

# Comparison of spatial structures of urban agglomerations between the Beijing-Tianjin-Hebei and Boswash based on the subpixel-level impervious surface coverage product

CAO Shisong, HU Deyong, <sup>\*</sup>HU Zhuowei, ZHAO Wenji, CHEN Shanshan, YU Chen

College of Resource Environment and Tourism, Capital Normal University, Beijing 100048, China

**Abstract:** Under the background of China's rapid urbanization, study on comparative analysis of the spatial structure of urban agglomerations between China and the US can provide the policy proposals of space optimization for the Chinese government. Taking the Beijing-Tianjin-Hebei (BTH) and Boswash as study area, we mapped the subpixel-level impervious surface coverage of the BTH and Boswash, respectively, from 1972 to 2011. Further, landscape metrics, gravitational model and spatial analysis were used to analyze the differences of the spatial structures between the BTH and Boswash. The results showed that (1) the area of the impervious surface increased rapidly in the BTH, while those remained stable in the Boswash. (2) The spatial structure of the BTH experienced different periods including isolated cities stage, dual-core cities stage, group cities stage and network-style cities stage, while those of the Boswash was more stable, and its spatial pattern showed a “point-axis” structure. (3) The spatial pattern of high-high assembling regions of the impervious surface exhibited a “standing pancake” feature in the BTH, while those showed a “multi-center, local aggregation and global discrete” feature in the Boswash. (4) All the percentages of the impervious surface of ecological, living, and production land of the BTH were higher than those of the Boswash. At last, from the perspective of space optimization of urban agglomeration, the development proposals for the BTH were proposed.

**Keywords:** impervious surface coverage; urban agglomeration; spatial structure comparison; landscape pattern; ecological-living-production land

## 1 Introduction

In today's world, with the trend of globalization and economic integration, urban agglomeration has become a new theme of urban development and construction (Fang, 2014; Fang

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**Author:** Cao Shisong (1989–), PhD Candidate, specialized in remote sensing and urban ecology and environment. E-mail: [caoshisong@gmail.com](mailto:caoshisong@gmail.com)

**<sup>\*</sup>Corresponding author:** Hu Zhuowei (1979–), PhD and Associate Professor, specialized in geographic information modeling and application. E-mail: [huzhuowei@mail.cnu.edu.cn](mailto:huzhuowei@mail.cnu.edu.cn)

*et al.*, 2010). The spatial structure of urban agglomeration is a combined result of its history, culture, economy, society and policy, and can directly reflect the functional structure of urban agglomeration (Kuang *et al.*, 2014b). The different spatial structures of urban agglomerations may have a positive or negative effect on their developments (Lu, 2015). Especially when the size of urban agglomeration becomes large, its spatial structure can exert considerable influence on its division of internal functions and ecological environment (Lu, 2015; Liu *et al.*, 2016). Under the background of China's rapid urbanization, study on comparative analysis of the spatial structures of urban agglomerations between the Beijing-Tianjin-Hebei (BTH) and Boswash can effectively absorb the experiences of cities' spatial layout derived from the developed countries or regions. This research also can provide the scientific understanding of historical process and driving mechanism in the spatial structure of urban agglomeration at different scales.

In the 1980s, foreign scholars began to study the spatial structures of urban agglomerations in the context of global integration. Hall (1971), Friedmann *et al.* (1982), Sassen (1991), Pyrgiotis (1991), and Kunzmann *et al.* (1991) studied the influences of different factors such as global economic integration and regional community network system on the spatial structures, and found that the spatial structures are influenced by the policies, economies and traffic layouts. Simeon *et al.* (2002) and Hidenobu (2004) studied the gravitational model of urban agglomeration and found that the gravitational model can reveal the inherent relationship among different cities. In China, Lu (1986) firstly studied the spatial structures of urban agglomerations and proposed the development model of "point-axis" in 1984. Then, many scholars carried out related studies, such as spatial pattern (e.g. Lu, 1986; Guan *et al.*, 2003; Zhu, 2004; Chen, 2005), spatial structure model (e.g. Xue, 2002; Wu, 1999; Nian *et al.*, 2002), quantitative measure of the spatial structure (e.g. Kuang *et al.*, 2014b; Liu *et al.*, 2014; Yao *et al.*, 2006), and driving force of the spatial structure (e.g. Chen *et al.*, 2011; Zhong *et al.*, 2012), of urban agglomerations. Based on the analysis of previous studies, we found that previous studies carried out few studies about the spatial analysis of the spatial pattern of urban agglomeration. Notably, there are few studies reported the comparisons of the spatial structure among different countries.

With the rapid development of remote sensing technology, the extraction of impervious surface of large area has become the hotspot research. Impervious surface refers to the artificial surface such as housing, roads, and so on (Weng, 2011). The United States Geological Survey (USGS) developed the impervious surface coverage data product (at a 30-m high resolution) of the United States at different decadal intervals, which includes 2001, 2006 and 2011, based on the Landsat Thematic Mapper (TM) images (Yang, 2003). The National Oceanic and Atmospheric Administration (NOAA) released the impervious surface dataset (at a 1-km resolution) of global built-up areas based on the Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) nighttime light data (Elvidge, 2007).

As a typical artificial landscape, the spatial distribution pattern of impervious surface directly affects the function of the urban ecosystem and climate (Kuang, 2014). The advantages of a subpixel impervious surface product used in the study of the spatial structure of urban agglomeration are as follows: (1) the subpixel-level impervious surface product is more accurate than the traditional pixel-level product; (2) it can not only characterize variations in extent of the impervious surface, but also monitor variations in intensity of the im-

pervious surface.

Based on the above discussion, we mapped the subpixel-level impervious surface coverage of the BTH and Boswash, respectively, from 1972 to 2011. Further, landscape metrics, gravitational model and spatial analysis were used to analyze the differences of the spatial structures between the BTH and Boswash. The specific objectives of this study therefore are as follows:

- (1) Monitor the impervious surface growth in the BTH and Boswash, respectively, from 1972 to 2011.
- (2) Quantify the differences of the spatial structures of urban agglomerations between China and the US.
- (3) Make suggestions for space optimization of the BTH based on the results of the above two objectives.

2 Study area and data

2.1 Descriptions of the study area

Our study area (Figure 1) includes the BTH and Boswash. The Boswash (Figure 1b), located between the north end, Boston, and the south end, Washington, includes one core city, the New York, four major cities, Boston, Philadelphia, Baltimore, and Washington, and more than 40 small and medium cities. Along with the coast, the Boswash is of ~600 km in length, and more than 100 km in width with an area of ~138,000 km<sup>2</sup>. The definition of the spatial scope of the BTH (Figure 1a) is the regional scope proposed by Lu (1986) in the context of the cooperation and development of the BTH. It includes two municipalities, Beijing and

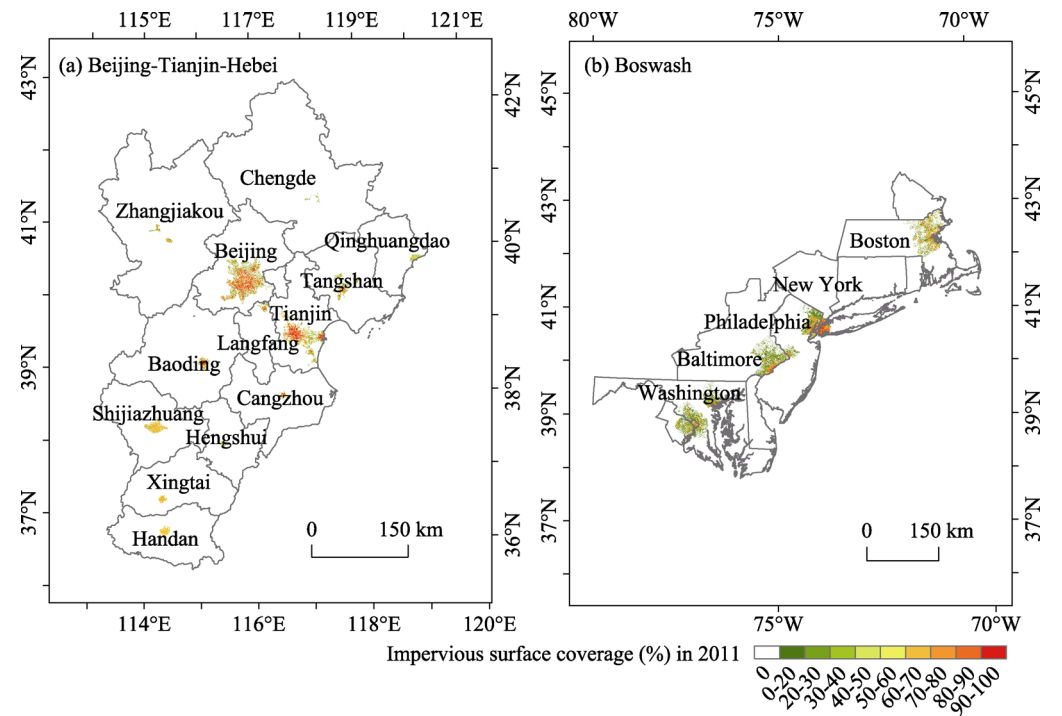


Figure 1 Overview of the study area

Tianjin, and other cities in Hebei Province, Tangshan, Baoding, etc. It covers approximately 183,000 km<sup>2</sup>. The BTH is the third economic growth pole among Chinese urban agglomerations after the Yangtze River Delta and the Pearl River Delta.

Currently, the world economic center is moving from the west to the east, and the developments of urban agglomerations are usually associated with the transfer of the world economic center. The BTH has the same opportunities as the Boswash in the 20th century. The BTH is located in 38.07°–41.05°N, and 114.94°–118.55°E; The Boswash is located in 37.89°–43.61°N, and 70.48°–79.93°W. The geographical locations of the BTH and Boswash are similar. Notably, the Boswash is the largest and most powerful urban agglomeration in the world. Although BTH is an important urban agglomeration in China, the overall competitiveness is relatively weak and is at the initial stage of urban agglomeration. Therefore, it is necessary to absorb the experiences of the development of the Boswash.

Because of the large differences of administrative divisions between China and the US, we selected the built-up areas of the main cities to perform the extraction of impervious surface and analysis of the spatial structures.

## 2.2 Data sources

The data used in this research are as follows: China's national standard geographical data, including city and county boundaries; American administrative division data, including state and county boundaries; American 30-m impervious surface dataset released by USGS (<http://glovis.usgs.gov/>); cloudy-free leaf-on and leaf-off Landsat TM data of cities in both the BTH and Boswash, and only the BTH, obtained from the USGS at decadal intervals of 1972, 1982, 1991, and 1995, and of 2001, 2006, and 2011, respectively; Multi-Spectral QuickBird high-resolution images (at a 2.4 m spatial resolution) of Beijing core area at 2006; DMSP/OLS night light data (<http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html>) and Digital Elevation Model (GDEM) (at a 30-m spatial resolution) of the study area; The land use/land cover (LULC) data of the BTH (<http://www.resdc.cn/Default.aspx>) and Boswash (<http://www.mrlc.gov/index.php>) for the extraction of ecological, production, and living land.

## 3 Methods

### 3.1 Gravitational model

Gravitation between two cities refers to the force of economic attraction or link between them. It reflects city's economy, culture, and political external radiation capacity. The stronger economic strength the city is, the higher value its gravitation is. Namely, human capitals and talents always tend to agglomerate in large urban areas. Gravitational model was effectively applied to the spatial structure of urban agglomeration (e.g. Liu *et al.*, 2014; Meng and Lu, 2012), regional economic linkages (e.g. Zhu, 2004), and inter-city interaction structure (e.g. Chen *et al.*, 2011) in previous studies.

The impervious surface reflects the intensity of human action on the natural surface. Moreover, Kuang *et al.* (2014a) found that the strong positive correlations existed between the area of impervious surface of built-up region, and GDP and population ( $R^2$  was higher than 0.86). This finding indicates that to some extent, a city's impervious surface area of

built-up region can characterize its overall strength. Thus, we took the area of impervious surface of built-up region as a city's quality, and then explored the spatial links of urban agglomerations among different cities:

$$\begin{cases} R_{ij} = K \frac{Q_i Q_j}{d_{ij}^r} \\ E_i = \sum_{j=1}^n F_{ij} \end{cases} \quad (1)$$

where  $R_{ij}$  is the gravitational value between city  $i$  and  $j$ ;  $Q_i$  and  $Q_j$  is the quality (the area of impervious surface) of city  $i$  and  $j$ , respectively;  $E_i$  is the gravitational potential of city  $i$ , which represents the aggregate capacity in the human capitals and talents of city  $i$ .

### 3.2 Spatial autocorrelation

The spatial autocorrelation is an important indicator for evaluating spatial dependence, and is commonly used in the classification and comprehensive evaluation of the spatial data. It can describe the spatial similarities or differences among different regions, and can characterize the reasons for those similarities or differences.

We selected the Local Moran's  $I$  to analyze the spatial autocorrelation of the impervious surface coverage (Chen, 2009):

$$\begin{cases} G_i^* = \frac{\sum_j^n W_{ij} x_j}{\sum_j^n x_j} \\ Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{\text{VAR}(G_i^*)}} \end{cases} \quad (2)$$

where  $W_{ij}$  represents the distance weighting between patches  $i$  and  $j$ , a significant positive value of  $Z(G_i^*)$  suggests that the impervious surface coverage of patches adjacent  $i$  is high, while a significant negative value of  $Z(G_i^*)$  reflects the opposite trend.

### 3.3 Landscape metrics

Landscape metrics can enrich the information of the correlational landscape patterns and reflect structural composition and characteristics of spatial structure. Based on the spatial map of the impervious surface of the BTH and Boswash, we selected landscape metrics at landscape scale, including PLAND and the normalized landscape shape index (NLSI), to quantify the differences of landscape patterns between the BTH and Boswash. The software of landscape pattern analysis, FRAGSTATS 4.2, was used for calculating landscape metrics. Table 1 exhibits the calculated formulas for the landscape metrics (Peng *et al.*, 2006).

### 3.4 Ecological-living-production land classification

The report at the Fourth Session of the Twelfth National People's Congress in 2016 emphasized that the objectives of land use should focus on the integrated development for production, living, and ecological land in China. In this context, study on comparative analysis of the

**Table 1** Landscape metrics and its ecological meaning

Landscape metric	Calculated formula	Ecological meaning
PLAND	$P_i = \frac{\sum_{j=1}^m a_{ij}}{A} * 100\% \text{ ①}$	The area proportion of a certain type landscape to the total landscape area
Landscape shape index	$LSI = \frac{0.25E}{\sqrt{A}} \text{ ②}$	The measure of patches aggregation or discrete, the higher value <i>LSI</i> is, the more discrete the patches are

(1) where  $i=1, 2, 3 \dots, n$  represents the types of patches;  $j=1, 2, 3 \dots, m$  represents the number of patches;  $a_{ij}$  represents the area of type  $i$ , and patch  $j$ ;  $A$  represents the total area of patches.

(2) where *LSI* represents the value of landscape shape index;  $E$  represents total patches perimeter;  $A$  represents the total patches area.

spatial patterns of ecological-living-production land between the US and China is very important for space optimization of the BTH. Thus, we divided the land of the BTH and Boswash into ecological, production, and living land according to Zhang *et al.* (2015). Table 2 shows the descriptions of ecological-living-production land.

**Table 2** Descriptions of ecological-living-production land

1st Level Class	Subclass	Description
Ecology land	Forestland	Such regions include woodlands, shrub lands, forest lands, etc.
	Grassland	Such regions include high coverage grasslands, medium coverage grasslands, and low coverage grasslands
	Water body	Such regions include river canals, lakes, reservoir ponds, beaches, etc.
Production land	Agricultural production land	Such regions include paddy lands and arid lands
	Industrial production land	Such regions include factories, quarries, mining, and oil-field wastes outside cities as well as land for special uses, such as roads and airports
Living land	Urban living land	Such regions include built-up areas of large, medium and small cities and counties
	Rural living land	Such regions include rural settlements outside cities and counties
Others	Unused land	Unused land such as sandy land, gobi, etc.

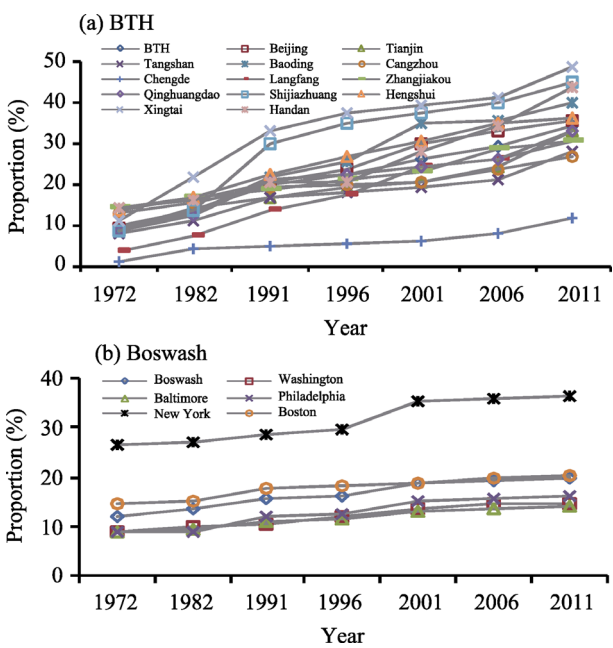
## 4 Results and discussion

### 4.1 Changes of the impervious surface

We extracted the impervious surface coverage of the BTH and Boswash by the method of CART, which is the main method of impervious surface coverage extraction used by the U.S. National Land Cover Database (Breiman, 1984; Yang *et al.*, 2003; Yang *et al.*, 2004). Total ~170 Landsat TM images and ~68 Landsat MSS images were used for the estimation of the impervious surface coverage. Four main steps were involved in extracting the impervious surface coverage:

**Step 1:** Extracted the impervious surface coverage (from 1% to 100% at a 30-m resolution) of Beijing built-up region in 2006 (the extraction results were divided into training and testing samples for the CART model);

**Step 2:** Selected the predicted independent variables for the CART model;



**Figure 2** Proportions of the impervious surface in the BTH and Boswash, respectively, from 1972 to 2011

rapid economic development of the BTH caused many natural surfaces replaced by impervious surfaces such as roads, buildings, etc.

(2) The proportion of the impervious surface remained stable in the Boswash from 1972 to 2011. New York had the highest proportion of the impervious surface, followed by Boston, Philadelphia, Washington and Baltimore.

(3) The proportions of the impervious surface of the BTH and Boswash increased from 10.00% and 12.01% in 1972 to 35.00% and 19.82% in 2011, an increase of ~2.5 and ~0.65 times, respectively.

Table 3 presents the growth rates of the impervious surface in the BTH and Boswash. As shown in Table 3:

(1) From the perspective of urban agglomeration, from 1972 to 2011, the growth rates of the impervious surface of the BTH and Boswash were  $47.63 \text{ km}^2 \text{ yr}^{-1}$  and  $32.96 \text{ km}^2 \text{ yr}^{-1}$ , respectively. The most rapid period of the expansion of the impervious surface of the BTH was from 2001–2011. Its annual rate was up to  $63.51 \text{ km}^2 \text{ yr}^{-1}$ . The growth rate of the Boswash remained stable.

(2) From the perspective of city, a large difference of the growth rates of the impervious surface in the BTH between core cities and non-core cities were observed from 1972–2011. Beijing and Tianjin had higher growth rates of  $19.99 \text{ km}^2 \text{ yr}^{-1}$  and  $13.54 \text{ km}^2 \text{ yr}^{-1}$ , respectively, than others. Shijiazhuang had a highest growth rate in non-core cities, which was  $4.42 \text{ km}^2 \text{ yr}^{-1}$ . However, a small difference among different cities in the Boswash was found. The growth rates of the impervious surface were ~2–8  $\text{km}^2 \text{ yr}^{-1}$ . Philadelphia and Baltimore had the highest and lowest growth rates, respectively.

**Step 3:** Estimated the impervious surface coverage of the BTH in 2006 based on the CART model;

**Step 4:** Estimated the impervious surface coverage of the BTH and Boswash, respectively, in 1972, 1982, 1991, 1995, 2001 and 2011 based on the impervious surface coverage results in 2006.

Based on the steps 1–4, we calculated the proportions of the impervious surface in the BTH and Boswash (Figure 2). Figures 2a and 2b present the variations in the proportions of the impervious surface of the BTH and Boswash, respectively. As shown in Figure 2:

(1) The proportion of the impervious surface of the BTH increased rapidly from 1972 to 2011. Since China’s reform and opening up, the

**Table 3** Growth rates of the impervious surface in the BTH and Boswash

	1972–1982		1982–1991		1991–2001		2001–2011		1972–2011	
	Overall variation (km <sup>2</sup> )	Variation rate (km <sup>2</sup> yr <sup>-1</sup> )	Overall variation (km <sup>2</sup> )	Variation rate (km <sup>2</sup> yr <sup>-1</sup> )	Overall variation (km <sup>2</sup> )	Variation rate (km <sup>2</sup> yr <sup>-1</sup> )	Overall variation (km <sup>2</sup> )	Variation rate (km <sup>2</sup> yr <sup>-1</sup> )	Overall variation (km <sup>2</sup> )	Variation rate (km <sup>2</sup> yr <sup>-1</sup> )
BTH	262.60	26.26	482.12	53.57	477.99	47.80	635.13	63.51	1857.84	47.63
Boswash	256.34	25.63	403.02	44.78	498.34	49.83	127.73	12.73	1285.43	32.96
Beijing	135.36	13.53	194.70	21.63	288.89	28.89	160.96	16.10	779.91	19.99
Tianjin	113.84	11.38	63.11	7.01	76.16	7.61	274.89	27.49	528.00	13.54
Tangshan	16.99	1.70	34.35	3.82	34.35	3.44	49.53	4.95	113.60	2.91
Baoding	11.25	1.13	22.81	2.53	33.56	3.36	13.86	1.39	81.48	2.09
Cangzhou	3.29	0.32	5.71	0.63	2.03	0.20	9.19	0.90	20.22	0.52
Chengde	2.90	0.29	0.65	0.06	1.11	0.11	5.56	0.56	10.22	0.26
Langfang	7.20	0.72	10.66	1.18	18.21	1.82	11.01	1.10	47.08	1.21
Zhangjiakou	3.88	0.39	3.46	0.38	7.48	0.75	11.92	1.19	26.74	0.69
Qinhuangdao	5.64	0.56	12.31	1.36	4.23	0.42	12.86	1.28	35.04	0.89
Shijiazhuang	25.27	2.53	77.10	8.57	35.18	3.51	34.69	3.47	172.24	4.42
Hengshui	1.59	0.16	3.63	0.40	5.22	0.52	3.36	0.34	13.80	0.35
Xingtai	12.66	1.26	13.18	1.46	8.04	0.80	11.43	1.14	45.31	1.16
Handan	3.15	0.32	9.39	1.04	17.68	1.77	34.30	3.43	64.52	1.65
New York	14.76	1.48	40.54	4.50	171.74	17.17	29.68	2.97	256.72	6.58
Washington	39.92	3.92	38.61	4.29	116.73	11.67	42.69	4.27	237.95	6.10
Baltimore	11.07	1.10	23.77	2.64	39.83	3.98	11.40	1.14	86.07	2.20
Philadelphia	12.28	1.23	125.62	12.56	125.40	12.54	50.76	5.07	314.06	8.05
Boston	13.06	1.30	135.24	13.52	47.23	4.72	72.93	7.29	268.46	6.88

In the past four decades, few changes of the proportions of the impervious surface of different cities in both BTH and Boswash were observed.

(1) The proportions of the impervious surface of different cities in the BTH remained stable from 1972 to 2011 and these proportions ranked from high to low as follows: Tianjin (~40%), Beijing (~27%), Tangshan (~7%), and others (~27%).

(2) The proportions of the impervious surface of different cities in the Boswash are more balanced than those in the BTH. Both New York and Boston had the highest proportion (~28%), and Baltimore had the lowest proportion (~7%).

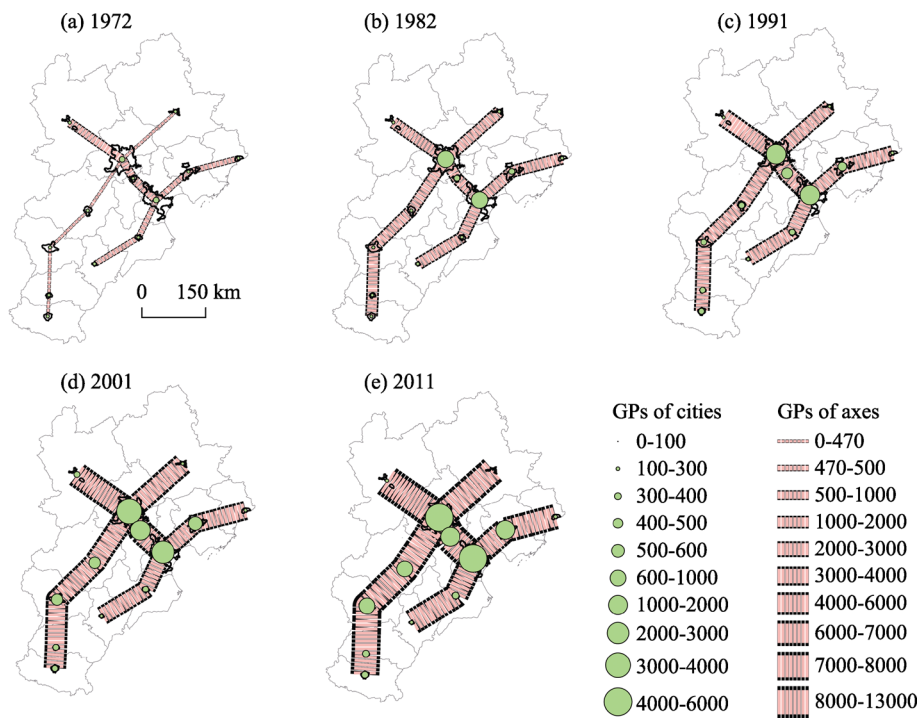
## 4.2 Results of gravitational model

Based on formula (1), we calculated the gravities and gravitational potentials of different cities. Moreover, according to the spatial patterns of the “one axis, two wings” structure in the BTH and those of the “point-axis strip” structure in the Boswash, we calculated gravitational potentials of axes, which are equal to the sum of gravitational potentials of the cities contained by the axis, in the BTH and Boswash, respectively. At last, we mapped the gravity spatial patterns in both BTH and Boswash (Figures 3 and 4). Figure 3 exhibits the spatial patterns of the gravity in the BTH:

(1) Before 1972, the BTH experienced the period of isolated cities stage. Its spatial struc-



ture showed a “sporadic point” feature. The advantages of dual-core cities were not highlighted.



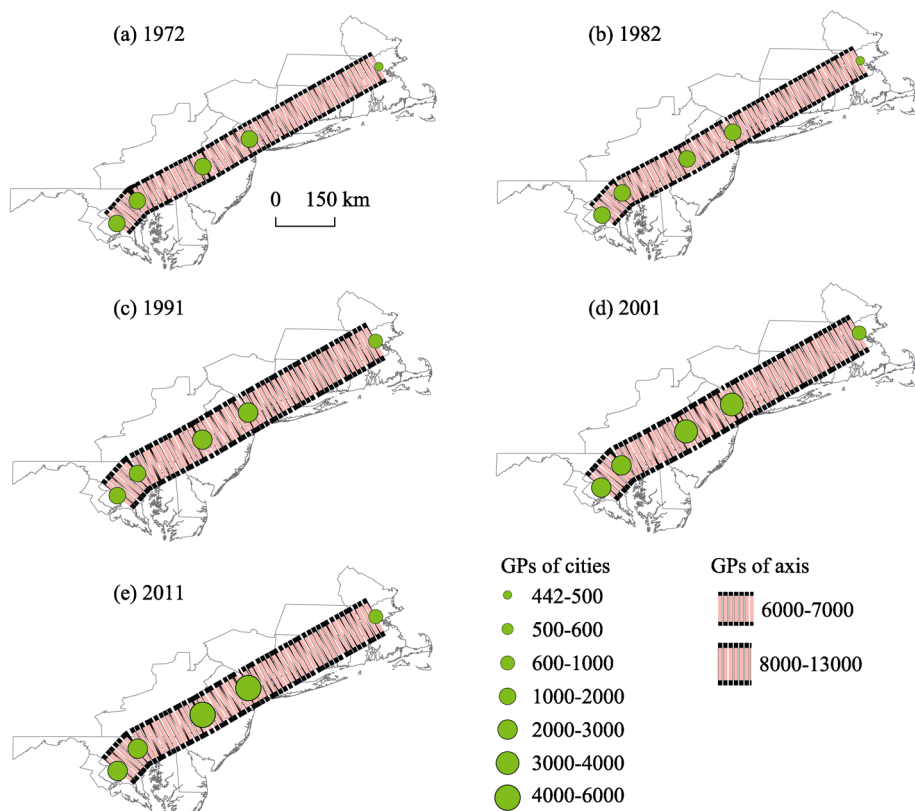
**Figure 3** Spatial patterns of the gravity in the BTH (GPs represents gravitational potentials)

(2) From 1792–1982, the BTH experienced the period of dual-core cities stage. Since China’s reform and opening up, with the rapid economic development of the BTH, the spatial pattern of the BTH showed a “dual-core” structure. The dual-core cities of Beijing and Tianjin had the highest gravitational potentials. Meanwhile, the concepts of “Beijing-Tianjin-Tangshan” and “capital circle” were proposed by government departments.

(3) From 1782–1991, the BTH experienced the period of group cities stage. Its spatial structure showed a “point-axis” feature. The gravitational potentials of axes showed a considerable influence. The new spatial pattern of a “one axis and two wings” structure was observed. Meanwhile, the formal regional cooperation mechanism of the BTH was proposed by government departments.

(4) From 2001–2011, the BTH experienced the period of network-style stage. Its spatial structure showed a “network” feature. The spatial pattern of the “one axis and two wings” feature was more significant. Notably, in this period, the economic and social development of the BTH was driven by the dual-core cities of Beijing and Tianjin, and supported by multi-node cities of Tangshan, Shijiazhuang and other cities.

Figure 4 exhibits the spatial patterns of the gravity in the Boswash, as shown in Figure 4, compared with the BTH, the spatial structure of the Boswash was more stable from 1972–2011. Its spatial pattern showed a “point-axis strip” structure. Few variations in its gravitational potentials of the cities and axis were observed. Moreover, the gravitational potentials of cities in the Boswash showed a “neck by neck” trend, while those in the BTH exhibited a large difference between the dual-core and non-core cities.



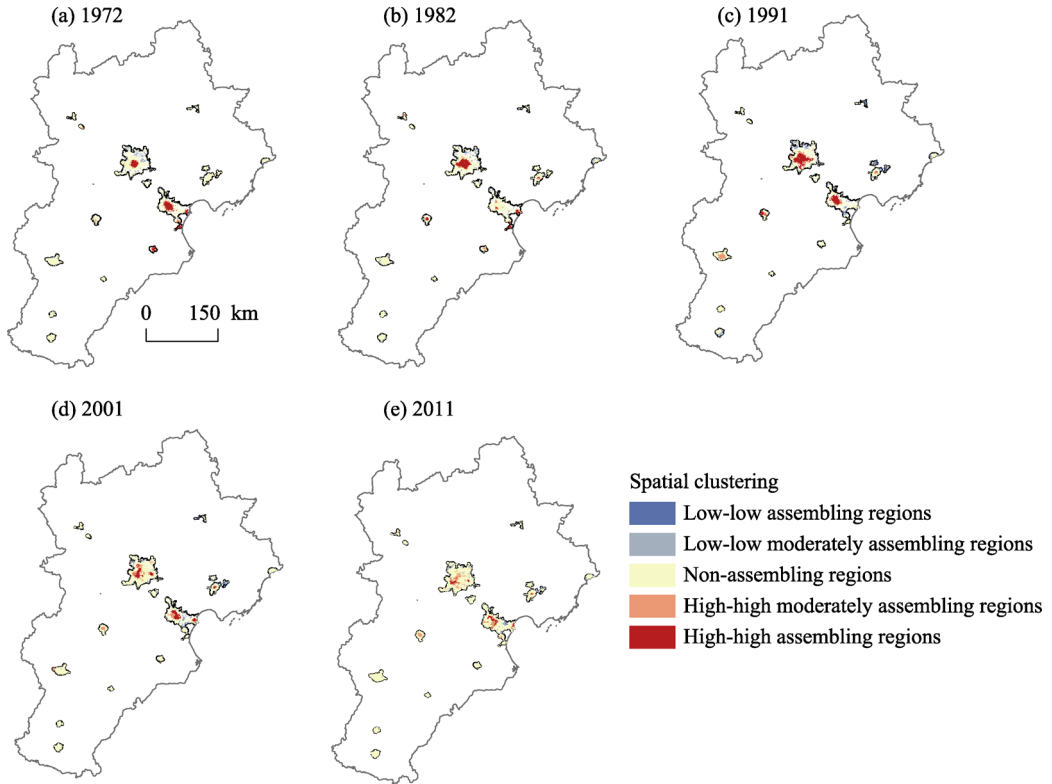
**Figure 4** Spatial patterns of the gravity in the Boswash (GPs represents gravitational potentials)

### 4.3 Results of spatial autocorrelation

#### 4.3.1 Urban agglomeration scale

To explore the spatial evolutions of the BTH and Boswash, the Local Moran's  $I$  were calculated at urban agglomeration scale (1 km resolution), and city scale (0.5 km resolution), respectively (Figures 5 and 6). Figure 5 presents the spatial hotspot map of the impervious surface in the BTH at urban agglomeration scale. As shown in Figure 5, a large difference between core and non-core cities in the BTH was observed caused by the rapid economic development of the BTH during 1972–2011. Meanwhile, high-high assembling regions showed great changes. (1) In 1972, high-high assembling regions were mainly located in the dual-core cities of Beijing and Tianjin. (2) In 1982, high-high assembling regions were mainly located in Beijing, and the extent of them in Tianjin showed a decrease. Notably, high-high assembling points appeared in Tangshan, Baoding and Cangzhou. (3) In 1991, high-high assembling regions were mainly located in Beijing, Tianjin, Tangshan, Baoding, and Shijiazhuang. (4) During 2001–2011, high-high assembling regions were mainly located in Beijing, Tianjin, Tangshan, and Baoding.

Figure 6 presents the spatial hotspot map of the impervious surface in the Boswash at urban agglomeration scale. As shown in Figure 6, few changes of spatial clustering of the impervious surface of the Boswash were observed over the past four decades. High-high assembling regions were mainly located in the core cities, including Boston, New York, Philadelphia, Baltimore and Washington. Its spatial structure exhibited a “point-axis” feature.



**Figure 5** Spatial hotspot map of impervious surface in the BTH at urban-agglomeration scale

#### 4.3.2 City scale

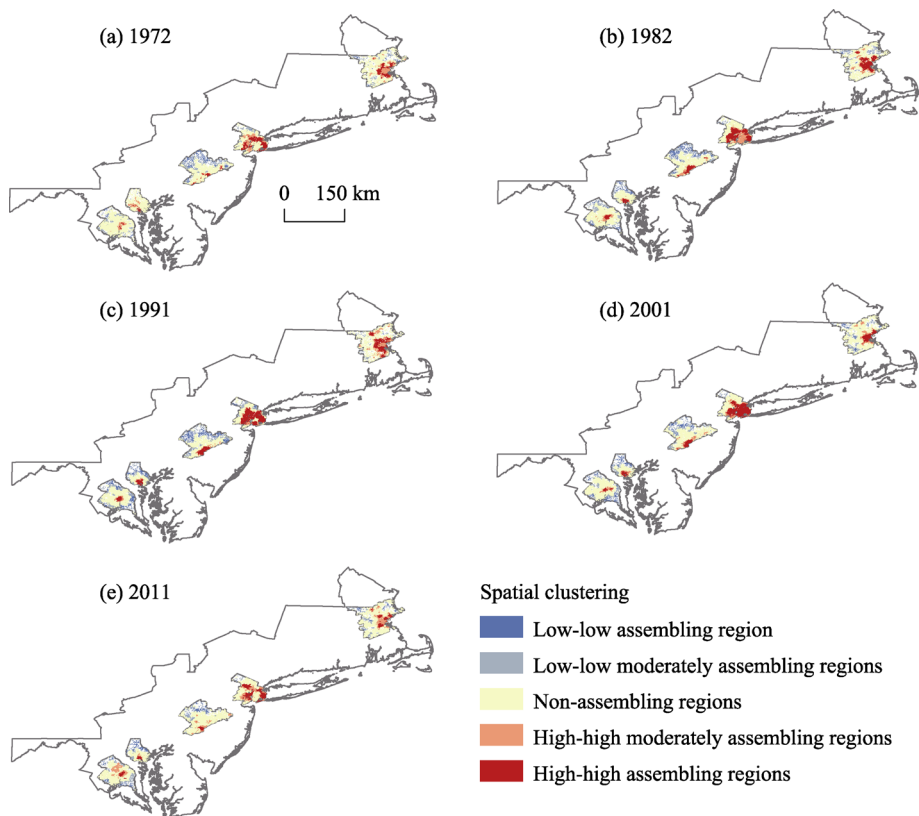
The typical cities of Beijing in the BTH and Boston in the Boswash were selected to analyze the spatial clustering at city scale. We mapped the spatial hotspot map of the impervious surface of those two cities (Figure 7). As shown in Figure 7:

(1) High-high assembling regions in Beijing showed a typical “standing pancake” feature. High-high assembling regions were mainly located in urban area, and low-low assembling regions, along with high-high assembling regions, located in the suburban area. Moreover, over time, high-high assembling regions rapidly spread as a model of concentric circles.

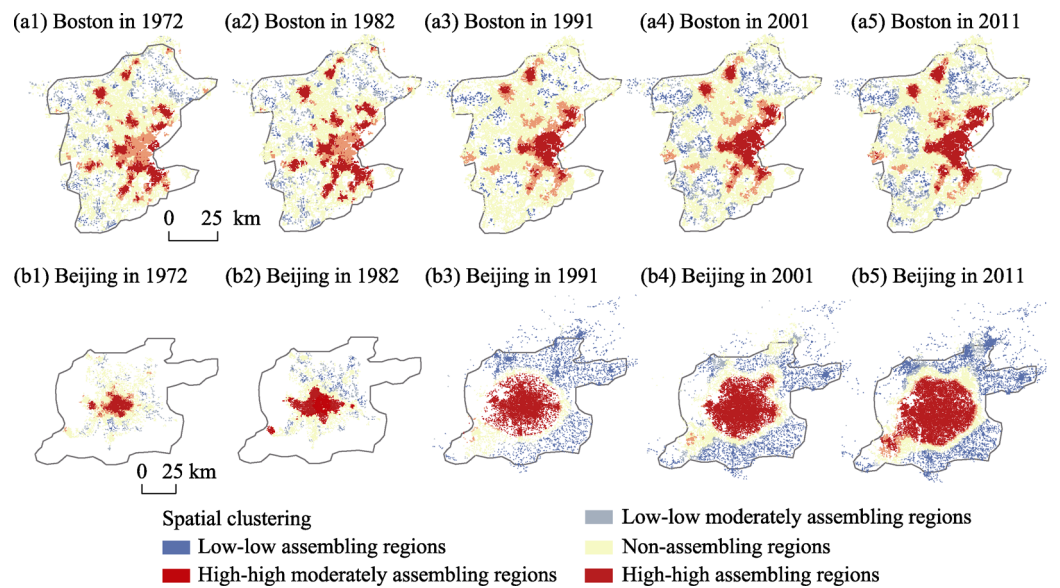
(2) Few changes of the spatial clustering were observed in Boston from 1972 to 2011. The spatial structure of high-high assembling regions showed a “multi-center, local aggregation and global discrete” feature in Boston influenced by the thought of “pastoral city”. Over the past four decades, the type of the impervious surface growth was categorized as contraction.

#### 4.4 Results of landscape metrics

Based on the theory of landscape ecology, we characterized the major landscape of the BTH and Boswash using the landscape of the impervious surface. Additionally, to quantify the changes of the impervious surface among different periods, impervious surface coverage was divided into five different types: high-density impervious surfaces, medium high-density impervious surfaces, medium-density impervious surfaces, medium low-density impervious surfaces, and low-density impervious surfaces. The associated subpixel impervious area percentages were (80%, 100%], (60%, 80%], (40%, 60%], (20%, 40%], and (0%, 20%], respectively.



**Figure 6** Spatial hotspot map of the impervious surface in the Boswash at urban agglomeration scale

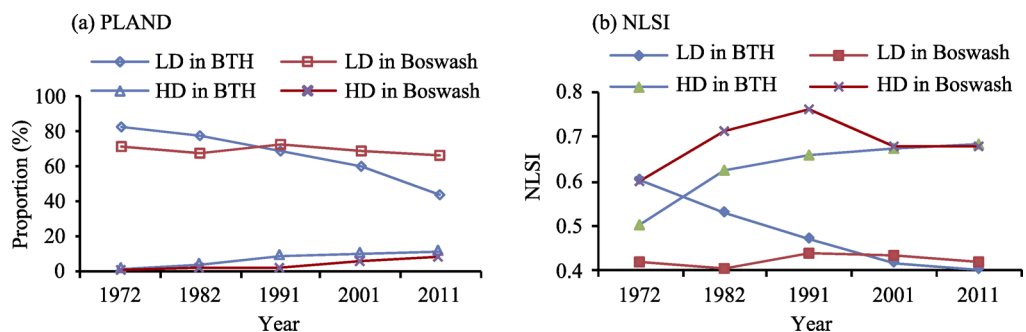


**Figure 7** Spatial hotspot map of impervious surface at urban scale

#### 4.4.1 Results of PLAND

Figure 8a presents the results of PLAND of the BTH and Boswash, respectively, from 1972 to 2011. As shown in Figure 8a, PLAND values of high-density impervious surfaces of the

BTH were higher than those of the Boswash from 1972 to 2011. PLAND Values of low-density impervious surfaces of the BTH were higher, and then lower than those of the Boswash before 1982, and after 1991, respectively.



**Figure 8** Landscape metrics of the BTH and Boswash (LD represents low-density impervious surfaces, and HD represents high-density impervious surfaces)

4.4.2 Results of NLSD

NLSD represents landscape aggregation or scatter. The smaller value of NLSD is, the higher degree of its aggregation is. Figure 8b presents NLSD of the BTH and Boswash, respectively, from 1972 to 2011. As shown in Figure 8b:

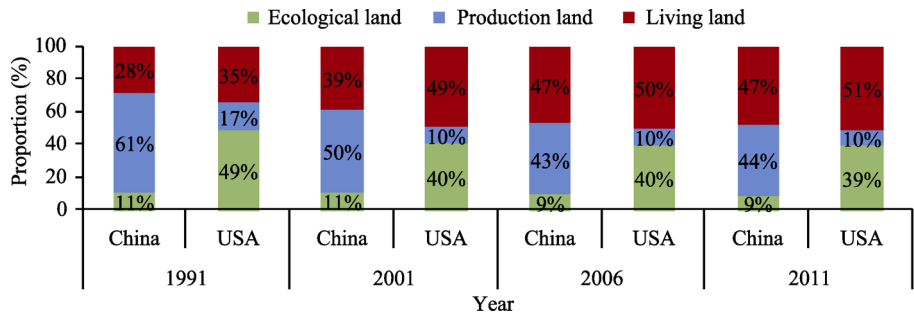
(1) Over time, the degrees of aggregation of low-density impervious surfaces of the BTH exhibited an increasing trend, while few changes of those of the Boswash were observed. The degrees of aggregation of low-density impervious surfaces of the Boswash were higher, and then lower than those of the BTH before 1991, and after 2001, respectively.

(2) From 1972 to 1991, the degrees of aggregation of high-density impervious surfaces of the Boswash were higher than those of the BTH. Since 2001, the similar degrees of aggregation of high-density impervious surfaces between the BTH and Boswash were observed.

4.5 Results of ecological-production-living land

According to the above classification of ecological-living-production land, we calculated the proportions of ecological, living, and production land of the BTH and Boswash from 1991 to 2011 (Figure 9). Notably, the following findings are illustrated in Figure 9:

(1) In the BTH, few changes of the proportion of ecological land were observed, the proportion of ecological land decreased from 11% in 1991 to 9% in 2011. Meanwhile, the proportion of production land seriously decreased, a decrease from 61% in 1991 to 44% in 2011,



**Figure 9** Ecological-living-production land area proportions of the BTH and Boswash

while that of living land increased rapidly, an increase from 28% in 1991 to 47% in 2011.

(2) In the Boswash, the proportions of ecological, living, and production land decreased, increased, and decreased from 49%, 35%, and 17% in 1991 to 39%, 51%, and 10% in 2011, respectively.

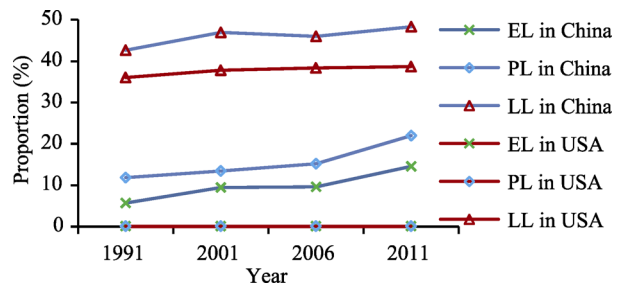
(3) The area of ecological land in the Boswash was ~4 times higher than those in the BTH.

To explore the differences of the proportions of the impervious surfaces of ecological, living, and production land between the BTH and Boswash, we calculated these proportions in the BTH and Boswash from 1991 to 2011 (Figure 10). The following conclusions can be drawn from Figure 10:

(1) From 1991 to 2001, the impervious surface of the BTH increased rapidly, while that of the Boswash remained stable.

(2) The proportions of the impervious surface of both ecological and production land in the BTH were higher than those in the Boswash due to the large differences of population densities, cities' size, and developmental stages between the BTH and Boswash.

(3) The proportion of the impervious surfaces of living land of the BTH was higher than that of the Boswash.



**Figure 10** Proportions of the impervious surface of ecological, living, and production land (note: EL, PL, and LL represent ecological, living, production land, respectively)

## 5 Strategy of space optimization of the BTH

The comparison of the spatial structures between the BTH and Boswash can effectively absorb the experiences of cities' spatial layout derived from the developed countries or regions. This comparison also can provide the scientific understanding of historical process and driving mechanism of spatial structure of urban agglomeration at different scales. Overall, our study is of great significance for the Chinese government to optimize spatial structures of urban agglomerations, industrial layout and macro planning. Notably, the spatial structure of the BTH and Boswash are rooted in their natural conditions, history and culture, but varied considerably based on their social and economic development. Boswash, the largest and most powerful urban region of the world, is the leading urban agglomeration of not only the USA but also the world. BTH, as the economic, political and cultural center of northern China, is the third economic growth pole among Chinese urban agglomerations after the Yangtze River Delta and the Pearl River Delta. However, currently, the overall competitiveness of the BTH is relatively weak. The BTH is still at the initial stage of urban agglomeration and needs to absorb the experiences of the social and economic development of the Boswash. The past four decades is the shaping development stage of the BTH. It is a well-known fact that the speed of the formation and evolution of the BTH is much faster than those of the Boswash. Thus, a series of problems, including industry convergence, deterioration of ecological environment, and low traffic network level, is inevitable in the ur-



ban process of the BTH. Based on the above results in this study, from the perspective of spatial optimization of urban agglomerations, we propose the following suggestions in the process of the development of the BTH:

(1) The evacuation of the industries in core cities while the re-aggregation of those in non-core cities, namely, the implementation of a development strategy of “dual-core and multi-center”

The largest differences of gravitational potentials between core cities and non-core cities in the BTH indicate that the rapid economic and social development of Beijing and Tianjin did not drive effectively the development of the others. Notably, as shown in the map of the spatial patterns of ecological, living, production land of the BTH and Boswash, we found that production land in the Boswash is mainly located in Washington, Baltimore, and Philadelphia, while that in the BTH is located in all cities, especially in core cities, Beijing and Tianjin. These findings indicate that the urban functional orientation of the BTH does not achieve the effective division of labor. Therefore, we should highlight the evacuation of industries in core cities while the re-aggregation of those in non-core cities. The functional orientation of cities should be further improved. Additionally, the spatial structure of the BTH should transfer from a “one core” to the “dual core” structure. Overall, the development of the BTH should improve the urban network, expand the urban development space and promote the balanced development of the whole region.

(2) The improvement of urban ecological environment

China experienced rapid urbanization and industrialization during the past decades, and these processes are expected to continue in the 21st century. The “standing pancake” structures were exhibited in most of Chinese cities. However, the urban planners in the USA pay more attention to the construction of urban ecological green space. Thus, to a certain extent, the ecological greenbelt and surface cover of American cities are better than those of Chinese cities. In this research, we found that the ecological land of American cities is much higher than that of Chinese cities. Moreover, the impervious surface of Chinese cities is higher than that of American cities. Therefore, we consider that the following suggestions should be implemented in the future development: the protection of vegetation and woodland in water-deficient areas, the development of urban ecological green space, and the improvement of the urban surface covers.

(3) The construction of integrated transport network system

The development of regional traffic technology has brought the renewal of urban spatio-temporal concept, which brings new possibilities for regional spatial structure adjustment. Thus, we should actively promote the construction of the inter-city rapid track network, and strengthen the channel carrying capacity, for the spatial restructuring of the BTH.

## 6 Conclusions

In this paper, we analyzed the differences of the spatial structure of urban agglomerations between China and the US in the past four decades. Notably, the impervious surface product was firstly applied to study the spatial structure of urban agglomeration. This study, to a certain extent, enriched the application of subpixel level impervious surface product. Additionally, the impervious surface landscape was used to characterize the major landscape of

urban agglomerations, and both the remote sensing and geographic information system technology were used in this study. The main conclusions of the study are as follows:

(1) From 1972 to 2011, the impervious surface of the BTH increased rapidly due to the rapid economic development, while those of the Boswash remained stable. In the past 40 years, the spatial structure of the BTH experienced the different periods, including isolated cities, dual-core cities, group cities and network-style cities stage, while that of the Boswash was more stable, and its spatial pattern showed a “point-axis strip” feature. The gravitational potentials of cities in the Boswash exhibited a “neck by neck” trend, while those in the BTH had a large difference between dual-core and non-core cities.

(2) From 1972 to 2011, there was a large difference between core and non-core cities caused by the rapid economic development of the BTH. Meanwhile, high-high assembling regions had great changes. Few changes of the impervious surface of the Boswash were observed in the past four decades. High-high assembling regions were mainly located in core cities, such as Boston, New York, Philadelphia, Baltimore and Washington. Its spatial structure exhibited a “point-axis” feature. In Beijing, high-high assembling regions were mainly located in urban area, and low-low assembling regions, along with high-high assembling regions, located in the suburban area. Moreover, over time, high-high assembling regions rapidly spread as a model of concentric circles. In Boston, high-high assembling regions showed a “multi-center, local aggregation and global discrete” influenced by the thought of “pastoral city”. Over the past four decades, the type of the impervious surface growth was categorized as contraction.

(3) From 1972 to 2011, in the BTH, the proportions of ecological land exhibited few changes. Notably, the proportion of production land seriously decreased, a decrease from 61% in 1991 to 44% in 2011, while that of living land increased rapidly, an increase from 28% in 1991 to 47% in 2011. In the Boswash, the proportions of ecological, living, and production land decreased, increased, and decreased from 49%, 35%, and 17% in 1991 to 39%, 51%, and 10% in 2011, respectively. All the percentages of the impervious surface of ecological, living, and production land of the BTH were higher than those of the Boswash.

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