et al. 2005b), the urbanization of Nanjing and Xi'an might be less developed relative to Houston. As a result, Nanjing and Xi'an showed spatiotemporal signatures of urbanization in the transition phase from diffusion to coalescence instead of the coalescence phase as Houston did. Second, the spatial scales might be different, which often leads to different spatiotemporal patterns of urbanization (Wu et al. 2011). The study areas of California (Dietzel et al. 2005a) and Houston (Dietzel et al. 2005b) only covered the urban cores and suburban areas with an area of 300–400 km^2, while these study areas were across a large spatial scale including the concentrated urbanized, suburban, and exurban areas, with an area of 6,587 km^2

J. Urban Plann. Dev., 2015, 141(4): 05014029

for Nanjing and 9,984 km^2 for Xi'an. The dispersed and isolated areas, such as the scattered towns or villages in the exurb, would greatly affect the trend of landscape metrics, strengthening the influence of diffusion and outlying and counteracting the effect of coalescence and infilling (Sun et al. 2012). This also could explain the discrepancies of the current results with those of Xu et al. (2007) who examined the urbanization in Nanjing and supported this theory. The extra areas included in this study relative to Xu et al. (2007) were two counties in the exurb, covering more than 40% of the whole Nanjing area. Therefore, the diffusion-coalescence theory might be more suitable for highly spatial agglomerated urban areas. The small-scale and scattered distant urban areas increased the uncertainty of the measures of landscape metrics. Third, the particularity in the urbanization process of Chinese cities, which is highly related to the social system, land ownership and market, etc., might have contributed to the discrepancies as well. Different from the market-oriented urbanization mode in Western countries, China's urbanization mode faces a conflict between the desire for economic liberalization and ongoing political leading, which makes distinct features of China's urbanization (Heilig 1997; Liu and Li 2007). The policy-led model of urbanization process could increase the similarity in the way of urbanization across various cities in general, which can be seen in these cases.

Conclusions

Using remote sensing data, integrated with landscape metrics and urban growth type analysis, the authors quantified the spatiotemporal dynamics of urbanization in two moderately developed Chinese cities (i.e., Nanjing and Xi'an) over the past three decades. The rapid urbanization in both cities was evidenced by the dramatic growth of urban areas. From 1980 to 2010, the urban area of Nanjing increased from 200.7 to 1,438.2 km^2 with an annual growth rate of 6.5%, and that of Xi'an increased from 135.4 to 1,142.8 km^2 with an annual growth rate of 7.0%.

As the representatives of second-tier cities in China, Nanjing and Xi'an shared relatively similar urbanization dynamics and patterns. The urbanization process of both cities can be divided into two distinct stages. In the first stage, NP increased greatly, MPS and ENN_MN decreased, and outlying was more likely to be the dominant type because most new urban areas tended to develop in the form of small-scale and scattered ones, which would increase the fragmentation of the city. As urban growth developed into the second stage, new urban areas were merged or connected, then the proportions of edge-expansion and infilling increased and MPS increased, which made the urban patterns aggregated and compact. The current study results for both cities roughly supported the "diffusion-coalescence" urban development theory. The first stage was in the phase of diffusion, and the second stage was neither in the diffusion phase nor in the coalescence phase, but might be in the preparation phase from diffusion to coalescence.

Understanding how urbanization evolves and affects the landscape is important for urban planners and administrators. Similarity and differences of general trends of urbanization and spatially-explicit urban growth patterns in Nanjing and Xi'an might provide insights for future efforts on a comprehensive understanding of urbanization in China.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (#31321061 and #41071050). We are grateful to D. C. Zhou, D. Huang, and W. Y. Qu for providing technical assistance.

References

Antrop, M. (2000). "Changing patterns in the urbanized countryside of western Europe." *Landscape Ecol.*, 15(3), 257–270.

Antrop, M. (2004). "Landscape change and the urbanization process in Europe." *Landscape Urban Plann.*, 67(1), 9–26.

Berling-Wolff, S., and Wu, J. (2004). "Modeling urban landscape dynamics: A case study in Phoenix, USA." *Urban Ecosyst.*, 7(3), 215–240.

Burgess, E. W. (1925). *The growth of the city: An introduction to a research project*, Chicago Press, Chicago.

Camagni, R., Gibelli, M. C., and Rigamonti, P. (2002). "Urban mobility and urban form: The social and environmental costs of different patterns of urban expansion." *Ecol. Econ.*, 40(2), 199–216.

Darrel Jenerette, G., and Potere, D. (2010). "Global analysis and simulation of land-use change associated with urbanization." *Landscape Ecol.*, 25(5), 657–670.

Dietzel, C., Herold, M., Hemphill, J. J., and Clarke, K. C. (2005a). "Spatio-temporal dynamics in California's Central Valley: Empirical links to urban theory." *Int. J. Geog. Inf. Sci.*, 19(2), 175–195.

Dietzel, C., Oguz, H., Hemphill, J. J., Clarke, K. C., and Gazulis, N. (2005b). "Diffusion and coalescence of the Houston Metropolitan area: Evidence supporting a new urban theory." *Environ. Plann. B: Plann. Des.*, 32(2), 231–246.

Foody, G. M. (2002). "Status of land cover classification accuracy assessment." *Remote Sens. Environ.*, 80(1), 185–201.

Grimm, N. B., et al. (2008). "Global change and the ecology of cities." *Science*, 319(5864), 756–760.

Han, J., Hayashi, Y., Cao, X., and Imura, H. (2009). "Evaluating land-use change in rapidly urbanizing china: Case study of Shanghai." *J. Urban Plann. Dev.*, 10.1061/(ASCE)0733-9488(2009)135:4(166), 166–171.

He, L., and Cui, G. (2000). "Study on the urban spatial expansion of Nanjing City." *Urban Plann. Forum*, 6, 56–60.

Heilig, G. K. (1997). "Anthropogenic factors in land-use change in China." *Popul. Dev. Rev.*, 23(1), 139–168.

Herold, M., Goldstein, N. C., and Clarke, K. C. (2003). "The spatiotemporal form of urban growth: Measurement, analysis and modeling." *Remote Sens. Environ.*, 86(3), 286–302.

Irwin, E. G., and Bockstael, N. E. (2007). "The evolution of urban sprawl: Evidence of spatial heterogeneity and increasing land fragmentation." *Proc. Natl. Acad. Sci. U.S.A.*, 104(52), 20672–20677.

Kong, F., Yin, H., Nakagoshi, N., and James, P. (2012). "Simulating urban growth processes incorporating a potential model with spatial metrics." *Ecol. Indic.*, 20, 82–91.

Liu, X., Li, X., Chen, Y., Tan, Z., Li, S., and Ai, B. (2010). "A new landscape index for quantifying urban expansion using multi-temporal remotely sensed data." *Landscape Ecol.*, 25(5), 671–682.

Liu, Y.-f., and Li, T.-s. (2007). "An appraisal of dynamic change of land use in Xi'an City." *Sci. Technol. Manage. Land Resour.*, 6, 008.

Martellozzo, F., and Clarke, K. C. (2011). "Measuring urban sprawl, coalescence, and dispersal: A case study of Pordenone, Italy." *Environ. Plann. Part B*, 38(6), 1085–1104.

McGarigal, K., Cushman, S., Neel, M., and Ene, E. (2002). *FRAGSTATS: Spatial pattern analysis program for categorical maps*, Univ. of Massachusetts, Amherst, MA.

McGarigal, K., and Marks, B. J. (1995). *Fragstats: Spatial pattern analysis program for quantifying landscape structure*, USDA Forest Service, Vallejo, CA.

Michishita, R., Jiang, Z., and Xu, B. (2012). "Monitoring two decades of urbanization in the Poyang Lake area, China through spectral unmixing." *Remote Sens. Environ.*, 117(1), 3–18.

Murakami, A., Medrial Zain, A., Takeuchi, K., Tsunekawa, A., and Yokota, S. (2005). "Trends in urbanization and patterns of land use in the Asian mega cities Jakarta, Bangkok, and Metro Manila." *Landscape Urban Plann.*, 70(3), 251–259.

Nanjing Statistical Bureau. (2011). *Nanjing statistical yearbook 2011*, China Statistical Press, Beijing.

Portugali, J. (2000). *Self-organization and the city*, Springer, Berlin.

Schneider, A., Seto, K. C., and Webster, D. R. (2005). "Urban growth in Chengdu, western China: Application of remote sensing to assess

planning and policy outcomes." *Environ. Plann. B: Plann. Des.*, 32(3), 323–345.
Schneider, A., and Woodcock, C. E. (2008). "Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information." *Urban Stud.*, 45(3), 659–692.
Seto, K. C., and Fragkias, M. (2005). "Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics." *Landscape Ecol.*, 20(7), 871–888.
Seto, K. C., Sánchez-Rodríguez, R., and Fragkias, M. (2010). "The new geography of contemporary urbanization and the environment." *Annu. Rev. Environ. Resour.*, 35(1), 167–194.
Shi, Y., and Li, S. (2007). "Research on rational urban growth and land-use issues." *J. Urban Plann. Dev.*, 10.1061/(ASCE)0733-9488(2007)133:2(91), 91–94.
Shi, Y., Sun, X., Zhu, X., Li, Y., and Mei, L. (2012). "Characterizing growth types and analyzing growth density distribution in response to urban growth patterns in peri-urban areas of Lianyungang City." *Landscape Urban Plann.*, 105(4):425–433.
State Statistical Bureau (SSB). (2012a). *China city statistical yearbook*, China Statistics Press, Beijing (in Chinese).
State Statistical Bureau (SSB). (2012b). *China statistical yearbook*, China Statistics Press, Beijing.
Sudhira, H. S., Ramachandra, T., and Jagadish, K. (2004). "Urban sprawl: Metrics, dynamics and modelling using GIS." *Int. J. Appl. Earth Obs. Geoinf.*, 5(1), 29–39.
Sun, C., Wu, Z.-F., Lv, Z.-Q., Yao, N., and Wei, J.-B. (2012). "Quantifying different types of urban growth and the change dynamic in Guangzhou using multi-temporal remote sensing data." *Int. J. Appl. Earth Obs. Geoinf.*, 21, 409–417.
Tian, G., Jiang, J., Yang, Z. et al. (2011). "The urban growth, size distribution and spatio-temporal dynamic pattern of the Yangtze River Delta megalopolitan region, China." *Ecol. Model.*, 222(3), 865–878.
Turner, M. G., and Gardner, R. H. (1991). *Quantitative methods in landscape ecology*, Springer, New York.
Turner, M. G., Gardner, R. H., and O'Neill, R. V. (2001). *Landscape ecology in theory and practice: Pattern and process*, Springer, New York.
Turner, M. G., O'Neill, R. V., Gardner, R. H., and Milne, B. T. (1989). "Effects of changing spatial scale on the analysis of landscape pattern." *Landscape Ecol.*, 3(3), 153–162.
United Nations, Department of Economic, and Social Affairs, Population Division. (2012). *World urbanization prospects: The 2011 revision*, United Nations, New York.
United States Geological Survey. (1879). "Science for a changing world." ⟨http://earthexplorer.usgs.gov/⟩ (Apr. 12, 2012).
Wang, H., Tian, P.-P., and Liu, H. (2006). "Spatial structuring of the 'new economies' in Xi'an and its mechanisms." *Geog. Res.*, 25(3), 539–550.
Wang, L., et al. (2012). "China's urban expansion from 1990 to 2010 determined with satellite remote sensing." *Chin. Sci. Bull.*, 57(22), 2802–2812.
Wei, Y., and Zhang, Z. (2012). "Assessing the fragmentation of construction land in urban areas: An index method and case study in Shunde, China." *Land Use Policy*, 29(2), 417–428.
Weng, Q. (2002). "Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling." *J. Environ. Manage.*, 64(3), 273–284.
Wu, F., and Yeh, A. G. O. (1997). "Changing spatial distribution and determinants of land development in Chinese cities in the transition from a centrally planned economy to a socialist market economy: A case study of Guangzhou." *Urban Stud.*, 34(11), 1851–1879.
Wu, H. A., Jiang, J., Zhou, J., Zhang, H., Zhang, L., and Ai, L. (2005). "Dynamics of urban expansion in Xi'an city using Landsat TM/ETM+ Data." *Acta Geog. Sin.*, 60(1), 15.
Wu, J., and David, J. L. (2002). "A spatially explicit hierarchical approach to modeling complex ecological systems: Theory and applications." *Ecol. Model.*, 153(1), 7–26.
Wu, J., Jenerette, G. D., Buyantuyev, A., and Redman, C. L. (2011). "Quantifying spatiotemporal patterns of urbanization: The case of the two fastest growing metropolitan regions in the United States." *Ecol. Complexity*, 8(1), 1–8.
Wu, Q., and Ren, D. (1999). "The transformation of metropolitan area structure and sustainable development since reform—A case study of metropolitan Nanjing." *Scientla Geog. Sin.*, 19(2), 108–114.
Xi'an Statistical Bureau. (2011). *Xi'an statistical yearbook 2011*, China Statistical Press, Beijing.
Xu, C., Liu, M. S., Zhang, C., An, S. Q., Yu, W., and Chen, J. M. (2007). "The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China." *Landscape Ecol.*, 22(6), 925–937.
Yeh, A. G. O., and Xia, L. (2001). "Measurement and monitoring of urban sprawl in a rapidly growing region using entropy." *Photogramm. Eng. Remote Sens.*, 67(1), 83–90.
Zhang, L., Lei, J., Li, X., and Gao, C. (2011). "The features and influencing factors of urban expansion in China during 1997–2007." *Prog. Geog.*, 30(5), 607–614.
Zhao, S., Da, L., Tang, Z., Fang, H., Song, K., and Fang, J. (2006). "Ecological consequences of rapid urban expansion: Shanghai, China." *Front. Ecol. Environ.*, 4(7), 341–346.
Zheng, Z., and Bohong, Z. (2012). "Study on spatial structure of Yangtze River Delta urban agglomeration and its effects on urban and rural regions." *J. Urban Plann. Dev.*, 10.1061/(ASCE)UP.1943-5444.0000095, 78–89.