Research article

Spatiotemporal differentiation and the factors influencing urbanization and ecological environment synergistic effects within the Beijing-Tianjin-Hebei urban agglomeration

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\textbf{ABSTRACT}

Numerous environmental problems have been seen due to the “high energy consumption, high pollution, high emissions” economic model in the Beijing-Tianjin-Hebei urban agglomeration (BTHUA). The coupling coordination degree model is applied to provide a coordination of urbanization and ecological environment composite system (CUECS) value while a geographic detector is applied to explore the dominant factors controlling it. This study reached the following conclusions. (1) The CUECS types are mainly low coordination, but which generally exhibit positive evolutionary trend. The change trend can be characterized as urbanization lags followed by system equilibrium followed by ecological environmental lags. (2) The CUECS conforms to a core-edge distributional pattern that comprises plain high mountain low, inland high coastal low. Industrialization played a key role in the development of BTHUA, the landform type was the important factor controlling CUECS. (3) Social consumer goods, gross domestic product, the disposable income of urban residents (all per capita) are the core factors controlling CUECS within different spatial units. Urbanization rate, per capita social consumer goods, the proportion of tertiary industrial population are the core factors controlling CUECS during different urbanization development stages. (4) The relative impacts of urbanization and ecological environmental sub-systems on CUECS are (in decreasing order of importance) population urbanization, economic urbanization, social urbanization, ecological environment subsystem. Therefore, green urbanization remains the primary path for sustainable development within the urban agglomeration. It is unsuitable for rapid urbanization development model in the mountainous areas that encapsulate ecological and environmental security as their main functions, so the government urgently needs to amend its ‘one size fits all’ policy system.

1. Introduction

On the basis of data collected by the United Nations, it has been estimated that about 70% of the world’s population will live in cities by 2050 (UN, 2018) and so these agglomerations will inevitably lead to ever more severe ecological environmental problems as the living and production requirements of an excess population are satisfied (Koop and Leeuwen, 2017). This problem is very apparent in China. Since the Chinese economic reform in 1978, urbanization processes have been constantly accelerating in China, the urban population proportion has continued to rise (Wu et al., 2014). The Chinese rate of urbanization increased from 17.90% in 1978 to 58.52% by 2017, an average annual increase of 1.04%. The 2017 national urbanization level in China was about 2.5% higher than global average. The rapid increase of urbanization rate is reflected in the rapid agglomeration of urban population and the rapid expansion of urban space, the urban agglomeration gradually formed simultaneously. Urban agglomeration usually refers to a cluster of cities, including a core megacity and at least three large cities, as the basic components in a specified area. The cities comprising an urban agglomeration are related, compact in geography, and closely connected in economy, and rely heavily on well-developed infrastructure networks such as transportation and communication. Ultimately, high levels of integration are achieved among cities in urban agglomerations (Fang, 2014). In this context, as a highly developed urban complex with a spatial form, the city is therefore highly integrated into such an agglomeration, itself characterized by the fact that

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internal elements tend to be highly concentrated in larger cities (Fang and Yu, 2017), which provides residents with convenient and modern living places. It is also the case that rapid urbanization and industrialization within China have led to increasingly serious resource and ecological environmental pressures which have caused cities to face numerous sustainable development challenges (Normile, 2016), including air pollution (Xia et al., 2014), carbon emissions (Zhang and Da, 2015), traffic congestion (Rana, 2011), water quality (Seilheimer et al., 2007), ecosystem degradation (Grumbine, 2016), regularization of urban landscape (Fang et al., 2016a) and fragmentation (Dobbs et al., 2017) as well as energy shortages (Qureshi et al., 2016). The PM$_{2.5}$ air pollution problems have seriously affected the daily life and physical health of citizens (Wang and Fang, 2016). The above aspects have restricted urbanization development, reducing urban area urbanization quality, ecological environment carrying capacities and sustainable development (Acuto et al., 2018). Similarly, urban agglomerations remain the hardest hit by ecological damage and environmental pollution.

Throughout this process, however, Chinese urban agglomerations have faced serious problems due to a lack of coordination between urbanization and ecological environmental systems (Fang et al., 2017b), generally manifested in two ways; the coercive effect of urbanization on the ecological environment and the constraint effect of the latter variable on the former (Fang et al., 2016b). As noted by Stiglitz, a Nobel laureate in economics, ‘as the world’s largest developing country, China’s urbanization and high-tech development in the United States will be two major issues that will profoundly affect human development in the 21st century’. It is therefore urgent to conduct empirical analytical research on the synergistic effects of urbanization and the Ecological environment system within Chinese urban agglomerations; these approaches will enable a clearer understanding of the laws controlling the coordinated development of urbanization and ecological environment systems within such agglomerations, allowing differentiation of the main factors controlling the coordinated development of these systems. The Beijing-Tianjin-Hebei urban agglomeration (BTHUA) is one of the regions with the most severe urbanization and the most serious environmental pollution in China, and it is typical in the world. The research goal of this paper is to reveal the main controlling factors and mechanism of the decline of ecological environment quality caused by the rapid urbanization process in BTHUA, and provide reference for the sustainable development of other urban agglomerations in China and the world.

The existing research literature that discusses the factors underlying urbanization and the ecological environment system has mainly emphasized the variables that influence single systems within urban areas and has assessed the impact of land conservation (Stott et al., 2015), land use change (Long et al., 2014), human demands (Stanley et al., 2016), vegetation coverage (Li et al., 2016), and the urban landscape (Chen and Yu, 2017) on regional systems. Previous analyses have also assessed the impacts of land reclamation (Chen et al., 2016), economic growth (Bai et al., 2012), and climate change (Gu et al., 2011) on regional urbanization systems as well as the impact of urbanization on energy consumption (Zhang and Lin, 2012), air quality (Han et al., 2014), socioeconomic sustainable development (Cao et al., 2014), urban multifunctional landscape (Peng et al., 2016) and ecosystem services (Delphine et al., 2016). A limited number of previous studies have addressed the factors that influence the synergy between urbanization and the ecological environment as a composite system from different temporal and spatial scales.

Therefore, the study applied both human and natural element panel data spanning the period between 2000 and 2015 to research the degree of coordination between urbanization and the ecological environmental composite system and the factors that influence these variables in BTHUA. To reduce the deviation of subjective and objective weights, this paper uses the principle of minimum information entropy to synthesize subjective and objective weights. The Coordination Degree Model was used to measure the degree of urbanization and ecological environment system coordination, to consider the level of index value at the same time. The principle of coordination degree classification is further set to determine the type of synergistic development effect of composite systems. The Geo-Detector Method was then used to analyze dominant coordination degree factors in terms of the composite system and the interactions between factors, to overcome the limitation of statistical method in processing variables. Several relevant suggestions are then made to improve agglomeration urbanization as well as the coordinated and sustainable development of the ecological environment system in order to provide a development model that can be applied in developing countries.

2. Research area, data source, and an evaluation index system

2.1. Research area and data source

The BTHUA is a core regional component of the Chinese economy and an important area that contributes to national competitiveness. This region including two municipalities, Beijing and Tianjin, as well as 11 prefectural-level cities, Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Zhangzhou, Langfang, and Hengshui. The rate of urbanization within the BTHUA increased from 38.99% in 2000 to 62.72% in 2015, in concert with a significant improvement in this process. However, alongside a rapid accumulation in population and industry as well as a continuous improvement in the socioeconomic scale of cities, the BTHUA ecological environment is becoming more-and-more intense, and the BTHUA has the largest contradictions between the eco-environment and urbanization development within China (Wang and Fang, 2016). The ecological safety index has now reached a state of warning. This paper therefore emphasizes the synergistic effects of the BTHUA composite and the factors that underlie this system (see Fig. 1).

The urbanization and ecological environmental data utilized here were sourced from the Beijing Statistical Yearbook, the Tianjin Statistical Yearbook, the Hebei Statistical Yearbook, the China Regional Economic Statistical Yearbook, the China Urban Statistical Yearbook, the Beijing Water Resources Bulletin, the Tianjin Water Resources Bulletin, the Hebei Water Resources Bulletin, the China Science and Technology Statistical Yearbook, the China Environmental Monitoring Official Website, and the Statistical Bulletin on National Economic and Social Development. The carbon emission data used here was obtained via reference to the variable energy standard coal and carbon emission reference coefficient; in this context, the energy consumption elasticity coefficient was obtained by calculating the average growth rate of energy consumption over a given time period and then comparing it to either average GDP growth rate or that of industrial and agricultural production over the same period. Missing data was then computed using the comprehensive growth rate estimation method, based on either a multi-year historical average or a segmental average growth rate.

2.2. The evaluation index system

2.2.1. Constructing an urbanization index system using the PESS model

The development of urbanization is a complex and dynamic process that is accompanied by changes in population, industry, society, space, ecology, and other multi-dimensional factors (Chen et al., 2010). Researchers have recently tended to construct scientific and rational indicators to comprehensively assess the development status of urbanization within a given region (Li and Wei, 2014). Thus, building on this background and extending existing research works (Li et al., 2012), a PESS model is proposed here to comprehensively evaluate urbanization development level from four dimensions of population growth, economic development, life improvement and spatial expansion (Huang and Fang, 2003). Which correspond to population urbanization, economic urbanization, social urbanization and spatial urbanization.
respectively, and 20 evaluation indicators are selected in total. Population urbanization is the basis of urbanization development, and population concentration to city is the basic carrier of regional urbanization development. Economic urbanization is the core content of urbanization development, and economic development is the engine of urbanization development. Social urbanization reflects the diffusion of civilization and the level of people’s living standards, enriching the connotation of urbanization. Spatial urbanization is an important part

Table 1
Evaluation index system and index weight of urbanization.

<table>
<thead>
<tr>
<th>System</th>
<th>Subsystem</th>
<th>Evaluation indicators</th>
<th>Unit</th>
<th>Subjective weight</th>
<th>Objective weight</th>
<th>Comprehensive weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanization comprehensive index</td>
<td>Population urbanization (PU)</td>
<td>Urbanization rate</td>
<td>–</td>
<td>0.573</td>
<td>0.320</td>
<td>0.443</td>
</tr>
<tr>
<td></td>
<td></td>
<td>population density</td>
<td>10,000 people/km²</td>
<td>0.225</td>
<td>0.314</td>
<td>0.276</td>
</tr>
<tr>
<td></td>
<td></td>
<td>proportion of the second industry population</td>
<td>–</td>
<td>0.090</td>
<td>0.145</td>
<td>0.118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>proportion of the third industry population</td>
<td>–</td>
<td>0.112</td>
<td>0.221</td>
<td>0.163</td>
</tr>
<tr>
<td></td>
<td>Economic urbanization (EU)</td>
<td>Per capita GDP</td>
<td>Yuan</td>
<td>0.453</td>
<td>0.169</td>
<td>0.366</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second, third industry account for the proportion of GDP</td>
<td>–</td>
<td>0.153</td>
<td>0.058</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita social fixed assets investment</td>
<td>Yuan/people</td>
<td>0.061</td>
<td>0.191</td>
<td>0.143</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita industrial output value</td>
<td>Yuan/people</td>
<td>0.037</td>
<td>0.198</td>
<td>0.113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita fiscal revenue</td>
<td>yuan/people</td>
<td>0.037</td>
<td>0.362</td>
<td>0.153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GDP growth rate</td>
<td>–</td>
<td>0.259</td>
<td>0.022</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>Social urbanization (SU)</td>
<td>Per capita social consumer goods retail sales</td>
<td>Yuan/people</td>
<td>0.026</td>
<td>0.229</td>
<td>0.088</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita disposable income of urban residents</td>
<td>Yuan/people</td>
<td>0.433</td>
<td>0.160</td>
<td>0.299</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of health institutions the beds per 10,000</td>
<td>One/10,000 people</td>
<td>0.064</td>
<td>0.090</td>
<td>0.086</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of doctors per 10,000 people</td>
<td>One/10,000 people</td>
<td>0.264</td>
<td>0.126</td>
<td>0.207</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of Internet users per 10,000 people</td>
<td>One/10,000 people</td>
<td>0.155</td>
<td>0.194</td>
<td>0.197</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of college students per 10,000 people</td>
<td>One/10,000 people</td>
<td>0.058</td>
<td>0.200</td>
<td>0.122</td>
</tr>
<tr>
<td></td>
<td>Spatial urbanization (SPU)</td>
<td>Urban construction land accounts for the proportion of city area</td>
<td>–</td>
<td>0.497</td>
<td>0.332</td>
<td>0.437</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita highway mileage</td>
<td>km/1,000 people</td>
<td>0.085</td>
<td>0.351</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Traffic line density</td>
<td>km/km²</td>
<td>0.290</td>
<td>0.135</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capita urban construction land area</td>
<td>km²/10,000 people</td>
<td>0.128</td>
<td>0.182</td>
<td>0.164</td>
</tr>
</tbody>
</table>
of urbanization, while the change of land use structure and the development level of transportation facilities can directly reflect the level of urbanization construction.

2.2.2. Constructing an ecological environment index system using the PSR model

The pressure-state-response (PSR) model was first utilized to analyze the relationship between ecological environment pressure, current status, and responses (OECD, 1993). This model is often used in ecological environment assessment, and is considered by many governments and organizations to provide the currently most effective framework as it is based on a relatively scientific system and affords comprehensive evaluation (Neri et al., 2016). Ecological environmental stress in the PSR model refers to the load brought by human activities or natural factors on ecological security, namely ecological stress. The state of ecological environment indicates the state and change of ecological environment and natural resources under the pressure. The effect of ecological environment indicates the response of government, social organizations and related groups to the protection of ecological environment in the face of the realistic state of the environment (Wolfslehner and Vacik, 2008). The PSR model has formed an organic dynamic cycle mechanism through the characteristics of dynamic conduction mechanism in the process of pressure, state and response. Therefore, it is applicable to construct the evaluation index system of urban agglomeration ecological security by using PSR model. A total of 21 evaluation indexes are selected.

3. Research methods

Differences in the purpose and meaning of evaluation indicators can lead to different dimensions and magnitudes for these variables. Standardized processing methods were therefore used here to eliminate the influence of different dimensions and orders of magnitude on indicators and to reduce the interference of random factors. The analytic hierarchy process (AHP) (Dong et al., 2010), entropy method (Xie et al., 2012), projection pursuit model (Huang and Lu, 2014), technique for order preference by similarity to an ideal solution (TOPSIS) (Huang et al., 2018) are commonly used in terms of weight calculation. The AHP-entropy combination method was used to calculate the index weight synthetically in this paper. The subjective and objective weighting results are more scientific compared with single weighting method. A one to nine subjective empowerment scale method was applied here; thus, the opinions of 40 experts from the Chinese Academy of Sciences, Peking University, Tsinghua University, Beijing Normal University, and other scientific research institutions were used to create a judgment matrix which was then tested for consistency. The subjective (w_s) and objective weights (w_o) of model indicators were calculated using an AHP and the entropy method. Comprehensive values for subjective and objective weights were therefore calculated using the principle of minimum information entropy in order to reduce the deviation of subjective and objective weights. All subjective and objective weights calculated here for urbanization and ecological environment system evaluation indicators are shown in Table 1 and Table 2; these were calculated as follows:

### Table 2
Ecological environment evaluation index system and index weight.

<table>
<thead>
<tr>
<th>System Subsystem</th>
<th>Evaluation indicators</th>
<th>Unit</th>
<th>Subjective weight</th>
<th>Objective weight</th>
<th>Comprehensive weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecological environment pressure (EEP)</td>
<td>Per capita water consumption</td>
<td>$M^3$/people/year</td>
<td>0.030</td>
<td>0.154</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>Per capita energy consumption</td>
<td>Kilogram</td>
<td>0.052</td>
<td>0.084</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>Per capita carbon emissions</td>
<td>g/m²</td>
<td>0.396</td>
<td>0.338</td>
<td>0.388</td>
</tr>
<tr>
<td></td>
<td>Regional development index</td>
<td>–</td>
<td>0.020</td>
<td>0.107</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>Elasticity coefficient of energy consumption</td>
<td>–</td>
<td>0.087</td>
<td>0.054</td>
<td>0.072</td>
</tr>
<tr>
<td>Ecological environment state (EES)</td>
<td>Ecological risk index</td>
<td>–</td>
<td>0.261</td>
<td>0.181</td>
<td>0.230</td>
</tr>
<tr>
<td></td>
<td>Population natural growth rate</td>
<td>–</td>
<td>0.154</td>
<td>0.081</td>
<td>0.118</td>
</tr>
<tr>
<td></td>
<td>Forest cover rate</td>
<td>–</td>
<td>0.329</td>
<td>0.249</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>Per capita water resources</td>
<td>$M^3$/people</td>
<td>0.109</td>
<td>0.132</td>
<td>0.126</td>
</tr>
<tr>
<td></td>
<td>Ecological land area per 10,000 people</td>
<td>Km/10,000 people</td>
<td>0.254</td>
<td>0.460</td>
<td>0.358</td>
</tr>
<tr>
<td></td>
<td>Green area coverage in built-up areas</td>
<td>–</td>
<td>0.152</td>
<td>0.031</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>Per capita industrial sulfur dioxide emissions</td>
<td>Ton/10,000 people</td>
<td>0.073</td>
<td>0.033</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>Per capita industrial wastewater discharge</td>
<td>Ton/people</td>
<td>0.027</td>
<td>0.026</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>Per capita industrial solid waste discharge</td>
<td>Ton/people</td>
<td>0.016</td>
<td>0.026</td>
<td>0.022</td>
</tr>
<tr>
<td>Ecological environment response (EER)</td>
<td>PM$_2.5$ concentration</td>
<td>10,000 ton/year</td>
<td>0.040</td>
<td>0.044</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Harmless treatment rate of domestic garbage</td>
<td>–</td>
<td>0.084</td>
<td>0.023</td>
<td>0.066</td>
</tr>
<tr>
<td></td>
<td>Sewage treatment plant centralized treatment rate</td>
<td>–</td>
<td>0.244</td>
<td>0.024</td>
<td>0.116</td>
</tr>
<tr>
<td></td>
<td>Comprehensive utilization of industrial waste</td>
<td>–</td>
<td>0.157</td>
<td>0.389</td>
<td>0.373</td>
</tr>
<tr>
<td></td>
<td>Per capita R&amp;D investment</td>
<td>Yuan/people</td>
<td>0.028</td>
<td>0.314</td>
<td>0.142</td>
</tr>
<tr>
<td></td>
<td>Patent authorization</td>
<td>One/10,000 people</td>
<td>0.043</td>
<td>0.227</td>
<td>0.149</td>
</tr>
<tr>
<td></td>
<td>Energy consumption per 10,000 yuan</td>
<td>Tons of standard coal</td>
<td>0.444</td>
<td>0.023</td>
<td>0.153</td>
</tr>
</tbody>
</table>

3. Research methods

At present, the research method of the relationship between urbanization and ecological environment is mainly from the microscopic perspective, using ecological footprint model (Liao et al., 2018), support vector machine (SVM) method (Lu and Yao, 2018) and Industrial Ecology Virtual Laboratory (Baynes et al., 2018) to study the impact of urbanization on the ecological environment system. Panel data is rarely used from a macro perspective to explore the influencing factors of the synergy between urbanization and ecological environment systems. Therefore, this paper uses the coupling coordination degree model and the geo-detector model to explore the coupling relationship and main controlling factors of urbanization and ecological environment from the macro level.
\[ w_i = \frac{(w_{i1} \cdot w_{i2})^{1/2}}{\sum_{j=1}^{n} (w_{j1} \cdot w_{j2})^{1/2}} \]  

(1)

### 3.2. Comprehensive evaluation model

A linear weighting method was used to calculate index values for population, economic, social, and spatial urbanization subsystems as well as ecological environment pressure, state, response subsystem, and urbanization and ecological environment system evaluation. These values were calculated as follows:

\[ f(x) = \sum_{i=1}^{n} w_i \cdot x_i, \quad g(y) = \sum_{j=1}^{m} w_j \cdot y_j \]  

(2)

\[ F(x) = \sum_{i=1}^{n} W_i \cdot f(x), \quad G(y) = \sum_{j=1}^{m} W_j \cdot g(y) \]  

(3)

In these expressions, \( f(x) \) and \( g(y) \) denote comprehensive evaluation values for urbanization and ecological environment subsystems, respectively, while \( F(x) \) and \( G(y) \) denote comprehensive evaluation values for urbanization and ecological environment systems, respectively. Similarly, \( x_i \) and \( y_j \) refer to standardized values for urbanization and ecological environment assessment indicators, respectively, while \( w_i \) and \( w_j \) denote the comprehensive weights of urbanization and ecological environment assessment indicators, respectively, and \( W_i \) and \( W_j \) denote the weights of urbanization and ecological environment subsystems, respectively. Subsystems were considered of equal importance in this analysis and so equal weights were applied.

### 3.3. Coupling coordination model

A series of complex interactive and cohesive mechanisms are involved in urbanization and the ecological environment. These manifest in two ways, comprising either a coercive effect of urbanization on the ecological environment or the binding effect of the latter on the former. A classic paradigm was therefore used to study the synergistic developmental effects of urbanization and the ecological environment in this study; evolutionary trends were analyzed and the different kinds of coordinated development were determined and sub-divided.

#### 3.3.1. A coupling degree model for urbanization and the ecological environment

Coupling degree is a concept from physics that refers to the phenomenon where two (or more) systems influence each other via various interactions between themselves and the outside world. Due to similarities in coupling relationships between systems, this phenomenon is now widely applied to study the relationships between urbanization and ecological interactions, calculated as follows:

\[ C = \left[ \frac{F(x) \cdot G(y)}{\left( F(x) + G(y) \right)^{1/2}} \right]^{k/2} \]  

(4)

In this expression, \( C \) denotes the degree of coupling between urbanization and the ecological environment system such that \( 0 \leq C \leq 1 \). At the same time, \( F(x) \) is the comprehensive evaluation value for the urbanization system, \( G(y) \) is the comprehensive evaluation value for the ecological environment system, and \( k \) is the adjustment coefficient (usually \( k = 2 \)).

#### 3.3.2. An urbanization and ecological environment coordination model

A coordination degree model was used in this study to more accurately assess the degree of coordination between the two systems, calculated as follows:

\[ T = \alpha F(x) + \beta G(y) \]  

\[ D = \sqrt{C^2} \]  

(5)

In this expression, \( D \) denotes the degree of coordination, \( T \) is the comprehensive development index of urbanization and the ecological environment system, and \( \alpha, \beta \) denotes the weight due to each contributed share of the two variables, respectively. Thus, assuming that urbanization is just as important as ecological environment protection, \( \alpha = \beta = 0.5 \).

#### 3.3.3. Classifying synergies between urbanization and the ecological environment

The types of synergies seen between urbanization and the ecological environment were divided here into three categories, four sub-categories, and 12 system type states according to their degree of coordination (D), the evaluation value of an urbanization system \( (F(x)) \), and this value for the ecological environment system, \( G(y) \) (Li et al., 2012) (Table 3).

### 3.4. Geo-detector

A geo-detector approach was first applied to explore the influence of geospatial zoning factors on disease risk (Wang et al., 2010). As these kinds of models do not encapsulate many assumptions and can overcome the limitations otherwise inherent to statistical methods when dealing with variables, they have been widely utilized in assessing the impact mechanisms of socio-economic and natural environmental factors. Geo-detector factor detection can therefore be used to identify influencing factors; an interaction detector can be used to explain the relations between factors influencing the dependent variable (Wang and Hu, 2012).

#### 3.4.1. Factor detector

The core idea that underlies the use of factor detector is to compare whether, or not, a given change in an environmental factor and a geographical entity exhibit significant spatial consistency. In other words, if an environmental factor and variation in a geographical entity are consistent with one another, then the former can be considered decisive for the occurrence and development of the latter. This relationship is expressed as follows:

\[ q_{DU} = 1 - \frac{1}{n_{DU}} \sum_{i=1}^{m} \sigma_{DU}^2 \]  

(6)

In this expression, \( q_{DU} \) denotes the impact detection index of factors influencing the degree of coordination between urbanization and an ecological environment composite system, \( n \) is the number of research units, \( n_{DU} \) denotes the number of samples comprising the second-level research unit, \( m \) is the number of secondary research units, \( \sigma_{DU}^2 \) is the degree of variance of coordination with the urban agglomeration complex system, and \( \sigma_{DU}^2 \) is the degree of variance within sub-composite system coordination. The model is therefore established assuming \( \sigma_{DU}^2 \neq 0 \) and with a value range of \( q_{DU} \) is \([0,1]\); thus, if \( q_{DU} = 0 \) then the spatial distribution of degree of coordination within the composite system is not driven by influencing factors. The larger the value of \( q_{DU} \), the greater the influence of natural factors on the degree of composite system coordination.

#### 3.4.2. Interaction detector

An interaction detection can be used to quantitatively characterize the relationship of two influencing factors on composite system degree of coordination. Thus, if factors A and B influence the degree of composite system coordination, a new layer (C) is formed by spatially superimposing the initial pair. The attributes of the C layer are then determined by both A and B; thus, comparing the factorial influence of layers A and B with that of C enables a judgement as to whether, or not, the interactive influence of the initial two factors on composite system coordination degree is stronger or weaker (see Fig. 2).
Table 3
Classification of urbanization and ecological environment synergistic development.

<table>
<thead>
<tr>
<th>Category</th>
<th>Coordination degree</th>
<th>Subcategory</th>
<th>Index comparison</th>
<th>Tertiary category</th>
<th>Code</th>
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<tr>
<td>Uncoordinated development</td>
<td>0 &lt; D ≤ 0.2</td>
<td>Severe imbalance</td>
<td>( G(y) = F(x) &gt; 0.1 )</td>
<td>Urbanization lag</td>
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<td>0.2 &lt; D ≤ 0.4</td>
<td>Moderate imbalance</td>
<td>( G(y) = F(x) &lt; -0.1 )</td>
<td>Ecological environment lag</td>
<td>I3</td>
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<td>Transformation and</td>
<td>0.4 &lt; D ≤ 0.6</td>
<td>Low coordination</td>
<td>( G(y) = F(x) &gt; 0.1 )</td>
<td>Urbanization lag</td>
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<td>development</td>
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<td></td>
<td>0.6 &lt; D ≤ 0.8</td>
<td>Moderate coordination</td>
<td>( G(y) = F(x) &lt; -0.1 )</td>
<td>Ecological environment lag</td>
<td>I3</td>
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<td>Coordinated development</td>
<td>0.8 &lt; D ≤ 1</td>
<td>Advanced coordination</td>
<td>( G(y) = F(x) &gt; 0.1 )</td>
<td>Urbanization lag</td>
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Fig. 2. Redefined interaction relationships.

4. Results

4.1. Coordination between urbanization and the ecological environment system index

4.1.1. Time series trends in urbanization and the ecological environment system index within the BTHUA

The entropy method and AHP were both applied to enable subjective and objective comprehensive weighting of indexes, with urbanization and ecological environment system evaluation values calculated using formulae (2) and (3). In order to analyze time series trends, a graph for urbanization and ecological environment system index values (Fig. 3) was constructed for different regions of the BTHUA.

(1) BTHUA urbanization system index (USI) values are characterized by a rapid increase and linear growth over time (Fig. 3). Comparing average values, the level of urbanization seen in Beijing and Tianjin mean that these cities occupy the first echelon within the region, far in excess of others to the extent that these municipalities possess obvious advantages. It is also clear that Shijiazhuang and Tangshan comprise second echelon cities as their values are higher than the average; within these data, the provincial capital city Shijiazhuang occupies the high first position, while Tangshan, the central city of the Beijing-Tianjin-Tang Industrial Base, possesses obvious resource advantages. The cities of Langfang and Qinhuangdao comprise the third echelon within these data, with higher than average values in some years. Indeed, the degree of urbanization seen in Langfang is rapidly increasing and subsequent to 2010, will likely be ranked in the top four within the BTHUA. Subsequent integration of the Beijing-Tianjin agglomeration means that there will be room for improvement in the future. Data show that the remaining cities comprise the fourth echelon and that their potential for development requires further exploration.

(2) The BTHUA ecological environment system index is characterized by both slow growth and fluctuations. The ecological environment levels within Chengde and Beijing are consistent with first echelon cities, in both cases far above average. As the national capital, Beijing enjoys a strong sense of environmental protection due to a high degree of regulation, while Chengde is located within the northern part of the BTHUA and forms a natural green ecological barrier and environmental protection support area for the Capital Region. Data show that ecological environment levels within Zhangjiakou, Qinhuangdao, Baoding, and Shijiazhuang are consistent with their characterization as second echelon cities; within these, the first three boast higher than average values. The city of Zhangjiakou is an ecological conservation area urban agglomeration and an important source of water, while Qinhuangdao is an ecological model city. This latter agglomeration adheres to the principles of "ecological market" and that "lucid waters and lush mountains are invaluable assets". In contrast, the cities of Baoding and Shijiazhuang are notable because they are actively carrying out industrial upgrading and optimization reforms, seeking to develop a green, sustainable, innovative urbanization development road. The other cities within this dataset comprise the third echelon of the BTHUA.

4.1.2. Spatiotemporal differentiation in synergistic effects between urbanization and the eco-environment

Degrees of coupling and coordination of urbanization and the eco-environment within the BTHUA were calculated using formulae (4) and (5) (Table 5). Degree of coupling can be used to analyze correlations between systems, while degree of coordination not only reflects
correlation between systems but also the size of a system index. Degrees of coordination were therefore selected for analysis; as outlined in Table 4, degrees of urbanization and ecological environment coordination were divided into different levels (Fig. 4) for use in an inductive coordinated development model (Table 5).

The coordination degree subcategory within the BTHUA is mainly moderate-to-low; these data reveal an overall upward trend and a good development condition within this region. The degree of coordination on plains areas is higher than that of mountain regions and, overall, this variable conforms to a core-edge distribution pattern within the BTHUA. Industrialization plays a central role in the development of the BTHUA and geomorphological type is also a key factor influencing coordination between urbanization and the eco-environment. Data show that between 2000 and 2010, the degree of coordination between urbanization and the ecological environment system was dominated by low values. Although the issue of ecological environment protection has not received enough attention during rapid urbanization, an upward trend is nevertheless evident overall within the BTHUA. Subsequent to 2011, and implementation of the national ‘Twelfth Five-Year Plan’, a process of BTHUA integrated development was officially proposed to build a capital economic circle and so composite system coordination entered a rapid improvement phase. In 2015, 62% of cities had attained moderate coordination; specifically, Beijing had reached an advanced level of coordination, while southern cities such as Gansu, Zhangzhou, Xingtai, and Hengshui remained on the verge of low coordination. This result is consistent with the current situation as this region remains an area of serious air pollution within China. The relationship between urbanization and ecological environment protection remains in a state of dislocation.

(2) Coordinated development induction type for urbanization and the eco-environment. Within the BTHUA. According to the classification criteria laid out in this study for assessing the degree of coordination between urbanization and the ecological environment composite system (Table 3), types and stages of these variables within the BTHUA between 2000 and 2015 were analyzed.
Table 5
Summary table of coordination index of urbanization and ecological environment system of the BTHUA 2000-2015.

Table 6.

Data show that degree of coordination subcategories between urbanization and the eco-environment within the BTHUA have generally increased over time, but that improvements have been slow. Subsequent to 2003, all cities within this region had either reached a moderate level of coordination or above, while the number to attain a high degree of coordination has increased over time, but that improvements have been slow.

The coordination degree of urbanization and the eco-environment sub-category within the BTHUA is characterized by urbanization lag which leads to balanced development which in turn leads to ecological environment lag. This process means that improvements in the quality of the eco-environment are imminent. Indeed, the level of urbanization and the eco-environment within the BTHUA have generally increased over time, but that improvements have been slow.
4.2. Dominant factors influencing the degree of coordination between urbanization and the eco-environment composite system

4.2.1. Different spatial scales

Dominance factors within the CUECS are different at the three spatial scales considered here, the BTHUA urban agglomeration, across provinces, and within prefectural-level cities. Specifically, per capita social consumer goods retail sales, GDP, and the disposable incomes of urban residents are examples of the top five factors (Fig. 5). Which are related to factors such as higher consumption level, faster economic development, and the higher wage income of residents within the BTHUA. The siphon effect is significant within this region while spillover effects are not obvious when emphasis is placed on the development of technology-based and service industries. Hebei acts as a barrier to defend Beijing and Tianjin, and has absorbed the elimination of industries from within the former regions; two high and one low industry have promoted economic improvements but have also led to the destruction of the eco-environment.

The top five most important factors within the CUECS are urbanization rate, per capita social consumer goods retail sales, per capita GDP, the proportion of tertiary industrial population, and the per capita disposable income of urban residents; in all cases, the impact coefficient is higher than 0.6 and all pass a significance level test at 0.05. The first two of these variables markedly affect the CUECS; urbanization rate, GDP, per capita disposable income of urban residents; all of these variables pass a significant test at the 0.05 level. Urbanization rate also strongly influences the CUECS, as does the degree of urbanization within the BTHUA. The top five factors influencing the CUECS are urbanization rate, per capita social fixed asset investment, the per capita disposable income of urban residents, per capita GDP, and sewage treatment plant centralized treatment rate within the 11 cities of Hebei Province; all these variables pass a significant test at the 0.05 level. Urbanization rate also strongly influences the CUECS, as does sewage treatment plant centralized treatment rate and other factors. Hebei Province is mainly characterized by low-end, heavy, and infrastructure construction industries and the level of urbanization is much lower here than in Beijing and Tianjin. As this region is also influenced by the siphon effect of Beijing and Tianjin, there is a poverty-stricken area around the two larger cities in Hebei Province with many high-consumption, high-pollution, and low-efficiency industries.

4.2.2. Different temporal scales

Urbanization development stage was divided according to comparisons of different subsystems and mean values. Data show that this is strongest when four subsystems are all higher than the average and is also stronger when just three are above average. Thus, based on the number of cities characterized by strongest and stronger urbanization between 2000 and 2015, the BTHUA can be classified as being in a stage of gentle urbanization development between 2000 and 2006, being in a stage of medium-speed urbanization development between 2007 and 2011, and being in a stage of high-speed urbanization development between 2012 and 2015.

In different stages of development, urbanization rate, per capita social consumer goods retail sales, and the proportion of tertiary industrial population are amongst the top five factors influencing the CUECS (Fig. 6). This change is related to a significant improvement in the level of urbanization, an enhanced level of consumer consumption, and a high developmental level of both financial and high-tech services within the BTHAU. The top five factors that influenced the CUECS within the gentle urbanization development stage (between 2000 and 2006) of the BTHAU were urbanization rate, the proportion of tertiary industrial population, the extent to which secondary and tertiary industries accounted for the proportion of GDP, per capita social fixed asset investments, and the number of health institutions beds per 10,000 people; all of these variables passed significance level tests with 0.05 confidence. The first two of these variables most markedly influenced the CUECS while all others had a great influence. Indeed, GDP increased nearly two-fold over this period while the level of urbanization increased from 38.9% to 51.19% within the BTHAU between 2000 and 2006. The development of integrated urbanization also had a

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**Table 6**


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significant impact on the CUECS.

The top five factors influencing the CUECS within the medium-speed urbanization development stage (between 2007 and 2011) of the BTHAU were per capita social consumer goods retail sales, the proportion of tertiary industrial population, urbanization rate, per capita fiscal revenue, and per capita carbon emissions; all of these variables passed significance level tests with 0.05 confidence. The first of these factors most markedly influenced the CUEC while all others greatly affected the CUECS. Since the onset of the global financial crisis, the Chinese government has spent 4 trillion yuan to boost domestic demand

Fig. 5. Summary of the dominant factors influencing CUECS at different spatial scales across the study area.

Fig. 6. Summary of the dominant factors of CUECS at different stages of Urbanization development.
and consumption and to promote rapid development of the service industry.

The top five factors influencing the CUECS within the rapid urbanization development stage (between 2012 and 2015) of the BTHAU were the per capita disposable income of urban residents, forest cover rate, proportion of tertiary industrial population, per capita social consumer goods retail sales, and urbanization rate; all of these passed the significance level test of 0.05, all of these variables passed significance level tests with 0.05 confidence. The first two of these extremely affected the CUECS while all others greatly affect the CUECS. The Chinese national “Twelfth Five-Year Plan” requires the accelerated construction of a resource-conserving and environmentally-friendly society and will enhance the ecological civilization level. This implies that the government is paying more-and-more attention to improving the well-being of citizens as well as protecting the ecological environment.

4.2.3. An interaction analysis for the BTHUA

The data presented here reveal that the interaction between two elements is higher than the degree of influence on the CUECS of any single factor; this suggests that each individual element exerts a positive influence on the CUECS and that strong synergy is also present. Urbanization rate and per capita carbon emissions both exert the highest comprehensive impact on the CUECS, suggesting that the two interact to the strongest extent. Urbanization rate also significantly influences the CUECS by dictating urbanization quality, while greenhouse gas emissions (such as carbon dioxide) are closely related to industrial development and the lives of the population. Both variables significantly influence the CUECS. The interaction between traffic network density and forest coverage rate is independent, however, and indicates that the impact of these two elements on the CUECS remains relatively discrete. Interactions between traffic line density and per capita water consumption, per capita water consumption and forest cover rate, per capita water consumption and green area coverage in built-up areas, per capita water consumption and sewage treatment plant centralized treatment rate, per capita water consumption and energy consumption per 10,000 yuan, forest cover rate and green area coverage in built-up areas, forest cover rate and sewage treatment plant centralized treatment rate, forest cover rate and Energy consumption per 10,000 yuan, and per capita carbon emissions and sewage treatment plant centralized treatment rate are all nonlinear in this analysis; this means that these interactions are more significant and that others comprise two-factor enhanced interactions with insignificant effects.

Data show that the kinds of impacts due to urbanization and ecological environment subsystems on the CUECS can be ranked in sequence from largest-to-smallest as population urbanization, economic urbanization, social urbanization, and the ecological environment subsystem. Interactions between population urbanization factors are also significantly higher than other subsystem factors which suggests that the impact of population urbanization on the CUECS is more significant. This result is consistent with the aim of new urbanization within China which emphasizes harmonious coexistence between man and nature. The interactions between elements of the spatial urbanization subsystem and the eco-environment pressure and status subsystem are also more significant; this result demonstrates the presence of a strong correlation between spatial urbanization and the eco-environment. Expansions in urban land space should therefore fully consider ecological environment benefits in this context and aim for the most optimal use of land resources.

5. Discussion and conclusions

5.1. Discussion

Taken together, forming an adjacent super-large city, the Beijing and Tianjin exert a strong “siphon effect” (Liu et al., 2017). On the one hand, a high concentration of factors leads to an imbalance in the urban agglomeration scale system in this case and so the number and size of large and medium-sized cities within this region remain weak and it is difficult to support the balanced development of the entire BTHUA. This has also led, in contrast, to a number of urban diseases including the rising price of land, traffic congestion, and environmental pollution (Fang et al., 2017a). As is typical for mega-cities, development of the BTHUA has been driven by political, cultural, and economic factors which reflect the problems in urban architecture, functional and spatial structure, and the eco-environment that exist within this rapid development stage. The Chinese government has therefore implemented a coordinated development strategy for the BTHUA and has systematically and appropriately dispelled the non-capital functions of Beijing other than at the national level, adjusted the economic structure of complementary urban functions, balanced supply and demand, modified the spatial developmental structure of large, medium, and small cities, and actively promoted an urban agglomeration developmental model to integrate transportation and ecological environment protection integration, and upgrade and transfer industrial (Fang, 2017). These innovations have led to good practical results and can provide a reference for the sustainable development of other urban agglomerations in developing countries.

Industrialization has played a central role in the development of the BTHUA; the rapid industrialization of urban agglomerations has driven a similarly fast process of urbanization which has led to excessive consumption of the eco-environment and energy resources and reduced the function of ecological services. This rapid series of processes has therefore created tremendous pressure on the ecological environment system within the BTHUA. In this case, the northern mountainous area, an important ecological environment support area for the sustainable development of urban agglomerations as well as a functional water conservation zone, provides an important source of both this resource and wind for the BTHUA. A low degree of coordination in northern mountainous areas indicates that these regions perform a dominant ecological security function but are not suitable for use in a rapid urbanization development model. The government must therefore change the current urbanization development policy system of ‘one size fits all’ across this whole region; it is also urgent to implement a differentiated policy system according to the variable resource environments of different cities.

It is therefore urgent to gradually reduce the speed of urbanization within the BTHUA and improve overall quality in combination with regional characteristics, stimulate the scale of social green consumption, optimize industrial structures, increase support policies for tertiary industries, adhere to the “people-oriented” new urbanization development road, and effectively improve the well-being of citizens. The Chinese government should emphasize the development of various advantages of the BTHUA as part of the process of promoting urbanization while at the same time avoiding the negative impacts of factors via the role of multi-factorial clusters to illustrate gathering and scale effects of this region. The primary task of coordinated urbanization and ecological environment system development is therefore to regulate population mobility and decrease the sheer number of people who inhabit megacities. At the same time, it is also important to take economic supply side and social welfare structures into account in order to optimize industrial configurations and guarantee a welfare level for residents. These approaches will also create solid foundations for adjustments to economic and social structures in the future.

5.2. Conclusion

From 2000 to 2015, the urbanization shows a trend of rapid rise and linear growth in the BTHUA, while the quality of the ecological environment increases slightly in the fluctuations. The degree of coordination between urbanization and the ecological environment system within the BTHUA is mainly due to the onset of dysfunction as
well as moderate coordination; the overall trend within this region is therefore upward and the status of BTHUA development is good. This has a major bearing on the country’s strict environmental protection measures in the region. The degree of coordination between urbanization and the ecological environment composite system reveals a core-edge distribution pattern that is manifest as high values on plains, low ones in mountainous areas, high records inland, and low values in coastal areas, it’s spatial differences is obvious. The type of landform is also an important factor influencing the coordination of urbanization and ecosystem.

Data shows that between 2000 and 2015, the five most significant factors controlling the coordination of urbanization and the eco-environment within the BTHUA are urbanization level, per capita social consumer goods retail sales, per capita GDP, the proportion of tertiary industrial population, and the per capita disposable income of urban residents. Indeed, during different developmental stages, urbanization level, per capita social consumer goods retail sales, and the proportion of tertiary industrial population remain among the top five factors, indicating that urbanization, social consumption, and the scale of service industries continue to influence the coordination of urban agglomerations. Data shows that at different spatial scales, including urban agglomerations, provinces (municipalities), and cities, variables such as per capita social consumer goods retail sales, per capita GDP, and the per capita disposable income of urban residents remain within the five most important factors indicating that social consumption, economic level, and household income all exert important influences on degree of coordination across both different scales and city types. The interactive impacts on dual elements of urban agglomeration with respect to the degree of coordination of this composite system are greater than those of any single element. The impacts of urbanization and ecological environment subsystems on the degree of coordination of composite systems (in descending order of importance) are population urbanization, economic urbanization, social urbanization, and the ecological environment subsystem. The results of this analysis also show that population concentration within the BTHUA has been the most significant factor controlling coordination, followed by economic development and social integration.

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Appendix A. Supplementary data

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