Landscape Ecol (2013) 28:1875–1888
DOI 10.1007/s10980-013-9933-6

RESEARCH ARTICLE

Quantifying the speed, growth modes, and landscape pattern changes of urbanization: a hierarchical patch dynamics approach

Cheng Li · Junxiang Li · Jianguo Wu

Received: 9 April 2013 / Accepted: 12 August 2013 / Published online: 21 August 2013

Abstract Urbanization transforms landscape structure and profoundly affects biodiversity and ecological processes. To understand and solve these ecological problems, at least three aspects of spatiotemporal patterns of urbanization need to be quantified: the speed, urban growth modes, and resultant changes in landscape pattern. In this study, we quantified these spatiotemporal patterns of urbanization in the central Yangtze River Delta region, China from 1979 to 2008, based on a hierarchical patch dynamics framework that guided the research design and the analysis with landscape metrics. Our results show that the urbanized area in the study region increased exponentially during the 30 years at the county, prefectural, and regional levels, with increasing speed down the urban hierarchy. Three growth modes—infilling, edge-expanding, and leapfrogging—operated concurrently and their relative dominance shifted over time. As urbanization progressed, patch density and edge density generally increased, and the connectivity of urban patches in terms of the average nearest neighbor distance also increased. While landscape-level structural complexity also tended to increase, the shape of individual patches became increasingly regular. Our results suggest that whether urban landscapes are becoming more homogenous or heterogeneous may be dependent on scale in time and space as well as landscape metrics used. The speed, growth modes, and landscape pattern are related to each other in complicated fashions. This complex relationship can be better understood by conceptualizing urbanization not simply as a dichotomous diffusion-coalescence switching process, but as a spiraling process of shifting dominance among multiple growth modes: the wax and wane of infilling, edge-expansion, and leapfrog across the landscape.

Electronic supplementary material The online version of this article (doi:10.1007/s10980-013-9933-6) contains supplementary material, which is available to authorized users.

C. Li · J. Li (✉)
Department of Environmental Science, East China Normal University, Shanghai 200062, China
e-mail: jxli@des.ecnu.edu.cn

Present Address:
C. Li
Guangdong Institute of Eco-Environment and Soil Sciences, Guangzhou, Guangdong 510650, China

J. Li
Shanghai Key Laboratory of Urbanization and Ecological Restoration, Shanghai 200062, China

J. Wu
School of Life Sciences and Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287, USA

J. Wu
Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100875, China

Keywords Urbanization · Urban growth modes · Landscape pattern analysis · Hierarchical patch dynamics · Diffusion-coalescence hypothesis · Landscape structural homogenization · Yangtze River Delta, China

Introduction

During the past century, urbanization has mushroomed across the world at an accelerating rate, resulting in fundamental changes in the structure and function of the global ecosystem (Grimm et al. 2008; Schneider and Woodcock 2008; Wu 2008, 2010). About 70 % of the world's population will live in urban areas by 2050, and most of the increase will take place in developing countries (Bloom 2011). Undoubtedly, challenges for understanding and solving urbanization-induced environmental problems will continue to rise. To meet these challenges, a necessary first step is to adequately quantify spatiotemporal patterns of urbanization (Jenerette and Wu 2001; Luck and Wu 2002). Because urban systems are multi-scaled, social-ecological systems, a hierarchical approach is needed for understanding their structure, function, and dynamics (Pickett et al. 1997, 2001; Wu and David 2002; Bürgi et al. 2004). As Batty (2008) pointed out, "City morphology is reflected in a hierarchy of different subcenters or clusters across many scales, from the entire city to neighborhoods, organized around key economic functions." In particular, the hierarchical patch dynamics paradigm (HPDP; Wu and Loucks 1995) has been widely applied in urban landscape studies (Grimm et al. 2000; Wu and David 2002; Alberti 2008; da Silva et al. 2012; Xu et al. 2012; Zhang et al. 2013). In this present study, HPDP was used as a conceptual framework for designing the research and interpreting the results.

At least three aspects of the spatiotemporal patterns of urbanization need to be considered: the speed of urbanization (i.e., the rate of urbanization in terms of urban population or urbanized area), urban growth modes (i.e., the ways in which urbanized areas continue to expand), and changes in landscape pattern due to urbanization (including alterations in both landscape composition and configuration). Three urban growth modes (or urban growth phases) have been widely discussed in the literature: infilling, edge-expansion, and leapfrog development (Berling-Wolff and Wu 2004; Xu et al. 2007; Liu et al. 2010). Infilling refers to new urban growth taking place in an area surrounded mostly by existing urban land; edge-expansion is new urban growth taking place at the edge of existing urban land; and leapfrog development (i.e., the so-called "outlying expansion" in Liu et al. 2010) refers to new urban growth taking place in an area away from or not directly attached to existing urban land. Apparently, these urban growth modes affect the overall speed of urbanization, on the one hand, and landscape pattern, on the other.

During past few decades, our abilities to quantify urbanization patterns have been greatly enhanced by the use of remote sensing, GIS, and landscape pattern analysis methods (Wu et al. 2000; Jenerette and Wu 2001; Herold et al. 2002; Luck and Wu 2002; Wu and David 2002; Wu et al. 2011). However, most of the great numbers of urban studies so far have focused on individual cities and only one or two aspects of the spatiotemporal patterns of urbanization. To move forward, empirical studies that simultaneously quantify the speed, growth modes, and resultant changes in landscape pattern of urbanization across multiple hierarchical levels of urban regions are needed.

By so doing, some of urban theories and hypotheses can be re-examined in a hierarchical context. For example, the diffusion-coalescence hypothesis Dietzel et al. (2005a) states that urbanization is a cyclic process of two alternating phases: diffusion (dispersed or leapfrog development) and coalescence (dominated by infilling). As noted by Dietzel et al. (2005a), this hypothesis is conceptually related to the earlier ideas of urban growth phases (e.g., Hoover and Vernon 1959; Winsborough 1962) and wave-like urban development (e.g., Blumenfeld 1954; Boyce 1966). However, this hypothesis has only been examined partially by a few studies, and the results were not congruent (Yu and Ng 2007; Jenerette and Potere 2010; Wu et al. 2011; Li et al. 2013). Also, Jenerette and Potere's (2010) study suggests that urbanization tends to decrease the spatial heterogeneity of landscapes, resulting in homogenization of urban landscape structure, which apparently echoes the hypothesis of biotic homogenization by urbanization (McKinney 2006; Olden 2006). These hypotheses need to be tested further at the landscape and regional scales. Thus, this study had two main objectives: (1) to quantify the speed, growth modes, and landscape pattern changes of urbanization in the central region of the Yangtze River Delta, China from a hierarchical patch dynamics perspective; (2) to test the diffusion-coalescence hypothesis and the landscape structural homogenization hypothesis.

Data and methods

Study area

Our study area is the central region of the Yangtze River Delta (YRD), covering $\sim$23,700 km^2 (119–122°E and 30–32°N) and dominated by northern subtropical monsoon climate, with a mean annual temperature of 16–18 °C and a mean annual precipitation of 950–1,500 mm (Fig. 1). As one of the earliest test-beds for China's "opening-up" policy of economic liberalization, the central YRD region is one of the most densely populated and economically developed in the country. In 2009, its total population reached 28.6 million and its total GDP exceeded 3,030 billion yuan (approximately 489 billion US dollars), accounting for 21.1 and 41.7 % of the totals for the entire YRD, respectively (National Bureau of statistics 2010). With rapid economic development during the past several decades, many new cities have emerged, and existing ones have expanded and coalesced into increasingly larger urban clusters, throughout the region.

To achieve our research objectives, we divided the study region into spatial units according to the Chinese urban system hierarchy. The geospatial pattern of Chinese urban systems is determined primarily by two factors: the administrative hierarchy and population mobility restrictions (Chan 2010). The urban administrative hierarchy of China consists of several levels, including provincial-level, prefectural-level, county-level, and township-level cities. The central YRD region includes one provincial-level city: Shanghai (the largest city in China); 3 prefectural-level cities: Suzhou, Wuxi, and Changzhou; and 15 county-level cities altogether (Fig. 1). For our analysis, we constructed a spatially nested urban landscape hierarchy with three distinctive levels: the urban region (i.e., the central YRD), the provincial and prefectural-level cities (Shanghai, Suzhou, Wuxi, and Changzhou), and the county-level cities that belong exclusively to the four higher-level cities (Fig. 1). Cities at each level in the central YRD landscape hierarchy have comparable geophysical and socioeconomic characteristics.

More specifically, as shown in Fig. 1, the provincial-level city of Shanghai includes its city proper (the original urban municipality encompassing the historical city center—i.e., City of Shanghai) and six county-level cities: Chongming (CM), Qingpu (QP), Nanhui (NH), Songjiang (SJ), Fengxian (FX) and Jinshan (JS); the prefectural-level city of Suzhou includes its city proper (City of Suzhou) and five county-level cities: Taicang (TC), Kunshan (KS), Wujiang (WJ), Changshu (CS), and Zhangjiagang (ZJG); the prefectural-level city of Wuxi includes its city proper (City of Wuxi) and two county-level cities: Jiangyin (JY) and Yixing (YX); the prefectural-level city of Changzhou includes its city proper (City of Changzhou) and two county-level cities: Liyang (LY) and Jintan (JT).

Data acquisition and processing

Remote sensing imagery from Landsat MSS (1979; spatial resolution = 79 m) and Landsat TM/ETM+ (1987–1991, 1995–1997, 2000–2001, and 2004–2005; spatial resolution = 30 m) was acquired from the U.S. Geological Survey (USGS) and the Chinese Academy of Science (Supplementary Material, Table S1). In addition, Chinese-Brazil Earth Resource Satellite data (CBERS-02B; 2008; spatial resolution = 20 m) were obtained through the China Center for Resources Satellite Data and Application (http://www.cresda.com). Image pre-processing included geometric and terrain correction, radiometric calibration, and atmospheric correction (Fig. 2). The geometric and terrain correction for Landsat MSS, TM/ETM+ was carried out by U.S. Geological Survey EROS. The CBERS-02B images were geometrically rectified using polynomial method, with root mean square errors (RMSE) of rectification less than half a pixel, and then resampled to have a spatial resolution of 30 m by nearest neighborhood resampling method. Radiometric calibration was done using the procedures set forth by Chander et al. (2009) and Li et al. (2011). To remove atmospheric effects, we further performed atmospheric correction using methods built in the software ENVI (v4.7).

These remote sensing data were then used to produce a series of land use and land cover maps for

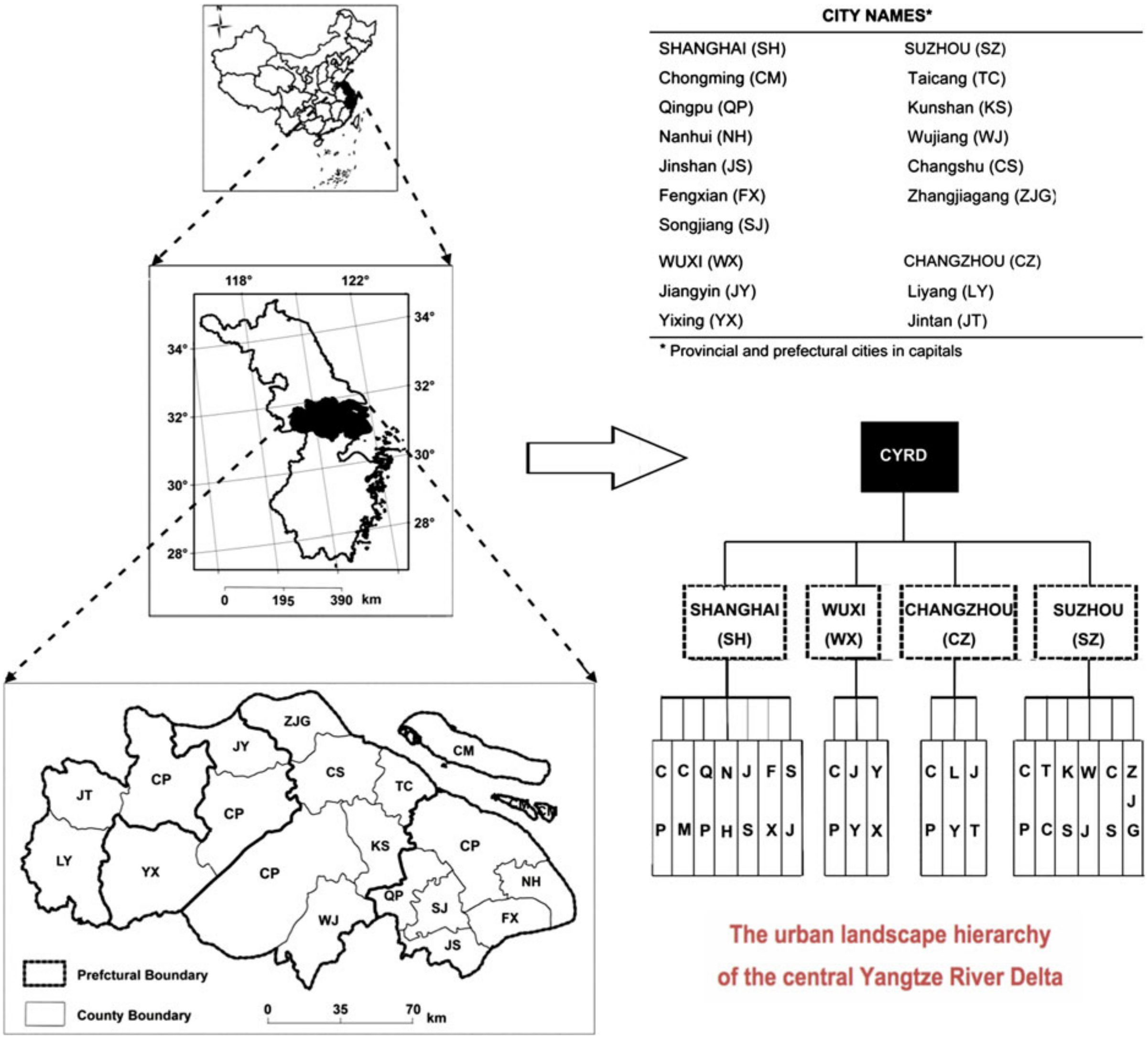


Fig. 1 Location of the central region of the Yangtze River Delta in China and the urban landscape hierarchy used for analysis. The urban landscape hierarchy includes three levels: the urban region, the prefectural-level cities, and the county-level cities

6 different times spanning over 30 years: 1979, 1990, 1995, 2000, 2005, and 2008 (Fig. 2). Because the focus of this study was on the spatiotemporal dynamics of urban land use and land cover, the maps had only two classes: urban and non-urban. The threshold-value NDVI approach (Chen et al. 2006), in combination with NDBI which is sensitive to built-up area (Zha et al. 2003), was used to retrieve the urban land use and land cover (the threshold values of NDVI and NDBI shown in Table S1). Bare land patches that had similar spectral characteristics to built-up areas were corrected based on high-accuracy (>95 %) land use and land cover maps produced by the Institute of Geographic Sciences and Natural Resources Research (Liu et al. 2005) and MODIS maximum NDVI in growing seasons (provided by USGS). Using methods presented in Pontius and Millones (2011), we tested the accuracy of the urban land use and land cover maps for all the six time periods, based on 500 randomly samples (300 sampling points for the map of 1979). Neither quantity disagreement nor allocation disagreement exceeded 3 %; that is, the map accuracy was over 97 % in terms of both the amount and spatial arrangement of urban land (Table 1). We further

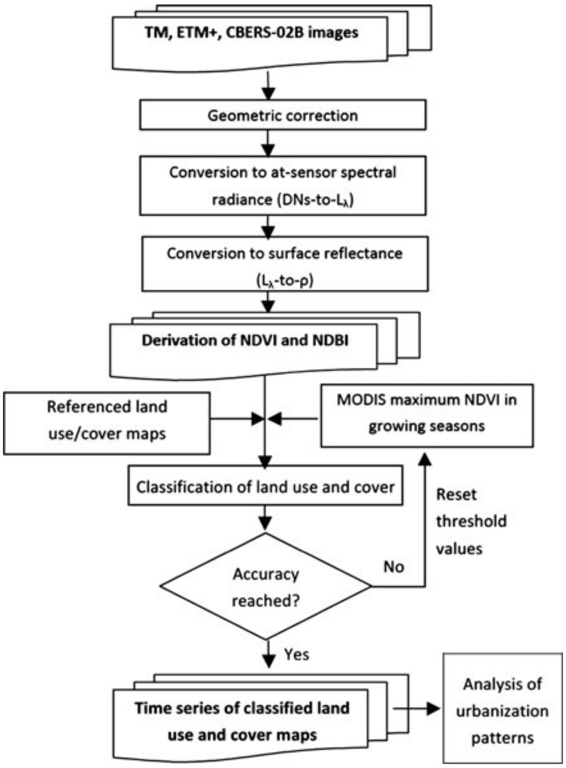


Fig. 2 Flowchart showing the procedures for data acquisition and processing

computed adjusted standard Kappa, and the result confirmed the high accuracy of the classified maps.

Quantifying spatiotemporal patterns of urbanization

We used several landscape metrics to quantify the spatiotemporal patterns of urbanization. As a non-spatial overall measure of urbanization in terms of its spatial extent, the annual growth rate of urbanized land (*AGRUL*) was computed according to:

$$AGRUL = \left(\sqrt[n]{\frac{UL_{t+n}}{UL_t}} - 1\right) \times 100\,\% \tag{1}$$

where UL_{t+n} and UL_t are the urban land area in year $t + n$ and year t, respectively.

The above equation assumes that urban growth is an exponential process, and is mathematically identical to the annual rate of compound interest. This formula has been used widely in estimating forest change rates (Puyravaud 2003) as well as quantifying urban growth (Seto and Fragkias 2005). We calculated *AGRUL* using several different formulations discussed in Puyravaud (2003), and found that the results were quite similar, especially in terms of temporal trends. Thus, in this paper we report only the results from Eq. 1.

Given an urban growth rate, urbanization may assume different urban growth modes (i.e., infilling, edge-expansion, and leapfrog). To describe and detect these growth modes, we used the Landscape Expansion Index (LEI), proposed by Liu et al. (2010):

$$\mathrm{LEI} = 100 \times \frac{A_o}{A_o + A_v} \tag{2}$$

where A_o is the intersection between a predefined buffer around a new urban patch and previously existing urban land, and A_v is the intersection between the buffer and non-urban area. To use LEI, a buffer distance must be defined, and this was set to 1 m in our study. A new urban patch is infilling when LEI is between 50 and 100, edge-expansion when LEI is between 0 and 50, and leapfrog when LEI is zero (Liu et al. 2010).

To get a sense of the relative dominance among the different forms across a landscape or over time, we also computed the area-weighted mean expansion index (AWMEI):

$$AWMEI = \sum_{i=1}^{N} LEI \times \left(\frac{a_i}{A}\right) \tag{3}$$

where LEI_i is the value of *LEI* for a newly grown patch i, a_i is the area of this new patch, and A is the total area of all these newly grown patches. Larger values of AWMEI correspond to more compact urban growth while smaller values of AWMEI imply the prevalence

Table 1 Quantity disagreement, allocation disagreement, and adjusted standard Kappa coefficient for classified urban land use and land cover maps

Years	Quantity disagreement (%)	Allocation disagreement (%)	Adjusted standard Kappa
1979	2.34	0.53	0.61
1990	1.72	1.30	0.93
1995	1.95	0.78	0.86
2000	1.24	0.96	0.91
2005	0.29	1.55	0.95
2008	1.29	2.24	0.92

of leapfrog development or urban sprawl (Liu et al. 2010).

Based on previous work from the Central Arizona-Phoenix Long-Term Ecological Research Project (Wu et al. 2000; Jenerette and Wu 2001; Luck and Wu 2002; Buyantuyev et al. 2010; ; Wu et al. 2011) and Shanghai (Li et al. 2013), we selected a number of landscape metrics, including: patch density (PD), edge density (ED), landscape shape index (LSI), mean patch fractal dimension (FRAC-MN), and mean Euclidean nearest neighbor distance (ENN-MN). All the metrics were computed at the regional, prefectural, and county-levels with the FRAGSTATS software (v3.3) (McGarigal et al. 2002).

In addition, one sample t-tests were used to determine whether there were significant changes in the magnitude of landscape pattern metrics for each time period at both the prefectural and county scales. One-way ANOVA with posthoc tests was used to examine the trends of urban growth rates, relative dominance of growth modes and landscape pattern at prefectural and county scales among five time periods. All statistical analyses were done with SPSS for Windows (version 18.0).

Results

Speed of urbanization at different levels of landscape hierarchy

From 1979 to 2008, urbanized area in the central YRD region increased exponentially across all the three levels of the urban landscape hierarchy (Fig. 3). The urbanized area for the entire region grew from 623.76 km^2 (2.6 % of the total area) in 1979 to 7124.45 km^2 (30.0 % of the total area) in 2008—a more than tenfold increase (Fig. 3A). The urbanized area for each of the prefectural-level cities increased in a similar fashion (SH: 314.0 to 2,902.5 km^2; SZ: 136.9 to 2,196.9 km^2; WX: 95.7 to 1,166.0 km^2; CZ: 77.1 to 859.3 km^2; Fig. 3B). The same urbanization trend was seen again for the county-level cities, most of which showed a 5- (LY) to 60-fold (FX) increase in urbanized area between 1979 and 2008 (Fig. 3C–F).

The annual growth rate of urbanized area was then computed for five time periods (1979–1990, 1990–1995, 1995–2000, 2000–2005, and 2005–2008) based on possible changes in socioeconomic and institutional changes during the 30 years. Considering all cities at the three hierarchical levels, the mean *AGRUL* ranged from 6.52 to 15.29 %, with substantially higher values for 1990–1995 and 2000–2005 (Fig. 4). For each time period, the mean *AGRUL* also varied across the three hierarchical levels, with the highest value for county-level cities and the lowest value for the entire region (Fig. 4). The mean values of *AGRUL* at the county-level were considerably more variable than those at the two higher levels over the five time periods (Fig. 4; Fig. S1).

Different urban growth modes across space and time

The rapid urbanization in the study region resulted from a combination of all three urban growth modes or processes (Fig. 5): infilling, edge-expansion, and leapfrog development, which were classified according to LEI values (described in the section of "Data and methods"). As urbanization continued during the 30 years from 1979 to 2008, the relative dominance of the three modes of urbanization changed. As new urban areas emerged and the old ones expanded, urban clusters evolved, enlarged, and coalesced, consequently forming one of the most noticeable urban agglomerations in China (Fig. 5). Specifically, the proportions of new urban patches for each growth mode varied considerably among the five different time periods, but remained quite similar among the three hierarchical levels (Fig. 6A–C). Likewise, the percent areas of new urban patches for each growth mode also varied over time, but remain similar across the landscape hierarchy (Fig. 6D–F). However, at each hierarchical level, the relative dominance of the three growth modes during each time period showed different patterns between the patch-number and patch-area representations (Fig. 6).

In terms of the number of new urban patches, the dominance order was leapfrog > edge-expansion > infilling during 1979–1990, and the order was reversed completely during 1990–1995 (Fig. 6A–C). Leapfrog became the most dominant once again during 1995–2000, but conspicuously less so in the following periods as the other two types (especially infilling) increased their shares substantially. Consequently, infilling dominated urban growth in the period of 2005–2008, resulting in again a dominance order contrary to that of 1979–1990 (Fig. 6A–C).

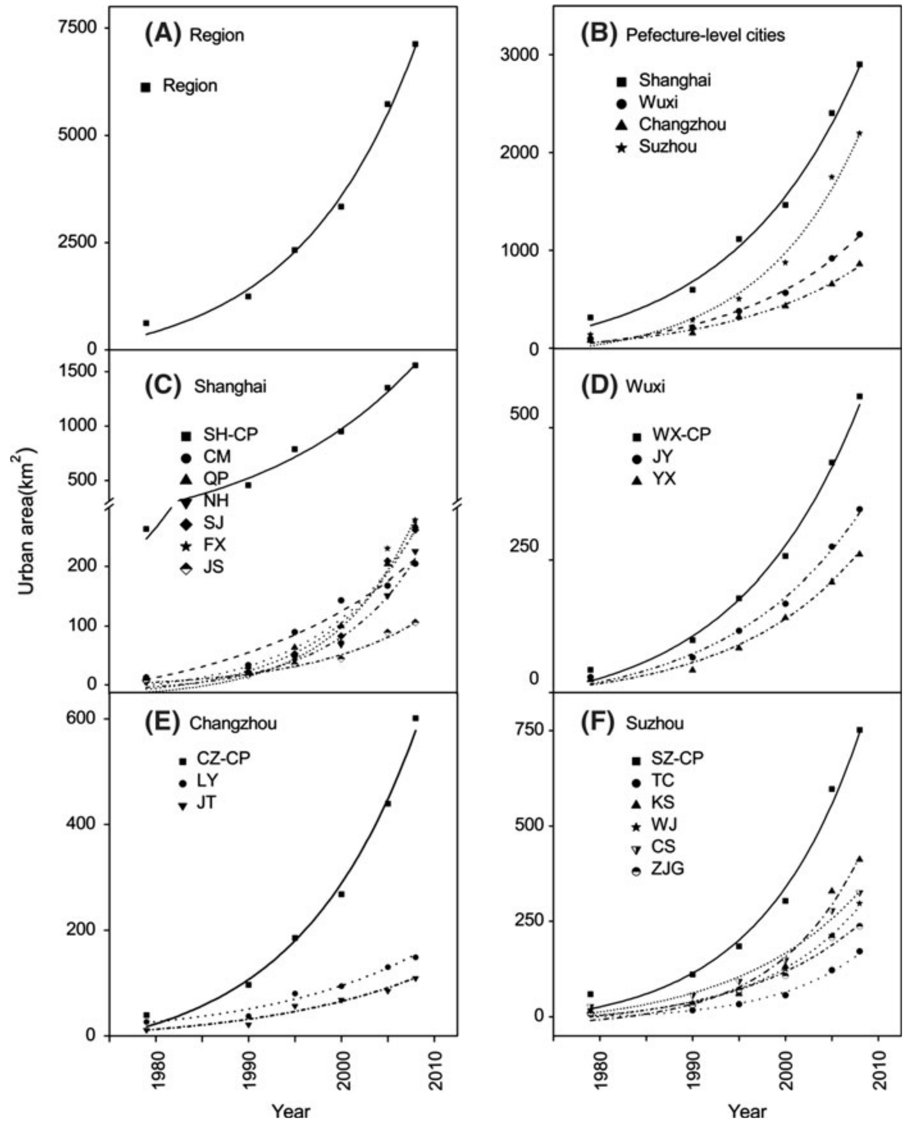


Fig. 3 Increase in urbanized area in the central Yangtze River Delta region between 1979 and 2008 at three hierarchical levels: **A** the regional level **B** the prefectural level, and **C**–**F** the county level. The *solid* and *dotted lines* represent exponential curve fittings ($p < 0.05$)

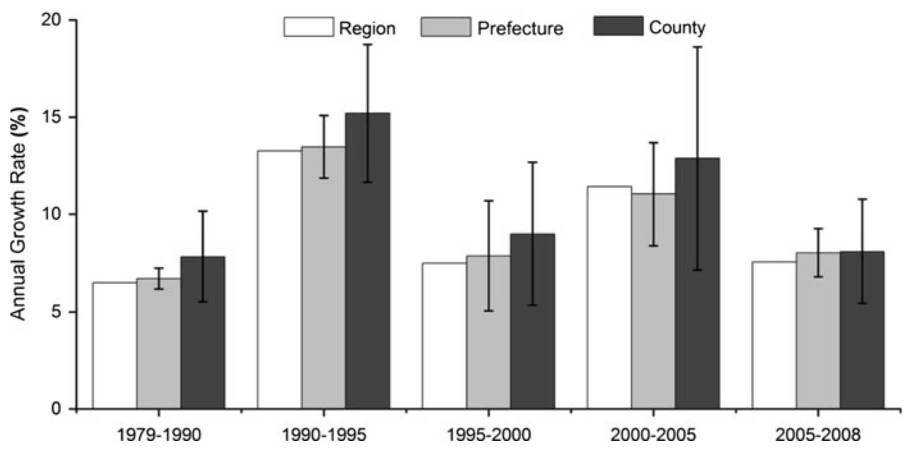


Fig. 4 Annual growth rates of urbanized area at the county, prefectural, and regional levels in the central Yangtze River Delta for five time periods between 1979 and 2008. The values for county and prefectural cities are means, and the associated *bars* indicate the standard deviation

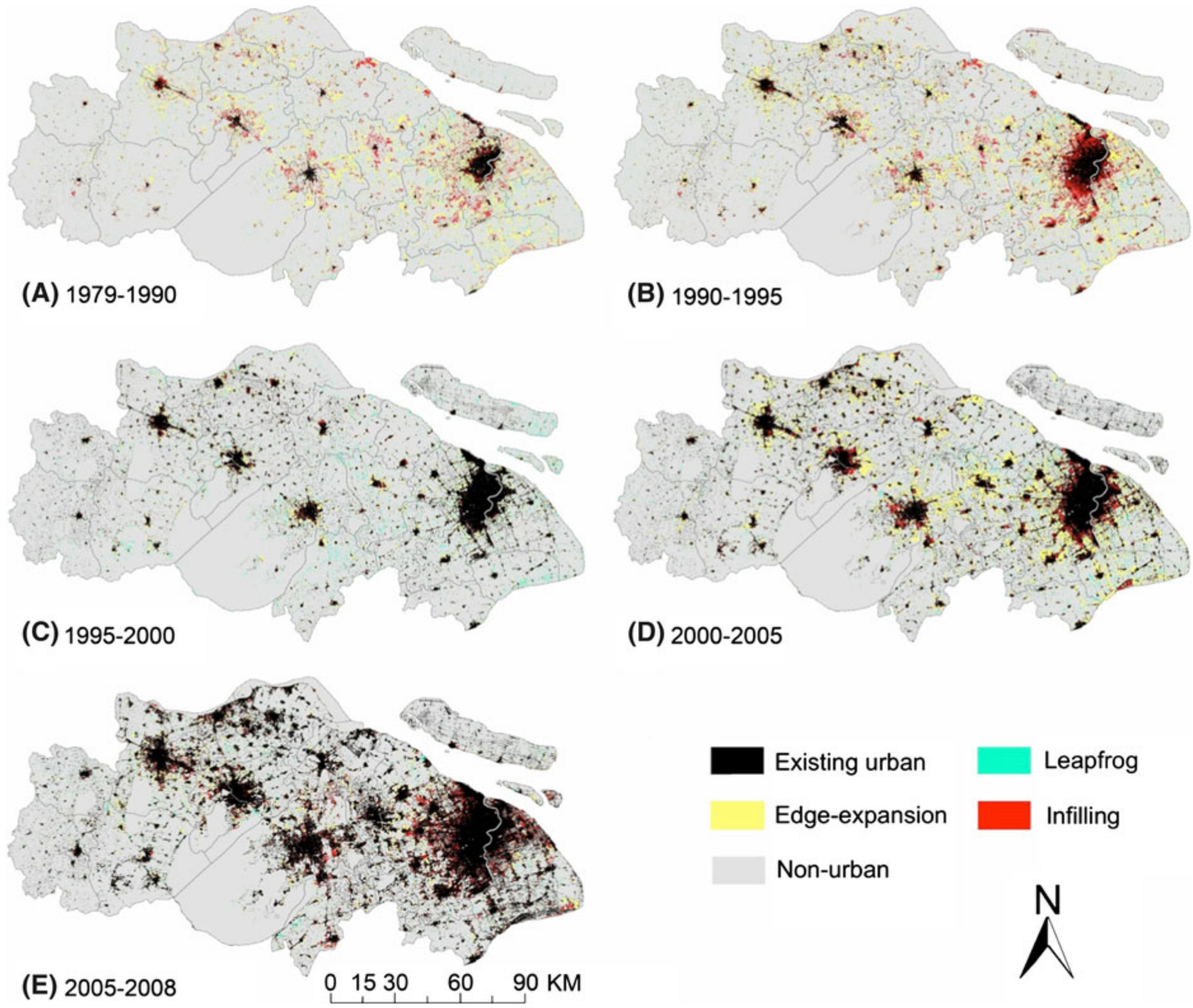


Fig. 5 Spatiotemporal patterns and growth modes (infilling, edge-expansion, and leapfrog) of urbanization in the central Yangtze River Delta region in five time periods between 1979 and 2008

Thus, infilling and leapfrog showed completely opposite trends, while edge-expansion remained relatively important throughout the 30 years. In terms of urbanized land area, however, edge-expansion was dominant during the study period and at all three hierarchical levels, while the general temporal patterns of the other two growth modes were similar to those revealed by patch number (Fig. 6D–F). Infilling and leapfrog again showed opposite trends over time (except for 2005–2008)—exhibiting an alternating pattern in the relative dominance between leapfrog and infilling—with edge-expansion as the most dominant mode from 1979 to 2008 (Fig. 6D–F). We conducted one-way ANOVA with posthoc tests, and the results confirmed the observed temporal switches in urban growth (Fig. S2). The 1990–1995 period did not fit the trend because this period was a transition between the two urban growth phrases, which was corroborated by our ANOVA analysis.

The area-weighted mean expansion index (AWMEI), averaged for all the cities at each hierarchical level, further confirmed the temporal pattern of relative dominance of the three urban growth modes (Fig. 7). The smaller AWMEI values in the periods of 1979-1990 and 1995-2000 reflected the relatively higher dominance by leapfrog development, while the larger values of AWMEI in the periods of 1990–1995, 2000–2005, and 2005–2008 indicated a more compact development due to the increased dominance by infilling (Fig. 7).

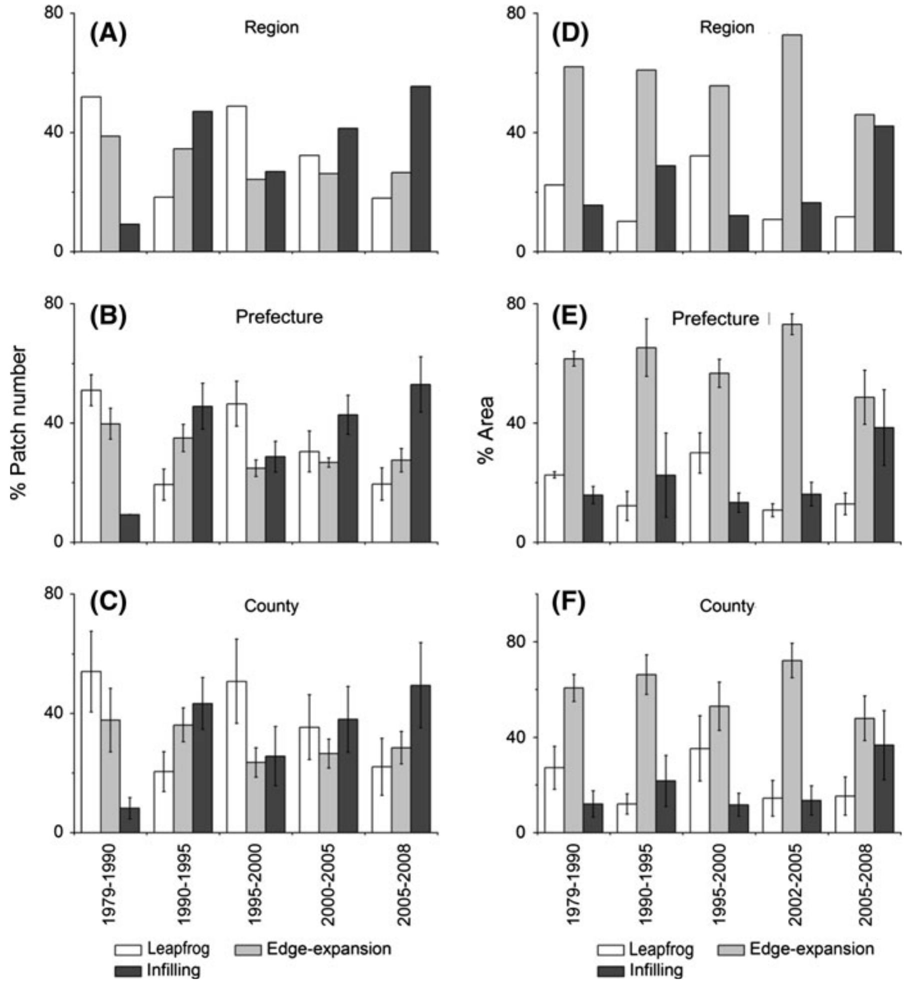


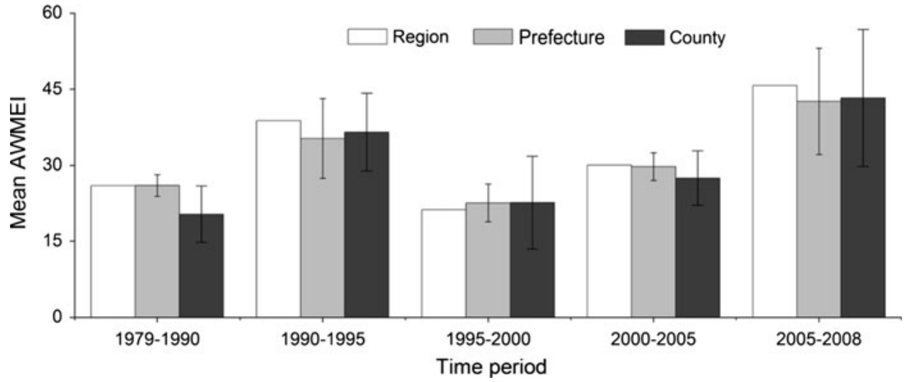
Fig. 6 Changes in the relative dominance of three growth modes (infilling, edge-expansion, and leapfrog) of urbanization at the county, prefectural, and regional levels over five time periods between 1979 and 2008 in terms of the number (**A–C**) and the area (**D–F**) of new urban patches

Changes in landscape pattern during urbanization

To quantify how landscape pattern changed during urbanization, we computed the differences in each landscape metric across the five time periods, i.e., *Difference in landscape metric i = Landscape metric* $i(t_2)$ − *Landscape metric* $i(t_1)$. For a given landscape metric, an increase in its value from t_1 to t_2 leads to a positive difference, and a decreases in its value from t_1 to t_2 results in a negative difference. Our results show that the selected landscape metrics had quite similar trends of change over the five time periods when they were computed at the three levels of urban landscape hierarchy (Fig. 8). The magnitude of change, though, varied among hierarchical levels. The largest changes in PD and LSI were observed at the regional level (Fig. 8A, C); the largest changes in mean patch fractal dimension and mean Euclidean nearest neighbor distance occurred at the county-level (Fig. 8D, E); and the magnitude of changes in ED were comparable among the three hierarchical levels (Fig. 8B).

Over the five time periods, PD and LSI increased considerably between 1979 and 1990, declined slightly between 1990 and 1995, increased again substantially between 1995 and 2000 and moderately between 2000 and 2005, and then decreased again slightly between 2005 and 2008 (Fig. 8A, C). Edge density, with its differences in value being positive for all periods, continued to increase during urbanization (Fig. 8B). These results suggest that, during the 30-year urbanization, the degree of landscape fragmentation (indicated by PD and ED) generally increased, so did the landscape-level structural complexity (indicated by LSI). Different from PD, ED, and LSI, mean patch fractal dimension increased during the first two time periods, but began to decrease after

Fig. 7 Changes in Area-Weighted Mean Expansion Index (AWMEI) at the county, prefectural, and regional levels over five time periods between 1979 and 2008. The values for county and prefectural cities are means, with the associated *bars* indicating the standard deviation



that (Fig. 8D). This means that, in contrast with the increasing landscape-level structural complexity (measured by LSI), the patch-level shape complexity began to decline in late stages of urbanization. Finally, Mean Euclidean nearest neighbor distance was the only metric that continued to decrease over the five time periods (Fig. 8E), indicating an increasing trend in the connectivity of urban patches.

Discussions

Varying speeds at different levels of urban hierarchy

Our study shows that urbanized area in the central region of the Yangtze River Delta increased exponentially over the 30 years from 1979 and 2008 at all three levels of urban landscape hierarchy: counties, prefectures, and the region. The annual growth rate of urbanized area differed among the three hierarchical levels (Fig. 4). That is, urban growth rate was fastest for county-level cities and lowest when measured for the entire region. The variability in area-based urban growth rate also increased from the region to the prefectural and county levels (Fig. 4; Fig. S1). These trends in urban dynamics are conceptually consistent with the predictions of spatially-extended complex systems from the Hierarchical Patch Dynamics (Wu and Loucks 1995; Wu and David 2002). This implies that the observed differences in urban growth rates at the three hierarchical levels were not merely due to the effects of analysis scale (i.e., spatial extent in this case); they were reflective of the hierarchical organization of the urban region under study. Some of the underlying socioeconomic drivers will be discussed below.

Shifting dominance in urban growth modes

By combining newly-developed landscape expansion indices (Liu et al. 2010) and commonly used pattern metrics, we were able to effectively detect and quantify the three common urban growth modes (infilling, edge-expansion, and leapfrog development), their temporal shifts in dominance, and associated changes in landscape pattern in the central YRD region (Figs. 5, 6, 7, and 8). As illustrated in our study, the temporal shifts in the relative dominance of the three urban growth modes revealed by patch number may differ from those discovered by patch area (Fig. 6). This is not a problem, but an opportunity because the two measures provide complementary information. In a sense, the number of new urban patches is indicative of “intensity” or “frequency” whereas the area of new urban patches signifies “footprint” or “extensiveness” of urbanization activities. In addition, the area-weighted mean expansion index also seems effective in quantifying the relative dominance among the three growth modes over different time periods of urbanization (Fig. 7). Our study suggests that using LEI and AWMEI together can facilitate the interpretation of seemingly complicated results.

Several studies have shown that urban growth may exhibit alternate diffusion and coalescence phases, and that landscape metrics can be used to quantify this sequential or cyclic process (Dietzel et al. 2005a, b; Xu et al. 2007; Yu and Ng 2007). For example, this urban growth pattern was found in Houston and several Californian cities in USA (Dietzel et al. 2005a, b), as well as in other Chinese cities, including Nanjing (Xu et al. 2007), Guangzhou (Yu and Ng 2007), and Dongguan (Liu et al. 2010). However, Wu et al. (2011)

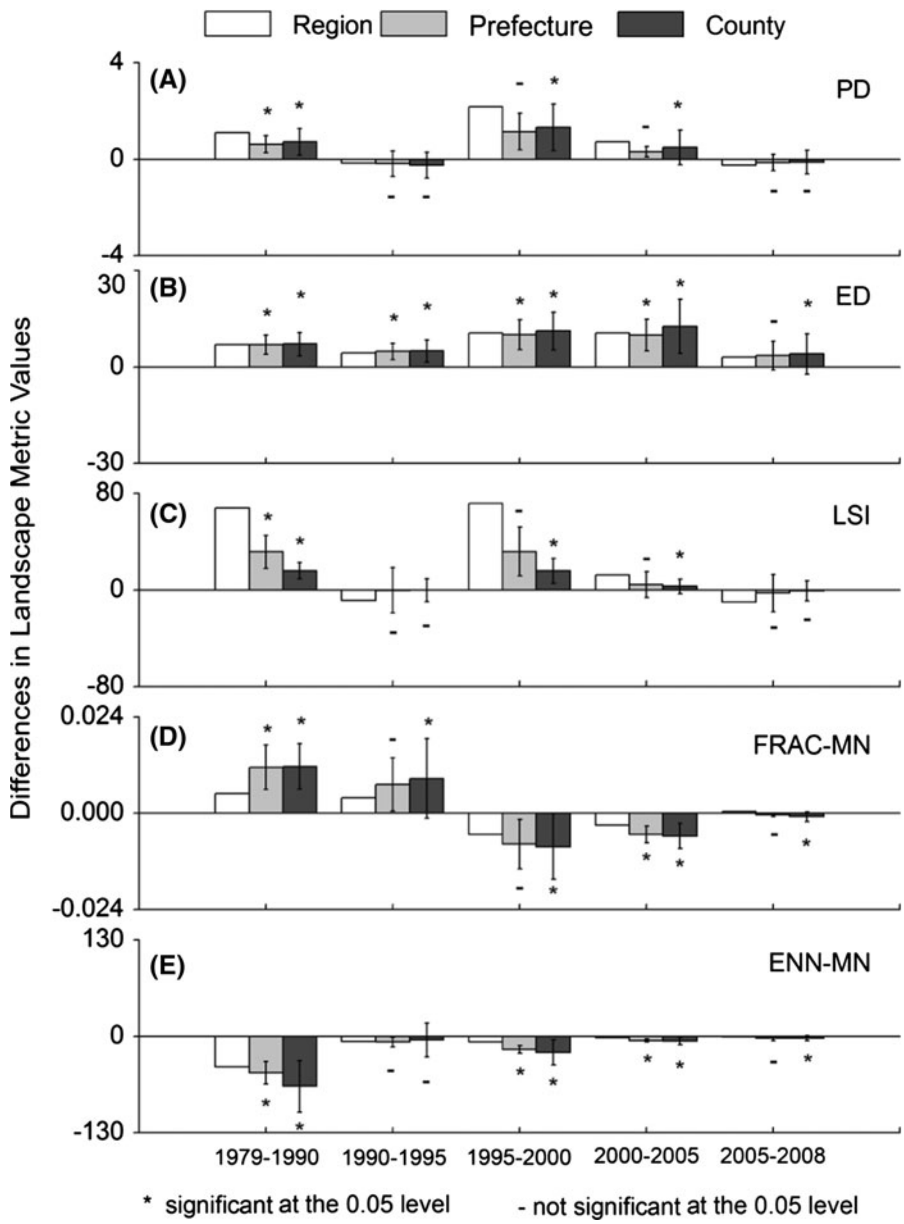


Fig. 8 Changes in landscape pattern metrics at the county, prefectural, and regional levels over five time periods between 1979 and 2008. The values for county and prefectural cities are means, with the associated *bars* indicating the standard deviation

did not find such diffusion-coalescence cyclic pattern in the Phoenix metropolitan region and Las Vegas—the two fastest growing cities in the United States—over a period of about 80 years. While these investigations focused on single cities or urban regions, our study tested this hypothesis simultaneously at three hierarchical urban units. Our results indicate that this wave-like urban growth pattern, to some extent, may manifest at both individual city and urban agglomeration levels. However, our study has illustrated that the two-phase diffusion-coalescence concept can be misleadingly over-simplistic because, in reality, all three urban growth modes operate simultaneously in the same landscape. From Fig. 6 it is evident that, in terms of either the number or the area of new urban patches, "coalescence" would always be dominant if infilling and edge-expanding were lumped together—thus no such thing as "diffusion-coalescence" dynamics. It is more plausible to view urbanization as a spiraling process that involves three growth modes of leapfrogging, edge-expanding, and infilling. In this case, leapfrog and infilling tend to alternate in their relative dominance while edge-expansion is likely to remain its importance throughout much of the urbanization process.

Changes in landscape pattern

The shifts in the relative dominance of the three growth modes apparently have important effects on the spatial pattern of the entire urban landscape. Our study has shown that the relationship between the urban growth modes and resulting changes in landscape pattern is, unfortunately, rather complicated. In general, high urbanization rates tend to increase the values of certain landscape metrics such as PD, ED, and LSI, seemingly corresponding to the dominance of leapfrog development, whereas infilling tends to reduce the values of landscape measures of connectivity (e.g., ENN-MN). However, because all the three types of growth processes take place concurrently in the same landscape and because different metrics are related to different aspects of landscape pattern, the relationships among urbanization rates, the types of urban growth process, and landscape structural changes do not seem predictable in reality.

Jenerette and Potere (2010) found that the temporal variation in urban landscape pattern for 120 cities worldwide decreased over a period of 1990–2000, suggesting that urban landscapes were becoming increasingly homogenous in their spatial pattern. These authors also found that, during the 10 years, PD, ED, LSI, and FRAC_MN all exhibited an increasing trend while ENN_MN and contagion index showed a decreasing trend. With a much longer time series of landscape change, our results also show that the coefficients of variation of the landscape metrics tended to decline over the study period (figures not shown here), corroborating the findings by Jenerette and Potere (2010). As shown in Fig. 8, the temporal variation in specific landscape metrics may decrease or increase, depending on the time scale of analysis. Also, the trends of changes in landscape metrics in response to urbanization are not always monotonic, as illustrated in our analysis. In addition, although the trends of changes in landscape metrics across the three different hierarchical levels seem similar (Fig. 8), as noted earlier, the values of the metrics varied considerably between hierarchical levels—which is expected from many previous urban landscape studies (e.g., Jenerette and Wu 2001; Wu 2004). Thus, whether urban landscapes are becoming more homogenous or heterogeneous is likely to be scale-, metric-, and context-dependent.

Conclusions

The central region of the Yangtze River Delta experienced an exponential increase in urbanized area during the 30 years between 1979 and 2008, epitomizing the rapid urbanization of China fueled by enormous economic development in the past several decades. Our study has shown that the rate of urban growth was progressively higher down the urban hierarchy, from the region to prefectural-level cities and county-level cities. Using a hierarchical approach, our study has demonstrated that a small set of landscape metrics can comprehensively capture the complex spatiotemporal dynamics of urbanization. The speed, growth modes, and landscape structural changes of urbanization were related to each other in general ways, but with high degrees of uncertainties. The process of urbanization was characterized by the wax and wane of infilling, edge-expanding, and leapfrogging growth modes across the landscape. Most cities in the study region seem to have experienced two cycles of the alternate urbanization phases—diffusion and coalescence—during the three decades, but a close scrutiny of the spatiotemporal patterns of urbanization reveals that this dichotomous simplification of urbanization is intriguing but grossly inaccurate. Urbanization is more of a spiraling process in which different growth modes operate concurrently with shifting relative dominance in space and time.

Acknowledgments This research has been supported in part by grants from National Natural Science Foundation of China (No. 30770384), Chinese Ministry of Education (No. 106079), and State Eleventh Five-Year ''211 Project'' to East China Normal University. We thank H. Niu for his assistance with LUCC data, and G. Sun and two anonymous reviewers for valuable comments on an earlier version of the manuscript.

References

Alberti M (2008) Advances in urban ecology: integrating humans and ecological processes in urban ecosystems. Springer, New York

Batty M (2008) The size, scale, and shape of cities. Science 319:769–771

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

Bloom DE (2011) 7 Billion and counting. Science 333:562–569

Blumenfeld H (1954) The tidal wave of metropolitan expansion. J Am Inst Plan 20:3–14

Boyce RR (1966) The edge of the Metropolis: the wave theory analog approach. Br Columbia Geogr Ser 7:31–40

Bürgi M, Hersperger AM, Schneeberger N (2004) Driving forces of landscape change—current and new directions. Landscape Ecol 19:857–868

Buyantuyev A, Gries C, Wu J (2010) Multiscale analysis of the urbanization pattern of the Phoenix metropolitan landscape of USA: time, space and thematic resolution. Landscape Urban Plan 94:206–217

Chan KW (2010) Fundamentals of China's urbanization and policy. China Rev 10:63–94

Chander G, Markham BL, Helder DL (2009) Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. Remote Sens Environ 113:893–903

Chen XL, Zhao HM, Li PX, Yin ZY (2006) Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. Remote Sens Environ 104:133–146

da Silva PM, Berg MP, Serrano ARM, Dubs F, Sousa JP (2012) Environmental factors at different spatial scales governing soil fauna community patterns in fragmented forests. Landscape Ecol 27:1337–1349

Dietzel C, Herold M, Hemphill JJ, Clarke KC (2005a) Spatio-temporal dynamics in California's Central Valley: empirical links to urban theory. Int J Geogr Inf Sci 19:175–195

Dietzel C, Oguz H, Hemphill JJ, Clarke KC, Gazulis N (2005b) Diffusion and coalescence of the Houston Metropolitan Area: evidence supporting a new urban theory. Environ Plann B 32:231–246

Grimm N, Grove JM, Pickett STA, Redman CL (2000) Integrated approaches to long-term studies of urban ecological systems. Bioscience 50:571–584

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. Science 319:756–760

Herold M, Scepan J, Clarke KC (2002) The use of remote sensing and landscape metrics to describe structures and changes in urban land uses. Environ Plan A 34(8):1443–1458

Hoover EM, Vernon R (1959) Anatomy of a metropolis: the changing distribution of people and jobs within the New York metropolitan region. Harvard University Press, Cambridge

Jenerette GD, Potere D (2010) Global analysis and simulation of land-use change associated with urbanization. Landscape Ecol 25:657–670

Jenerette GD, Wu J (2001) Analysis and simulation of land-use change in the central Arizona-Phoenix region, USA. Landscape Ecol 16:611–626

Li JX, Song CH, Cao L, Zhu FG, Meng XL, Wu JG (2011) Impacts of landscape structure on surface urban heat islands: a case study of Shanghai, China. Remote Sens Environ 115:3249–3263

Li JX, Li C, Zhu FG, Song CH, Wu JG (2013) Spatiotemporal pattern of urbanization in Shanghai, China between 1989 and 2005. Landscape Ecol 28: doi: 10.1007/s10980-013-9901-1

Liu JY, Zhan JY, Deng XZ (2005) Spatio-temporal patterns and driving forces of urban land expansion in china during the economic reform era. Ambio 34:450–455

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

Luck M, Wu JG (2002) A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA. Landscape Ecol 17:327–339

McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATS: spatial pattern analysis program for categorical maps, 3.1st edn. University of Massachusetts, Amherst

McKinney ML (2006) Urbanization as a major cause of biotic homogenization. Biol Conserv 127:247–260

National Bureau of statistics (2010) China city statistical yearbook. China Statistics Press, Beijing

Olden JD (2006) Biotic homogenization: a new research agenda for conservation biogeography. J Biogeogr 33:2027–2039

Pickett STA, Burch WR, Dalton SE, Foresman TW, Grove JM, Rowntree R (1997) A conceptual framework for the study of human ecosystems in urban areas. Urban Ecosyst 1:185–199

Pickett STA, Cadenasso ML, Grove JM, Nilon CH, Pouyat RV, Zipperer WC, Costanza R (2001) Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. Annu Rev Ecol Syst 32:127–157

Pontius RG, Millones M (2011) Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. Int J Remote Sens 32:4407–4429

Puyravaud JP (2003) Standardizing the calculation of the annual rate of deforestation. For Ecol Manage 177:593–596

Schneider A, Woodcock CE (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 45:659–692

Seto KC, Fragkias M (2005) Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landscape Ecol 20:871–888

Winsborough HH (1962) City growth and city structure. J Reg Sci 4:35–50

Wu JG (2004) Effects of changing scale on landscape pattern analysis: scaling relations. Landscape Ecol 19:125–138

Wu JG (2008) Making the case for landscape ecology: an effective approach to urban sustainability. Landscape J 27:41–50

Wu J (2010) Urban sustainability: an inevitable goal of landscape research. Landscape Ecol 25:1–4

Wu J, David JL (2002) A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol Model 153:7–26

Wu JG, Loucks OL (1995) From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. Q Rev Biol 70:439–466

Wu J, Jelinski DE, Luck M, Tueller PT (2000) Multiscale analysis of landscape heterogeneity: scale variance and pattern metrics. Geogr Inf Sci 6:6–19

Wu JG, Jenerette GD, Buyantuyev A, Redman CL (2011) Quantifying spatiotemporal patterns of urbanization: the case of the two fastest growing metropolitan regions in the United States. Ecol Complex 8:1–8

Xu C, Liu MS, Zhang C, An SQ, Yu W, Chen JM (2007) The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China. Landscape Ecol 22:925–937

Xu C, Liu MS, Hong C, Chi T, An SQ, Yang XJ (2012) Temporal variation of characteristic scales in urban landscapes: an insight into the evolving internal structures of China's two largest cities. Landscape Ecol 27:1063–1074

Yu XJ, Ng CN (2007) Spatial and temporal dynamics of urban sprawl along two urban-rural transects: a case study of Guangzhou, China. Landscape Urban Plan 79:96–109

Zha Y, Gao J, Ni S (2003) Use of normalized difference bulit-up in automatically mapping urban areas from TM imagery. Int J Remote Sens 24:583–594

Zhang C, Wu JG, Grimm NB, McHale M, Buyantuyev A (2013) A hierarchical patch mosaic ecosystem model for urban landscapes: model development and evaluation. Ecol Model 250:81–100