International Journal of Sustainable Development & World Ecology

ISSN: 1350-4509 (Print) 1745-2627 (Online) Journal homepage: <http://www.tandfonline.com/loi/tsdw20>

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To cite this article: Qiong Wu , Dan Hu , Rusong Wang , Hongqing Li , Yong He , Min Wang & Bihui Wang (2006) A GIS-based moving window analysis of landscape pattern in the Beijing metropolitan area, China, International Journal of Sustainable Development & World Ecology, 13:5, 419-434, DOI: [10.1080/13504500609469691](https://doi.org/10.1080/13504500609469691)

To link to this article: <http://dx.doi.org/10.1080/13504500609469691>

Published online: 20 Sep 2010.

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A GIS-based moving window analysis of landscape pattern in the Beijing metropolitan area, China

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Key words: Land-use pattern, moving window analysis, landscape metrics, urban ecology, Beijing

SUMMARY

Quantifying landscape pattern and its change is essential for monitoring and assessment of ecological consequences of urbanization. Using the GIS-based land-use data for 2002, we combined moving window analysis along an urban-rural gradient and around the urban centre with landscape metrics to quantify the spatial pattern of urbanization in Beijing. The results of moving window analysis along the urban-rural gradient indicated that, for class-level metrics, the spatial pattern of urbanization could be quantified using landscape metrics, different land-use types exhibited distinctive spatial signatures, and, for landscape-level metrics, the increase in urbanization in the metropolitan Beijing region has resulted in dramatic increases in patch density (PD), edge density (ED), and patch and landscape shape complexity, and sharp decreases in the largest and mean patch size (MPS), agriculture land-use type, and landscape connectivity. The results of moving window analysis around the urban centre showed that the direction of urbanization could be quantified using the class-level metrics, and landscape-level metrics indicated similar results to gradient analysis. In general, moving window analysis showed that the increasingly urbanized landscape became compositionally more diverse, geometrically more complex, and ecologically more fragmented.

INTRODUCTION

The phenomenon of urban development is a major force driving land-use change, which has inevitably resulted in effects on the structure, function and dynamics of ecological systems at a wide range of scales. The world's urban population was only about 3% of the global population in the 1800s, but increased to nearly 30% in 1950, and reached 50%

in 2000. In the United States, urban and built-up area increased 34% between 1982 and 1997, and this increase mainly came from conversion of croplands and forestland (Alig *et al.* 2004). In China, rapid urbanization caused an unprecedented scale and rate of urban expansion over the last two decades (Seto and Kaufmann 2003). Urban

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land will expand at a rapid rate in China because more than half of its population will be urban by 2030 according to a UN projection (United Nations 2001). With rapid urbanization, it is becoming increasingly important for ecological research and application to consider the dramatic urbanization-associated land transformations and their ecological consequences.

Urban morphology and its evolution have been studied by sociologists, economists, geographers and architects for centuries. For example, as early as 1825, the German economist von Thünen (1825) asserted that urban morphology of an isolated city would be characterized by concentric economic rings (e.g. business, residential, industrial, agricultural), as dictated by simple cost-benefit relations (the principle of marginal spatial utility; Portugali 2000). Burgess (1925) developed the concentric zone theory that depicts urban outward growth as different land use concentric rings with one or more business districts. Hoyt (1939) modified the concentric zone model and developed the sector model that allows for wedge-shaped patterns, or sectors of industrialization due to the influence of transportation networks. The multiple nuclei model (Harris and Ullmann 1945) recognized that a city did not fit the traditional concentric zone or sector models, cities included more than one centre of specialized activities (e.g. finance, industry, commerce, residence) resulting in an asymmetric patch mosaic pattern. These three classic urban morphology theories were all developed to generalize about the patterns of urban land use found in early industrial cities of the USA, and thus may be less applicable to cities in other countries (Thio 1989).

Although cities have different structures, their spatial pattern undoubtedly affects ecological, physical and socioeconomic processes within their boundaries and beyond. A major goal of urban ecology is to understand the relationship between the spatial pattern of urbanization and ecological processes (Sukopp 1990, 1998; Loucks 1994; Breuste *et al.* 1998; Wu and David 2002), and much literature has focused on urban ecology in recent years (e.g. LeBlanc *et al.* 1997; Pickett *et al.* 1997; Breuste *et al.* 1998; McIntyre *et al.* 2001; Goonetilleke *et al.* 2005). The spatial pattern of land use reflects underlying human processes and influences the ecology of the urban environment (Redman 1999). As humans modify their

environment intensively, the landscape becomes more fragmented by more and smaller patches. Forman and Godron (1986) postulated that patch characteristics exhibit generally predictable patterns along a landscape modification gradient (i.e. natural-managed-cultivated-suburban-urban). Zhang (2004) summarized this hypothesis as follows: (1) patch density increases exponentially; (2) patch shape regularity increases; (3) both the mean and variance of patch size decrease, but the latter decreases faster; and (4) landscape connectivity decreases. Zhang tested this landscape modification gradient hypothesis, but future studies are needed to further confirm these findings.

To relate the spatial pattern of urbanization to ecological processes, quantitative spatial analysis methods are needed. Among others, gradient analysis and landscape pattern analysis seem appropriate for such studies (Luck and Wu 2002). Many landscape metrics have been developed and widely applied for characterizing various landscape patterns in recent decades (O'Neill *et al.* 1988; Turner 1989; Frohn 1998), but their use in urban ecology is yet to be fully explored (Luck and Wu 2002). In this study, a series of rectangular windows moving along the urban-rural gradient and sector windows moving around the urban centre were integrated with landscape pattern metrics to quantitatively characterize the urbanization pattern of the metropolitan area of Beijing, the capital of China. Gradient analysis, developed in the context of vegetation analysis (Whittaker 1975), has been used to investigate the effects of urbanization on plant distribution (e.g., Kowarik 1990; Sukopp 1998) and ecosystem properties (McDonnell and Pickett 1990; Pouyat and McDonnell 1991; Pouyat *et al.* 1995; Zhu and Carreiro 1999; Reynaud and Thioulouse 2000). Using the gradient analysis, Luck and Wu (2002) and Zhang (2004) analyzed the landscape pattern in the Phoenix and Shanghai metropolitan areas, respectively. Unlike Shanghai and Phoenix, Beijing has a history as a capital city of more than 600 years, and the urban areas have been a rectangular pattern, particularly since the Ming dynasty. The landscape pattern difference between the rectangular planned old inner city and the outer newly developed areas and the hypothesis postulated by Forman and Godron (1986) need to be explored. Because the gradient analysis could not characterize the urbanization direction sufficiently, another method is needed to analyze the direction of

urbanization. In this study, we constructed a series of moving rectangular windows along the urban-rural gradients to analyze the change of landscape pattern along the gradient, as well as a series of moving sector windows around the urban centre to analyze the landscape patterns in the different directions of the Beijing metropolitan area. Our moving window analysis aimed to address several questions: (1) How do different land-use types change with an urban-rural gradient and with different directions? (2) Can the urban development axis of the urban plan be tested using landscape metrics? (3) Do different land-use types have their own unique spatial signatures (e.g. the shape of the change curve along an urban-rural gradient and around the urban area)? (4) Do the spatial signatures of the old inner city differ from the newly developed areas? (5) Can urbanization gradients and directions be detected using landscape pattern analysis? (6) How do the urbanization gradients and their directions differ between landscape metrics? (7) Can the classic urban morphology be tested using landscape metrics and moving window analysis? Identifying these gradients or patterns is an important first step to understanding the relation between urban morphology and ecological processes (Zhang 2004).

STUDY AREA

Beijing, located between latitudes 39°26'N and 41°03'N and longitudes 115°25'E and 117°30'E, has an area of about 16 400 km² (Figure 1). The geography of Beijing Municipality is characterized by alluvial plains in the south and east, with hills and mountains that dominate in the north, northwest and west, and the total plain area (below 100 m asl) located in the south and east is about 6340 km². Beijing has a climate with four distinct seasons characterized by hot, humid summers (due to the East Asian monsoon) and cold, windy, dry winters (reflecting the influence of the vast Siberian anticyclone). The average annual temperature is 12.5°C, and the average precipitation is 566.1 mm, as recorded from 1978 to 2001.

Historically, the old inner city of Beijing was built up during the Ming Dynasty (1368–1644), with a rectangular land-use pattern and city plan, and this was maintained during the Ming and Qing dynasties. Since 1949, when the People's Republic of China was established, Beijing has expanded from

its confines within the old inner city wall to the suburbs, and this expansion speeded up during the 1990s. According to urban planning, the south-north axis through the urban centre is the cultural axis, with most ICS (institutional, commercial and services) land distributed along this axis, while the east-west axis through the urban centre is the industrial axis, with most industrial land distributed along this axis. The total urban area of Beijing has reached 1100 km² (Wu *et al.* 2006), with more than 9 million urban inhabitants in 2002 (Beijing Municipal Statistical Bureau 2002).

DATA AND METHODS

Analysis of structural characteristics of the Beijing metropolitan landscape was based on the 2002 Beijing land-use dataset produced by BMICPD (Beijing Municipal Institute of City Planning & Design Planning Research Department) (Figure 1). A set of aerial remote sensing images with a resolution of 1 m (taken in 2002) was used to create the land map by manual interpretation of the images, combining them with necessary field survey and validation. The 1991 Beijing land-use map produced for the 1992 Beijing master plan from BMICPD and a topographic map of 2001 created from the Beijing Institute of Surveying and Mapping were also used to help interpretation. This land-use dataset was then compiled using Arc/Info and reclassified from 26 patch types into eight patch types (or classes): residential (R); industrial (I); agricultural (A); institutional, commercial and services (ICS); green land (G); transportation, communication and utilities (TCU); water (W); others (O) (Table 1).

To detect the landscape pattern along the urban-rural gradient and in different directions, we conducted a series of moving rectangular window analyses along west–east and south–north transects, cutting across the urban centre (Tiananmen Square), and a series of moving sector window analyses around the urban centre of Beijing metropolitan area (Figure 1). The two transects had three adjacent rows, each composed of 27 and 36 2 km × 2 km blocks (i.e. the west–east transect was 54 km long and 6 km wide, and the south–north transect 72 km long and 6 km wide). Both class and landscape level metrics were computed using 3 × 3 blocks (i.e. 6 km × 6 km, which is approximately the width and length of the old

Figure 1 2002 Land use map of the Beijing metropolitan area, China. The transects that the rectangular windows moved along the urban-rural gradients were west-east and south-north, and 54 km long and 6 km wide and 72 km long and 6 km wide, respectively. The size of the moving rectangular window was 3×3 blocks (i.e., 6 km $\times$ 6 km), the radius of the sector window with 30 degree centre angle moving around the urban centre was 21 km.

inner city; this size of moving rectangular window is helpful to detect the landscape pattern difference between the old inner city and the new developed area) with an overlapping moving window across the west-east and south-north transects with a moving step of 0.5 km. The overlapping moving sector window around the city centre is 21 km radius (the maximum radius of the urban area), with a 30 degree centre angle and a moving step of 15

degrees. The vector data of the moving rectangular and sector windows were then converted to raster format at a pixel size of 5 m $\times$ 5 m, and both class- and landscape-level metrics were computed using the raster version of FRAGSTATS (McGarigal and Marks 1995).

Landscape metrics are algorithms that quantify specific spatial characteristics of patches, classes of patches, or entire landscape mosaics. A plethora of

Table 1 Land use reclassification scheme

<i>Reclassified patch type</i>	<i>Abbreviation</i>	<i>Original land-use type (by BMICPD)</i>
residential	R	residential
industrial	I	industrial
agricultral	A	cropland
		grassland
		orchard
institutional, commercial and services	ICS	education
		government administration and service
		cultural and recreation
		sports
		hospital
		historic site
		military
		commercial and service
		warehouse
		other institutional
green land	G	forest
		parks
transportation, communication and utilities	TCU	railway
		airport
		roads
		utilities
water	W	rivers
		lakes
		reservoirs
others	O	unemployed
		land in construction

metrics has been developed to quantify categorical map patterns. These metrics fall into two general categories: those that quantify the composition (e.g. the number and relative abundance of patch types, patch size, and other related non-spatial measures) of the map and those that quantify the spatial configuration (e.g. patch shape, juxtaposition, contrast, and boundary characteristics) of the map (Gustafson and Parker 1992; McGarigal and Marks 1995). Several investigators have attempted to identify the major components of landscape pattern for the purpose of identifying a parsimonious suite of independent metrics (e.g. McGarigal and McComb 1995, Ritters *et al.* 1995). Although these studies suggest that patterns can be characterized by only a handful of components, consensus does not exist on the choice of individual metrics. In this study, eight non-spatial composition metrics and four spatial configuration metrics, both sensitive to changes and numerically reliable (i.e., showing consistent trends) were chosen for depicting landscape patterns of the Beijing metropolitan region. The eight

non-spatial composition metrics were percentage coverage (PLAND), patch density (patch number/km²) (PD), edge density (m/ha) (ED), Shannon diversity index (SHDI), Shannon evenness index (SHEI), largest patch index (%) (LPI), mean patch size (ha) (MPS), and patch size standard deviation (ha) (PSSD). The four spatial configuration metrics were: landscape shape index (LSI), area-weighted mean shape index (AWMSI), area-weighted mean fractal dimension (AWMFD), and contagion (CONT). Many of these landscape metrics reflected both aspects of landscape pattern to varying degrees (McGarigal and Marks 1995).

RESULTS

Synoptic characteristics of the Beijing metropolitan area landscape

Table 2 shows the synoptic characteristics of landscape pattern in Beijing. In 2002, 50.75% of the land was green land, mostly located in the

Table 2 Synoptic landscape characteristics for the total Beijing metropolitan area and its plain area

	<i>R</i>		<i>I</i>		<i>A</i>		<i>ICS</i>		<i>G</i>		<i>TCU</i>		<i>W</i>		<i>O</i>	
	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>	<i>total</i>	<i>plain</i>
%Cover of land-use type	5.66	12.52	2.04	4.61	29.81	59.72	2.26	5.03	50.75	6.94	2.04	4.11	3.69	5.45	3.70	1.49
Patch density (#/100 ha)	0.61	1.30	0.42	1.03	0.61	1.30	0.55	1.37	0.51	1.01	1.65	2.99	0.38	0.88	0.12	0.20
Largest patch index (% area)	0.04	0.10	0.04	0.11	1.08	2.80	0.06	0.12	7.48	0.23	0.82	1.74	0.83	0.46	0.19	0.19
Mean patch size (ha)	9.36	9.6	4.90	4.50	48.73	45.78	4.13	3.68	99.18	6.84	1.24	1.38	9.62	6.20	30.89	7.40

mountain and hill areas, while residential, industrial, agricultural, ICS, TCU, water and other land use accounted for 5.66, 2.04, 29.81, 2.26, 2.04, 3.69, 3.70%, respectively. In the plain area (below 100 m), where the urbanization level was very high, agricultural land occupied 59.72%, while residential, industrial, ICS, green land, TCU, water and other land use accounted for 12.52, 4.61, 5.03, 6.94, 4.11, 5.45, 1.49%, respectively. The mean patch size for the entire landscape was approximately 20.61 ha, and the mean patch density was 4.78 patches/km²; while for the plain area, the mean patch size and the mean patch density was 9.92 ha and 10.09 patches/km², respectively. PD increased from water to urban land uses (i.e. residential, industrial, ICS), agricultural land had a similar patch density to urban land uses, but TCU had the highest patch density. Similar to the pattern of the relative area of patch types, green land had the highest values of the largest patch index and MPS for the entire area, while agricultural land had the highest value for the plain area. The values of LPI and MPS decreased progressively from green land/agricultural land to main urban land (i.e. residential, industrial, ICS), both for the entire area and the plain area. Overall, the urban land uses had the smallest values for MPS and LPI and the second largest PD, both for the entire area and the plain area, together suggesting a high degree of fragmentation. For the proportion of cover and the values of LPI and MPS, green land had the highest value for the entire area and agricultural land had the highest value for the plain area, which indicated the least fragmented status outside the urban core and within the metropolitan boundary.

Moving window analysis with class-level metrics

The two approximately linear types, TCU and water, as well as other land (most of which was located in mountain areas) are not presented in this section for the purpose of an effective interpretation. In general, the south–north transect and the east–west transect showed similar patterns, therefore, we present here only the result of the south–north transect for class-level metrics.

Moving window analysis along the urban-rural gradient

The percentage cover for the land-use types of residence, industry, agriculture, ICS and green land varied with distance from the southern end of the landscape transect northward (Figure 2a) and, in general, the relative dominance of land-use types showed a somewhat symmetric pattern along the south–north transect: shifting from agriculture to industry/residence/ICS/green land and residence/ICS and then back to industry/residence/ICS/green land and agricultural. The distances (between –16 and 18 km, while 0 km indicated the urban centre) where the main urban land-use types (i.e. residential, industrial, ICS) peaked indicated the location of the central urbanization area in the Beijing metropolitan region. Agriculture was dominant at distances less than –18 km and again greater than 18 km, forming a ‘U’ shape. Industrial and green land exhibited two peaks at the fringe of the central urbanization area. In contrast, residential and ICS increased gradually towards the urban centre, ICS gradually peaked,

most prominently at the urbanization centre, except for a peak at –13 km, and residential exhibited two peaks on both edges of the old inner city (distances between –3 and 4 km). The area coverage of residence was consistently greater than that of industry and ICS in the central urbanization area.

The patch density of all land-use types was low from the southern end of the south–north transect to –16 km, with residential/ICS/industrial reaching high values on both edges of the old inner city (distances between –3 and 4 km) (Figure 2b). PD of green land exhibited multiple peaks in the central urbanization area. PD of all main urban land-use types (i.e. residential, industrial, ICS) decreased to the east of the urban centre. At distances less than –12 km, the mean patch size of agriculture was high. This then decreased to low values or zero at the urban centre, until 16 km, and increased again rapidly beyond that distance. MPS of main urban land-use types (i.e. residential, industrial, ICS) was consistently small along the south–north transect, except ICS which reached its peak at –6 km. The general pattern of MPS for agriculture mimicked the pattern of its percentage cover (compare Figures 2a and c). The variations of mean patch size for the main urban land-use types (i.e. residential, industrial, ICS) were less conspicuous along the south–north transect, partly because they were composed of relatively small patches.

Landscape shape index and area-weighted mean patch shape index of agriculture decreased at a distance of –10 km and then increased northward from a distance of 6 km (Figures 2d and e). Landscape shape index of residence/ICS increased from a distance of –15 km, reached its two peaks on both edges of the old inner city and then decreased northward, while industry/green land reached peaks in the vicinity of the urban centre, except for green land which indicated a peak at –16 km (Figure 2d). Area-weighted mean patch shape indices of all main urban land-use types (i.e. residential, industrial, ICS) were relatively less variable than those of agricultural land.

From Figure 2, an urbanization centre identified quantitatively by these landscape metrics existed between –16 and 18 km. The west–east transect (not shown) displayed a similar pattern as the south–north transect, and in the west–east direction an urbanization centre could be identified between –20 and 15 km. Within this urban core

area, the rankings of A, R, I and ICS in terms of their relative dominance were different between landscape metrics. The rankings were $R > ICS > I > A$ for percentage cover; $ICS > R > I > A$ for patch density; $ICS > R > I > A$ for patch size coefficient of variation; $R > ICS > I > A$ for landscape shape index. These results seemed to characterize the urban core of the Beijing metropolitan area accurately and precisely: agriculture patches were abundant and less fragmented, and urban land-use types were extensive, having many small patches, and were highly fragmented.

Moving window analysis around the urban centre

The percentage coverage for the land-use types of residence, industry, agriculture, ICS and green land varied with direction (Figure 3a) and, in general, agricultural land was dominant in the south, southeast, east, northeast and north, and reached its highest value in the southeast; industrial land was distributed mainly in the east and west (along the industrial axis); ICS distributed mainly in the west and northwest (along the cultural axis); green land reached a peak in the northwest; while residential land showed a somewhat centro-symmetric pattern around the urban centre, with more in the north. A large part of the main urban land (i.e. residential, industrial, ICS) was located in the north, northwest, west, northeast and east, and the percentage cover of urban land reached its highest value in the northwest by north, while the southern, southwest and southeast area has a relatively lower urban land (i.e. residential, industrial, ICS), and the percentage cover of urban land reached its lowest value in the southeast. The area coverage of residence was generally greater than that of industry and ICS in the analyzed area, which is similar to results of the transect analysis.

The patch density of ICS and residential land was low in the south and southeast, and reached the highest value in the west (Figure 3b). PD of industrial land reached two peaks in the southeast and southwest. PD of agricultural and green land indicated four peaks in the northwest, northeast, southwest and southeast, and PD of agricultural land was highest in the southeast, while PD of green land was highest in the southwest. Generally, PD of the main urban land (i.e. residential, industrial, ICS) was higher than that of agricultural and green land in all directions. MPS of the main urban land-use types

Figure 2 Changes in landscape pattern along the south–north transect by patch type, the values were averages obtained using a 3 × 3 overlapping moving window.

Figure 3 Changes in landscape pattern around the urban centre by patch type.

(i.e. residential, industrial, ICS) was consistently small in all directions and showed similar patterns to the percentage cover (compare Figure 3a and c). The pattern of MPS for agricultural land reached three peaks in the north, south and east (Figure 3c).

For the landscape shape index and area-weighted mean patch shape index, the main urban land (i.e. residential, industrial, ICS) indicated a somewhat centro-symmetric pattern around the urban centre, while green and agricultural land showed a similar pattern to their percentage cover

(Figure 3d and e). Landscape shape index and area-weighted mean patch shape indices of all main urban land-use types (i.e. residential, industrial, ICS) were relatively less variable than those of green and agricultural land.

From Figure 3, the direction with a higher degree of urbanization, as identified by these landscape metrics, existed in the north, northwest, west, northeast and east, where almost all of the class-level landscape metrics of urban land (i.e. residential, industrial, ICS) reached their highest values, and are highly fragmented in these directions; while the lowest degree of urbanization identified in the southwest, and all the landscape metrics of urban land (i.e. residential, industrial, ICS) reached their lowest values and were less fragmented in this direction. Figure 3 also showed that agriculture patches were abundant in the direction with a low degree of urbanization and were less fragmented; urban land-use types were extensive, having many small patches and were highly fragmented.

Moving window analysis with landscape-level metrics

In this section, the compositional landscape-level metrics are first presented, then the configurational landscape-level metrics for both the moving window along the urban-rural gradient and around the urban centre, combining all eight land-use types, to quantify the spatial pattern of urbanization along the west-east and south-north transects and around the urban centre.

Moving window analysis along the urban-rural gradient

The curves of compositional landscape-level metrics along the west-east and south-north transects exhibited qualitatively similar patterns (Figure 4). For the south-north transects, the density of both patches (PD) and their edges (ED) per moving window (6 km × 6 km) were low from the south ends of the transects, then increased and reached their first peaks on the south edge of the old inner city, and decreased at the urban centre, thereafter increased again and reached peaks on the north edge of the old inner city, and decreased to the north urban centre (Figure 4a and b). While PD and ED along west-east transects showed a similar pattern to the

same metrics along the south-north transects, except for PD along west-east transects which reached only one peak at the urban centre. An increase in PD and ED apparently occurred between -22 and 20 km along the west-east transect and between -16 and 20 km along the south-north transect, indicating a dramatic increase in the degree of landscape fragmentation – on average, the contiguous agriculture landscape has increasingly become a patchwork of different urban land-use types. While at the urban centre area, the two peaks of PD and ED on both edges of the old inner city indicated that the degree of fragmentation in the old inner city was lower than that in the newly developed area on the edge of the inner city. From Figures 4c-d, it is clear that the increasing diversity within the newly developed area and the decreasing diversity within the old inner city area are attributable mainly to the corresponding increasing and decreasing unevenness of the areal distribution of the eight land-use types. Comparing Figures 4c-d with Figure 2a reveals that the constant increase in SHEI corresponded to both the declining dominance of agriculture and the increasing proportions of the urban land-use types. That is, towards the urban centre, the Beijing metropolitan landscape became more fragmented and more evenly distributed among land-use types, although the landscape in the old inner city was less fragmented and less evenly distributed among land-use types due to the dominance of residential and ICS. The mean patch size within the landscape continued to decrease towards the urban centre, as expected, but the drastically faster decline in the urban area is noteworthy (Figure 4e). The absolute variation of patch size among all land-use types across the landscape (patch size standard deviation, PSSD) decreased dramatically within the urban area (Figure 4f). This was a direct result of the rapid decrease in patch size along both transects towards the urban centre (Figure 4e). The compositional aspect of the Beijing landscape pattern along the urban-rural gradient corroborated the interpretation of results of class-level metrics presented in the previous section.

The configurational landscape-level metrics showed both similar and different patterns as compared to the compositional landscape-level metrics along the west-east and south-north transects in the Beijing metropolitan landscape. Landscape shape index, a form of patch perimeter-area ratio

Figure 4 Changes in landscape-level compositional metrics (a, b, c, d, e, f) and configurational metrics (g, h, i, j) along the transects (south-north = bold line; west-east = dashed line)

at the landscape level, showed a similar pattern to the compositional landscape-level metrics of PD and ED (Figure 4 g). This pattern suggested that the shape of the landscape as a patch mosaic became more irregular with urbanization. The results of the area-weighted mean fractal dimension (Figure 4 h) showed a similar pattern to the land shape index (Figure 4 g), which indicated that large patches had more complex shapes. While contagion, measuring the degree of clumping of patches for both the compositional and configurational aspects of landscape pattern, declined in the urban area (Figure 4i). Its behaviour showed a similar pattern to that of MPS (Figure 4e). In general, these landscape-level indices showed that the landscape shape complexity and the degree of fragmentation (conversely related to CONT) of the Beijing metropolitan region increased considerably towards the urban centre. How did the shape of individual patches change towards the urban centre, and how did this relate to the landscape-level shape complexity? Figure 4j depicts the average changes in patch shape. Area-weighted mean shape index increased considerably in the urban area (Figure 4j), resembling the pattern shown by LSI (Figure 4a), AWMFD (Figure 4 h) and CONT (Figure 4i). The increasing AWMSI in the urban area also indicated that the large patches have more complex shapes. The double peaks in the four configurational landscape-level indices (LSI, AWMFD, CONT, AWMSI) indicated that the landscape shape in the old inner city is less complex and fragmented than that in the newly developed area on the edge of the old inner city with the highest level of urbanization.

Moving window analysis around the urban centre

The density of both patches (PD) (Figure 5a) and their edges (ED) (Figure 5b) reached the lowest value in the south and the highest value in the northwest, and PD also reached two peaks in the southwest and southeast due to the highest PD value of green land in the southwest and the highest PD value of agricultural land in the southeast, while ED in the west, northwest, north, northeast, and east with high percentage cover of the main urban land (i.e. residential, industrial, ICS) is higher than in the south and southeast, with a low percentage cover of the main urban land area (i.e. residential, industrial, ICS). Shannon diversity index (Figure

5c) and Shannon evenness index (Figure 5d) have similar patterns, that is, the value is high in the west, northwest, north, northeast, and east and low in the south and southeast. From Figures 5c-d, the increasing diversity in the west, northwest, north, northeast and east was mainly attributable to the increasing unevenness of the areal distribution of the eight land-use types. Comparing Figures 5c-d with Figure 5a reveals that the constant increase in SHEI corresponded to both the declining dominance of agriculture and the increasing proportions of urban land-use types. The higher degree of urbanization of the Beijing metropolitan landscape in the west, northwest, north, northeast and east became more fragmented and more evenly distributed among land-use types. Mean patch size reached its lowest value in the northwest by north (Figure 5e). The standard deviation within the landscape is higher in the southwest than that in the west, northwest, north, northeast and east (Figure 5f). In general, the compositional aspect of the Beijing landscape pattern around the urban centre corroborated the interpretation of results of class-level metrics presented in the previous section.

The configurational landscape-level metrics showed both similar and different patterns as compared to the compositional landscape-level metrics around the urban centre in the Beijing metropolitan landscape. Landscape shape index showed a similar pattern to the compositional landscape-level metrics of ED (Figures 5b and 5 g), which suggested that the shape of the landscape as a patch mosaic became more irregular with urbanization. The results of area-weighted mean patch fractal dimension showed a circular pattern around the urban centre (Figure 5 h). While contagion, measuring the degree of clumping of patches that pertains to both the compositional and configurational aspects of landscape pattern, declined in the west, northwest, north, northeast and east with high percentage cover of the main urban land (i.e. residential, industrial, ICS) (Figure 5i). In general, these landscape-level indices showed that the landscape shape complexity and the degree of fragmentation of the Beijing metropolitan region increased considerably in the west, northwest, north, northeast and east with a high percentage cover of the main urban land areas (i.e. residential, industrial, ICS). Area-weighted mean shape index, that indicated the shape of individual patch change around the urban

Figure 5 Changes in landscape-level compositional metrics (a, b, c, d, e, f) and configurational metrics (g, h, i, j) around the urban centre.

centre, reached two peaks in the west and northeast (Figure 5j).

DISCUSSION AND CONCLUSIONS

Our study has demonstrated that the centre and gradient pattern and direction pattern of urbanization in the Beijing metropolitan area can be quantified using a combination of landscape metrics and moving window analysis, and thus answers the questions posed earlier. The class-level metrics indicated that the different land-use types exhibited distinctive spatial signatures that were dependent on specific landscape metrics. These different land-use types may indeed show distinctive 'spatial signatures' as distance-based 'landscape pattern profiles' which may be used to compare urban developmental patterns between cities in different regions and dynamics of the same city over time.

The moving window analysis along the urban-rural gradient indicated that the degree of human impact on the Beijing landscape depended on the distance from the urban centre. The old inner city and the area abutting it can be clearly identified as the urban centre with the landscape metrics when plotted for both transects. It seemed that the old inner city, with the highest level of urbanization, did not have the same trend as the area on the edge of the old inner city that was rebuilt after 1949. The landscape on the edge of the old inner city and its outer vicinity are highly fragmented, while the landscape pattern within the old inner city was less fragmented than the edge area. This phenomenon may be attributed to the less evenly rectangular pattern of land use and the dominance of residential and ICS in the old inner city. The landscape pattern analysis around the urban centre indicated that the degree of human impact on the Beijing landscape has a directional characteristic. Processes and factors responsible for urbanization, such as socioeconomic activities, accessibility to transportation and services, natural conditions and urban planning, may result in the heterogeneous arrangement of land uses in the Beijing metropolitan area. The moving window analysis, both along the urban-rural gradient and around the urban centre, indicated that the increasingly urbanized landscape became compositionally more diverse, geometrically more complex and ecologically more fragmented.

The analysis of change of landscape pattern along the urban-rural gradient can also be used to test hypotheses on landscape structural responses along a human modification gradient, as postulated by Forman and Godron (1986). The results supported Hypothesis 1 (patch density, Figure 4a), Hypotheses 3 (patch size, Figures 4e and f) and 4 (connectivity, Figures 4a, b and i) in general. The results on patch shape seemed apparently at odds with the hypothesized pattern. These results are the same as found by Zhang (2004). However, our study also showed that the old inner city, which has the highest degree of urbanization, has a lower density and complexity than the area around it according to the extreme values on the edge, and further studies are needed to confirm this finding.

The results of this rapidly growing metropolitan Beijing area may provide interesting perspectives on urban morphology. It may be difficult to find such a city with a very old, well-protected inner city and a very young, outer new development area. The landscape pattern analysis along the urban-rural gradients revealed that different land-use zones were distinguishable: agriculture–industry–residential/ICS–industry–agriculture. The moving window analysis around the urban centre showed that the percentage cover of industrial land was very high in the west and east, and formed two industrial wedges west and east of Beijing metropolitan area. The combination of concentric zone theory and sector theory seems to be able to account adequately for the land-use pattern of the Beijing metropolitan region up to 2002.

Beijing is now undergoing rapid urban expansion, and urban planning plays an important role in its future morphology. Urban planning and decision-making for sustainable development urgently need data of high spatial resolution to establish the relationship between the socioeconomic performance of the urban system and its different subunits (i.e. housing schemes, commercial and industrial developments, services), on the one hand, and the environmental impacts of these subunits, on the other (Pauleit and Duhme 2000). Studying the effects of the urbanization pattern on ecological conditions and processes can help to understand the relationship between the landscape pattern and urban ecological processes (Hobbs 1988; Cook 1991; Foresman *et al.* 1997; Pickett *et al.* 1997; Antrop and Van Eetvelde 2000; Zipperer *et al.* 2000). Combining moving window analysis with

landscape metrics can help to identify quantitatively and to characterize the gradients and direction of the complex spatial pattern of urbanization, which can subsequently be related to ecological and socioeconomic processes (McDonnell *et al.* 1997).

ACKNOWLEDGEMENTS

This study is supported by the National Natural Science Foundation of China (40241009, 70573106). We are grateful for the support of the Beijing Municipal Institute of City Planning & Design Planning Research Department (BMICPD).

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