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Analyses of urban landscape dynamics using multi-temporal satellite images: A comparison of two petroleum-oriented cities

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ABSTRACT

Rapid urbanization, as a result of population growth and migration from rural to urban, has been recognized as a critical process in urban areas. This study analyzed the spatiotemporal landscape dynamics using multi-temporal satellite images in two petroleum-based cities: Houston, Texas in the United States and Daqing, Heilongjiang province in China. Both cities expanded rapidly on the basis of the petroleum industries during the last 50 years; however, under different socio-political contexts. Comparing the landscape pattern and dynamics in these two cities, we can identify how the urbanization in these two petroleum-based cities affects the landscape pattern, especially in the natural landscapes. A set of landscape indices with supplementary ecological meanings was chosen to facilitate our analyses of spatial dynamics over a span of 20 years. On the basis of the derived indices, a general trend of landscape change was revealed in these two cities: natural landscapes such as grassland and wetland were degraded or fragmented into a more heterogeneous pattern, while the human landscapes such as residential area expanded greatly by replacing other natural classes.

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1. Introduction

Rapid urbanization, as a result of population growth and migration from rural to urban, has been recognized as a critical process in urban areas. It changes both the structure and the function of cities (Frank, 1999) and affects the climatology of cities and the surrounding area (Orville et al., 2000). These changes will subsequently affect a number of aspects of urban condition, such as human settlement (Douglas, 1994), ecological diversity (Grove and Burch, 1997), energy flows (Breuste et al., 1998), and climatic conditions (Orville et al., 2000) from local to global scales. Therefore, urban landscapes present many challenges for urban planners, civil engineers, environmentalists, sociologists, economists and even remote sensing scientists (Mesev et al., 2001).

The necessity to understand urban evolution and preserve its resources has culminated in analyzing urban processes over a medium or long term (Ward et al., 2000). To analyze structure, function, and dynamics of urban systems, we need to link landscape pattern with its processes. The conceptual elucidation of these linkages, nevertheless, could seldom assert how the urbanization affects the urban environment. Moreover, increasing awareness of the importance of sustainability in natural resources is stimulating development of contemporary methods to better understand and quantify the causes and consequences of urban landscape evolution (Turner, 1987).

The purpose of the research presented in this paper is to compare the landscape pattern change in two petroleum-based Cities, Houston, Texas in the United States and Daqing, Heilongjiang province in China. The loss of forests and other natural landscape to industry-related urbanization are critical in both Houston and Daqing with expanding residential areas. The use of particular lands in these two cities has changed over time with some grassland and woodland converted to residential area in Houston and some grassland converted to urban or cropland in Daqing. Little research explores the environmental implication of these land-use transitions and the degree to which economical, social, and political factors may be affecting them. Moreover, although both cities expanded rapidly on the basis of the petroleum industries during the last 50 years, they are managed under different socio-political contexts. Comparing the landscape pattern and dynamics in these two cities, we can identify how the urbanization in the petroleum-based cities affects the landscape pattern, especially in the natural landscapes.

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The objectives of this study are twofold: (1) to analyze and interpret the landscape pattern as well as its change in both Houston and Daqing during the last 20 years using the classified maps from satellite images, and (2) to explore the inter-linkage between landscape change, economic development, and land management. To enable a comprehensive investigation and comparison of the complex and heterogeneous landscape in Houston and Daqing, we chose a set of landscape indices with inter-complementary ecological meanings. Lastly, these indices are analyzed to effectively examine both current landscape pattern and retrospective landscape pattern to monitor ongoing changes.

1.1. Urban dynamics detection using remote sensing

Many digital change detection techniques have been developed to detect and monitor urban dynamics using remote sensing data (Singh, 1989; Zhang et al., 2002) during the past two decades. Most change detection methods can be grouped into spectrum-based and post-classification method. The spectrum-based method assumes that significant changes in image pixel values are caused by the changes on the ground given the interference from atmospheric and other system variations have been removed (Singh, 1989). This method compares the multi-temporal image using map algebra, such as image difference (Yeh and Li, 1997) or image regression (Yuan and Elvidge, 1998), and detects the change area using a predetermined threshold. Notwithstanding the spectrum-based method is straightforward and widely used in the natural landscape change detection, such methods have three major drawbacks: (1) they are very difficult to capture the small change in the heterogeneous urban landscape, which often has frequent alternation of land use/cover types within a small area (Zhang et al., 2002; Yuan et al., 2005); (2) they only locate areas where changes occurred without further analyzing the two class types that were involved in the change; (3) these methods are time-consuming because they require both rigorous image registration and classification.

Alternatively, the post-classification method begins the analysis by classifying multi-temporal image; from this, the changes are detected through overlaying the classification results (Singh, 1989; Jensen, 1996; Zhao et al., 1996; Zheng et al., 1997; Mas, 1999; Tang et al., 2005). For the post-classification method, it is easy to identify and locate the change, but the detection errors come from not only the image registration but also the individual image classification. The effective of this detection technique relies mainly upon the accuracy of each individual classification. In addition, this method works well in large spectrally homogeneous area with an obvious change area, but not in highly heterogeneous regions with a minor change (Yang and Lo, 2002).

1.2. Landscape metrics analysis for landscape change detection

Instead of comparing two classified maps directly, the landscape metrics can be used to quantify the individual pattern to detect spatiotemporal pattern of landscape change (Fuller, 2001; Tang et al., 2005). Further information can be derived through the quantitative indices to describe the structure and pattern of a landscape, emphasizing the interaction between spatial pattern and ecological process (Macleod and Congalton, 1998; Miller et al., 1998; Mas, 1999; Roy and Tomar, 2001; Yang and Lo, 2002). These quantitative Landscape indices relate not only to the ecological functions of landscape but can also reflect its socio-economic status (Kong et al., 2007). Compared to the other change detection techniques, the landscape metrics techniques are advantageous in capturing inherent spatial structure of landscape pattern and biophysical characteristics of these spatial dynamic.

Within the landscape metrics techniques, a variety of landscape metrics have been proposed to characterize the spatial configuration for the individual landscape class or the whole landscape base (Patton, 1975; Forman and Gordron, 1986; Gardner et al., 1987; Schumaker, 1996; Chuvieco, 1999; Imbernon and Branthomme, 2001). For instance, patch size and patch shape indices have been widely used to convey meaningful information on biophysically changed phenomena associated with patch fragmentation at a large scale (Viedma and Melia, 1999; Fuller, 2001). As an indication of the shape of patches, these configuration indices usually correlate with the basic parameter of individual patch, such as the area, perimeter, or perimeter–area ratio. However, these indices perform poorly in reflecting the spatial location of patches within the landscape (Imbernon and Branthomme, 2001).

Heterogeneity-based indices were proposed to quantify the spatial structures and organization within the landscape. The dominance and contagion indices were first developed by O'Neill et al. (1988) on the basis of the information theory to capture major features of spatial pattern throughout the eastern United States. The proximity index quantifies the spatial context of patches in relation to their neighbors (Gustafson and Parker, 1992). For example, the nearest-neighbor distance index distinguishes isolated distributions of small patches from the complex cluster configuration of larger patches (Turner, 1989). The above two groups of indices, the patch-based and heterogeneity-based, reflect two aspects of the same spatial pattern, and complement each other. Although the choice of indices relies on the emphasis of a specific research, it is preferred to adopt both groups of indices when speculating on a spatial pattern (Turner and Gardner, 1990) because landscape pattern possesses both homogeneous and heterogeneous attributes.

2. Study sites and data preparation

2.1. Study sites

This research was conducted in two petroleum-oriented cities: Houston, Texas in the United States and Daqing, Heilongjiang in China. Houston, seat of Harris County, Texas, lies largely in the northern portion of the Gulf coastal plain, a 60- to 80-km wide swath along the Texas Gulf Coast, 80 km from the Gulf of Mexico (Moser, 1998). Centered at 95°22′W longitude and 29°46′N latitude, the whole urban region covers an area around, 1500 km^2 and a total population around 2 million in 2006, according to the United States Census Bureau. Houston has a rather low elevation, with the highest elevation in the area at 27 m and elevation rises approximately 0.2 m per meter inland (Houston City and Meeting Planners Guide, 2004) (Fig. 1).

Daqing lies in the middle of Songlen Plain in Heilongjiang Province in the northeastern of China, located about 159 km from the city Haerbing and 139 km from the city of Qiqihaer. Centered at 124°15′E longitude and 46°20′N latitude, the study area covers four major urban areas, Shaertu district, Ranghulu district, Longfeng district, and Honggang district. Daqing, the largest oil producer in China, maintains a variety of landscape types due to its unique geology and climate environment. The typical land use types include agriculture, urban or build-up, grass, saline or barren land, water, wetland, and woodland (Tang et al., 2006).

2.2. Data preparation

Our images for the two study areas run across three decades through the 1970s to 2000 (Table 1). All images for Daqing were acquired between the late June to September, which falls in the growing season of Daqing. The images for Houston have a wide

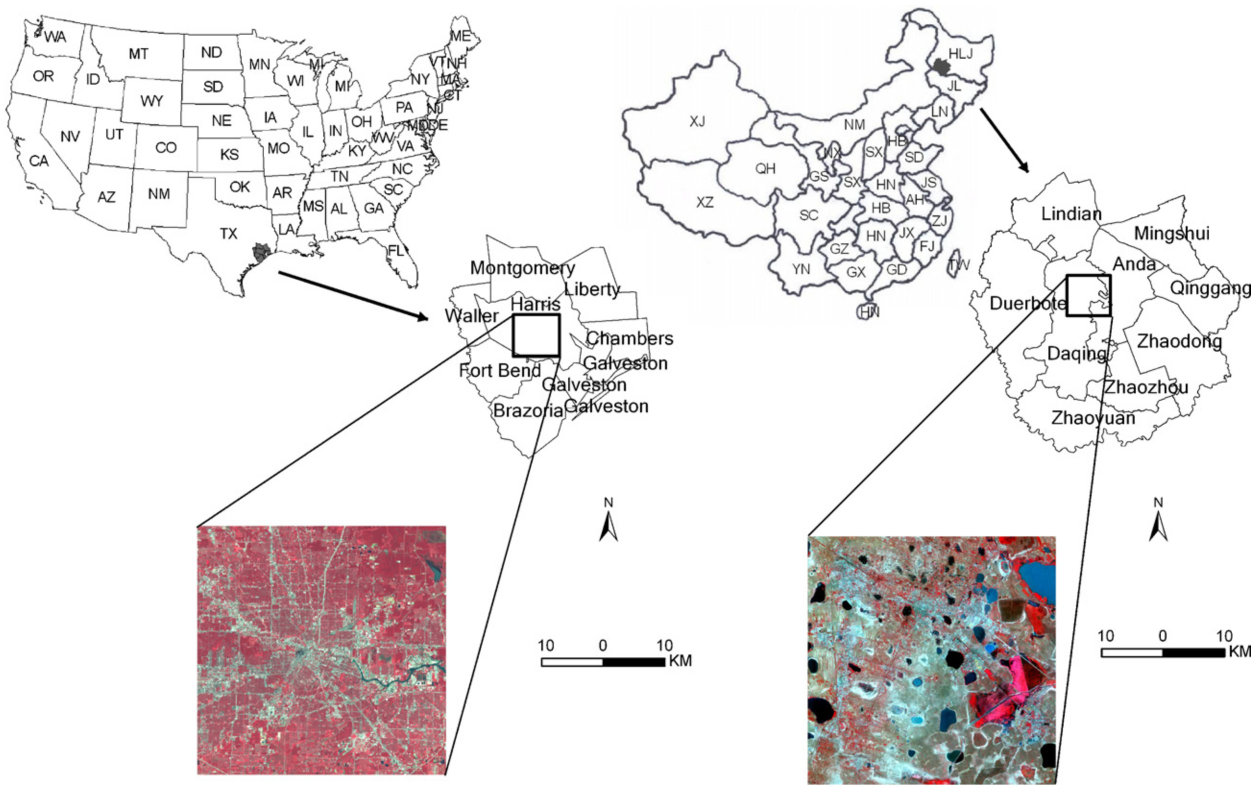

Fig. 1. Study areas – Houston in the United States and Daqing in China.

season range since the season change is not obvious in Houston. In order to make these two study areas comparable, two smaller areas were subset from the original images, covering around 1200 km^2 of the major metropolitan area in both Houston and Daqing. All images were registered to the UTM map projection on a SUN workstation using ERDAS™ software, achieving an accuracy of less than 0.5 pixel root mean square error (RMSE) for all images. A further resample was applied to the MSS and TM to reduce the error caused by different image resolutions.

The conventional Maximum Likelihood Classification was adopted to obtain six classified maps in our study areas. On the basis of the knowledge of geology, geography, vegetation and land use in Houston and Daqing, we set up two sets of classification schemes for Houston and Daqing, respectively. In the image, the residential area in Houston was represented as low albedo and the industrial/commercial area has high albedo, while most construction lands in Daqing has high albedo. Therefore, the urban area in Houston was further classified into residential area and industrial/commercial area. Considering agriculture is another economic base of Daqing city, the agriculture class is also included in its classification system. These classification schemes are listed and described in Table 2. We chose around 600 pixels for training samples at each year on the basis of the requirement of traditional Maximum Likelihood Classification and the size of our study area. Another set of test samples around 600 pixels was then chosen each year for both Houston and Daqing. The selection of separate training and test samples was guided by the characteristic description of each class (Table 2). The exact number of training and test samples and the classification accuracy of each class are shown in Table 3. In order to reduce the error caused by the different resolutions among MSS, TM, and ETM, the classification results were transformed into vector layers before we calculated the landscape ecology indices for these two cities.

3. Methodology

A set of landscape indices was selected for the fragmentation analysis. Although a wide variety of landscape indices have been applied in describing the spatial composition and configuration of landscape pattern, many of them substantially overlap with each other (Giles and Trani, 1999; Tischendorf, 2001). In order to reduce the redundancy, we tried to choose the indices which have the least mutual correlation and possess complementary ecological meanings (Table 4).

Table 1
Characteristics of the used satellite remote sensing images

Study area	Sensors	Dates	Data characteristics
	Landsat Multispectral Scanner (MSS)	10/1/1976	4 spectral bands, 60 m spatial resolution
Houston	Landsat Thematic Mapper (TM)	12/8/1990	7 spectral bands, 30 m spatial resolution
	Landsat Enhanced Thematic Mapper (ETM)	11/9/2000; 1/2/2003	8 spectral bands, 15 m spatial resolution
	Landsat Multispectral Scanner (MSS)	8/23/1979	4 spectral bands, 60 m spatial resolution
Daqing	Landsat Thematic Mapper (TM)	7/20/1990	7 spectral bands, 30 m spatial resolution
	Landsat Enhanced Thematic Mapper (ETM)	6/21/2000; 8/11/2001	8 spectral bands, 15 m spatial resolution

Table 2
Classification systems and the definitions of the training samples

	Landscape type	Training samples using color composite (bands 4, 5, 3)
Houston	Residential	Regular shape in brown, gray, and dark blue
	Industrial/commercial	Bigger and brighter than the residential roof, usually in brown, white, and gray
	Grassland	Light red and regular shape
	Woodland	Dark red and distributes along northeast of Houston
	Barren or soil	White or yellow and distributes along the river or grassland
	Water	Smooth, cyan, blue, and sometimes black
Daqing	Residential/other construction	Intensively used by buildings, and appears in the image as mixed pixels of light blue
	Agriculture	Primarily for the production of rice and fiber, shows in the image as light or dark red, green with strip texture
	Grassland	Mixed pixels of red, white, and light green
	Woodland	Dark red and distributes along northeast of Daqing
	Wetland	Identified on higher elevations, regular shape, in red or dark red
	Saline	White or light, most next to the water
	Water	Irregular shape, ultramarine

In this paper, two categories of landscape indices were chosen from the perspectives of the patch attributes and spatial heterogeneity. The patch-based indices consist of patch standard deviation (PSD), edge density (ED), landscape shape index (LSI), and area-weighted mean patch fractal dimension (AWMPFD) with aims to measure the changes in the area distribution and the shape among the patches. Regarding the spatial heterogeneity-based indices, we chose Shannon's diversity index (SHDI) to measure the landscape diversity, contagion index (CONT) to measure the composition and configuration of landscape, mean nearest-neighbor distance (MNND) to denote the fragmentation degree caused by the isolation, and core area percent of landscape Index (CPLI) to measure the interior fragmentation degree in the patches. The indices were calculated using FRAGSTATS (UMASS, 2004) and ARC/INFO software.

4. Result and discuss

4.1. Quantitative description of landscape dynamics

Fig. 2 is landscape maps of Houston in 1976, 1990 and 2000, and Daqing in 1979, 1990 and 2000, respectively. In Houston (Fig. 2A), most industrial/commercial area is distributed in the downtown area or along the major roads. This central business district is surrounded by the concentric rings of residential area, which sprawled greatly during 1976–2000. Residential buildings are surrounded by the grassland and woodland. This pattern can be attributed to the regional characteristics of Houston's neighborhoods. Located in the coastal biome in the gulf plains, the vegetation of Houston is classified as temperate grassland. Prevailing winds from south and southeast bring enough moisture from the Gulf of Mexico, which provides a favorable environment for the woodland in the northeastern Houston.

Fig. 2B is the landscape map of Daqing in 1979, 1990, and 2000. It reveals a north–south distribution throughout the whole study area. Most of the agriculture is distributed in the southeast and northwest of the study area, while the residential/other construction area lies along the railway line between the cities of Haerbin and Qiqihaer. Most lakes are distributed in the middle part of study area, with the grassland and saline distributed around them.

Grassland was the dominant class in Houston in 1976 and occupied 511.34 km^2 and 41.61% of the whole study area (Fig. 2 and Table 5). The residential area became the dominant class after the 1980s, occupying 479.78 km^2 (39.07%) in 1990 and 564.43 km^2 (45.97%) in 2000, respectively. The expansion of the residential area occupied a large area of grassland and woodland in the suburban area of Houston. Similar to Houston, the dominant class of Daqing was also grassland, occupying 432.67 km^2 and 35.21% of the whole study area with a large mean patch area (0.16 km^2/one) in 1979 (Table 5). From 1990, agriculture became the dominant class, occu-

Table 3
The accuracy assessment of landscape maps classified by MLC

	Train sample			Test sample			User accuracy (%)			Producer accuracy (%)		
	76	90	2000	76	90	2000	76	90	2000	76	90	2000
Houston												
Residential	632	648	607	624	626	621	91.72	98.01	99.72	97.79	94.25	99.90
Industrial/commercial	584	640	606	580	592	609	82.67	85.85	80.23	95.75	90.20	99.95
Grassland	592	540	629	557	604	608	95.12	90.72	99.99	84.48	94.69	99.89
Woodland	600	626	600	624	612	570	99.68	99.99	99.99	99.99	99.99	99.79
Barren or soil	640	636	596	632	594	586	88.77	82.84	98.99	80.06	81.87	70.47
Water	600	608	621	568	574	551	98.39	99.98	99.99	99.19	97.39	99.47
Overall accuracy (%): 92.58 (1979); 94.45 (1990); 96.19 (2000)												
Kappa: 0.92 (1979); 0.93 (1990); 0.95 (2000)												
Daqing												
Residential/other construction	574	557	608	600	556	571	88.60	99.23	99.99	96.40	98.85	90.67
Agriculture	612	580	564	616	566	610	72.83	90.25	77.88	61.22	85.49	91.88
Grassland	592	592	566	623	651	608	76.18	91.90	85.50	84.30	92.99	66.14
Woodland	592	536	586	552	570	558	87.16	87.08	92.11	83.77	87.08	84.39
Wetland	623	564	602	568	564	558	83.60	93.63	88.55	87.55	93.63	96.93
Saline	608	570	579	616	616	604	97.50	99.61	87.21	99.41	99.61	99.99
Water	624	588	576	568	556	582	99.36	99.64	99.99	92.81	99.64	99.99
Overall accuracy (%): 86.41 (1979); 93.07 (1990); 89.90 (2000)												
Kappa: 0.84 (1979); 0.92 (1990); 0.88 (2000)												

Table 4
Definitions of Landscape metrics used for urban dynamic analysis

	Landscape metric	Formula	Variables	Description
Patch-based	Patch standard deviation	$PSD=\sqrt{\frac{\sum_{i=1}^{m}[a_i-MPS]^2}{m}}\left(\frac{1}{1000}\right)$	a_i: patch area of ith class; m: patch number of ith class; mps: mean patch area	A typical index to indicate the distribution among the patches by finding out the area difference among patches (Forman and Gordron, 1986)
	Edge density	$ED=\frac{p_i}{a_i}$	p_i: perimeter of ith class; a_i: patch area of ith class	This index indicates the degree of fragmentation through the segmentation of edge
	Landscape shape index	$LSI=\frac{P_i}{2\sqrt{\pi a_i}}$	p_i: perimeter of ith class; a_i: patch area of ith class	A modified index of ED
	Area-weighted mean patch fractal dimension	$AEMPED=\sum_{i=1}^{m}\left[\frac{2\ln(0.25p_i)}{\ln(a_i)}\left(\frac{a_i}{A}\right)\right]$	p_i: perimeter of ith class; a_i: patch area of ith class; A: total area	Close to 2 in a highly convoluted perimeter due to an increasing complexity in the patch shape (Schumaker, 1996; Olsen et al., 1999; Read and Lam, 2002)
Heterogeneity-based	Shannon's diversity index	$SHDI=-\sum_{i=1}^{n}[P_i\ln(P_i)]$	P_i: percentage of class; n: number of landscape classes	It measures the landscape diversity (O'Neill et al., 1988; Viedma and Melia, 1999)
	Contagion index	$CONT=1+\sum_{i=1}^{m}\sum_{j=1}^{n}P_{ij}\ln(P_{ij})/2\ln(n)$ $P_{ij}=P_iP_{j/i},\quad P_{j/i}=m_{ij}/m_i$	P_{ij}: probability that a patch of ith class adjacent to jth class; m: patch number of ith class; n: number of landscape classes; P_i: randomly chosen probability; $P_{j/i}$: conditional probability	A large CONT reflects the clumping of large contiguous patches while a small CONT value reflects a landscape that is dissected into small patches (O'Neill et al., 1988; Turner, 1990; Li and Reynolds, 1993; Griffith et al., 2002)
	Mean nearest-neighbor distance	$MNND=\frac{\sum_{i=1}^{m}h_i}{m}$	h_j: distance from each patch to its nearest neighbor; m: the total number of nearest neighbors to this patch	It measures the degrees of isolation and fragmentation within the specified neighborhood of the focal patch (Gustafson and Parker, 1992)
	Core area percent of landscape Index	$CPLI=\frac{\sum_{i=1}^{m}a_i^c}{A}$	a_i^c: the undisturbed core area; A: total class area; m: patch number of ith class	This edge-to-interior index provides fragmentation information of the class (FRAGSTATS * ARC, 2004)

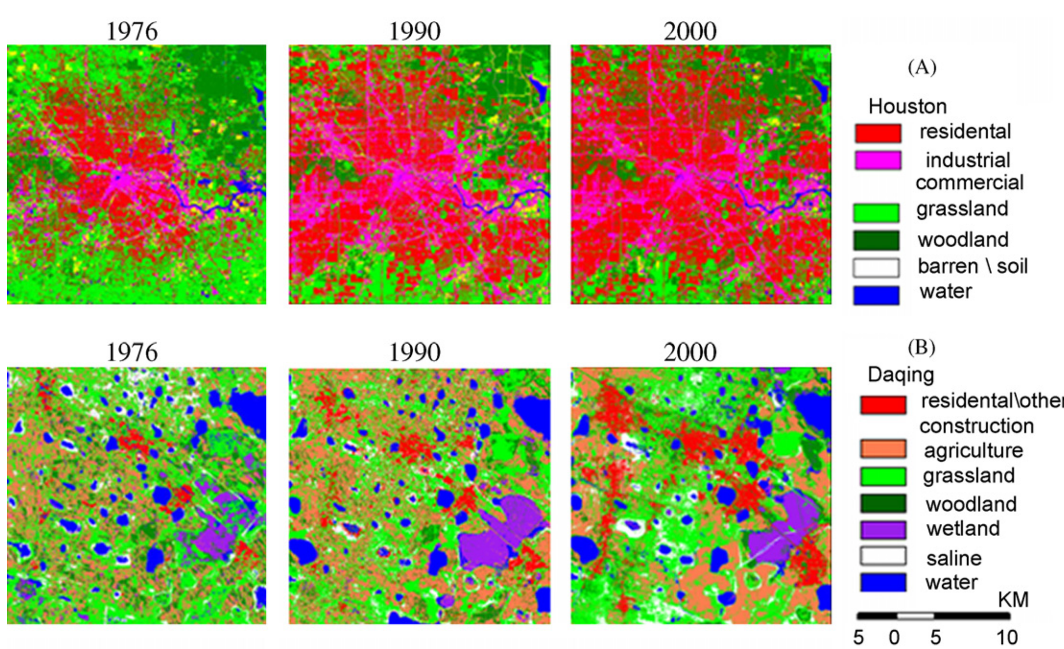

Fig. 2. The landscape maps of Houston and Daqing.

Table 5
The analysis of area change in Houston and Daqing

	Area (km^2)			Patch #			%Area			Average area (km^2)		
	1976	1990	2000	1976	1990	2000	1976	1990	2000	1976	1990	2000
Houston												
Residential	312.47	479.78	564.43	6401	16,689	18,712	25.43	39.07	45.97	0.05	0.03	0.03
Industrial/commercial	93.50	228.58	198.21	2282	12,402	12,286	7.61	18.62	16.14	0.04	0.02	0.02
Grassland	511.34	287.53	235.89	4416	19,693	22,052	41.61	23.42	19.21	0.12	0.01	0.01
Woodland	209.68	140.32	184.70	3325	4,003	15,048	17.06	11.43	15.04	0.06	0.04	0.01
Barren/soil	70.13	81.98	32.72	4404	19,751	12,364	5.71	6.68	2.66	0.02	0.00	0.00
Water	31.73	9.67	11.85	1655	722	1,133	2.58	0.79	0.97	0.02	0.01	0.01
Daqing												
Residential/other construction	33.38	79.55	148.07	464	6,333	5,352	2.72	6.47	12.06	0.07	0.01	0.03
Agriculture	362.90	403.33	419.63	6544	12,912	14,409	29.53	32.82	34.18	0.06	0.03	0.03
Grassland	432.67	383.19	285.93	2757	11,134	16,400	35.21	31.18	23.29	0.16	0.03	0.02
Woodland	141.00	85.61	97.06	3334	11,321	8,297	11.47	6.97	7.91	0.04	0.01	0.01
Wetland	70.18	72.05	62.90	1847	1,771	3,359	5.71	5.86	5.12	0.04	0.04	0.02
Saline	76.27	89.21	102.19	1570	10,421	8,929	6.21	7.26	8.32	0.05	0.01	0.01
Water	112.45	115.92	112.02	1499	1,220	1,700	9.15	9.43	9.12	0.08	0.10	0.07

pying 383.19 km^2 (32.82%) in 1990 and 419.63 km^2 (34.18%) in 2000, respectively. As a part of alluvial Songnen plain, large area of grassland in Daqing was cultivated into agriculture in the eastern area due to the fertile soil and sufficient rain conditions there.

Although grassland was the dominant class in both Houston and Daqing, it experienced a rapid decrease in its mean patch area in these two cites. In Houston, it decreased from 0.12 km^2/each to 0.01 km^2/each in 1990 and 2000. In Daqing, the mean patch area of grassland decreased from 0.16 km^2/each in 1979 to 0.03 km^2/each in 1990 and 0.02 km^2/each in 2000. This is in accordance with the fragmentation process caused by the urban sprawl. Woodland, similar with the grassland, experienced the fragmentation process from the 1970s to 2000, in both Houston and Daqing. It is interesting to find out that other impervious surfaces, i.e. residential or industrial/commercial area had a decreasing average area though their total area increased. This implies that these human-related lands had a more fragmented pattern than before. Although the water landscape does not own a large area in Daqing, its average patch area is larger than other classes (0.08 km^2/each in 1979; 0.10 km^2/each in 1990; and 0.07 km^2/each in 2000). The reason is obvious because water is found as lakes in Daqing and lakes are always naturally continuous in space.

Over the past 20 years, our study areas have experienced tremendous changes. The total change areas in Houston between 1976–1990 and 1990–2000 are 629.48 km^2 and 262.49 km^2 and the percentages are 51.22% and 21.38%, respectively. As indicated in Fig. 3A, the most significant change in Houston appears to be the spread of residential and build-up areas, and the loss of grassland. The total change areas in Daqing between 1979–1990 and 1990–2000 are 209.74 km^2 and 219.55 km^2 and the percentage are 17.07% and 17.87%, respectively (Fig. 3B). Compared with Houston, Daqing has a smaller change area. Only three classes have obvious changes: construction land and agriculture increased, and grassland decreased.

Table 6 shows the descending sort of the main changes in Houston and Daqing. This analysis of change landscape provides not only the 'from' and 'to' information, but also the quantity of the conversion area. The major changes can be summarized as follows:

- A large area of grassland was converted to human-disturbed landscapes in both Houston and Daqing. Although this conversion was slowed down in Houston and some agriculture converted back to grassland in Daqing, grassland was ranked as first in decreasing classes due to the urban expansion during the last two decades for these two cities.
- The human-disturbed landscape, especially the impervious surface in urban area increased greatly during these two decades. In Houston, the residential area kept increasing while the industrial/commercial area decreased from 18.60% in 1990 to 16.13% in 2000. Most of the decreasing area in industrial/commercial is transformed to residential (69.17 km^2), which made the residential area increase. Lacking zoning ordinances separating residential, business, and industrial areas, Houston is full of neighborhoods that mix of all three (Verhovek, 1993). This might cause the classification error between residential area and commercial/industrial area. Furthermore, the large supply of land and solid housing market in Houston stimulated more construction of residential area, either from the undeveloped suburban area or from the redeveloping area in urban interior (Kirkendall, 2008). In Daqing, both residential/other construction and agri-

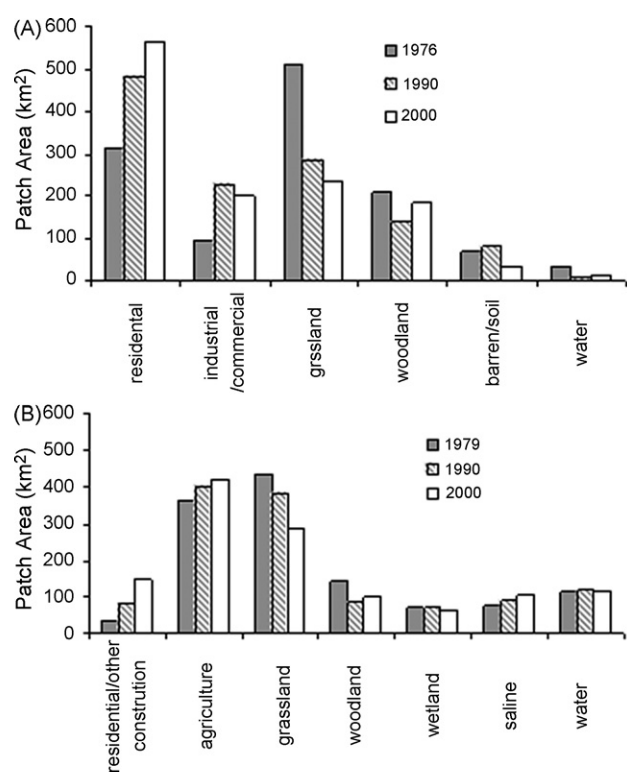

Fig. 3. Comparison of area change in Houston (A) and Daqing (B).

Table 6
The descending sort of the main changes in Houston and Daqing

Transform type (Houston)	1976–1990		Transform type (Houston)	1990–2000	
	Change area (km^2)	%Area		Change area (km^2)	%Area
Grassland to Residential	204.22	16.74	Industrial/commercial to Residential	69.17	5.67
Grassland to Industrial/commercial	51.94	4.26	Grassland to Residential	68.70	5.63
Residential to Industrial/commercial	49.45	4.05	Grassland to Woodland	44.84	3.68
Woodland to Grassland	40.75	3.34	Residential to Grassland	35.80	2.93
Grassland to Barren/soil	39.30	3.22	Residential to Woodland	32.05	2.63

Transform type (Daqing)	1976–1990		Transform type (Daqing)	1990–2000	
	Change area (km^2)	%Area		Change area (km^2)	%Area
Grassland to Agriculture	124.06	10.10	Grassland to Agriculture	135.04	10.99
Agriculture to Grassland	117.24	9.54	Agriculture to Grassland	76.04	6.19
Woodland to Agriculture	63.94	5.20	Residential/other construction to Grassland	66.75	5.43
Woodland to Grassland	38.58	3.14	Woodland to Agriculture	38.94	3.17
Grassland to Saline	35.75	2.91	Saline to Grassland	36.55	2.97

culture, experienced obvious increase during 1979–2000. Most these areas are transformed from grassland (26.42 km^2) and agriculture (20.73 km^2) and most cultivated land is converted from grassland (124.06 km^2) and woodland (63.94 km^2).

- Woodland experienced a significant decrease during the first period in Houston and Daqing. During the second period, both Houston and Daqing had slight increases in woodland. In Daqing, most woodland was transferred from agriculture (26.00 km^2) and grassland (28.96 km^2). The increase of woodland in Houston might be caused by the newly planted trees around the new houses in southern and northern Houston.
- A general trend of landscape change was revealed: grassland was taken over by impervious surface due to the urban sprawl. Some woodland was degraded into grassland, and trees were planted sporadically around the residential area, resulting in a more fragmented landscape.

4.2. *Landscape metrics analysis of dynamics*

We applied the chosen landscape metrics to characterize the change of patch attribute and spatial heterogeneity for each class throughout Houston and Daqing. Tables 7 and 8 show the changes of these indices in both Houston and Daqing. In this paper, we analyzed three major groups: (1) human landscapes, including residential area and commercial/industrial area in Houston, agriculture and residential/other construction land in Daqing; (2) natural landscapes, including grassland, wetland, and woodland; and (3) other barren surface, including the soil around the vegetation and barren area around the building.

In Houston, PSD of residential area decreased in the first period and then increased in the second period (Table 7). A possible explanation is that more irregular-shaped residential areas appeared and gradually replaced the grassland around the urban area. The increasing of other patch attribute indices also indicates that residential area became more irregular. All the patch indices of industrial/commercial area in Houston increased in the first period and then decreased in the second period. This might be because few industrial or commercial buildings were constructed in Houston due to the collapse of Houston's energy industry in the severe economic recession in the mid-1980s.

In Daqing, the human-disturbed landscapes have a very similar trend with Houston. Both residential/other construction and agriculture areas have an increasing trend in ED, LSI, and AWMPFD. For all the landscape types, Houston's residential area and Daqing's agriculture have an identical trend in the patch attribute indices. This also indicates that these two classes have similar change pattern: the new small patches in them was developed far away from the original patches, instead of sprawled from them.

Grassland and woodland have different trends in our study areas, indicating different manners of conversion between these two classes. Since most woodland is distributed in the northeastern corner of Houston, the edge of the woodland was likely to be replaced by the impervious surface due to urban sprawl between 1976 and 1990. At the same time, the grassland was fragmented into

Table 7
Patch attribute indices of Houston and Daqing

	PSD			ED			LSI			AWMPFD		
	1976	1990	2000	1976	1990	2000	1976	1990	2000	1976	1990	2000
Houston												
Residential	166.70	94.56	245.60	61.80	125.32	144.30	107.40	175.89	186.84	1.28	1.34	1.42
Industrial/commercial	44.25	98.88	42.70	19.44	71.52	59.27	61.68	145.35	130.54	1.18	1.32	1.26
Grassland	405.97	25.91	19.43	74.78	91.13	84.42	102.42	165.54	168.82	1.34	1.24	1.22
Woodland	162.22	40.09	21.27	26.69	25.68	54.94	57.16	66.84	124.28	1.22	1.19	1.19
Barren/soil	4.64	2.61	1.51	21.10	48.50	22.48	77.63	165.43	120.61	1.10	1.14	1.12
Water	22.46	17.77	14.18	7.53	2.41	3.46	41.06	23.67	30.83	1.13	1.20	1.20
Daqing												
Residential/other construction	44.39	15.35	68.82	5.06	27.63	35.88	26.96	97.14	90.48	1.19	1.23	1.32
Agriculture	143.48	74.01	221.04	77.67	113.08	124.32	125.79	173.26	186.79	1.28	1.35	1.41
Grassland	233.07	131.00	41.40	73.57	121.06	69.08	109.25	190.22	126.06	1.32	1.32	1.27
Woodland	15.97	7.25	11.53	29.25	38.09	35.86	75.82	126.58	112.02	1.15	1.18	1.20
Wetland	49.01	92.31	71.01	12.46	10.20	12.88	45.83	36.95	49.99	1.17	1.24	1.24
Saline	24.80	8.25	14.65	14.51	37.08	36.94	51.22	120.65	112.37	1.15	1.19	1.22
Water	69.00	78.43	65.02	9.99	8.43	12.19	29.17	24.16	35.72	1.09	1.09	1.12

Table 8
Spatial heterogeneity indices of Houston and Daqing

	SHDI			CONT			MNND			CPLI		
	1976	1990	2000	1976	1990	2000	1976	1990	2000	1976	1990	2000
Houston												
Residential	0.35	0.37	0.36	0.54	0.63	0.78	1.49	0.70	0.44	7.87	11.41	11.15
Industrial/commercial	0.20	0.31	0.29	0.61	0.67	0.84	2.05	0.91	0.60	2.03	3.13	2.73
Grassland	0.36	0.34	0.32	0.56	0.64	0.80	1.42	0.80	0.61	17.17	5.21	3.36
Woodland	0.30	0.25	0.28	0.73	0.82	0.84	1.88	1.12	0.69	9.11	5.16	4.69
Barren/soil	0.16	0.18	0.10	0.44	0.44	0.68	1.84	0.92	0.87	0.77	0.27	0.13
Water	0.09	0.04	0.04	0.58	0.79	0.87	2.90	2.51	1.81	0.75	0.33	0.33
Daqing												
Residential/other construction	0.10	0.18	0.26	0.73	0.67	0.75	2.94	1.07	0.97	1.13	1.10	3.35
Agriculture	0.36	0.37	0.37	0.47	0.64	0.59	1.37	0.76	0.76	7.33	6.70	5.86
Grassland	0.37	0.36	0.34	0.54	0.60	0.71	1.37	0.71	0.85	11.31	5.33	8.28
Woodland	0.25	0.19	0.20	0.59	0.58	0.63	1.84	0.92	1.01	3.09	0.75	1.15
Wetland	0.16	0.17	0.15	0.67	0.87	0.80	2.55	1.36	1.22	2.28	3.16	2.62
Saline	0.17	0.19	0.21	0.65	0.61	0.64	2.19	0.92	1.02	1.84	0.93	1.29
Water	0.22	0.22	0.22	0.83	0.93	0.89	2.70	1.63	1.26	6.26	7.10	6.03

small pieces. During 1990–2000, more grassland was fragmented into pieces and then replaced by the impervious surface. Thus, PSD and AWMPFD, in both grassland and woodland, kept decreasing during 1976–2000 with an increasing LSI.

It is also interesting to notice the different trends of grassland in Daqing and Houston. Although both of them have a decreasing patch area and increasing patch number, the LSI and AWMPFD indicated a different location of change area. For Houston, most of grassland was replaced by the new residential buildings sprawling from the central business district. In Daqing, the grassland was always cultivated into agriculture far away from the urban area; that is, the replacement always happened far away from the patch edge.

The result of spatial characterization indices suggests that these indices, as the indicators of relation between the patches, provide complementary information to those shape characterization indices (Table 8). In Houston, the CONT and MNND showed an identical trend in all landscape types. This trend implies that all classes have a more clustered pattern, with a less mixture with other classes. Residential area and industrial/commercial area have the same trend in the CPLI, which first increased and then decreased. This might be caused by the planting of trees around the new residential buildings, which brought meandering edges to these impervious surfaces. The decreasing CPLI, in both grassland and woodland, implies a more fragmented landscape associated with vegetation.

In Daqing, both agriculture and residential/construction land have an increasing SHDI and decreasing MNND. While in the CPLI, residential/other construction area decreased lightly first (1.13 in 1979 and 1.10 in 1990) and increased greatly (3.35 in 2000) in the second period. Agriculture kept on decreasing in CPLI during 1979–2000. This different trend in construction land and agriculture also denotes the different conversion in them. Since new agriculture patches were always small, the CPLI and MNND kept on decreasing. More and more small patches in residential/other construction were connected with the original large ones during the second period, their CPLI increased greatly during the second period though the MNND kept decreasing. As a typical decreasing landscape, grassland had a slight increase during the second period in the MNND and CPLI. The MNND and CPLI of grassland in Houston are different from those in Daqing. These different trends imply that the replacement of grassland in Houston always happened from the boundary to the core area. Similarly, the MNND and CPLI of woodland in Daqing have a same change trend: decreased greatly in the first period and increased slightly in the second period. On the contrary, direct replacement of forest patches along the boundary dragged both the MNND and CPLI down in Houston.

4.3. Social, economical, and political factors of the urbanization

Urbanization and its subsequent land use/land cover changes are governed by social, economical, and political factors, such as population growth, economic development, and socio-political reforms. The significant change in Houston, particularly in the first period, was the increasing residential area and the decreasing grassland. With the development of the petrochemical and petroleum manufacturing, the population's growth is a profound factor in driving urbanization, inasmuch as the new built factories need a significant amount of labors. Depending more on the availability of cheap fuel than other manufacturing cities, the oil production's decline started from the end of 1980s slowed down the expansion of the residential area and industrial/commercial area during the second period in Houston. Comparing with Houston, Daqing itself is an oil field and the oil exploration is 50 years later than Houston. With an instant increasing in the oil production from 1960, the human-disturbed landscapes expanded during two study periods in Daqing. Obviously, Houston has a concentric-zonal pattern on the basis of one central business district (CBD) while Daqing has a multiple-nuclei pattern in its exploration. This analysis further indicated that during the first period Houston experienced more change than Daqing, inasmuch as Houston's petroleum industry boom is 50 years earlier than Daqing. Daqing kept expanding in the second period, while the sprawl of Houston slowed down in the 1990s due to the decline of petroleum production.

Changes in landscape patterns as a result of economic policy have been similar in both Houston and Daqing. Since the economic recession from the late 1980s, Houston has made efforts to diversity its economy by focusing on aerospace and biotechnology, reducing the employment in petroleum industry from two-thirds in 1980 to less than one-third in 2006. Although the development of petroleum industry is 50 years later than Houston, Daqing has realized the importance of the diversity in its economic base and the sustainability in its natural resource from the late 1980s. Urged by the government's policy from the early 1990s, Daqing's farmers started to return the agriculture back into grassland or woodland, which brought a more homogonous pattern in both grassland and woodland during the second period.

Land management is another important human-driver in urban land use/land cover change. Different from other large cities in the United States, Houston did not adopt city zoning laws in its

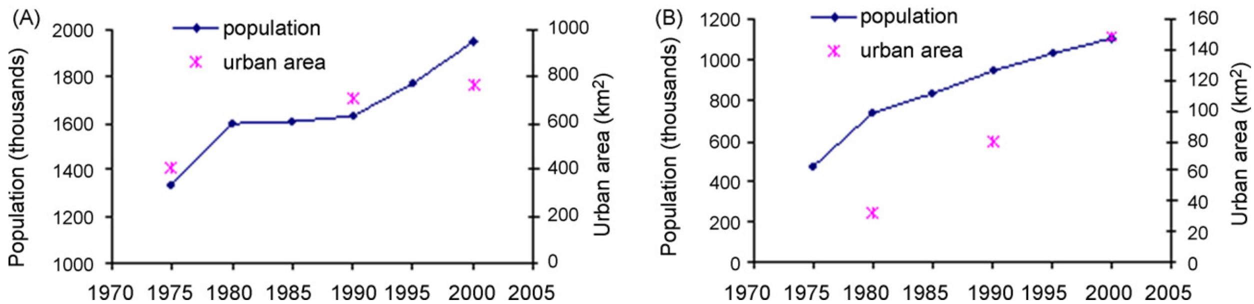

Fig. 4. The relationships between urban expansion and population growth in Houston (A) and Daqing (B).

urban planning. Lacking city zoning has led to an abundance of urban sprawls in Houston, resulting in a relatively large metropolitan area and low population density (Houston City and Meeting Planners Guide, 2004). In this circumstance, the urban sprawl process has been accelerated by all level of government in Houston by building more roads to the urban fringe than other cities (Lewyn, 2003).

Daqing, once a rural area, has experienced the similar urban sprawl during last 50 years due to the lack of management on land resources. In 1950s, the city was still in scattered spots near the petroleum exploration station. Gradually, the original spots connected to each other to form a zonal landscape (Zang et al., 2005) due to the urbanization in recent years. Lacking potent land resource managements during the urbanization process also led to serious waste in land resource and ecological environment degeneration (Zang and Huang, 2006) in Daqing. This character can be exhibited in the intensive expand of the construction land and agriculture and the heavily impact on the natural landscape by the rapid development of petroleum industrial system. For example, a large area of grassland in Daqing was degraded into barren/soil area soon after the pipeline and oil wells were constructed. Distributing like a transportation network in Daqing, these oil delivery pipelines and oil wells represents the peculiar landscape of oil field in Daqing (Zang et al., 2005).

Another major cause of landscape change, particularly in the urban area, was the population growth (Fig. 4) in these two cities. The population of Daqing has grown greatly during the last 20 years, increasing from 470,000 in 1975 to 1.2 million in 2000 (Statistic Bureau of Daqing, 2001). Human population growth, with the increasing petroleum production in Daqing, triggered not only the urban sprawl but also the intensive exploitation of agriculture during the last 20 years.

In Houston, the recession of petroleum slowed the population growth down during 1980–1990. In the middle of 1980s, Houston lost population for the first time. With a successful economic transfer from energy-based economy to the diversity economy, Houston's population started to increase from the beginning of 1990s. In 1981 energy related industries accounted for 84.3% percent of the City's economic base. By 1989 that percentage had dropped to 61%, and in 2002 it was 48.3% (City of Houston, 2005). A return to former prosperity in the late 1990s meant greater population, spatial and economic growth, and also created a movement toward greater economic diversification that required more labor and living spaces for them.

5. Conclusion

The quantitative analysis of landscape patterns using multi-temporal Landsat images enabled us to characterize the internal structure of landscapes, compare the landscape classes, and monitor the landscape dynamics throughout both Houston and Daqing. This study explored the potential of satellite remote sensing and GIS-related techniques in producing landscape maps and statistical analysis of the landscape pattern.

Petroleum is the major economic base in Houston and Daqing. Agriculture is another economic support in Daqing due to its historical development. Although Houston has a similar physical environment as Daqing, it has no farmland around the city centre. Therefore, different from Houston, Daqing has an obvious trend in cultivating grassland into agriculture as well as urban sprawl.

This study also revealed that landscape metrics were useful to detect landscape pattern and its changes. The patch attribute indices, PSD, ED, LSI, and AWMPFD, were found to be effective in the identification and description of the shapes of landscape types. The spatial heterogeneity indices, SHDI, CONT, MNND, and CPLI, The SHDI, provided abundant information to reveal the overall spatial pattern of landscape. In this research, the spatial statistics method demonstrates its unique in the quantitative analysis of landscape change regarding both the biophysical and social–economic factors.

Current research results can be further improved from the following two aspects. First, more detailed ecological, social, political, and economic factors should be incorporated in the analysis of change detection. More detailed awareness of the landscape context from these factors will assist us in making objective statements in dynamics analysis. Secondly, considering the study size and time range in these two cities, there is still some error propagated from the data source and classification process. How to quantify this uncertainty between multi-resolution, multi-temporal remote sensing will be a very interesting research topic.

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