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Landscape Ecology

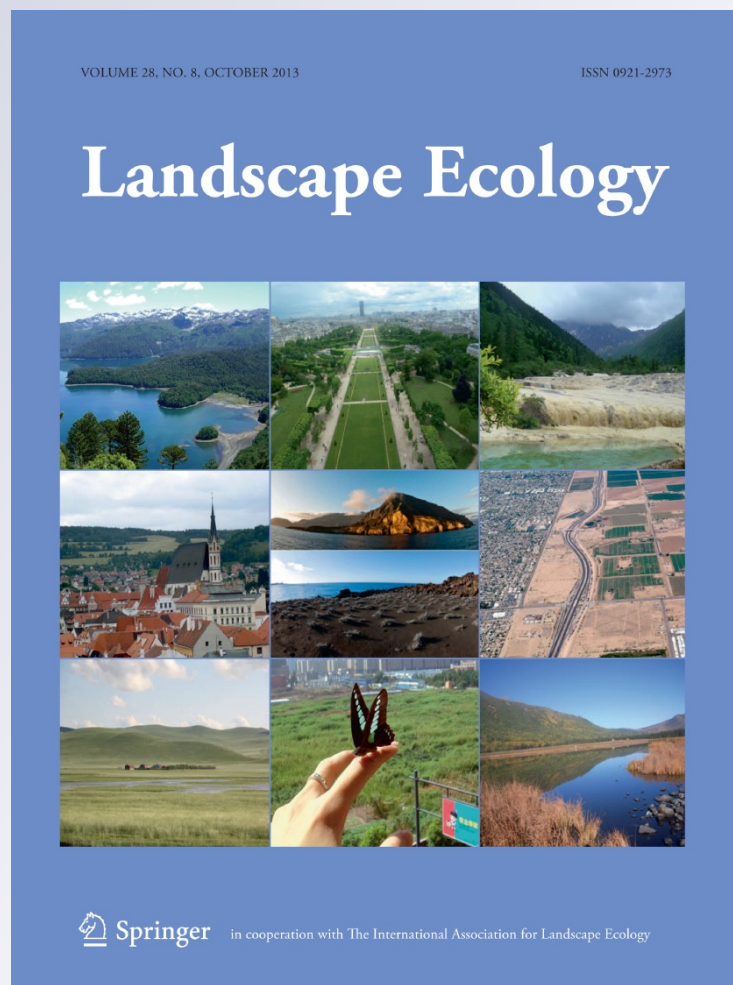
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Spatiotemporal pattern of urbanization in Shanghai, China between 1989 and 2005

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Abstract Quantifying the spatiotemporal pattern of urbanization is necessary to understand urban morphology and its impacts on biodiversity and ecological processes, and thus can provide essential information for improving landscape and urban planning. Recent studies have suggested that, as cities evolve, certain general patterns emerge along the urban–rural gradient although individual cities always differ in details. To help better understand these generalities and idiosyncrasies in urbanization patterns, we analyzed the spatiotemporal dynamics of the Shanghai metropolitan area from 1989 to 2005, based on landscape metrics and remote sensing data. Specifically, the main objectives of our study were to quantitatively characterize the spatiotemporal patterns of urbanization in Shanghai in

recent decades, identify possible spatial signatures of different land use types, and test the diffusion coalescence hypotheses of urban growth. We found that, similar to numerous cities around the world reported in previous studies, urbanization increased the diversity, fragmentation, and configurational complexity of the urban landscape of Shanghai. In the same time, however, the urban–rural patterns of several land use types in Shanghai seem unique—quite different from previously reported patterns. For most land use types, each showed a distinctive spatial pattern along a rural–urban transect, as indicated by landscape metrics. Furthermore, the urban expansion of Shanghai exhibited an outward wave-like pattern. Our results suggest that the urbanization of Shanghai followed a complex

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diffusion–coalescence pattern along the rural–urban transect and in time.

Keywords Landscape pattern · Landscape metrics · Gradient analysis · Urbanization · Thematic resolution · Urban growth hypothesis

Introduction

More than 50 % of the world population now live in urban areas, and urban population is projected to reach 6.3 billion in 2050, most of which will reside in less developed countries (UNPD 2012). Urbanization profoundly alters the spatial pattern and structure of natural landscapes, consequently affecting the sustainability of ecosystems far beyond the boundaries of cities (Luck and Wu 2002; Grimm et al. 2008). Thus, it is important to understand spatial patterns of urbanization and their impacts on ecological processes.

McDonnell and Pickett (1990) introduced the urban–rural gradient approach to study urban ecosystems, and this approach was further integrated with landscape pattern metrics (Luck and Wu 2002). Gradient analysis with landscape metrics has been widely used to characterize urbanization patterns and help understand urban ecological processes (López et al. 2001; McDonnell and Hahs 2008; Haase and Nuissl 2010). To better understand the urban landscape dynamics and their socioeconomic drivers, landscape pattern analysis with time series data of urban development is needed (Jenerette and Wu 2001; Seto and Fragkias 2005; Pickett et al. 2011).

A number of theories of urban morphology have been developed, but further testing is needed with more detailed data on spatiotemporal patterns of urban growth (Batty 2002; Dietzel et al. 2005a). Previous studies revealed that urban growth exhibited a spatial–temporal pattern of wave characteristic (Blumenfeld 1954) or wave-like profile (Newling 1969) in response to the growth of urban population. Based upon these theories, Dietzel et al. (2005a) recently proposed a hypothetical two-stage urban growth model: diffusion and coalescence based on studies conducted in the Central Valley of California. However, this hypothesis has been tested only in part in a few other studies (Yu and Ng 2007; Wu et al. 2011). A recent study analyzed global urban land use patterns for 120 cities did not support the hypothesis of diffusion and coalescence

dichotomy (Jenerette and Potere 2010). Therefore, its generality needs further examination. Shanghai, the biggest city in China, is undergoing rapid urbanization, and is in similar stage as those in the case studies. Therefore Shanghai could serve as a good example to further test the generality of the diffusion–coalescence hypothesis.

Studies on urbanization with remotely sensed data are usually based on coarse thematic resolution, i.e., binary urban and nonurban classes, to characterize its spatial patterns (Seto and Fragkias 2005; Weng 2007; Xu et al. 2007). In reality, urban landscapes are mosaics of numerous land use/cover types, each of which is associated with vital social and ecological functions, including but not limited to, residential, commercial, industrial, recreational areas (Wu et al. 2011). Therefore, coarse thematic resolution may not reveal the intrinsic connection between landscape patterns and ecosystem processes. Recent studies showed that thematic resolution can significantly affect landscape pattern analysis (Bailey et al. 2007; Buyantuyev and Wu 2007; Castilla et al. 2009). Urban landscape and ecosystem are characterized by their high spatial heterogeneity. The characterization of ecosystem structure, diversity and functions at finer spatial and temporal scales is increasingly desired (Wulder et al. 2004). To acquire finer thematic information, higher spatial resolution remotely sensed data are needed to enhance thematic accuracy (Mumby et al. 1997; Mumby and Edwards 2002). With the increased availability of various high spatial resolution remote sensing data, it is feasible to extract more detailed information of urban ecosystem and landscape (Blaschke et al. 2011) to facilitate the increasingly sophisticated urban ecosystem research. For instance, urban landscape structure in high spatial (2.5 m) and thematic (8 categories) resolutions can help accurately identify factors contributing to surface urban heat island (Li et al. 2011). Therefore, analysis with finer spatial and thematic resolution data provides an improved understanding of the relationship between landscape patterns and ecosystem processes.

As the largest city in China with a history of over 700 years, Shanghai has witnessed rapid economic growth and urban development in the past two decades since China adopted new policies to further develop Shanghai into an international center for economy, finance and trade in the early 1990s (the Master urban planning of Shanghai, 1999–2020). Shanghai has had

the highest degree of urbanization in China since 2008 with a gross domestic production (GDP) of about US\$215 billion a year, accounting for 4.49 % of China's GDP. Its urbanization intensity and spatial extent are unrivaled in China. Therefore, Shanghai provides a suitable case to understand urbanization patterns and processes in general.

In this study, we take advantage of a rare dataset of high spatial resolution remotely sensed data over Shanghai at multiple times to quantify the city's spatiotemporal patterns of urbanization from 1989 to 2005, using gradient analysis of landscape metrics. These images capture the most dynamic urban expansion of Shanghai in history, offering a rare opportunity to study the spatiotemporal pattern of rapid urbanization of megacities. The images had previously been classified into detailed urban land-cover/land-use classes, which would not be possible with coarser spatial resolution data, such as Landsat imagery. We addressed the following questions in this study: (1) What are the spatiotemporal patterns of the major land-use types along an urban–rural transect? (2) How do the spatial signatures of different land use types in high spatial and thematic resolutions compare with those identified in literature? (3) Does the urban growth pattern of Shanghai conform to the diffusion–coalescence hypothesis for urban growth?

Study area

Our study area encompasses the entire territory of Shanghai, covering 6,340.5 km². The Shanghai metropolitan region (30°40'–31°53'N, 120°51'–122°12'E) situates on the eastern edge of the Yangtze River Delta, with Yangtze River bound the north, the East China Sea the east, the Hangzhou Bay the south, and Jiangsu and Zhejiang provinces as its western neighbors (Fig. 1). The average elevation of Shanghai is about 4 m above the sea level because the vast majority of its territory belongs to a flat alluvial plain with a few exceptions of remnant hills in the southwest. Shanghai is located in the northern subtropical monsoon climate zone with a mean annual temperature of 16.0 °C, and a mean annual precipitation of 1,158.1 mm (1951–2008, data courtesy from the Central Weather Bureau of China). Its characteristic native vegetation includes subtropical evergreen broadleaf forest and evergreen broadleaf and deciduous broadleaf mixed forest (Zhou 1984; Gao 1997).

As the largest city in China, Shanghai has experienced a rapid economic development since the beginning of the 1990s. Its registered population grew from 10.98 million in 1978 to 13.79 million in 2009 (or 19.21 million including the non-registered rural-to-urban migrants). Shanghai's GDP increased from 27.28 billion RMB in 1978 to 1,504.65 billion RMB in 2009 (~US\$215 billion) (Shanghai Municipal Statistics Bureau, SMSB) (2010). There is no sign that the rapid urbanization in the Shanghai metropolitan region will slow down in the near future.

Methods

Land use/land cover classification

Land use data were derived from a time-series of false-color infrared aerial photos acquired in 1989, 1994, 2000 and 2005, respectively. The photogrammetric scale is 1:50,000, and the spatial resolution was set to 2.5 m when the photos were digitized. These aerial photos were then georeferenced to the Shanghai local geographical coordinate system and were mosaicked to cover the entire Shanghai metropolitan area (done by the Shanghai City Development Research and Information Center). Forty-eight land use/land cover classes (Table 1) were identified according to the criteria of ecological land use classification scheme (Li et al. 2004). The vector land use dataset was created by digitizing aerial photos with visual interpretation using ArcInfo GIS (version 9.0, ESRI). First, the georeferenced aerial photos were imported into the ArcGIS platform, then each patch of land-use/land-cover type in the photos were delineated as a polygon through visually interpretation, and the corresponding land-use/land-cover type for the polygon was recorded as an attribute. After the visual interpretation, we carried out an accuracy assessment. We first generated a 3 × 3 km grid over the whole study area and randomly selected one site for each grid. We collected 576, 577, 577 and 573 samples for the 2005, 2000, 1994, and 1989 maps, respectively. We did not collect samples on the islands of Chongming, Changxing and Hengsha as well as the isles in the sea. We checked each site on the original images with field survey if necessary. The overall accuracy for 2005, 2000, 1994 and 1989 are 93.9, 95.3, 95.8 and 96.3 percent, respectively. For the analysis of structural characteristics of the Shanghai metropolitan

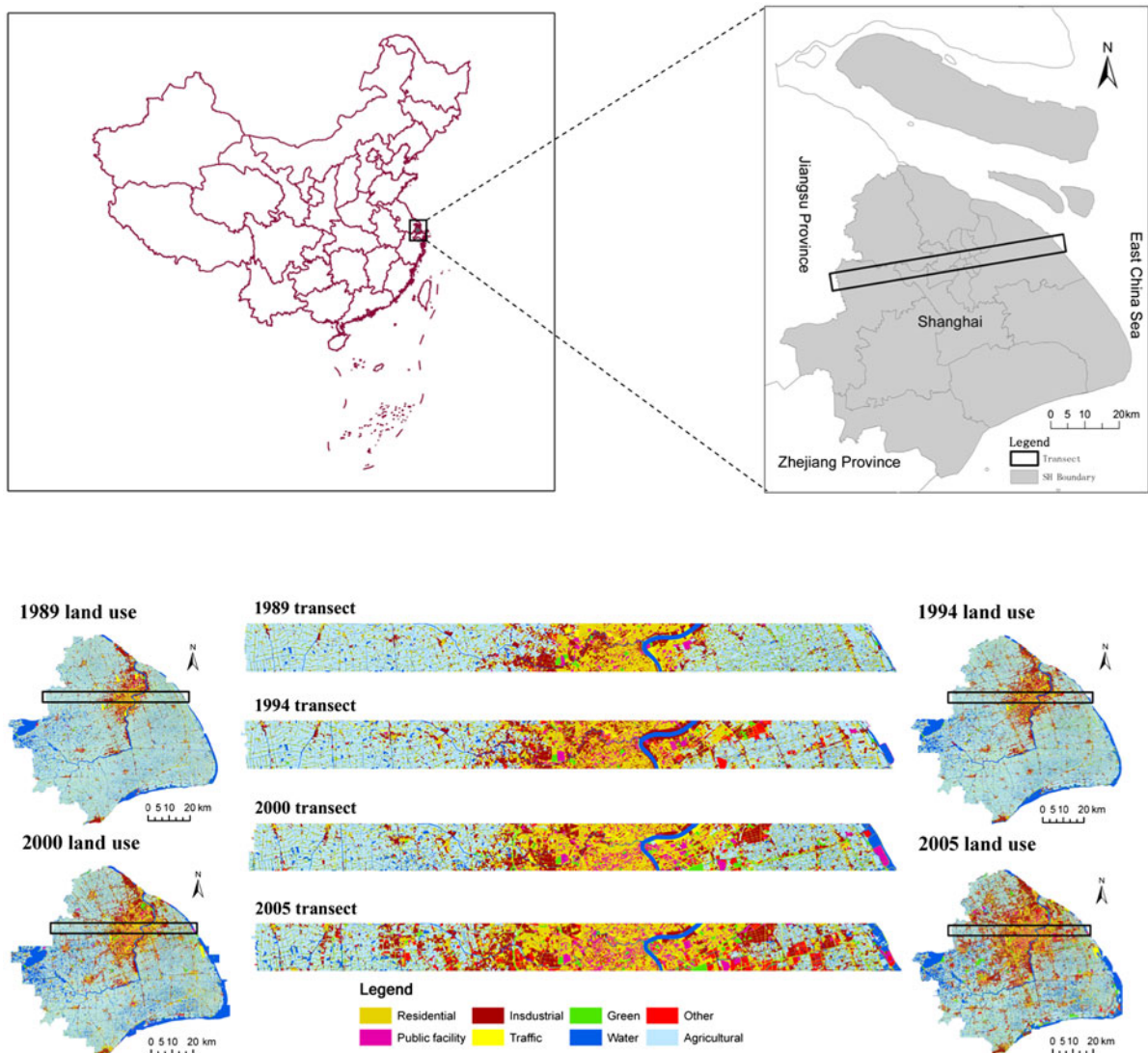


Fig. 1 Location map of the study area and land use map of Shanghai metropolitan region. The transect is oriented East–West, cutting across the city center

landscape, the 48 land-use/land-cover classes were aggregated into 8 broader categories: agriculture, industry, residential, public facility (PF), water, green land, traffic, and the others (see Table 1 for detailed descriptions). The original vector data were then converted to raster grids with a spatial resolution of 5×5 m.

Landscape pattern metrics selection

Numerous pattern metrics have been developed to characterize landscape patterns, and many of them are

frequently used to quantitatively measure spatiotemporal dynamics of urban landscape (Herold et al. 2002, 2003; Seto and Fragkias 2005; Schneider and Woodcock 2008). However, landscape metrics are, to a large extent, related to each other, therefore, minimal indicators was encouraged to be used to characterize the urban landscape patterns and/or forms (Schwarz 2010). Although previous studies utilized various landscape metrics to measure different aspects of urban landscape, major concerns on urban landscape patterns focus on size, density, shape, edge, clustering, diversity/evenness, connectivity, and compactness. For instance, Dietzel

Table 1 Land use reclassification scheme

Reclassified landscape type	Original land use type
Agriculture (AG)	Farmland
	Vegetable plot
	Orchard
	Nursery
Green land (GR)	Forest
	Shrub
	Grass land
	Park
	Botanic garden, zoo garden
	Natural conserve
Water (WA)	Green space around rural area
	River and aqueduct
	Lake and reservoir
	Pond and aquafarm
Residential (RE)	Tidal flat and wetland
	Old house (low-rising old and humble house with green cover less than 10 %)
	Low-rise buildings (under 6 stories)
	LR-1: low-rising house (less than 7 stories) with green cover less than 10 %
	LR-2: low-rising house with green cover between 10 and 30 %
	LR-3: low-rising house with green cover between 30 and 50 %
	LR-4: low-rising house with green cover over 50 %
	High-rise buildings (7–18 stories)
	HR-1: high-rising house with green cover less than 10 %
	HR-2: high-rising house with green cover between 10 and 30 %
	HR-3: high-rising house with green cover between 30 and 50 %
	HR-4: high-rising house with green cover over 50 %
	Superhigh-rise buildings (Over 18 stories)
	SR-1: superhigh-rising house with green cover less than 10 %
	SR-2: superhigh-rising house with green cover between 10 and 30 %
	SR-3: superhigh-rising house with green cover between 30 and 50 %
SR-4: superhigh-rising house with green cover over 50 %	
Garden houses and Villa	
Rural residence	

Table 1 continued

Reclassified landscape type	Original land use type
Public facility (PF)	The administrative organization
	Commercial and financial
	Cultural and sports
	Hospital
Industry (IN)	Education and research institute
	Public utilities
	Heavy industrial
	Light industrial area
Traffic (TR)	High-tech industry
	Warehouse
	Railway
Other (OT)	Road
	Harbor
	Airport
	Construction site
	Special land use type i.e., jailhouse, military, cemetery
	Human historical relic
	Natural historical relic

et al. (2005a) employed 8 landscape metrics to evaluate urban growth dynamics for four medium-sized cities in the Central Valley of California, USA, and they further tested the diffusion–coalescence hypothesis for urban growth with these metrics. Schwarz (2010) identified six main factors concerning the size, density, clustering, evenness in size, edge density (ED), and compactness to characterize the urban forms of 231 European cities. To quantify the spatial patterns of urbanization in Shanghai, and for easy comparisons with other studies, similar landscape pattern metrics were selected in this study, including percentage of landscape (PLAND), patch density (PD), mean patch size (Area-MN), ED, largest patch index (LPI), Euclidean mean nearest neighborhood distance (ENN-MN), area-weighted mean patch fractal dimension (FRAC-AM), contagion (CONTAG), and Shannon’s diversity index (SHDI). All the metrics were calculated using FRAGSTATS 3.3, as described in McGarigal et al. (2002).

Landscape metrics analysis

There are two ways to implement an urban–rural gradient analysis with landscape metrics. One is

transect-based approach, in which a transect of landscape is delineated from the urban center to rural area, using a moving window to calculate landscape metrics (Schneider et al. 2005). The other is based on the buffer zones, with which landscape pattern metrics are derived for a series of concentric zones with respect to the urban center (Seto and Fragkias 2005). We performed a set of gradient analyses based on the landscape pattern metrics along an East–West transect running through the Shanghai metropolitan area (Fig. 1). We selected this direction because the west–east orientation is the master axis of urban planning and development of Shanghai and is the most representative of urban-to-rural gradient that includes the urban core, the fastest urbanizing region of Pudong New Areas and vast rural hinterland in Shanghai. The transect, which encompasses all land use types in the city, is 65 km in length and 5 km in width, and is composed of 28 blocks. Each block is 5×5 km in size with 2.5 km overlap with neighboring blocks. The blocks were designed to facilitate the analysis of spatiotemporal patterns along the urban–rural gradient over time without restrictions from the administrative boundaries. Landscape pattern metrics at both class and landscape levels were computed for each block in sequence along the transect. This procedure can smooth out noise caused by fine-scale and possible local variations (Luck and Wu 2002).

Results

Urbanization pattern at the metropolitan landscape level

Between 1989 and 2005, the total area of agriculture decreased by more than half from 17,993.7 ha (54.6 % of the region) to 8,948.1 ha (26.7 % of the region), whereas the total area for each of the remaining 7 land use types increased, indicating their expansion is at the expense of agricultural land. The land use types that almost doubled their area from 1989 to 2005 include PF, industry, traffic, and green space (Fig. 2a). The mean patch size of agriculture, water, green space and traffic decreased gradually, whereas the mean patch size of PF, industrial and residential decreased first from 1989 to 1994 and then increased from 1994 to 2005 (Fig. 2b). PD increased with time for all land use types. The ranking of PD is residential > agricultural > green

space > water > industrial > PF > traffic > other in 1989, but it changed to green space > residential > traffic > agricultural > industrial > water > PF > other in 2005 (Fig. 2c). Similar to PD, ED (Fig. 2d) also increased for most land use types (except for water and agriculture) from 1989 to 2005. While area-weighted mean patch fractal dimension (Fig. 2e) decreased except for green space and water, meaning sustained urbanization results in the simplification of shapes for most land-use types. The LPI kept decreasing for most land use types except for PF, traffic and water (Fig. 2f).

At the landscape level, mean patch size (Fig. 3a) decreased rapidly in the central urban area and rural areas during urbanization. Mean patch size exhibited a multi-peak pattern in the earlier stage, but showed a bimodal pattern and increased gradually from rural to suburban areas. PD (Fig. 3b) exhibited a nearly complete opposite spatial pattern. In this study, the mean patch size and PD exhibited inverse pattern along the transect on both sides of the urban center. This is because of the high watercourse density (3.38 km/km^2), which measures the total length of watercourse within a unit ground area (Li et al. 2004), and increased road density dissected the homogeneous agriculture landscape into smaller patches. Similar situation due to topographically fragmented landscape was reported in Dane County, Wisconsin, USA (Weng 2007). Mean Euclidian nearest neighborhood (ENN-MN) distance should decrease with urbanization at diffusion stage, while ENN-MN increases because of coalescence of adjacent urban areas (Dietzel et al. 2005b). From 1989 to 1994, ENN-MN decreased along the entire transect, indicating urban diffusion. This was mainly due to the addition of large new urban development units. But from 1994 to 2000, the suburban areas and the western rural areas demonstrate coalescence characteristics in ENN-MN, while the eastern rural areas are in the mode of diffusion. From 2000 to 2005, the whole transect is in the diffusion mode again, perhaps as a result of renewed urban expansion beyond their original boundaries. Therefore, the diffusion–coalescence process in Shanghai is not unidirectional in time, but an iterative process. These processes can also be seen based on changes in PD (Fig. 3b) and mean patch size (Fig. 3a) along the transect over time. Increase in PD and decrease in mean patch size are associated with diffusion, and the opposite pattern with coalescence. One may expect that further urbanization will lead to

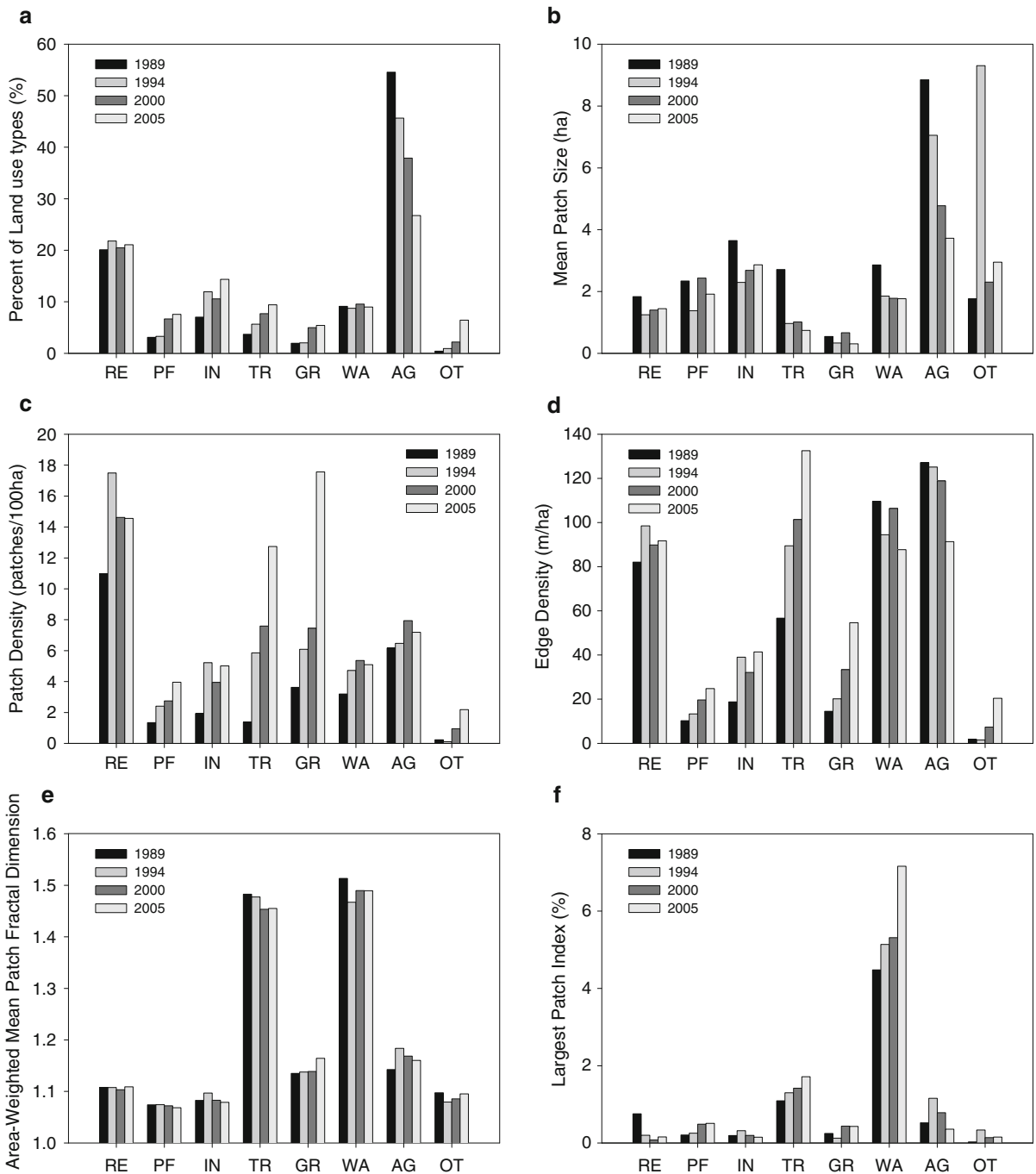


Fig. 2 Synoptic landscape characteristics of the East–West transect from 1989 to 2005 (*RE* residential land use, *PF* public facility, *IN* industrial land use, *TR* traffic land use, *OT* the other land use, *AG* agricultural land use, *GR* urban green land use, and *WA* water)

coalescence in the recently developed area from diffusion. The iterative diffuse–coalescence pattern of urbanization we observed in Shanghai is very different from the unidirectional diffusion–

coalescence pattern observed in Huston, USA by Dietzel et al. (2005b).

The area-weighted mean patch fractal dimension (Fig. 3d) depicted a different change patterns along

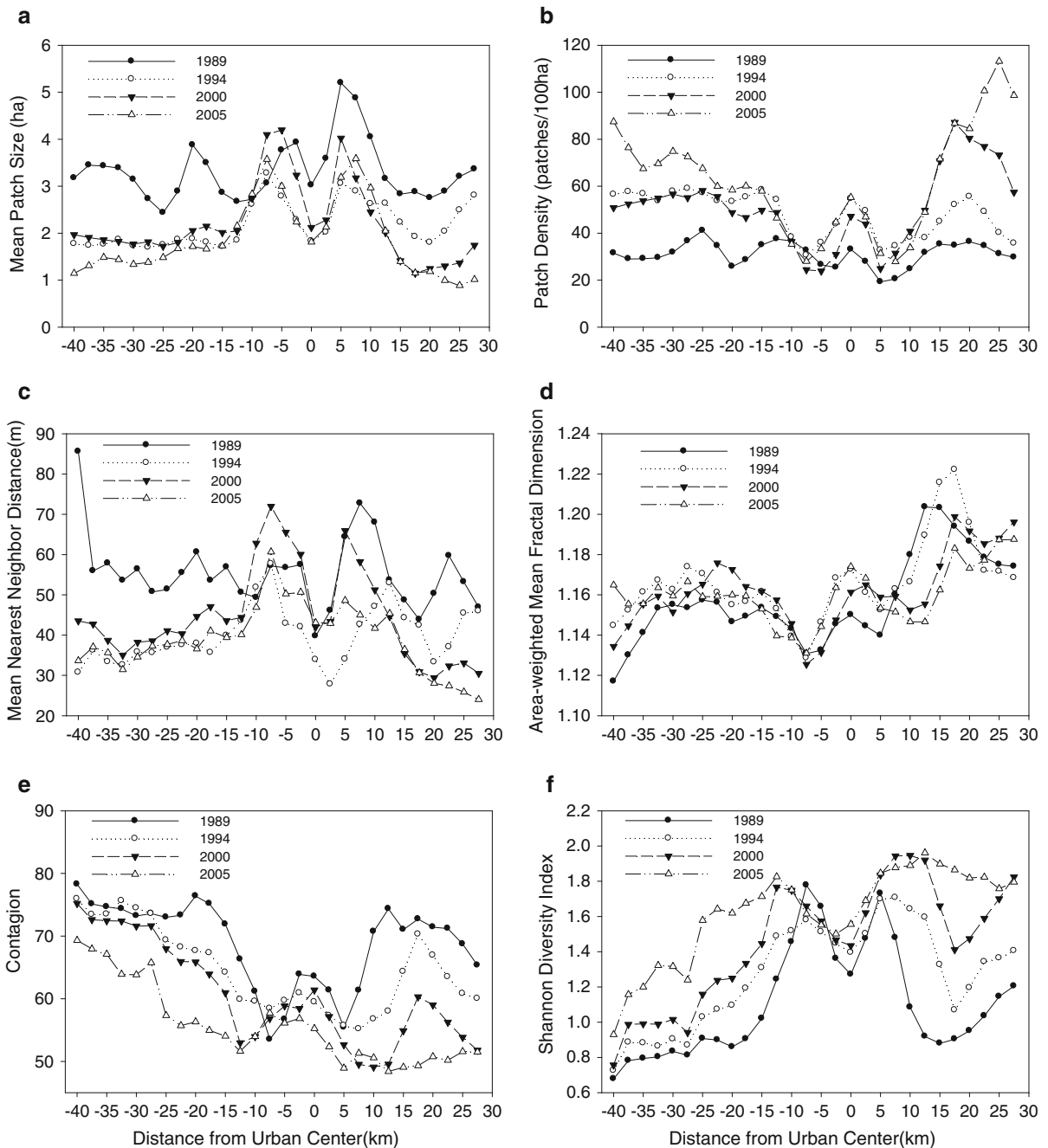


Fig. 3 Landscape pattern metrics at landscape level along the East–West transect across metropolitan Shanghai

the transect. It was relatively high in urban core area and western rural area over time, and the highest in Pudong New Area in the eastern suburb. This indicates that urbanization first resulted in a complex-shaped landscape, later a simpler one would emerge with advanced urbanization. It should be noted that the

values of the fractal dimension presented increase in the urban core demonstrating a shape-complex landscape, which is different from previous studies (Yu and Ng 2007; Xu et al. 2007). This may due to our high thematic resolution remotely sensed data that enabled us identify more detailed land-use/land-cover types,

such as the various residential, public facilities, etc., revealing the urban landscape dynamics caused by the urban renewal in the central urban area. In the early stage of urbanization, the pattern of contagion index showed two valleys in the suburban areas (Fig. 3e), indicating a highly fragmented and heterogeneous landscape at the urban fringe, which spans the transition zone between the urban areas and the surrounding countryside (Theobald 2001), while the rural areas with larger and relatively homogeneous landscape possessed a high contagion index. From rural to urban area, the contagion index decreased gradually as landscape fragmentation increases with increasing urbanization. As urbanization and urban sprawling continue, the valleys of the contagion index moved outward with time. This is especially conspicuous in Pudong New Area where rapid urbanization took place during the study period. Contrary to the patterns of contagion index, SHDI (Fig. 3f) exhibited a clear bimodal pattern in space with the urban center having relatively low values but increasing over time similar to fractal dimension in the urban center, and the transition zone between urban core and suburban areas having the highest value. There is significant increase in SHDI in the rural area with time, indicating increase in landscape complexity as urbanization encroaches in.

Urban landscape pattern at the class level

At the class level, percent landscape, ED, PD, area-weighted mean patch fractal dimension, and mean patch size were calculated for the 28 blocks along the transect. The signature of these metrics was mapped for each land use types from west to east along the transect as presented below.

The percent agricultural land, as expected, decreased gradually from rural to suburban, then sharply decreased to zero from the suburban to the urban center. The shape of the trajectory of percent agricultural land varied with distance from the urban center along the transect, showing that the urban fringe had been sprawling into the surrounding agricultural land over time (Fig. 4a). The span of the urban fringe was <5 km in 1989 but expanded to approximately 15 km in 2005. Urbanization of Shanghai has decreased the agricultural land dramatically during the study period. Most of the decrease occurred in suburban area, and this decrease is moving increasingly outward along

the urban–rural gradient. The loss of agricultural land in the east was faster than that in the west probably due to the limited space available. The mean patch size (Fig. 4b) and LPI (Fig. 4f) for agricultural land continued to decrease in suburban and rural areas from 1989 to 2005, indicating a decline of agricultural land dominance. The PD (Fig. 4c) kept decreasing in the areas from urban center to suburban, meaning that agricultural land was still being encroached, but PD doubled in the west and east rural areas, indicating urbanization has resulted in dramatic fragmentation of agricultural landscape over time. The ED (Fig. 4d) and the area-weighted mean patch fractal dimension (Fig. 4e) both decreased in suburban areas along the transect over time, while in the west and east rural areas they exhibited an increasing trend first, and then a decreasing one over time. Urbanization first led to increase in shape complexity of agricultural land, then decrease later.

The proportion of green land (Fig. 5a) in central urban area decreased from 1989 to 2000, and increased from 2000 to 2005 due to the urban renewal and greening campaign initiated by the Shanghai municipal government during the urbanization processes since 1996, while in suburban and eastern rural areas, the percentage value increased gradually over time. This was particularly obvious in the eastern section of the city where the Pudong New Area locates. The increase was unprecedented. In the western rural area (−40 ~ −20 km), the percentage decreased in the earlier stage of urbanization and increased later as some agricultural lands were transformed into green areas such as garden nursery and public gardens. The mean patch size (Fig. 5b) of green land continue to decrease along the transect over time except in the eastern suburban area where mean patch size kept increasing. The PD (Fig. 5c) and ED (Fig. 5d) and the area-weighted mean patch fractal dimension (Fig. 5e) showed similar spatiotemporal patterns. The trajectories of above landscape metrics and their variations revealed a high degree of spatiotemporal dynamics for green space caused by the human activities. But closer examination and comparison of the green spaces among the historical aerial photos show that the decrease of urban green in the earlier urbanization stage was mainly natural or semi-natural green spaces, such as woodlands and riparian forest patches, while the increased green spaces later on were almost all artificial green spaces. The LPI (Fig. 5f) does not

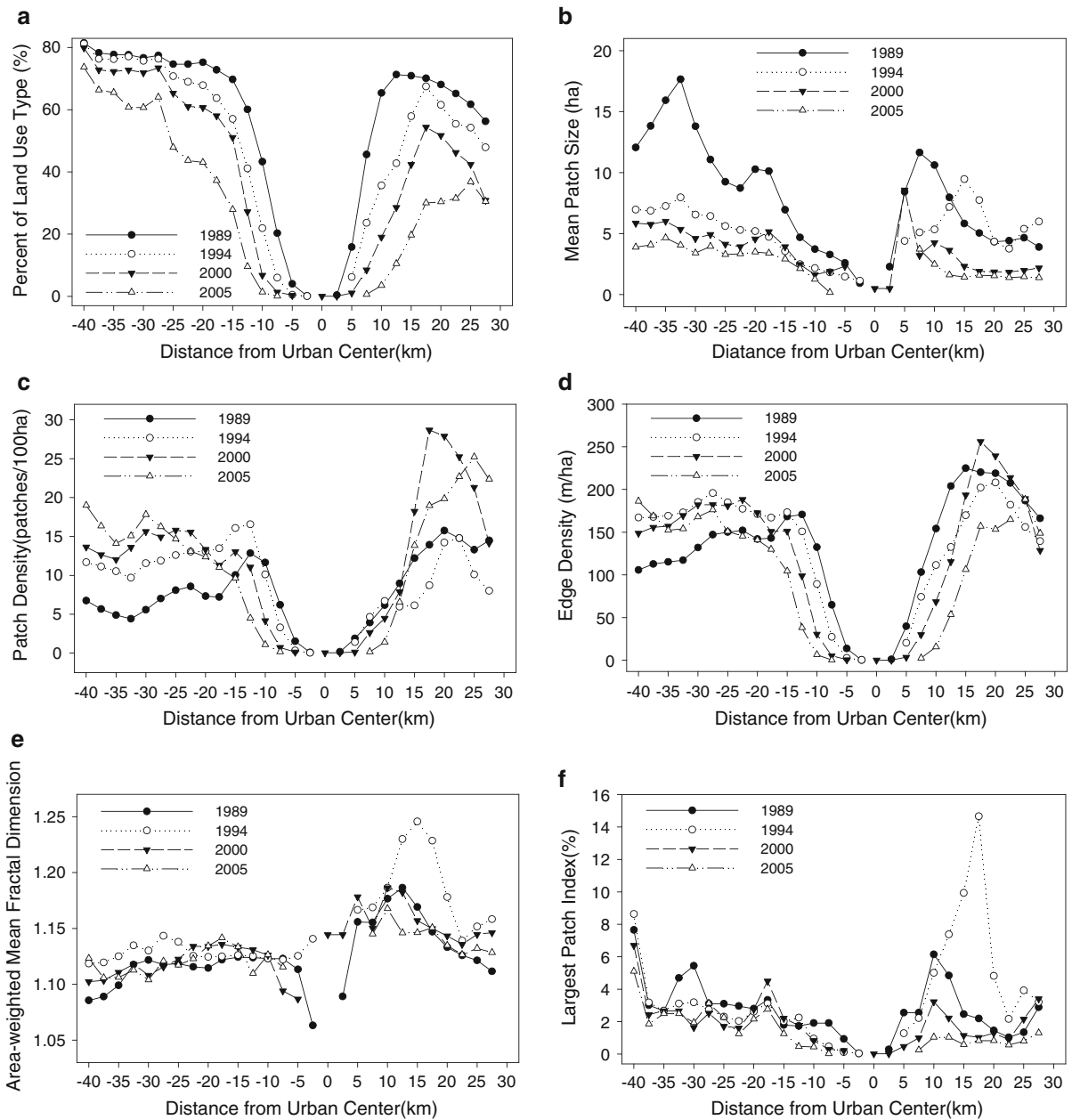


Fig. 4 Landscape pattern metrics for agricultural land along the East–West transect from 1989 to 2005

change very much with time along the transect, except a sudden jump in the eastern suburban area in the east in 2005 because of the establishment of the large park of the Outer Ring Road greenbelt, and significant decrease in the far end of the transect to the east.

The percent residential land use (Fig. 6a) grew monotonically from rural to urban areas and peaked in the urban center, but the peak waned over time as other

land use types entered the scene and/or some of the old residential house were demolished during the urban renewal. In the meantime, percent residential land use steadily increased and expanded outward from 1989 to 2005 in the western suburban areas near the city center, indicating that the population gradually moved from central urban to suburban possibly because of both price and space limitation in the central urban

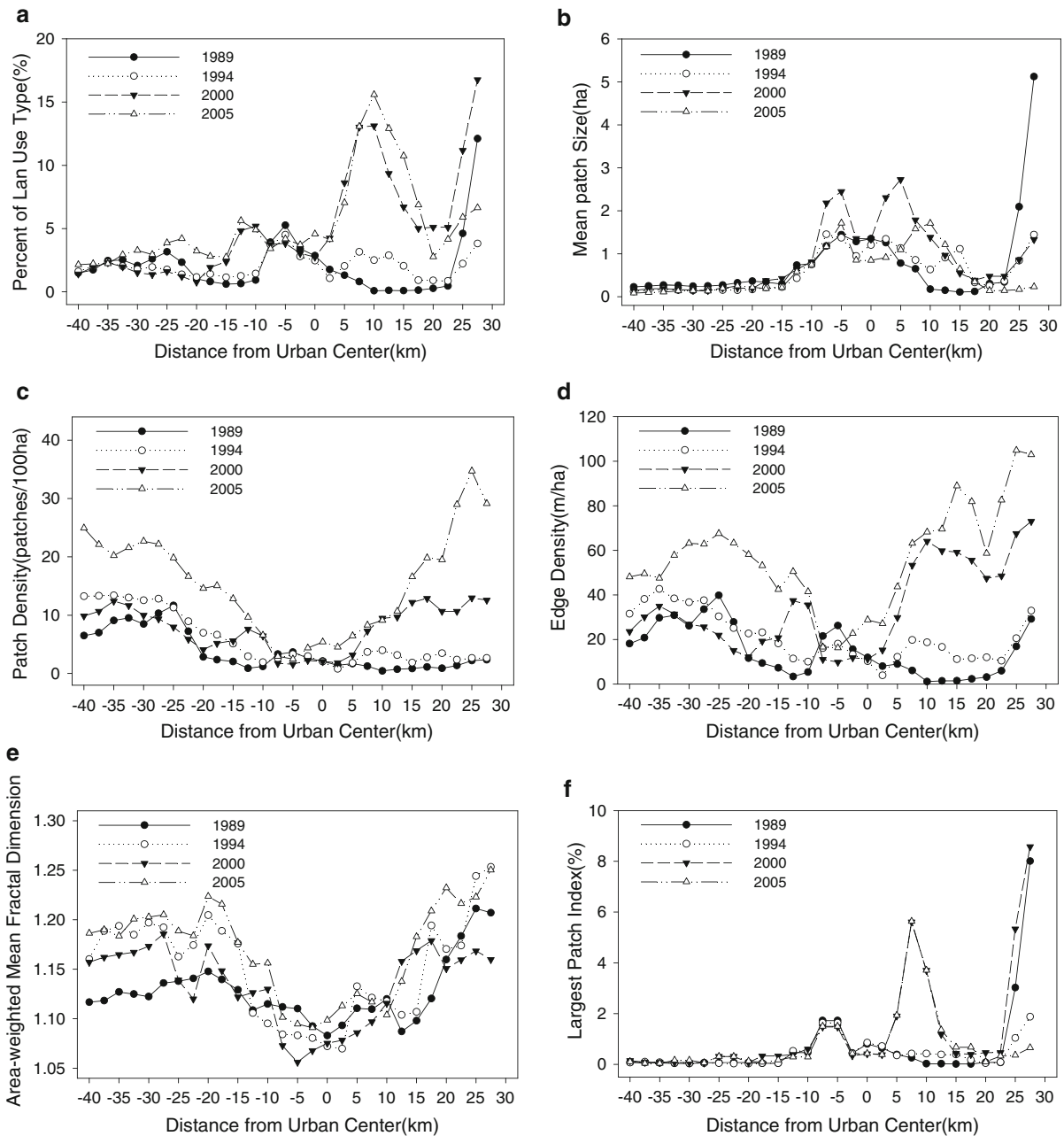


Fig. 5 Landscape pattern metrics for urban green land along the East–West transect from 1989 to 2005

area. The mean patch size (Fig. 6b) of residential land use decreased over time. This is particularly clear in the central urban area. As one moves away from the urban center in either direction, the mean patch size increases first and then decreases, creating a bimodal spatial pattern along the transect. The expansion of the central business district (CDB) with time is increasingly

pushing more residential land use outward as can be seen that the peak mean patch size is migrating away from the CBD. A near opposite spatial pattern is seen in PD (Fig. 6c) due to the increase in land use complexity in and around CDB with time. PD kept increasing over time and exhibited a wave-like shape along the transect, but the dramatic increase occurred

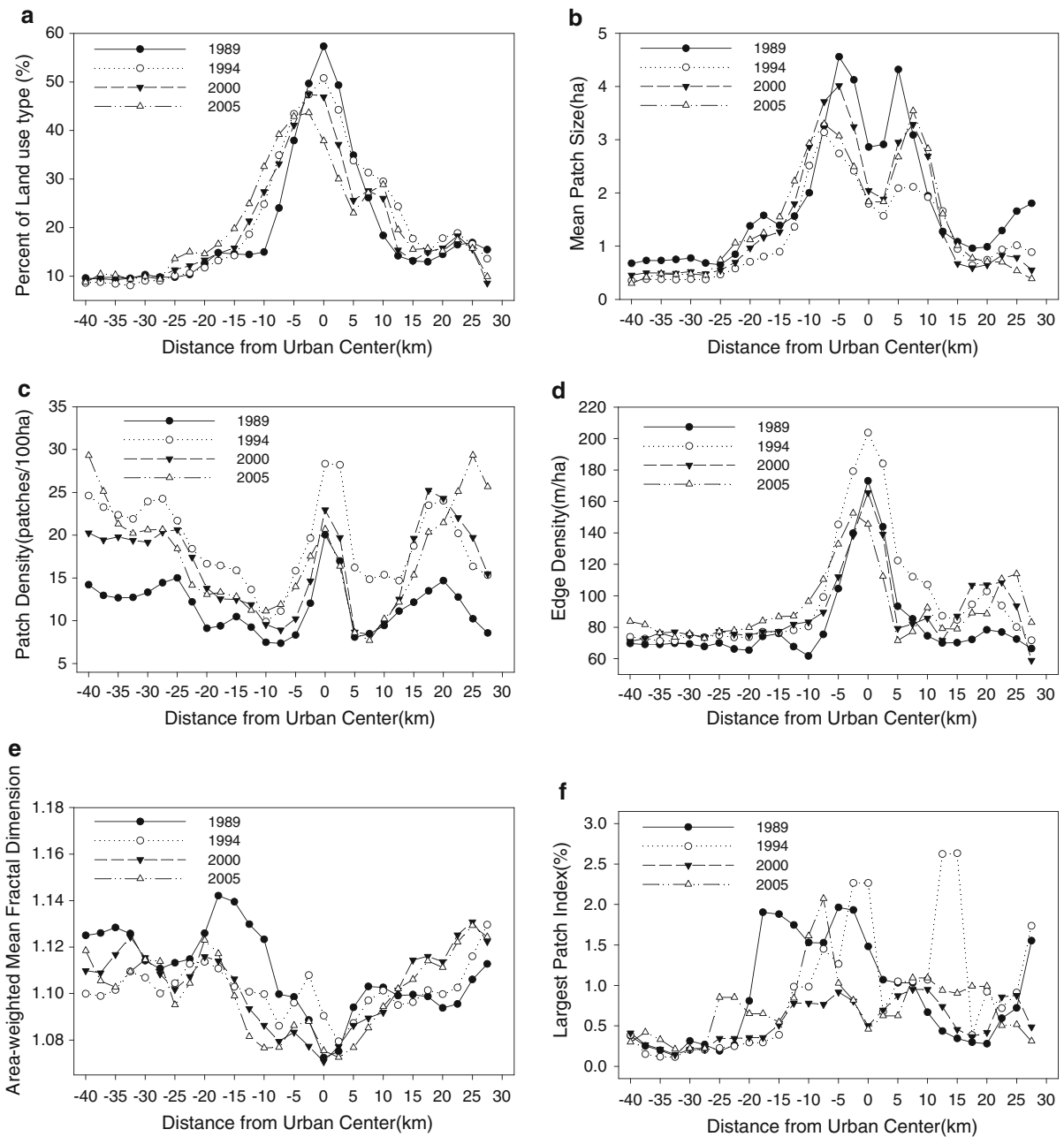


Fig. 6 Landscape pattern metrics for residential land along the East–West transect from 1989 to 2005

in the rural areas. Small mean patch size combined with high PD indicates residential patches are well separated from each other in space. The ED (Fig. 6d) generally increased along the transect over time except in urban center. Spatially, the area-weighted mean patch fractal dimension (Fig. 6e) increased from urban

center to rural areas along the transect. Temporally, the area-weighted mean patch fractal dimension kept decreasing in central urban, suburban, and the western rural areas, but increased in eastern rural area, because the original irregular-shaped old urban or rural residence were replaced by urbanized residential areas.

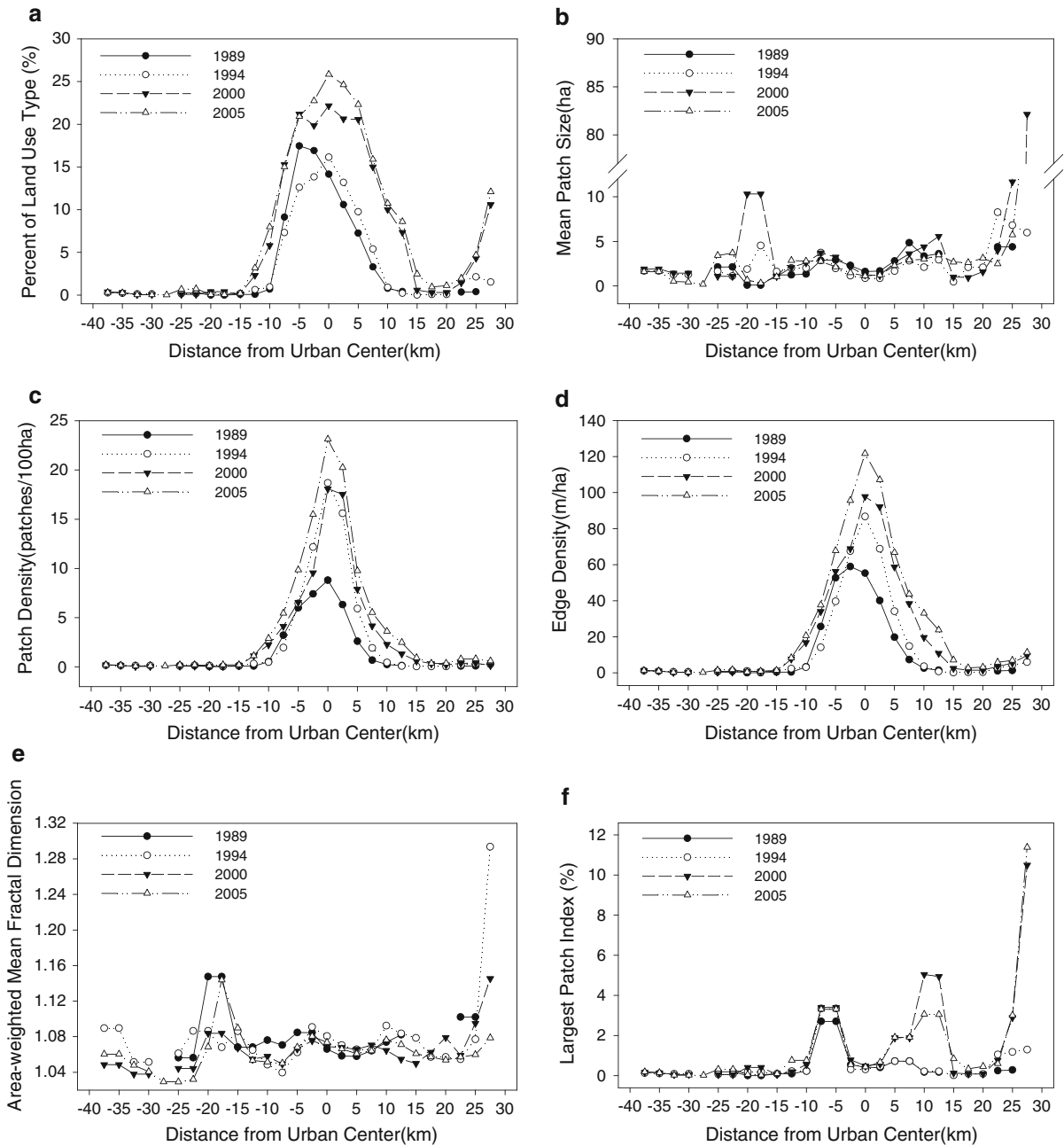


Fig. 7 Landscape pattern metrics for public facility land along the East–West transect from 1989 to 2005

The decrease in fractal dimension in the western rural and suburban regions with time may be caused by some coalescence of adjacent residential patches. The LPI (Fig. 6f) of residential land use exhibited a multi-peak pattern along the transect in different years. The overall spatiotemporal patterns of these indices are

characteristic of the diffusive expansion of new residential development along the urban–rural gradient.

The public facilities exhibited a similar pattern for percentage (Fig. 7a), PD (Fig. 7c), and ED (Fig. 7d): single peak at urban center, monotonically increasing

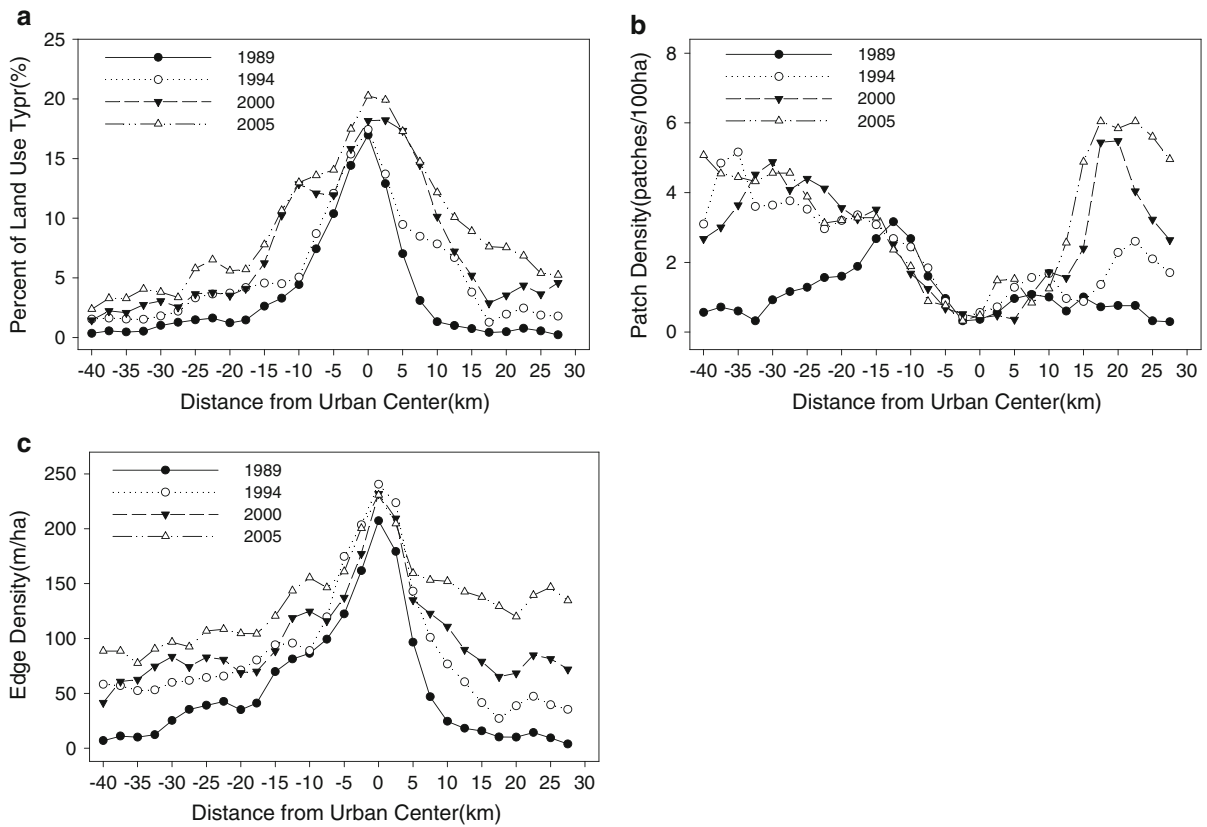


Fig. 8 Landscape pattern metrics for traffic land along the East–West transect from 1989 to 2005

from rural to urban areas, and kept increasing over time. The largest increase among the three metrics occurred in the urban core and suburban areas. The values of the metrics more than doubled, especially in the eastern part of the transect, where the Pudong New Area is located. In contrast, the public facilities increased very little in rural areas where the urbanization is accelerating. The mean patch size (Fig. 7b) and area-weighted mean patch fractal dimension (Fig. 7e) shown no significant systematic changes along the transect over time. The two distinct peaks of LPI (Fig. 7f) along the transect were likely caused by isolated new developments as the mean patch size in these locations did not show corresponding changes.

For the traffic land use, we only presented its proportion, density and shape characteristics here because it is a linear feature over the landscape. The percentage (Fig. 8a) and ED (Fig. 8c) peaked at the urban center and decreased dramatically but monotonically

from the urban center to the rural area. There is a general trend of increase in both metrics over time, indicating improvement of public transportation, particularly in the suburban and rural regions. The increase undoubtedly enhanced land accessibility, which in turn resulted in more development, such as increase in residential and industry land uses, in rural areas. The PD (Fig. 8b) varied little in central urban and suburban areas, but the highest value occurred in rural areas. Low PD and high percent land use at urban center are also indicative of the coalescent nature of traffic land use at this location, while increasing PD and percent land use are manifestation of its diffusion. The high density of traffic land use increased the fragmentation of natural or semi-natural landscape. The increased traffic landscape facilitates the diffusion of other urban land use (Bürgi et al. 2004).

The industrial land use experienced rapid increases during the study periods except in central urban area, from which it was pushed out. There were two marked

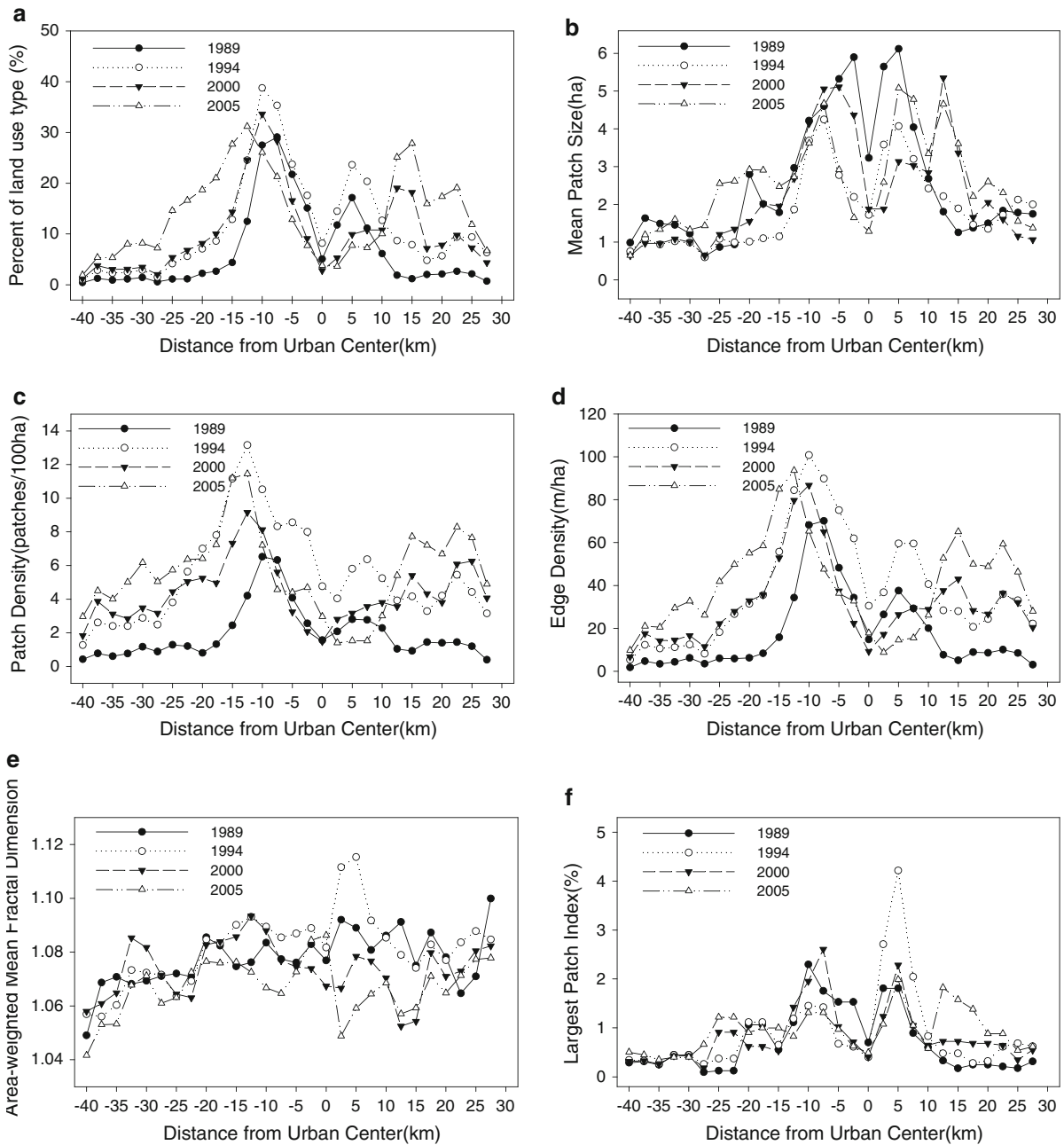


Fig. 9 Landscape pattern metrics for industrial land along the East–West transect from 1989 to 2005

peaks located in eastern and western suburban areas in the earlier stage of urbanization, but the peak gradually declined and moved outward along the transect and increased rapidly in rural areas over time. The spatiotemporal signature of percent landscape presented multiple peaks and followed a wave-like

pattern (Fig. 9a), which revealed the progressive diffusion of industrial land use from urban areas to the suburban and rural areas during the urbanization. This is due to two reasons: first earlier urbanization is characterized by rapid industrialization primarily in manufacturing and chemical industries, which were

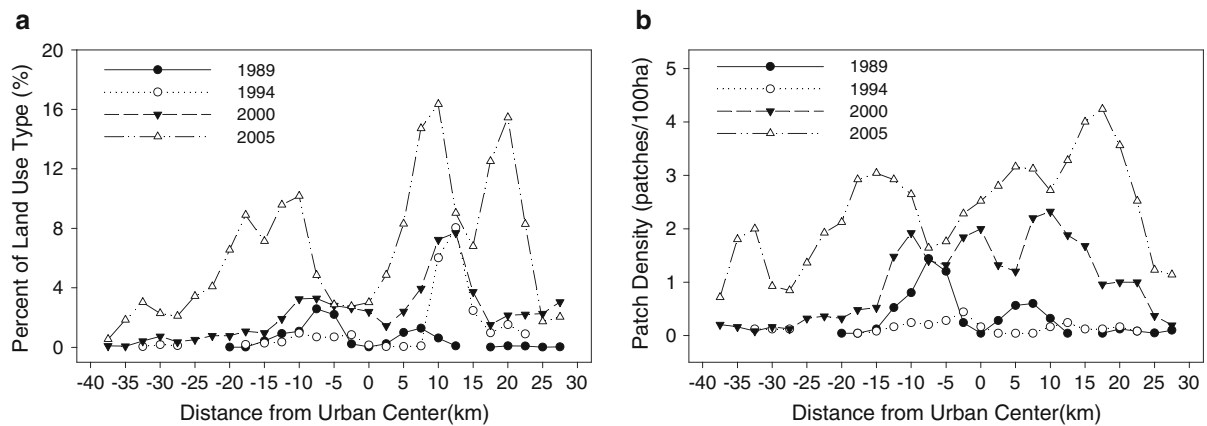


Fig. 10 Landscape pattern metrics for other land use type (mainly construction sites) along the East–West transect from 1989 to 2005

set up in high-tech parks located in suburban areas; second the eco-city and environmental campaigns initiated by Shanghai municipal government since 2000 have banned industries with heavy pollution to operate in or near central urban areas. These industries were moved to suburban and rural areas after technology improvement. As a result, the mean patch size (Fig. 9b), PD (Fig. 9c), and ED (Fig. 9d) of the industrial land use exhibited a similar spatiotemporal pattern to that of percentage metric. The multi-peak pattern of LPI (Fig. 9f) further confirmed the diffusion of industrial land use. The area-weighted mean patch fractal dimension (Fig. 9e) indicated the shape of industrial land use simplified in time with urbanization. The increase of industrial land use was spatially coincided with that of residential and traffic land use, which together indicate the wave-like dispersal of urban growth.

The signature of percentage (Fig. 10a) and PD (Fig. 10b) of other land use type exhibited a rapid increase and multiple peaks along the transect, indicating continued diffusion of the build environment, which could serve to expand or connect to existing infrastructure.

Discussion

General spatiotemporal pattern of urbanization

The overall spatial pattern of urbanization in Shanghai is largely symmetrical in the west and the east of the urban center along the transect, as indicated by most of

the landscape pattern metrics (Figs. 3, 4, 5, 6, 7, 8, 9, 10). Landscape diversity and heterogeneity peaked at the urban fringe, and decreased toward the urban center (Fig. 10e, f). Along the rural–urban–rural gradient, two patterns of landscape change can be recognized: W-shaped and M-shaped. Some urban land uses, such as the residential and industrial, exhibited a wave-like pattern (Figs. 6, 9). Urbanization increased the degree of landscape fragmentation with increasing PD (Figs. 3b, 4c) and decreasing mean patch size (Figs. 3a, 4b). Increase in landscape diversity, fragmentation, and shape complexity occurred also in the urban center (Fig. 3), a pattern that was also found for Guangzhou, China (Yu and Ng 2007) but not in Santa Barbara, California, or Madison, Wisconsin, USA (Herold et al. 2002; Weng 2007). This discrepancy may be related to the spatial and thematic resolutions of the land use data used for these different analyses.

Each land use type showed a different change patterns in landscape pattern metrics along the transect. For example, agricultural land use experienced area-shrinking, fragmentation change patterns. The profile of percent agricultural land reveals the expansion of urban fringe at a speed of 0.5 km per year. While urban land use types, such as industrial, residential, PF and traffic land exhibited a monotonic increase from the rural to urban center along the transect and marked increase over time as revealed by the spatiotemporal signatures of percent land use, mean patch size, and ED metrics. The multi-peaked LPI of urban land use types indicates a wave-like expansion of urban development. Green land use

showed increases in percentage, PD, ED and area-weighted mean fractal dimension along the transect over time. The gain of green land use comes from artificial green spaces, such as newly developed urban parks and lawns, while most natural or semi-natural green spaces were lost during the process. The situation is different from that in Guangzhou (Yu and Ng 2007) but consistent with those in Jinan (Kong and Nakagoshi 2006) and Shijiazhuang (Xiao et al. 2006).

The impacts of spatial and thematic resolution on landscape pattern analysis

Spatial resolution can affect the results of landscape pattern analysis, and the issue has been widely studied (Turner et al. 1989; O'Neill et al. 1996; Wu 2004). Recent studies also demonstrated that thematic resolution influences the landscape pattern analysis (Baldwin et al. 2004; Buyantuyev and Wu 2007; Castilla et al. 2009). Thus, selecting suitable thematic, temporal and spatial resolutions is essential to accurately quantify urbanization patterns (Buyantuyev et al. 2010). Our results demonstrates that high spatial and thematic resolution data of land use could reveal the detailed urban land use change patterns and provide insights for urban planning and land use management. For example, the landscape patterns in central urban area shown an increased PD, ED, area-weighted mean patch fractal dimension, and Shannon diversity index and decreased contagion index and mean patch size (Fig. 3), which together indicate urbanization resulted in a more fragmented, diversified and heterogeneous landscape in central urban areas in Shanghai. These fine-scale patterns were not revealed in previous studies that lumped urban land uses into a single land use category (Seto and Fragkias 2005; Weng 2007; Xu et al. 2007; Yu and Ng 2007).

It should be noted that the coarse and fine spatial resolutions are relative (Strahler et al. 1986). Coarse resolution refers to the situation where pixel size is larger than the object of interest. High resolution images have pixel size smaller than the object of interest, such as the images used in this study. O'Neill et al. (1996) argued that grain size that is 2–5 times smaller than the spatial features of interest should be considered high resolution imagery. Images with pixel sizes between the high and low resolutions are considered intermediate spatial resolution images.

Generally, there is no single correct scale or optimal scale for characterizing and comparing ecosystems or landscape patterns (Levin 1992; Wu and Loucks 1995; Wu 2004). What spatial resolution is suitable to study the landscape patterns and changes depends on the characteristics of study area, the details the researcher wants to explore and the approaches used. It is clear from our study that the binary urban/nonurban thematic classes based on Landsat TM/ETM+ spatial resolution cannot provide critical information associated with urbanization that we derived in this study.

Urban growth hypothesis

Dietzel et al. (2005a) proposed a hypothetical two-stage urban growth model: diffusion and coalescence. Under this model, urban growth starts with the expansion of urban seeds or core areas, and then diffuses from these seeds outward. Further diffusion from these new core areas eventually meet the outward expansion of existing urban areas, leading to the coalescence of previously isolated urban areas. The diffusion–coalescence urban growth model seems able to capture the major spatiotemporal characteristics of urban expansion in several other Chinese cities. Liu et al. (2005) revealed that the diffusion process could take place in numerous forms: concentric, leapfrog, linear and multi-nuclei, or a combination of the above. But recent studies found that the multi-nuclei diffusion was more common in the growth of Chinese megacities such as, Guangzhou (Yu and Ng 2007), Nanjing (Xu et al. 2007), Chengdu (Schneider et al. 2005), and Chongqing (Mu et al. 2008).

The hypothetical diffusion–coalescence process can be detected using spatiotemporal signatures of a series of landscape metrics (Dietzel et al. 2005a). During a full urbanization cycle, the contagion index is expected to be highest at the beginning and end of the cycle, but to be lowest in the intermediate stage. The mean nearest neighbor distance, PD and ED increase first, then peak respectively in sequence at different times, but ultimately decrease, resulting in a unimodal shape over time.

We found the monotonic increase in areas for all urban land use types over time (Fig. 2). However, only the PD and ED in our study exhibited a monotonic increase, and contagion index a monotonic decrease. This is consistent with those in Phoenix and Las Vegas, USA reported by Wu et al. (2011). The

hypothesized unimodal shape for PD, ED and mean Euclidian nearest neighborhood, and U-shape for the contagion index, did not show in our study. These discrepancies may be attributed to several factors. First, the 20 years of land use data for Shanghai are short, compared to 100 years of data used in Dietzel et al. (2005a). Second, thematic resolution apparently influenced the results of landscape pattern analysis (Buyantuyev and Wu 2007). There are five categories of urban land use types in our study, while previous studies only use one urban land use type. Third, the urbanization speed and extent occurred in Shanghai metropolitan area are quite different from the cities reported previously (Antrop 2004; Weng 2007; Buyantuyev et al. 2010; Wu et al. 2011). Our results showed urbanization of Shanghai followed a complex diffusion–coalescence pattern. Diffusion and coalescence can happen simultaneously along the rural–urban transect where coalescence happens in the more developed area while diffusion occurs in less developed areas. Moreover, diffusion and coalescence are not unidirectional in time. Renewed diffusion can happen in areas beyond the existing urban boundaries after coalescence.

Implications for land use planning and management

Our study found that urban expansion in Shanghai is at the expense of croplands, which is typical for most of the Chinese megacities, such as Beijing (Mu et al. 2007), Guangzhou (Yu and Ng 2007), Nanjing (Xu et al. 2007), Hangzhou (Deng et al. 2009), and Chengdu (Schneider et al. 2005). This has profound implications for land resource management in China. Conservation of arable land is critical to food security in China because of its already low arable land per capita (Lin and Ho 2003). How to feed a population of 1.34 billion in the Mainland is a great challenge. The Chinese government set 1.8 billion mu (c. 120 million ha) as the bottom line of cropland area for the country (XinhuaNet 2007, 2010). According to statistics, the cropland in Shanghai decreased from 324,013 ha in 1989, to 237,300 ha in 2005 (SMSB 2006), a net loss of 86,713 ha or 27 % during the study period. An earlier governmental document showed that Shanghai municipality planned to preserve no less than 3.28 million mu (or ~218,667 ha) primary cropland for the city (XinhuaNet 2009). However, more recent

statistics show that the total cropland in Shanghai was 201,000 ha by the end of 2010 (SMSB 2011) much lower than the target set by the Shanghai municipal government. Urbanization has consumed more croplands than the government originally allowed in Shanghai. To better conserve cropland, Shanghai adopted the “dynamic equilibrium farmland” policy, which requires developers to reclaim equal farmland area locally or elsewhere before a development project takes place (Lin and Ho 2003). As a result, large amount of coastal wetlands has been reclaimed. There were 26,700 ha coastal wetlands that have been reclaimed from 1980 to 2000, and an additional 33,300 ha wetlands were planned to be reclaimed from 2001 to 2010 (Shi et al. 2003). Although the reclaimed area has reached 30,126 ha from 2000 to 2009 (Ruan et al. 2011), the current land use policy did not meet the goal in preserving farmland in Shanghai. On the other hand, it has resulted in a large amount of losses of coastal wetlands. Excessive loss of agricultural land exists in other megacities in China (Liu et al. 2005; Schneider et al. 2005; Seto and Fragkias 2005; Long et al. 2009). More efficient regulations or laws are urgently needed to protect the ever-shrinking arable land in China.

Vegetation or urban green space within a city is a vital component of the urban ecosystem (Jim 1999), and provide wildlife habitats (Sandström et al. 2006) and other ecosystem services (Bolund and Hunhammar 1999). Our study revealed that the green land experienced a process of decrease first and increase later due to urban renewal and urban greening campaign which intends to increase urban green space up to 35 % by the end of 2020 by constructing a “Circle, Wedge, Corridor and Garden” green systems in central urban area in Shanghai (the Master Planning of Shanghai 1999–2020). Although green space has increased in Shanghai eventually over time, the natural and semi-natural green space decreased, and the increase of green space manifests as man-made parks and lawns, primarily for urban recreation. These newly created and highly managed green spaces cannot fulfill the ecological functions that were provided by the natural/semi-natural ones due to the difference in structure and species composition. Managed green spaces were dominated by non-native species in Shanghai (Zhao et al. 2006). For example, only 26 of 142 woody plants are native in the recently established Yanzhong green space within the city, whereas in some wildness area

such as Sheshan, over half of the native plant species disappeared from 1980s to 1990s (Xu et al. 1999). Therefore it is important to conserve or/and restore natural or semi-natural green space in the urban areas in Shanghai. To do so, the recommended approaches are to construct quasi-natural forest using potential natural vegetation theory in urban areas (Da and Song 2008) and to restore forest corridors along the existing linear landscape types such as river, road and coastline etc., in Shanghai (Li et al. 2008).

Our results revealed that urban sprawling is accompanied with the development of residential, industrial, traffic and public facilities. The increase of traffic was almost synchronous with that of residential and industrial landscape. But the public facilities' increase mainly happened in central urban areas; it did not spatially match well enough with the increases of residential and industrial land in newly developed areas. The green spaces, which provide limited precious recreations for urban dwellers, did not even exist in the rural west and east parts of the transect. Therefore, people who live in these areas get fewer opportunities to be served than those who live in the central urban area.

Conclusions

Our study has shown that urbanization in Shanghai took place at the expense of cropland. At the landscape scale, land use types became increasingly more diverse, less contagious, and more complex in spatial configuration. Each land use type exhibited a distinct change pattern along the urban–rural gradient over time. Urban green space and public facilities tended to be more concentrated toward the urban center, leaving residents in the rural and suburban areas under-served. These detailed landscape pattern analysis with high thematic and spatial resolutions provide valuable information for land use and urban planning and management. Our results indicate that the urbanization in the Shanghai metropolitan region followed a complex diffusion–coalescence growth pattern in which diffusion and coalescence can happen simultaneously along the rural–urban transect, and renewed diffusion can happen beyond the existing urban boundary after coalescence. Also, different land use types responded to urbanization differentially. These

results are useful for urban planning and sustainable development in the Shanghai metropolitan region.

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