Studying the coupling coordination degree between socio-economic and eco-environment of Jing-Jin-Ji urban agglomeration during 2001-2015

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Abstract. With the fast urbanization process of China, many problems also have arisen. Under such background, pursuing the coordinated development of the socio-economic subsystem and eco-environment subsystem has become a hot spot. However, existing researches seldom investigated the regional coupling coordination degree at the gridded level. In this study, combined with the coupling coordination degree model, remote sensing datasets, and other socio-economic datasets at the raster format, we explored the coupling coordination degree of JJJ from 2001 to 2015 at the gridded level. The result of our study showed that (1) The eco-environment of JJJ had improved during 2001–2015, among it, the eco-environment with high RSEI value mainly located in the mountainous area of JJJ, including the Yanshan mountain, and Taihangshan mountain. In contrast, the eco-environment with relatively low RSEI value was mostly located in the central Hebei plain and urban zone. (2) The spatial coupling coordination degree of JJJ showed a decreased trend, with the decrease of high, relatively high, and medium grades area, and the increase of low, and relatively low grades area. Generally, these high coupling coordination degree regions mainly located in the city’s central zone, while these mountainous regions and central Hebei plain mainly displayed a low coupling coordination degree due to the socio-economic lag. These findings may provide more useful information for the relevant policy-makers.

1. Introduction

The eco-environment, defined as “the total quantity and quality of water resources, land resources, biological resources and climate resources that affect human survival and development,” is a social-economic-natural compound system. It not only provides human natural resources and living environment service but also is the foundation and core of regional social and economic sustainable development [1]. In the past forty years, significant changes have taken place in mainland China, especially in the aspects of spatial urbanization, population expansion, industrialization, etc. [2-3]. However, accompanied by the rapid economic development, the eco-environment has been dramatically influenced, for instance, water and soil loss [4], urban heat islands [5], vegetation coverage decrease[6], air pollution [7], and so forth, which can pose a threat to the realization of regional coordinated development goals [8]. Previous studies have paid much attention to this topic. For instance, Cui et al. assessed the sustainability of urbanization by a coordinated development index...
[9]; Zang and Su constructed a coordinated development index system and assessed the level of China’s 283 cities [10]. Generally, it is a hot issue to study regional coordinated development.

Before studying the coupling coordinated development, it is necessary to understand the concept of each item. Coupling, which was first promoted in the physics field, refers to a phenomenon that two or more subsystems in one physical system affect each other [11]. Coordination is defined as the sound interaction among various sectors of a system, which can be applied to describe the region’s sustainable development state [12-13]. To sum up, the definition of coordinated development is the harmonious and consistent development of each subsystem and their relationship [14-15].

To date, numerous studies have been investigated to reveal regional coordinated development situation. For instance, Fan et al. examined the coupling coordinated development state of Chinese provincial capital cities [15]; Shi et al. focused on the tropical and subtropical regions of China and disclosed the economic development and ecological environment coupling coordination degree [16]. Li and Yi studied the city sustainability among economy, society, and environment based on coupling coordinated development [17]. Generally, existing studies have been performed on many spatial scales, including city-level, provincial-level, climatic region level, urban agglomeration level, etc. As for the study method, it can be mainly divided into three methods, which are the development model, coordination model, and coupling coordination model. Based on these existing studies [18-20], we found that existing researches mostly focused on the statistical data to study the regional coupling coordination degree. Besides, previous studies mainly concluded their quantitative result at an administrative boundary scale. That is to say, we can only acquire one coupling coordination value at the administrative level.

An urban agglomeration is a highly developed spatial form of integrated cities, with a research history traced back to 100 years ago [21]. In 2014, the Chinese government issued a development roadmap of “National New Urbanization Plan,” which pointed out to optimize and upgrade eastern urban agglomerations, establish a coordinated mechanism for urban agglomerations development, and to achieve the green development goals based on protecting the eco-environment [22]. As one of the five large urban agglomerations [21], it is vital to realize coordinated development.

Under such circumstances, we integrated the coupling coordination model with remote sensing and geographical information system technologies and took the Jing-Jin-Ji (JJJ) urban agglomeration as the study area to investigate the coupling coordination degree at the gridded level, which could provide more detailed information for relevant policy-makers.

2. Materials and methods

2.1. Study area

JJJ is located in north China (36°05′~42°40′N, 113°27′~119°50′E) and covers approximately 218,000 km². It includes two municipalities and eleven prefecture-level cities, which are Beijing (BJ), Tianjin (TJ), Shijiazhuang (SJZ), Tangshan (TS), Qinhuangdao (QHD), Handan (HD), Xingtai (XT), Baoding (BD), Zhangjiakou (ZJK), Chengde (CD), Cangzhou (CZ), Langfang (LF) and Hengshui (HS) (Figure 1). This region has a temperate semi-humid and semi-arid monsoon climate with the average temperature in July and annual precipitation of 18~27 °C and 524.4 mm, respectively. Nowadays, JJJ is considered as the “third engine of China” in the 21st century. Specifically, in 2017, the total population and gross domestic product reached 95.74 million and 8058.04 billion yuan, which accounts for 6.89% and 9.77% of that of the whole country (http://www.stats.gov.cn). However, along with the fast urbanization, it was urgent to seek a coordinated development between the socio-economic and eco-environment subsystem.
2.2. Data sources

In our study, the data sources can be divided into two groups, which are socio-economic datasets and eco-environment datasets. Socio-economic datasets include population density and regional gross domestic product raster data at 1000 m resolution. Eco-environment datasets include MOD09A1 and MOD11A2 raster data at 500 m and 1000 m resolution, respectively. Table 1 is the overview information of all datasets.

Table 1. Overview of various datasets and their source.

| Name                  | Unit         | Time          | Resolution/m | Source                                      |
|-----------------------|--------------|---------------|--------------|---------------------------------------------|
| MOD09A2               |              | 2001,2015     | 500          | https://lpdaac.usgs.gov                      |
| MOD11A1               |              | 2001,2015     | 1000         | https://lpdaac.usgs.gov                      |
| SRTM                  | m            | 2000          | 90           | http://srtm.csi.cgiar.org                    |
| Population density    | Person/km²   | 2000,2015     | 1000         | https://resdc.cn                             |
| Regional gross        |              | 10000 yuan/km²| 2000,2015    |                                             |
| domestic product      |              |               |              |                                             |

2.3. Methods

2.3.1. RSEI calculation. Remote sensing ecological index, promoted by Prof. Xu in 2013, is a convenient and efficient index to describe the eco-environment situation in the vast region. It integrates four aspects of one region’s eco-environment, which are greenness, wetness, heat, and dryness. Eq. (1)-(3) is the three indicators’ calculation formula.

\[
\text{Greenness} = \frac{(\rho_{nir} - \rho_{red})}{(\rho_{nir} + \rho_{red})} \quad (1)
\]

\[
\text{Wetness} = 0.1084 \times \rho_{red} + 0.0912 \times \rho_{nir} + 0.5065 \times \rho_{blue} + 0.4040 \times \rho_{green} - 0.2410 \times \rho_{mir1} - 0.4658 \times \rho_{mir2} - 0.5306 \times \rho_{mir3} \quad (2)
\]
\[
\text{Dryness} = \frac{1}{2} \left( \frac{2 \times \rho_{\text{mir2}} - \rho_{\text{nir}} - \rho_{\text{green}}}{\rho_{\text{mir2}} + \rho_{\text{nir}} + \rho_{\text{green}} + \rho_{\text{mir2}}} \right) + \frac{1}{2} \left( \frac{(\rho_{\text{mir2}} + \rho_{\text{red}}) - (\rho_{\text{mir2}} + \rho_{\text{blue}})}{(\rho_{\text{mir2}} + \rho_{\text{red}}) + (\rho_{\text{mir2}} + \rho_{\text{blue}})} \right)
\]

(3)

Where \( \rho \) is the band surface reflectance, blue, green, red, nir, mir1, mir2, mir3 are the MODIS bands at 459-479 nm, 545-565 nm, 620-670 nm, 841-876 nm, 1230-1250 nm, 1628-1652 nm, and 2105-2155 nm respectively. Heat is represented by land surface temperature and can be directly acquired from the MOD11A2 dataset. Then, the spatial principal component analysis (SPCA) method is adopted to integrate four subindexes. The first component (PC1) is selected to acquire RSEI. Eq. (5)-(6) is the calculation formula.

\[
RSEI_{\text{origin}} = 1 - \text{PCI} \left[ f\left(\text{Greeness, Wetness, Heat, Dryness}\right) \right]
\]

(4)

\[
X_{\text{rescale}} = \left( X_i - X_{\text{min}} \right) / \left( X_{\text{max}} - X_{\text{min}} \right)
\]

(5)

2.3.2. Coupling coordinated degree model. Two gridded datasets (population density and regional gross domestic product) were selected to represent the socio-economic subsystem. Besides, the RSEI value was utilized to represent the eco-environment subsystem. In our study, a coupling coordinated degree model was applied to explore the regionally coordinated development degree at the gridded level. Eq. (6)-(8) are the calculation formula.

\[
C = \left( E_{SE}^k \times E_{EE}^k \right) / \left( \alpha E_{SE} + \beta E_{EE} \right)^{2k}
\]

(6)

\[
T = \alpha E_{SE} + \beta E_{EE}
\]

(7)

\[
CCD = \sqrt{C \ast T}
\]

(8)

Where \( C \) is the coupling degree; \( T \) is the comprehensive coordination index; \( CCD \) is the coordination degree. \( \alpha \) and \( \beta \) stand for the contributions of two subsystems, \( E_{SE} \) and \( E_{EE} \) were the calculation result of the socio-economic subsystem and eco-environment subsystem, respectively. Here, we treated that the socio-economic subsystem and eco-environment subsystem were equally contributed. \( k \) was the adjustment coefficient; here, we set \( k \) to be 2.

3. Result and analysis

3.1. Eco-environment quality change of JJJ during 2001~2015

Figure 2 illustrates the spatial distribution of the RSEI in JJJ. Generally, we found that the northern part of JJJ had a better eco-environment, with a higher RSEI value relative to the northwestern, central, and southeastern parts. This is under the actual situation, as the northern part is mainly covered with vegetation and is a mountainous area, which names Yanshan mountain and Taihang mountain. As for these regions with a lower RSEI value, they were mainly distributed in the central and east Hebei plain; this region was typically covered with arable land and construction land. Combined with ArcGIS 10.6 software, the zonal statistical result showed that the RSEI average of JJJ increased from 0.43 in 2001 to 0.46 in 2015, indicating that the overall eco-environment of JJJ had improved. The overall eco-environment of JJJ had improved, which had a great relationship with the series policies implemented by the government, such as ‘Returning Farmland to Forest (grass) Project,’ ‘Three-North Shelter Forest Program,’ ‘Beijing-Hebei Ecological Water Resources Protection Forest Project,’ which were launched in 2000, 1979, and 2009. To sum up, the eco-environment of JJJ had improved with ongoing projects launched by the government.
3.2. Variations of coupling coordination degree in JJJ during 2001~2015

Figure 3 shows the coupling coordination degree grades result of JJJ in 2001 and 2015 at the gridded level. The grade rule applied the natural breaks (Jenks) method to divide the whole region into five grades, which were low, relatively low, medium, relatively high, and high. According to Figure 3, we found that the mountainous areas coupling coordination degree were all the low grade, while these areas with a high coupling coordination degree located in central Beijing city, Tianjin city, Shijiazhuang city, and other regions which were distributed sporadically. Besides, regions at the relatively high grade were mainly located in central Hebei plain, in which the primary land-use type was farmland. Regions with relatively high grades and high grades were mostly connected. Table 2 shows the area statistical result of each grade. Combined with Table 2, the area of high grade decreased from 1.28% to 0.72%. The area of relatively high grade decreased from 2.68% to 1.25%. The area of medium decreased from 12.00% to 5.31%, while the area of relatively low grade and low grade increased from 36.12%, 47.89% to 38.41%, 54.31%, respectively. Generally, the overall coordination degree of the socio-economic subsystem and eco-environment subsystem showed a decreased trend, mainly due to the area decrease of high, relatively high, and medium grades, and the area increase of relatively low, and low grades.

| Coupling coordination degree grade | 2001             | 2015             |
|------------------------------------|------------------|------------------|
|                                    | Area/km²         | Percentage/%     | Area/km²         | Percentage/%     |
| High                               | 2656.00          | 1.28             | 1488.00          | 0.72             |
| Relatively high                    | 5568.00          | 2.68             | 2608.00          | 1.25             |
| Medium                             | 24976.00         | 12.00            | 11040.00         | 5.31             |
| Relatively low                     | 75184.00         | 36.15            | 79888.00         | 38.41            |
| Low                                | 99616.00         | 47.89            | 112976.00        | 54.31            |
4. Discussion

4.1. Theoretical implications

Based on the above analysis, we found that the eco-environment of JJJ had improved as the government had put a series of environmental protection projects into practice, like ‘Returning Farmland to Forest (grass) Project,’ ‘Three-North Shelter Forest Program,’ ‘Beijing-Hebei Ecological Water Resources Protection Forest Project,’ etc. This indicated that government intervention exerted an influence on the restoration of JJJ’s eco-environment. To be specific, in the northern part of JJJ, especially in Zhangjiakou city and Chengde city, the project of the ‘Three-North Shelter Forest Program,’ which was launched in 1979, exerted significant ecological benefits for the region’s eco-environment. As for the ‘Returning Farmland to Forest (grass) Project,’ which was launched in 2000, till now, Hebei province had achieved 1.86 million hectares. Besides, since 2009, the government of Beijing had signed an agreement on the Beijing-Hebei Ecological Water Source Protection Forest Construction Project. Based on the document, from 2009 to 2011, Hebei province had planted trees covering 13.33 thousand hectares.

Besides, we found that the coupling coordination degree of the whole JJJ showed a decreased trend. Different from existing researches, the coupling coordination degree of JJJ showed an increasing trend. This was mainly because of the different processing methods. Traditional methods mostly took the statistical data at the administrative boundary level; however, in our study, we investigated the coupling coordination degree of JJJ at the gridded level. To be specific, the eco-environment of JJJ’s mountainous areas was high; however, the coupling coordination degree was low; this had a relationship with these regions had a low population and regional gross domestic product. Hence, in the final coupling coordination degree result, these regions were at a low grade. Oppositely, in these regions in the main central cities, the coupling coordination degree was high. For instance, Beijing city had the largest population and the highest regional gross domestic product, combined with the eco-environment of Beijing, in the final coupling coordination degree result, Beijing showed a relatively high level, which provided a suitable model for other cities in JJJ (Table 3). Of course, in these suburb regions of Beijing, the coupling coordination degree was gradually decreased.

Table 3. All cities’ GDP in 2001 and 2015.

| Year | BJ  | TJ  | TS  | SJZ | BD  | CZ  | HD  | LF  | XT  | ZJK | CD  | QHD | HS  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2001 | 0.37| 0.19| 0.10| 0.10| 0.06| 0.04| 0.05| 0.03| 0.03| 0.02| 0.01| 0.02| 0.03|
| 2015 | 2.29| 1.65| 0.61| 0.54| 0.33| 0.32| 0.31| 0.24| 0.17| 0.13| 0.13| 0.12| 0.12|

4.2. Limitations and further study

Generally, in our study, even the coupling coordination degree at the gridded level had achieved; however, there still have shortcomings. Firstly, only two indicators in the socio-economic subsystem. The coordinated development research referred to many aspects, not just in the aspects of population density and gross regional product; even they were representative. In the future study, the density index of the architectural heritage, the density of inhabited settlements, the second industrial proportion, which can be processed at the raster type and integrated with the existing indicators. Hence, more detailed information can be acquired. Secondly, the period of this study only included two years. Fifteen years was enough to study the coordination level. However, it was hard to show detailed information at a different year. Therefore, it still needs to spend much time collecting datasets at different years and explore their differences. Thirdly, since there have sprung out numerous models to explore the regional coupled coordinated degree, more work needs to compare the difference of various models’ results. To sum up, even there remains too much work to do in the future work, the information of our actual work provided suggestions for JJJ’s relevant policy-makers and managers to pursue a more coordinated development.
5. Conclusions
In this study, combined with the coupling coordination degree model, remote sensing datasets, and other socio-economic datasets at the raster format, we investigated the coupling coordination degree of JJJ from 2001 to 2015 at the gridded level. The main conclusions were as follows:
1) The eco-environment of JJJ had improved during 2001~2015. Among it, the eco-environment with high RSEI value mainly located in the mountainous area of JJJ, including the Yanshan mountain and Taihangshan mountain. In contrast, the eco-environment with relatively low RSEI value was mostly located in the central Hebei plain and urban zone.
2) The spatial coupling coordination degree of JJJ showed a decreased trend, with the decrease of high, relatively high, and medium grades area, and the increase of low, and relatively low grades area. Generally, these high coupling coordination degree regions mainly located in the city’s central zone, while these mountainous regions and central Hebei plain mainly displayed a low coupling coordination degree due to the socio-economic lag.

Abbreviations
JJJ Jing-Jin-Ji
ArcGIS One professional software of geographical information system
RSEI Remote sensing ecological index
CCD Coupled coordinated degree

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