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ORIGINAL ARTICLE

Quantifying spatiotemporal patterns of urban expansion in three capital cities in Northeast China over the past three decades using satellite data sets

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Abstract Urban expansion is probably the most drastic form of land conversion and its impacts far transcend city's physical boundaries. Many studies have documented China's rapid urban expansion while the urban expansion in the traditional industrial base in Northeast China was understudied. Based on multi-temporal remote sensing images and landscape metrics, this study characterized the spatiotemporal patterns of urban land use changes in the metropolitan regions of three capital cities (i.e., Shenyang, Changchun and Harbin) in the Northeast China's traditional industrial base over the past three decades. The urban land in Shenyang, Changchun and Harbin expanded from 209.8, 202.0, and 239.6 km^2 in the late 1970s to 836.3, 682.4 and 567.9 km^2 in 2010, with an annual growth rate of 4.6, 4.0 and 2.6 %, respectively. The newly developed urban lands were largely distributed around the edge of urban districts. For all cities, the edge expansion was the dominant urban growth type (>50 %), followed by infilling growth, and the proportion of outlying growth type was relatively low (<20 %). City landscape became more complicated and fragmented, and landscape composition became evener. Despite these general similarities, there are differences in the magnitude and spatial patterns of urban expansion among three cities. Shenyang and Changchun generally had higher urban growth rates and expansion became compact earlier than Harbin. However, entering the twenty-first century, all cities went into a new era of urban expansion. Old industrial bases and newly established high-tech development districts have become urban expansion hotspots, and natural barriers to urban expansion weakened, stimulated by the policy of "Revitalizing Old Industrial Base of Northeast China". Managing the tradeoffs between urban expansion and environmental protection would be a great challenge for the local governments.

Keywords Urban growth · Remote sensing · GIS · Landscape metrics · NE China

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Introduction

Entering the Century of the City, urbanization, characterized by demographic and land use change processes, will present unprecedented impacts on the society, economy and environment (Seto et al. 2010). More than half of the world's population now live in cities and this figure is projected to increase to 60 % by 2030 (UN 2014). In the meantime, urban areas around the world are expanding on average at twice the speed of its population growth in recent years (Angel et al. 2011). By 2030, urban land cover will be of high probabilities to increase by 1.2 million km^2, which is a 185 % increase from circa 2000 (Seto et al. 2012). Urban expansion is the most drastic and irreversible form of land conversion affecting Earth's ecosystems and its impacts far transcend city's physical boundaries (Folke et al. 1997; Grimm et al. 2008), resulting in alterations in landscape (Jenerette and Wu 2001; Wu et al. 2011), energy flows (Decker et al. 2000; Barles 2009), biogeochemical cycles (Baker et al. 2001; Kaye et al. 2006) and biodiversity (Seto et al. 2012; He et al. 2014) at multiple spatio-temporal scales. In fact, quantifying the spatial and temporal patterns of urban expansion is a critical first step to understanding the urbanization itself and its ecological consequences, given that urbanization will continue to be one of the biggest challenges for humankind in the twenty-first century (Seto and Fragkias 2005; Wu et al. 2011).

Remote sensing provides consistent data over a large geographical area with a spatially explicit manner and high time frequency, which enables its wide use in detecting land cover and land use change. Combined with Geographical Information Systems (GIS), remote sensing has made spatially explicit monitoring of urban expansion possible. Landscape metrics have been commonly used to quantify the spatial pattern of urban landscapes, study urban morphology and evaluate the ecological implications of urban expansion (Herold et al. 2002; Zhu et al. 2006; Li et al. 2010; Aguilera et al. 2011). With increasing availability of remote sensing data and rapid development of landscape metrics, there have been many literatures documenting spatial and temporal dynamics of urban expansion (Herold et al. 2003; Seto and Fragkias 2005; Weng 2007; Wu et al. 2011; Aithal and Sanna 2012).

China has experienced unprecedented urban expansion since its Reform and Opening-Up policy started in the late 1970s, which has attracted widespread concern. Previous studies on China's urban expansion have mainly focused on the large cities in the coastal economic zone on a city-by-city basis, such as Guangzhou (Weng and Yang 2004; Sun et al. 2012), Shenzhen (Seto and Fragkias 2005; Lv et al. 2011), Shanghai (Zhao et al. 2006; Zhu et al. 2006), Beijing (Tan et al. 2005b; Wu et al. 2006), and cities with a long humanity history and relatively high level of economic development such as Nanjing (Xu et al. 2007). There are few studies characterizing the urban expansion in northeastern cities, and comparative studies on urban expansion among different cities with high temporal frequency and spatial resolution over a relatively long period are sorely lacking in this region (Liu et al. 2005a; Hu et al. 2008).

As an important traditional industrial base of the country, the Northeast China was once the highly urbanized region of China and then went through a relatively low economic development in the 1990s when the region was confronted with tremendous challenges from resource depletion, environmental pollution and business reconstructing (Dickerson et al. 2007; Li and Tong 2008), consequently, its urban expansion process falling behind the southern coastal cities. However, the "Revitalizing Old Industrial Base of Northeast China" strategy proposed in 2003 has promoted the economic recovery of the region and brought a brand new era of urban expansion in Northeast China (Hu et al. 2008) and the three capital cities (i.e., Shenyang, Changchun and Harbin) are among the fastest growing ones, showing great polarization effect in this region (Wang et al. 2014). Therefore, the knowledge of urban expansion in the northeast, especially a comparison among cities over a relatively long period, would be an integral part for a comprehensive understanding on urban expansion in China (Hu et al. 2008). This study quantified and compared spatial and temporal patterns of urban expansion in three capital cities in Northeast China from the late 1970s to 2010 at a roughly 5-year interval using multiple-temporal Landsat remote sensing data integrated with landscape metrics. The objectives of this study were to (1) dynamically map the locations and extents of urban land covers, (2) characterize the spatiotemporal patterns of urban expansion, and (3) compare the similarities and differences of the magnitude, spatially explicit urban growth patterns, and temporal change of landscape metrics for three capital cities (i.e., Shenyang, Changchun and Harbin) in the Northeast China's traditional industrial base over the past three decades.

Data and methods

Study areas

Shenyang, Changchun and Harbin, the capital cities of Liaoning, Jilin and Heilongjiang provinces, are the most developed cities in Northeast China (Fig. 1). Although all of them are traditional industrial cities, they differ in population, economic level and municipal infrastructures (Table 1). The study areas are the metropolitan regions of these three cities.

The Shenyang metropolitan region lies on the transition zone from the branch range of Changbai Mountain to the flood plain of Liao River in Northeast China, covering an area of 3,426 km^2. Its western region is typical of alluvial plain topographically, and the northeast and southeast parts are hilly lands. The Hun River runs through the central part of the metropolitan region. Shenyang has a semi-humid continental and monsoon climate, with an average annual temperature of 7.9 °C. As the capital of Liaoning province and the biggest central city in Northeast China, Shenyang is an important transport hub with one of the densest highway networks in China. The Changchun metropolitan area is located in the middle part of the Songliao Plain, with an area of 1,525 km^2. Changchun also has the semi-humid continental and monsoon climate, with an average annual temperature of 4.8 °C. As the capital city of Jilin Province, Changchun is the biggest automobile industry city of China. Although Harbin is the biggest provincial city of China, the metropolitan region of Harbin is 1,651 km^2, covering 3.1 % of the overall city area, less than that of Shenyang and Changchun which is 26.6 and 7.4 %, respectively. The metropolitan zone is located in the western low-lying and flat terrain, far away from eastern mountains. The Songhua River runs through this region dividing the metropolitan region into two parts and the

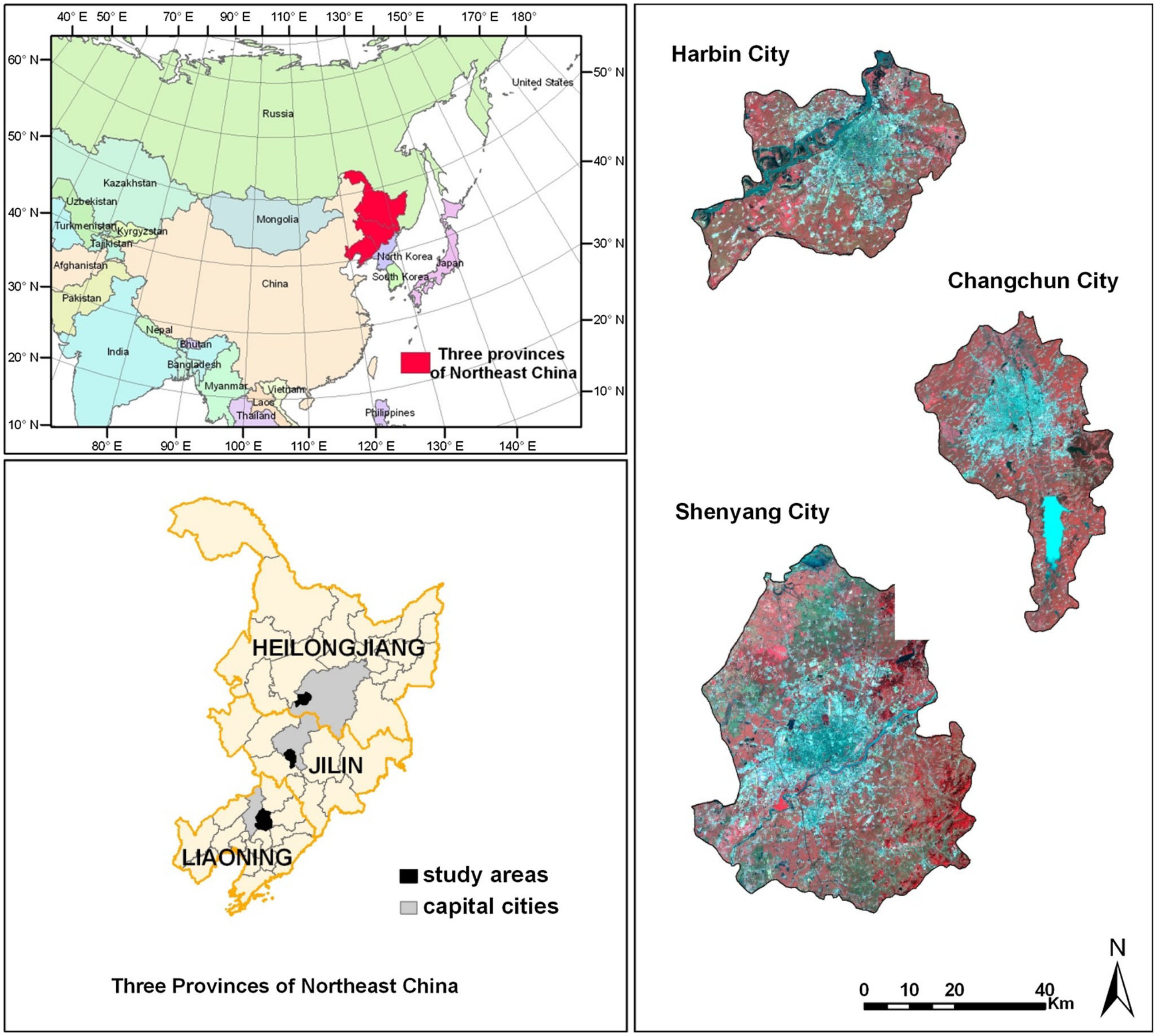

Fig. 1 Locations of the study areas. The background maps of Shenyang, Changchun and Harbin are the *true color* composite satellite images

most part lies on the south of the Songhua River. Harbin has a similar climate to that of Shenyang and Changchun except a low-average annual temperature of 3.2 °C. Harbin has the international direct train to Moscow and has played an important role in the international communication between China and Russia.

Data and data processing

Land use and land cover maps of the study areas were produced using Landsat MSS (bands 1–4), TM (bands 2, 3, 4, 5 and 7), and ETM + (bands 2, 3, 4, 5 and 7) data (http://www.usgs.gov/ and http://datamirror.csdb.cn/). Images with least clouds and snow mainly from June to September, covering sever time periods (circa 1980, 1985, 1990, 1995, 2000, 2005, and 2010) at a roughly five-year interval, were selected. Dates of some images which are around the years mentioned above, such as 1979, 1984, 1989, 1999, 2006 or 2009, were referred to as the seven periods for simplification purposes. Detailed information of the selected Landsat images is shown in Table 2.

Classification maps were produced using ERDAS Imagine version 9.1. All images were first geo-referenced to those from 2000 and then other preprocessing (e.g., re-projection, mosaic, histogram equalization) was conducted. According to the features of the spectral reflectance and the objectives of the analysis, land covers were classified into five types using the maximum likelihood classification method: cropland, green land, urban land, water body and unused land (Fig. 2; Table 3). Because the purpose of this study was primarily to depict the spatial and temporal pattern of urban expansion, the urban land type was analyzed in detail. MSS images were re-sampled to the resolution of 30 m × 30 m to be consistent with the resolution of TM/ETM + images. ArcGIS version 9.3 was used for some post-classification processing and mapping. The accuracies of classification results were assessed for each city following the approach of Zhou et al. (2012). Specifically, the accuracies of classification results of 2010 and the classification results before 2010 in the areas where land cover remained unchanged from 1980 to 2010 were assessed using Google Earth Pro® (GE), which is an effective method to evaluate the land cover classification results (Luedeling and Buerkert 2008). Results show that the overall Kappa coefficient and Kappa coefficients for individual land cover types were more than 0.75 for Shenyang, Changchun and Harbin, and those for urban land were higher than 0.80 (Table 4), which met the accuracy requirement of land cover change evaluation (Janssen and van der Wel 1994).

Table 1 Socioeconomic indicators for three cities from 1990 to 2010

	Population[a]	Average salary[b] (¥)	Length of paved roads (km)	Per capita living area (m^2)
1990				
Shenyang	3,603,712	2,309	1,640[c]	NA
Changchun	1,679,270	1,980	671	5.89
Harbin	2,443,398	2,095	370	5.62
2000				
Shenyang	3,948,644	9,799	3018	8.37[c]
Changchun	2,170,084	9,257	1,064	9.53
Harbin	2,635,900	9,244	903	9.03
2010				
Shenyang	4,270,109	38,553	2,895	32.8
Changchun	2,578,904	38,862	2,572	31.1
Harbin	2,996,712	35,035	1,427	22.1

Shenyang, Changchun and Harbin Statistical Yearbook

[a] Non-agricultural population

[b] On post-staff and workers in non-privately owned enterprises including state owned, collective owned and others

[c] Shenyang Economic Statistical Yearbook

Data analyses

Annual urban growth rate

Annual urban growth rate (AGR_a) in area (km^2 $year^{-1}$) and standardized annual urban growth rate (AGR_s) (%) were used to quantify and compare the urban expansion speed of three cities over the past three decades. AGR_a can reflect the temporal patterns of urban expansion for each city and AGR_s can be used to make better comparison among those cities as it excludes the impact of different initial city sizes. The two indexes are defined as follows:

$$AGR_a = (A_{end} - A_{start})/n \quad (1)$$

$$AGR_s = \left((A_{end}/A_{start})^{1/n} - 1 \right) \times 100\ \% \quad (2)$$

where AGR_a is the annual urban growth rate in area (km^2 $year^{-1}$) and AGR_s is the standardized annual urban growth rate (%); A_{end} and A_{start} are the urban area at the end and start of the period, respectively, and n is the duration between the start and end time (in years).

Urban expansion types

Identifying different types of urban growth in a quantitative method is essential to help land use planners better analyze the characteristics of urban sprawl at local to regional scale. Three urban expansion types (i.e., infilling, edge-expansion and outlying) can be identified using the E index according to Xu et al. (2007):

Table 2 Remote sensing data for land cover classification used in the study

Period	Landsat path/row (WRS2)						
	Shenyang	Changchun			Harbin		
	119/31	118/29	118/30	119/29	117/28	119/29	118/28
1980	1979-09-29	1981-05-22	1978-09-14	1978-08-23	1976-07-04	1976-07-04	1976-07-05
1985	1984-09-05	1984-09-14	1985-09-14	1984-09-21	1983-05-24	1983-05-24	1983-08-19
1990	1992-10-13	1989-09-12	1989-09-23	1989-08-02	1991-08-26	1991-08-26	1989-09-12
1995	1995-05-15	1993-09-07	1993-09-07	1996-05-03	1996-05-19	1996-05-03	1995-09-29
2000	2000-10-27	1999-08-15	2000-09-18	2001-08-13	2001-08-13	2001-08-13	2001-09-21
2005	2006-09-18	2005-09-08	2005-09-18	2006-09-18	2006-09-20	2006-09-20	2006-09-27
2010	2010-09-29	2010-09-22	2010-06-02		2010-09-15	2010-09-15	2010-09-22

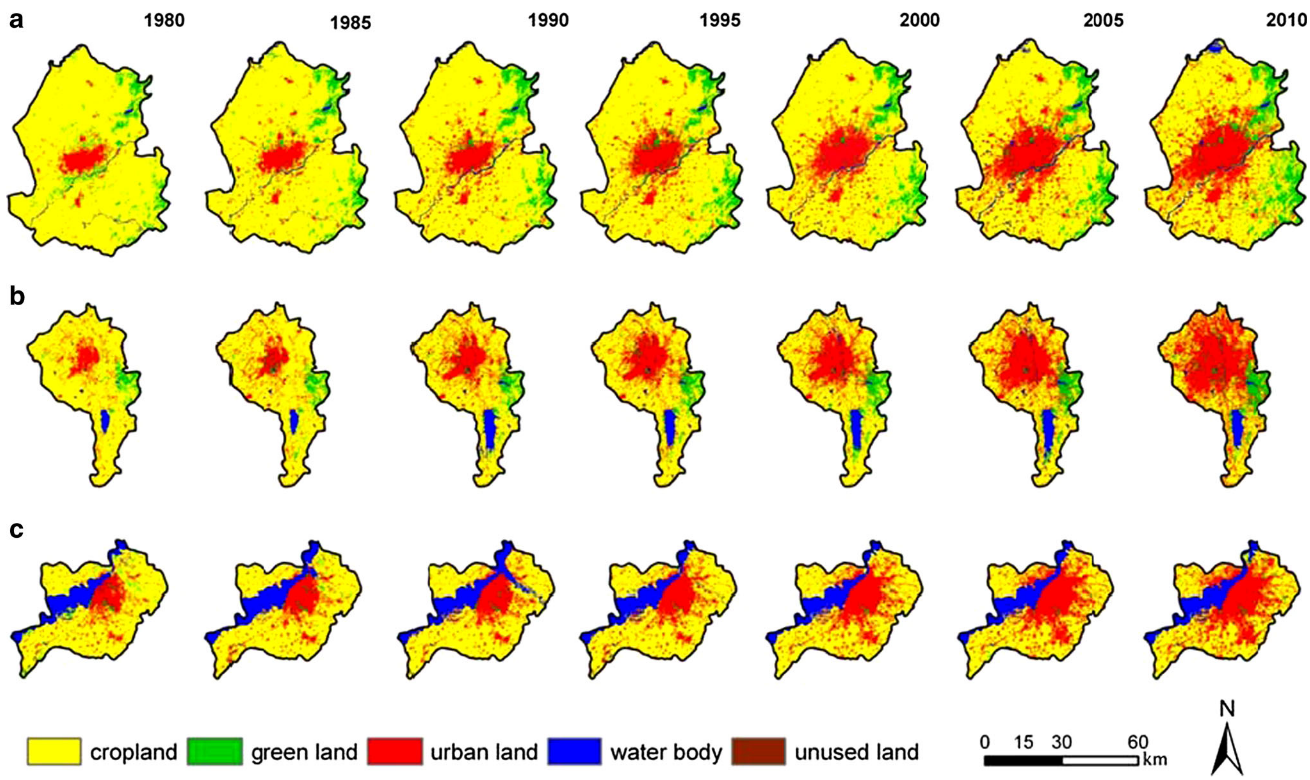

Fig. 2 Spatiotemporal distribution of land covers in Shenyang (**a**), Changchun (**b**) and Harbin (**c**) over the past three decades

Table 3 Descriptions for land cover types

Land cover type	General description
Cropland	Land for agricultural use, including paddy field and upland field
Green land	Land covered with natural or planted forests, roadside trees, grass land
Urban land	Land for industrial, business, educational, residential and institutional uses in cities and counties, and transportation lines and airports was also included
Water body	Rivers and flooded land, reservoirs, ponds and lakes
Unused land	Sand, saline-alkali land and bare rocks

$$E = L_{\mathrm{com}}/P_{\mathrm{new}} \tag{3}$$

E represents urban expansion type, P_{new} is the perimeter of a newly developed urban patch, and L_{com} is the length of common edge of this newly developed urban patch and existed urban patch or patches. The value of E will range from 0 to 1. Urban expansion type is defined as infilling when $E > 0.5$, edge-expansion when $0 < E \leq 0.5$, and outlying when $E = 0$.

Table 4 Accuracy assessment of land cover classifications for Shenyang, Changchun and Harbin

Land cover types	Kappa coefficient					
	Shenyang		Changchun		Harbin	
	Prior 2010	2010	Prior 2010	2010	Prior 2010	2010
Cropland	0.82	0.87	0.87	0.87	0.92	0.89
Green land	0.90	0.85	0.93	0.91	0.76	0.80
Urban land	0.91	0.82	0.91	0.82	0.94	0.81
Water body	0.89	0.85	0.93	0.76	0.85	0.85
Unused land	NA	NA	NA	0.76	NA	NA
Overall	0.86	0.85	0.90	0.83	0.88	0.84

Urban expansion intensity

Urban expansion intensity index (UII) was generated to evaluate the spatial distribution of urban expansion at different periods. UII is defined as follows:

$$UII_{i,t-t+n} = \left[\frac{UA_{i,t+n} - UA_{i,t}}{n}\right] \times \frac{100}{TA_i} \tag{4}$$

where $UII_{i,\, t\text{–}t+n}$ is the urban expansion intensity for spatial unit i during the time span t and $t + n$; $UA_{i,t+n}$ and $UA_{i,t}$ represent the urban land area of spatial unit i at the time $t + n$ and t; TA_i stands for the total area of spatial unit i. The spatial unit was a 2 km × 2 km grid in this study, and the UIIs at the spatial unit level were divided into five classes by a custom standard <10 %, 10–20 %, 20–40 %, 40–70 %, 70–100 %, which corresponds to the urban expansion intensity of very low, low, moderate, rapid and highly rapid, respectively.

Landscape metrics

Two sets of metrics at the landscape and class levels were calculated to quantify the impacts of urban expansion in all three cities using FRAGSTATS (version 3.3) (McGarigal et al. 2002). In consideration of the objectives of this study and the redundancy among these metrics, eight metrics were selected to identify the shape, composition and spatial distribution of landscape. Landscape shape index (LSI), Shannon's diversity index (SHDI), Shannon's evenness index (SHEI) and Contagion index (CONTAG) are calculated in landscape level; Number of patches (NP), Large patch index (LPI), Mean patch size (MPS) and Area-weighted mean shape index (SHAP_AM) are calculated for the land cover type of urban land. Detail description for each metric is listed in Table 5.

Results

Temporal changes of urban land

Over the past 30 years, all cities have experienced a rapid urban expansion at the expense of other land covers (Fig. 2 and Table 6). From the late 1970s to 2010, the urban land of Shenyang expanded from 209.8 to 836.3 km^2, with a growth rate of 20.2 km^2 $year^{-1}$ on average. Changchun expanded from 202.0 to 682.4 km^2, with an average growth rate of 15.5 km^2 $year^{-1}$. In contrast, Harbin expanded from 239.6 to 567.9 km^2 with a relatively low growth rate of 9.7 km^2 $year^{-1}$ on average (Table 7).

These increases, however, varied across six time periods (Table 7). As for Shenyang, the urban expansion speed kept steady with AGR_a ranging from 15.6 to 18.6 km^2 $year^{-1}$ during 1980–2005 until a sharp increase (39.2 km^2 $year^{-1}$) occurred in the last period (2005–2010). Changchun experienced a generally slow development of urban growth before 2000 except the period 1985–1990 with a relatively high growth rate of 17.1 km^2 $year^{-1}$. Entering the twenty-first century, however, AGR_a of Changchun increased dramatically and reached 34.1 km^2 $year^{-1}$ in 2005–2010. In contrast, the urban expansion process of Harbin was the slowest in the study period evidenced by the values of AGR_a all below 15.0 km^2 $year^{-1}$except a relatively high annual growth rate of 17.2 km^2 $year^{-1}$ in the period 1995–2000.

The standardized annual growing rates (AGR_s) for Shenyang, Changchun and Harbin over the past three decades are 4.6, 4.0 and 2.6 %, respectively (Table 7). During the initial period of implementing the Reform and Opening-up Policy (1980–1985), the fastest urban expansion happened in Shenyang with a growth rate of 7.3 % and the slowest was in Harbin (2.6 %). Entering the twenty-first century, Changchun expanded fast with the high AGR_s of 5.1 and 5.9 % during 2000–2005 and 2005–2010, respectively. It is noticeable that a high urban growth rate (5.3 %) for Shenyang occurred in 2005–2010, ending its continual decline since 1980. Over the entire study period, Shenyang

Table 5 Landscape metrics used in the study based on McGarigal and Marks (1995)

Landscape metric	Abbreviation	Description	Range
Number of patches	NP	The total number of a certain land cover type (or whole landscape)	NP ≥ 1
Mean patch size	MPS	The total area of a certain land cover type (or whole landscape) divides by the NP of this class (or whole landscape)	MPS > 0
Large patch index	LPI	The proportion of total area occupied by the largest patch of a land cover type	0 < LPI ≤ 100
Landscape shape index	LSI	A modified perimeter-area ratio of the form that measures the shape complexity of the whole landscape or a specific land cover type	LSI > 0
Area-weighted mean shape index	SHAP_AM	The shape index weighted by relative patch area which measures the average shape complexity of individual patches for the whole landscape or a specific land cover type	SHAP_AM > 0
Shannon's diversity index	SHDI	Equals the minus sum, across all land cover types, of the proportional abundance of each land cover type multiplied by the logarithm of that proportion, divided by the logarithm of the number of land cover types	SHDI ≥ 0
Shannon's evenness index	SHEI	A measurement of patch diversity, which is determined by the distribution of different types of land cover in landscape	0 ≤ SHEI ≤ 1
Contagion index	CONTAG	A measurement to depict the degree of agglomeration or the trend of extension of different land cover types in the landscape	0 < CONTAG ≤ 100

and Changchun kept a faster urban expansion rate than Harbin except 1995–2000 when the highest growth rate (4.4 %) was in Harbin.

Table 6 Land cover changes of Shenyang, Changchun and Harbin (in km^2)

Land cover types	Cropland	Green land	Urban land	Water body	Unused land
1980					
Shengyang	2,929.7	246.5	209.8	39.4	1.0
Changchun	1,211.4	79.0	202.0	32.0	0.4
Harbin	1,114.2	61.4	239.6	231.9	4.3
1985					
Shenyang	2,816.7	262.0	299.1	48.2	0.5
Changchun	1,153.2	93.3	242.4	35.5	0.3
Harbin	1,066.9	27.0	286.4	264.2	6.9
1990					
Shenyang	2,699.4	267.1	408.4	51.2	0.3
Changchun	9,97.9	110.9	328.1	80.3	7.6
Harbin	1,028.0	20.2	320.8	279.6	2.7
1995					
Shenyang	2,611.1	288.9	479.3	47.2	NA
Changchun	9,67.6	116.6	367.5	64.5	8.5
Harbin	1,023.4	17.9	357.7	245.9	6.4
2000					
Shenyang	2,502.7	302.2	568.0	53.7	NA
Changchun	903.6	146.1	399.3	72.2	3.4
Harbin	969.6	8.7	443.9	229.2	NA
2005					
Shenyang	2347.1	306.8	679.5	93.1	NA
Changchun	768.2	143.5	511.7	91.1	10.2
Harbin	885.8	14.9	514.9	235.7	NA
2010					
Shenyang	2,100.6	415.8	836.3	73.7	NA
Changchun	571.6	202.6	682.4	67.8	0.19
Harbin	812.4	41.7	567.9	229.4	NA

Types of urban expansion

The contributions of each urban growth type to the newly developed urban land for three cities among the neighboring periods are illustrated in Fig. 3. Over the entire study period, edge expansion is the dominant growth type (>50 %) for all cities, and the outlying growth type generally accounts for the least proportion except for the first two periods for Shenyang and the first period for Changchun when infilling is the least contributor. For Shenyang, the proportion of edge-expansion growth type kept more than 60 % before 1990, and then decreased with the alternative increasing proportion of infilling growth type from 13.1 to 31.0 % before an obvious increase occurred during 2006–2010. The contribution of outlying growth type ranged from 14.3 % during 2000–2006 to 23.3 % during 1979–1984. The composition of three urban growth types in Changchun was generally similar to that of Shenyang but the highest share of edge expansion (72.6 %) occurred in 2005–2010. The temporal patterns of the composition of three growth types for Harbin are quite different from those for Shenyang and Changchun. Over the past three decades, the proportion of edge-expansion type for Harbin has exhibited a Bell-shaped pattern and the highest value was 65.9 % during 1989–1995, but infilling type of urban expansion in Harbin has showed an inverted bell-shaped trend. The share of outlying type growth in Harbin was more than 15 % in the 1980s, and then declined to 7.4 % in the period 2000–2006, followed by an abrupt increase to 15.2 % in the last period (2006–2010).

Urban expansion intensity

In consideration of distinct development stages of three cities, spatial distributions of UII have been evaluated in a ten-year interval and the whole study period (Fig. 4). Arterial highways, secondary highways and tertiary highways of each city are added for better understanding of the

Table 7 Annual urban growth rate for Shenyang, Changchun and Harbin

Period	Annual growth rate in area (km^2 $year^{-1}$)			Standardized annual growth rate (%)		
	Shenyang	Changchun	Harbin	Shenyang	Changchun	Harbin
1980–1985	17.8	8.1	6.7	7.3	3.7	2.6
1985–1990	15.6	17.1	5.7	4.6	6.2	1.9
1990–1995	17.7	7.9	6.2	4.1	2.3	1.8
1995–2000	17.7	5.3	17.2	3.5	1.4	4.4
2,000–2005	18.6	22.5	11.8	3.0	5.1	2.5
2005–2010	39.2	34.1	13.2	5.3	5.9	2.5
1980–2010	20.2	15.5	9.7	4.6	4.0	2.6

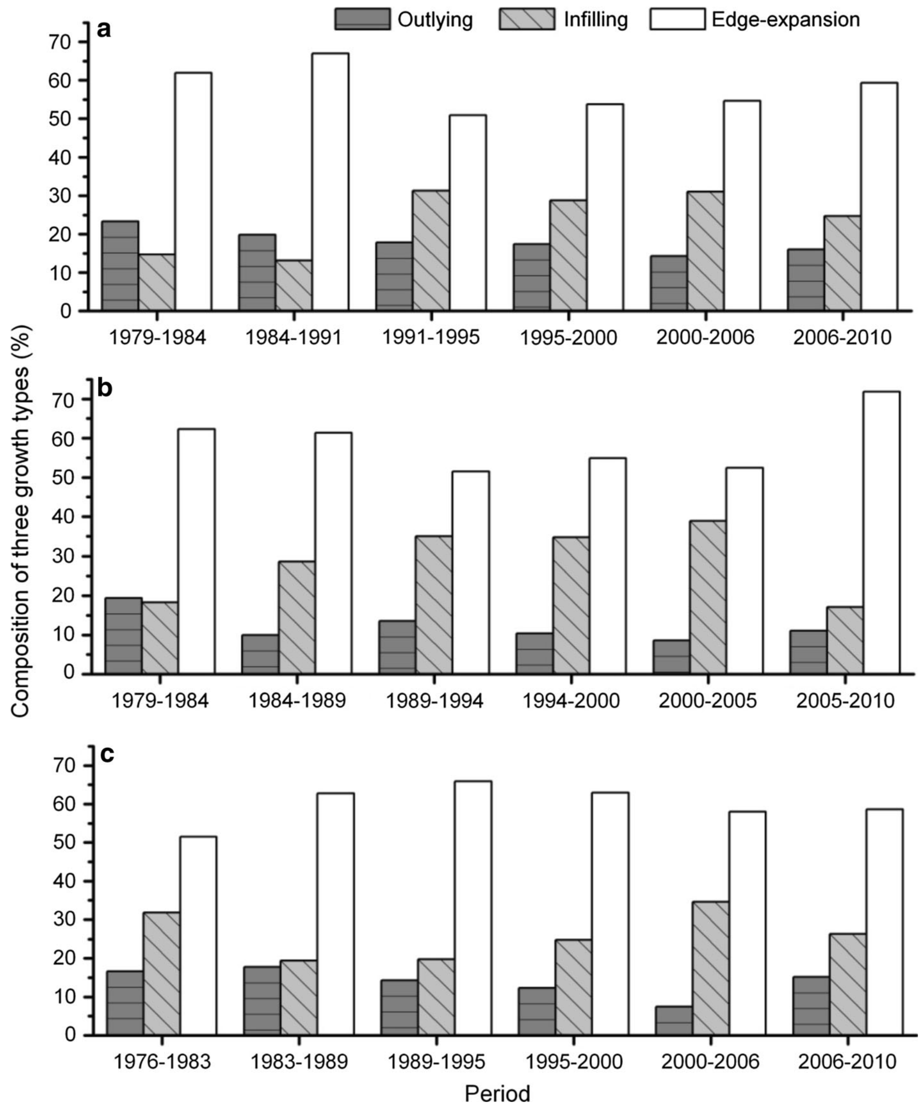

Fig. 3 The proportion of three urban growth types (outlying, infilling and edge expansion) for newly developed urban areas in Shenyang (**a**), Changchun (**b**) and Harbin (**c**) among the neighboring periods over the past three decades

spatial patterns of UII. Although not all highways are constructed in the same period, they all have been completed in 2010.

For Shenyang, most of the rapid and highly rapid expansion grids were rather dispersed in the 1980s and distributed aggregately after 1990. For Changchun, cells of highly rapid expansion did not increase significantly until 2000. As for Harbin, mass cells of rapid expansion mainly appeared in the 1980s, which were distributed in the old city areas. And there was a highly rapid expansion region in the northeast of Harbin in the 1990s. Although since 1990 Harbin did not have blocks of highly rapid expansion grids like Shenyang and Changchun, its Songbei District, located in the north of Songhua River, became a hot region of urban expansion in the twenty-first century.

Overall, most of the fast urban expansion areas illustrated by rapid and highly rapid expansion grids were around the edge of the built-up districts, while the distribution patterns of the highly rapid expansion areas in each city were distinct. There was an obvious southwest direction for urban expansion in Shenyang towards Tiexi District and there also existed some dispersed highly rapid expansion grids in northern and southern regions, all of which were quiet relevant to the patterns of arterial highways marked by black color. For Changchun, southwestern and southeastern parts were the main areas where highly rapid expansion occurred. Different from Shenyang, it was the secondary highways and tertiary highways marked by gray and green colors that were more relevant to the distribution of highly rapid expansion grids in Changchun. As for Harbin, Daoli and Taiping Districts located in the central parts of Harbin experienced the highly rapid expansion. It is apparent that the city center of Harbin was still under construction while Shenyang and Changchun's urban expansion had already being expanding around city centers.

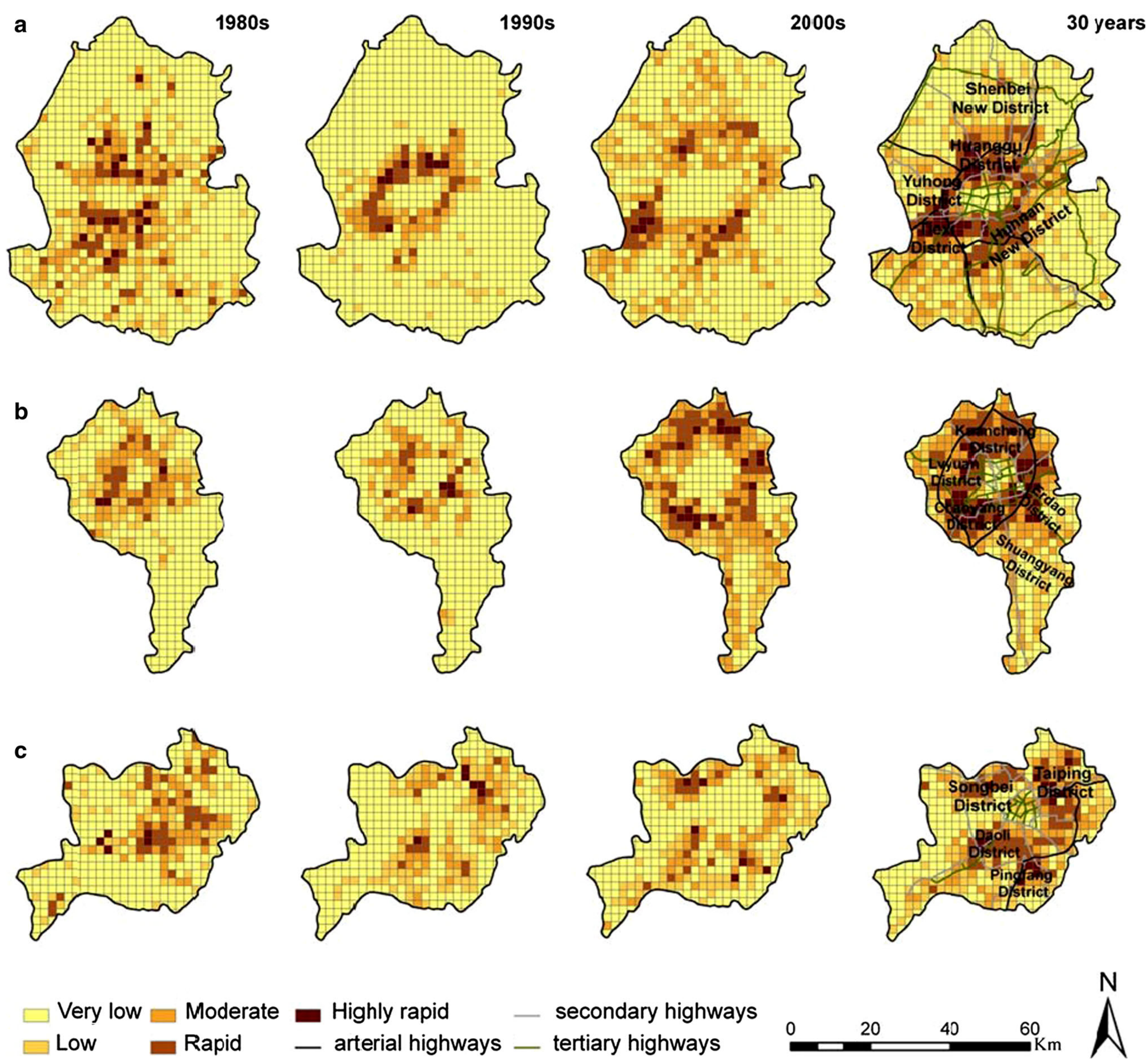

Fig. 4 Spatial distribution of urban expansion intensity index (UII) for Shenyang (**a**), Changchun (**b**) and Harbin (**c**) in the 1980s, 1990s, 2000s and the entire study period

Landscape metrics

Changes in urban land

To investigate the temporal patterns of urban land change in Shenyang, Changchun and Harbin, four class-level landscape metrics including NP, MPS, LPI and SHAP_AM are calculated (Fig. 5). NP for all cities increased at first and then decreased, exhibiting a roughly bell-shaped pattern although the peak value for each city occurred in different year (1995, 1994 and 2000 for Shenyang, Changchun and Harbin, respectively). The curves of MPS display an almost opposite shape compared to NP. These results reveal an alternate pattern of fragmentation and aggregation of urban patches over time in all cities. LPI for all cities increased along with the urban expansion process, suggesting the rapid expansion of the urban center, and it was more obvious for Changchun than the other two cities. SHAP_AM which measures the average shape complexity of individual patches, continuously increased over the past three decades, indicating an increase in the complexity of urban land in three cities and this trend was especially obvious for Changchun.

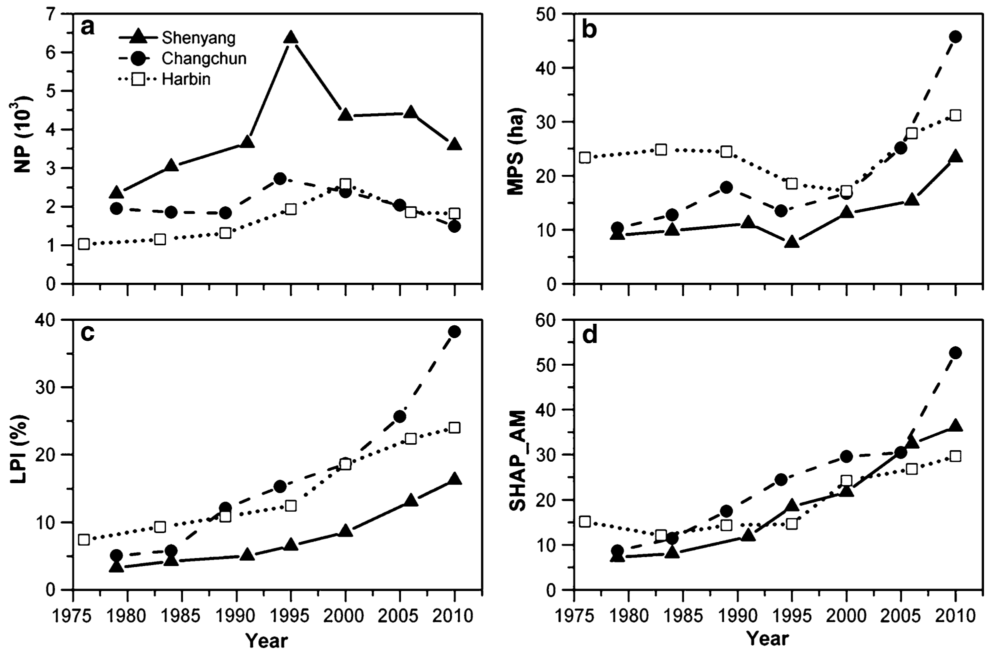

Fig. 5 Temporal patterns of four urban land level metrics (NP, LPI, SHAP_AM and MPS) for Shenyang, Changchun and Harbin

Changes in the regional landscape

As urban expansion proceeded, landscape of all three cities became more fragmented as indicated by a continuous decline in CONTAG, which measures the degree of clumping of patches at the landscape level, and it decreased by 33.6, 27.8 and 19.8 % for Shenyang, Changchun and Harbin, respectively (Fig. 6). The entire landscape in each city became more evenly distributed among different land use types, which was evidenced by the smooth increase of SHDI, as well as the extremely similar change of SHEI. It should be noted that there was not an evident change in the three landscape metrics mentioned above for Harbin until 1995, in comparison with a continual trend from the late 1970s to 2010 for both Shenyang and Changchun. In addition, the increase of LSI indicates that patch shape became more complicated and irregular for all cities. It increased from 41.4 to 92.6 for Shenyang and 44.8 to 79.1 for Changchun, but there was not a similar rise for Harbin.

Discussion

Temporal changes of urban land

Results show that three cities in Northeast China have experienced a rapid urban expansion process over the past three decades. Shenyang, Changchun and Harbin expanded 3.0 times, 2.4 times and 1.4 times more than the initial area of each city, respectively (Fig. 2). Urban expansion tends to proceed at the expense of valuable cropland (Seto et al. 2000), and this phenomenon is particularly evident in the case of China (Liu et al. 2005c). As the capital cities in Northeast China, one of the most important grain bases for a long history, the contribution rate of land conversion from cropland to the newly developed urban land over the past three decades amounted to 56.6, 33.4 and 71.4 % for Shenyang, Changchun and Harbin, respectively. Previous studies have found that rapid urban expansion can also encroach on green land (Yin et al. 2011; Zhou and Wang 2011) and this situation was also observed in Changchun as indicated by the fact that 52.3 % of its urban land came from green land (Fig. 2; Table 6).

Overall, Shenyang has the highest AGR_s (4.6 %) over the past 30 years, followed by Changchun (4.0 %) and Harbin is with the lowest (2.6 %) (Table 7). Relatively low level of economic development in Harbin during the 1960s and early 1970s might retard its following urban expansion (Zhang et al. 2007), as urban expansion is closely associated with economic development (Gar-on Yeh and Li 1999; Davis and Henderson 2003). The standardized urban growth rates of Shenyang and Changchun were faster than that of Harbin across the entire study period except the period 1995–2000. The most fast expansion period for Harbin was 1995–2000, which was attributed to the construction of economic and technological development districts, especially the Songbei Development District, set up in 1995. The policy of establishing development district carried out throughout China in the 1990s stimulated the urban expansion process of many cities (Schneider et al. 2005; Xiao et al. 2006; Hu et al. 2008). The development zones of Harbin such as the Yingbin Road High-tech Zone

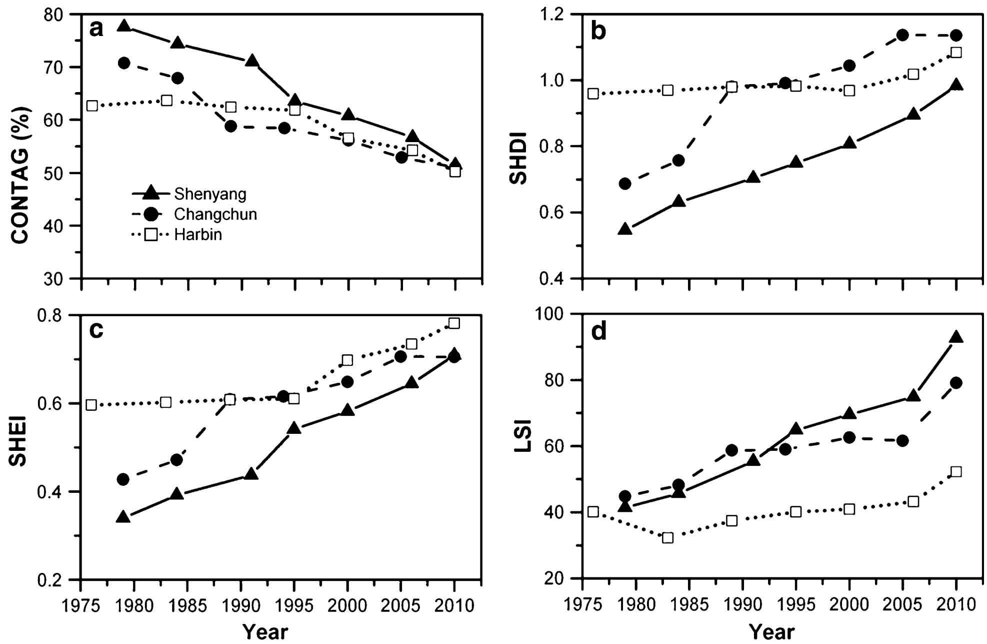

Fig. 6 Temporal patterns of four landscape level metrics (CONTAG, SHDI, SHEI and LSI) for Shenyang, Changchun and Harbin

were set fairly close to the city center, which accorded with the relatively small percentage of urban areas due to the limitation of Songhua River in the 1990s. Therefore, land construction within and surrounding those development zones not only resulted in increase of urban areas but also enhanced the connectivity and consequently accelerated urban expansion of Harbin. Shenyang, admittedly, was the leading city in the first five-year period (1980–1985) thanks to its previous base of a relatively advanced economic capacity (Xi et al. 2012). But, during the period 1985–1990, the fastest urban expansion occurred in Changchun, mainly due to the construction of southeastern economic and technological development zone and southwestern advanced automobile industrial park. Northeast China is a typical industrial region with the highest urban expansion level in China. However, at the initial period of Reform and Opening-up policy, Northeast China was confronted with the tough reconstruction challenge when state owned enterprises closed down, many factory buildings were abandoned and unemployment and laid-off workers greatly increased. Changchun and Harbin were greatly affected by the economic downturn. In addition, AGR_s of three cities in the 1990s kept relatively low, which revealed the continuity of the mentioned stagnated urban expansion process. Entering the twenty-first century, the new policy called "Revitalizing Old Industrial Base of Northeast China" has played a significant role in the urban expansion process of Northeast China (Wu et al. 2009; Liu et al. 2010). The AGR_a for all cities increased considerably since 2000, and Changchun possessed the highest AGR_s, followed by Shenyang and Harbin (Table 7). On the other hand, China has started to regulate the use of land for construction to insure "bottom line" of 120 million hectares (ha) of arable land since 2006, due to the considerable reduction of agricultural land and the large population of about 1.3 billion. Therefore, the pressure, Northeast China confronted with, from the contradiction between urban expansion and arable land protection, definitely not only comes from itself, as the traditional and vital agricultural base of China, but also from the national arable land protection policy to guarantee the whole country's food safety. In this context, the already severe transformation in Northeast China from woodlands, grasslands, bottomlands of rivers and lakes to croplands might keep aggravating in the future urban expansion process (Liu et al. 2005c, 2010; Hu et al. 2008).

Spatiotemporal patterns of urban expansion

The spatiotemporal patterns of urban expansion varied with city. Urban expansion of Shenyang was quiet dispersed in the 1980s and Changchun expanded in a pie style in the same period, which might be attributed to the stimulation of outlying and edge-expansion types of urban growth (Heimlich and Anderson 2001). This phenomenon has also been manifested by other urban expansion studies in Guangzhou (Sun et al. 2013) and Nanjing (Xu et al. 2007). While in the 1990s, most of the rapid and highly rapid expansion girds for Shenyang and Changchun are distributed in cities' central areas and the overall spatial patterns of two cities were more compact than those in the 1980s (Fig. 4). The more compact urban expanding pattern in the

1990s was consistent with the significant increase of infilling type of urban growth for Shenyang and Changchun (Fig. 3). In the 1990s, land resources became less sufficient than those in the 1980s and meanwhile the investment, working and living environment became more and more important for the development of a city. Subsequently, urban planning began to play a great role in the urban development. The first City Planning Law of the People's Republic of China was proposed in 1989 and put into effect in 1990, which underlined the principle of strictly controlling the size of large cities. Constructions were then carried out on a rational basis and the infilling type of urban expansion promoted the land usage of inner city (Ellman 1997). While for Harbin, spatial pattern of urban expansion did not became more aggregated in the 1990s, which might be attributed to the difficulties of old town development such as the protection of historic buildings (Couch and Karecha 2006; Al-hagla 2010).

Entering the twenty-first century, there appeared some evident intensive expansion districts in each city. Previous studies show that income played an important role in China's urban growth (Deng et al. 2008). The economic development of China over the past several decades brought about the simultaneous increase of average salary, which benefited the increase of living area per capita and transportation land per capita, exerting direct effect impetus on urban land expansion (Liu et al. 2005b). The average salary for Shenyang, Changchun and Harbin increased by 15.7, 18.6 and 15.7 times from 1990 to 2010, respectively (Table 1). The rapid increase of average salary enhanced people's purchasing power and thus might stimulate the improvement of living environment and the construction of new housing. Spatial and temporal processes of urban expansion are also closely related to the development of transportation and high-tech industry. Especially, urban transportation infrastructure construction guides urban expansion directions and thus urban forms (Reilly et al. 2009; Müller et al. 2010). The arterial highways (Number: G1501), also called "the ring road", were once identified as the urban boundary of Shenyang in the 1990s. Afterwards, good transportation network of tertiary highways facilitated the later urban expansion and that boundary was broken. The year 2000 witnessed the opening of MTR in Shenyang, which made Shenyang the first city of Northeast China to have metro. Advanced traffic lines and infrastructures ensured Shenyang's most rapid urban expansion among the three capital cities in Northeast China (Wang et al. 2008). In addition, the newly implemented policy "Revitalizing Old Industrial Base of Northeast China" which was aimed to push Northeast China into transition phrase stimulated the urban expansion in all three cities, and old industrial areas are the key areas, for their vital economic engine effect in terms of economic development. Figure 4 shows that regions where most of old industrial zones of each city located became new growth poles of the urban expansion from 2000 to 2010, such as Tiexi District of Shenyang, Erdao District of Changchun and Pingfang District of Harbin (Fig. 4). There was a large area under construction from 2000 to 2010 in Kuancheng District, which is believed to be one of the most potential developing areas in Changchun City. Results also demonstrate another regional expansion feature that the natural barriers (e.g., rivers, mountains) to urban expansion weakened in the twenty-first century. Hunnan High-tech Development District in Shenyang, Jingyue Tourism Development District in Changchun, and Songbei New District that is famous for Sun-island Scenic Zone in Harbin have become noticeable urban development zones which are once separated by river or mountains from city centers. It might be attributed to the stimulation of tertiary industry such as tourism, education and real estate (Tan et al. 2005a).

Urban expansion induced landscape change

Urban expansion has brought about significant alternations of urban landscape. Overall, the degree of fragmentation in landscape level for Shenyang, Changchun and Harbin, evidenced by the decreasing value of CONT and the increasing value of LSI, has been aggravating under the impact of urban expansion over the past three decades. The constant increase of SHDI and SHEI indicates an intensive land use and land cover change caused by rapid urban expansion in those three central cities of Northeast China. With cropland, the most substantial type of land cover, being occupied by urban land, landscape of each city became more complicated and landscape composition became evener, which are consistent with previous studies that the proportion of different land use types is evener in urban areas than in rural landscapes (Weng 2007). Urban expansion not only occupies high-quality arable land but also wetland. As illustrated in Fig. 4, the highly rapid expansion region during the 1990s was located at the river basin in Taiping District of Harbin, which might imply that the highly rapid urban expansion in that period was accomplished at the cost of valuable wetland there. Intensive land cover change will inevitably threaten biodiversity through habitat loss and fragmentation (Gagné and Fahrig 2007; McKinney 2008). With the acceleration of urban expansion in the twenty-first century, revealed in this study, biodiversity conservation will become a true challenge for the local governments of Shenyang, Changchun and Harbin. Moreover, increased impervious area due to urban expansion (e.g., streets, highways, parking lots and sidewalks) can have negative impacts on the environment such as runoff pollution, soil erosion and heat island effect

(Arnold and Gibbons 1996; Voogt and Oke 2003; Gluch et al. 2006). Although landscape change induced by urban expansion is local, its environmental effects will extend far beyond the city's boundaries as urban ecological footprint can be hundreds of times of the city area itself (Kaye et al. 2006; Grimm et al. 2008).

Conclusions

Urban expansion has been one of the major human impacts on the environment and it is believed to be one of the biggest challenges for Chinese government in the following decades. Currently, there are few comparative studies on urban expansion in northeast cities of China. In light of the historical and current urban expansion and developing potentials of Northeast China, understanding and monitoring their emerging spatiotemporal patterns of urban expansion are both timely and necessary, which is an integral part for a complete knowledge of urban expansion process in China.

This study detected and compared the spatiotemporal patterns of urban growth in the metropolitan areas of three capital cities in Northeast China, Shenyang, Changchun and Harbin, from the late 1970s to 2010 using remote sensing and landscape metrics. Results show that all three cities have experienced rapid urban expansion over the past three decades, with an annual growth rate of 4.6, 4.0 and 2.6 %, respectively. Despite the general similarity in temporal trend of urban land, the composition of urban growth type for the newly developed urban land, and urban expansion-induced changes in landscape metrics among three cities, there are differences in the magnitude and spatial patterns of urban expansion among them. Shenyang and Changchun generally urbanized faster than Harbin and their urban expansion became compact earlier than Harbin.

Stimulated by the policy of "Revitalizing Old Industrial Base of Northeast China" implemented in the early 2000s, all three cities went into a new era of urban expansion, especially since 2005 when they all went through an abruptly rapid urban expansion. Old industrial bases and newly established high-tech development districts have become urban expansion hotspots, and natural barriers (e.g., rivers, mountains) to urban expansion weakened. With the acceleration of urban expansion in the twenty-first century, managing the tradeoffs between urban expansion and environmental protection would be a great challenge for the local governments of Shenyang, Changchun and Harbin.

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