Scientific and Social Research, 2024, Volume 6, Issue 4
https://ojs.bbwpublisher.com/index.php/SSR

Spatiotemporal Coupling between Urbanization and Eco-environment based on Google Earth Engine and Nighttime Light Data: A Case Study of the Yellow River Delta

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Abstract: Based on the cloud platform of Google Earth Engine and ArcGIS, this paper uses daytime optical remote sensing and nighttime light (NTL) remote sensing data to extract the comprehensive nighttime light index (CNLI) and remote sensing ecological index (RSEI) respectively, then constructed and quantitatively analyzed the coupling coordination distance model of urbanization and eco-environmental quality in the study area from 2001 to 2020. The results show that the average value of RSEI fluctuated from 0.446 in 2001 to 0.518 in 2020 from 2001 to 2020. The average value of CNLI from 2001 to 2020 continued to rise from 0.101 in 2001 to 0.238 in 2020. From 2001 to 2020, the average value of the coupling coordination degree showed a downward trend, from 1.356 in 2001 to 1.256 in 2020, and the coupling coordination degree gradually developed in a good direction. The research results can provide data support and theoretical suggestions for promoting the sustainable development of the Yellow River Delta.

Keywords: Urbanization; Eco-environment; Spatiotemporal coupling; Yellow River Delta

Online publication: April 29, 2024

1. Introduction

The impact of human activities on the environment has grown significantly in recent years, with one of the most notable being the widespread urbanization movement occurring globally [1–2]. In response to this dire issue, the member states of the United Nations approved the 2030 Agenda for Sustainable Development in 2015 [3]. The Sustainable Development Goals (SDGs) were also adopted, consisting of 17 goals and 169 targets [4]. Among these goals, sustainable cities and communities (SDG11) is one of the main goals. In the past 30 years, developing countries have played a significant role in global urbanization, with China being a prime example [5]. The urbanization development of China has now reached the average global standard, with an urbanization rate of 64.72% in 2021. So there is an unprecedented need to improve the eco-environmental quality in these urban areas due to the growth. Therefore, in the current stage of development, it is crucial to conduct quantitative research on the relationship between urbanization and eco-environmental quality, taking into account their spatial and temporal heterogeneity.

The research on the relationship between urbanization and the eco-environment has attracted the attention of many scholars. Through existing research, several typical methods have emerged that help to understand the relationship between the urbanization process and the eco-environment. These findings have greatly enriched and advanced theoretical research in this field. These include the Garden City theory proposed by Owen and Howard, the Environmental Kuznets Curve, the pressure-state-response (PSR) evaluation theory framework, the driver-pressure-state-impact-response (DPSIR) framework, decoupling theory, and so on [6–9]. Secondly, empirical research has been conducted by numerous scholars on the relationship between urbanization and the eco-environment in various countries such as the United States, the Republic of Korea, and Pakistan [10]. Through case studies, it has been found that there are intricate interactions between urbanization and the eco-environment, leading to diverse development outcomes [11]. Furthermore, scholars within China have conducted empirical research on the correlation between urbanization and the eco-environment in various regions throughout the country, encompassing different provinces, cities, and urban agglomerations such as the Yangtze River Delta, Beijing-Tianjin-Hebei, and coastal areas [11–14]. In the above empirical research, they comprehensively analyze the nonlinear relationship between two elements from different perspectives, including measurement analysis, change characteristics, and systemic research [15–16]. These researches utilize various methods, such as the fuzzy matter-element model, coupling coordination degree model, and entropy change equation model, to explore the coupling regularity between the two elements [13, 17].

Therefore, this study focuses on the Yellow River Delta as the research subject. Utilizing the GEE cloud platform, the study integrated remote sensing to compare and analyze the eco-environment, urbanization intensity, and their coupling and coordination characteristics during the development process. The primary objective of this study is to establish a rapid and efficient method that utilizes remote sensing technology to quantify the eco-environmental quality and urbanization level of the Yellow River Delta and to introduce the concept of coupling, measure the temporal and spatial distribution of urbanization and remote sensing ecological index (RSEI) at the grid scale, and extend the research findings to the national level.

2. Study area and data sources

2.1. Study areas

The Yellow River Delta is one of the three major economic deltas in China, and it is also a land-sea ecotone with high value. Among them, Dongying City is the main city of the Yellow River Delta, including Dongying District, Hekou District, Kenli District, and Lijin County. The geographical location of the region is 36°55’–38°10’N, 118°07’–119°10’E, with sufficient light, cold winter and hot summer, four seasons, and the average annual precipitation is 530–630 mm (**Figure 1**).

2.2. Data sources

First, the daytime optical remote sensing data are from the Landsat Surface Reflectance Tier 1 series data (https://earthengine.google.com/) provided by the GEE cloud processing platform, with a spatial resolution of 30 m. All image preprocessing tasks, including radiation correction, geometric correction, cloud removal, and water mask, are performed on this platform. The remote sensing images used in this study are Landsat data in 2001 and 2020. To avoid the influence of seasonal differences on data processing results, the data time range is from May to August. Since the nighttime light (NTL) data of DMSP/OLS and NPP/VIIRS are derived from two different sensors, there are differences in resolution. By simulating the regression relationship between

DMSP/OLS and NPP/VIIRS data in 2013, a power function relative correction model was established, and then the model was used to correct the NPP-VIIRS NTL data in 2020, so that the data sources were consistent and scientific, reducing the experimental error [18].

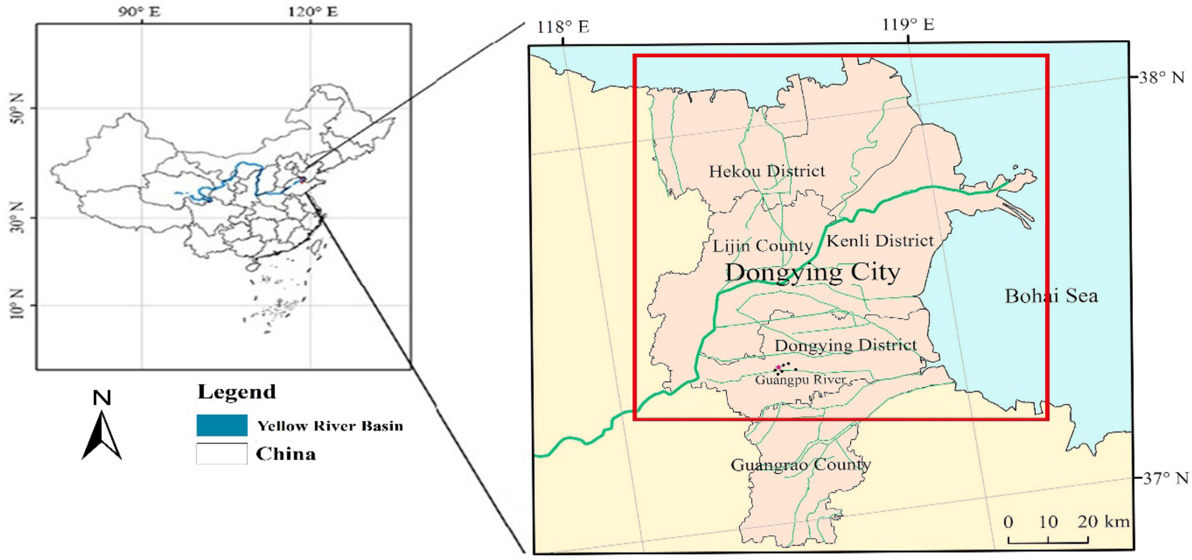

Figure 1. Geographical location of the study area

3. Methods

3.1. Remote sensing ecological index (RSEI)

The RSEI index incorporates four evaluation indexes, which include the vegetation index (normalized difference vegetation index, NDVI), wet component (WET), land surface temperature (LST), and soil index (normalized difference bare soil index, NDBSI), which represent the four ecological elements of greenness, wetness, heat, and dryness respectively. The calculation process of RSEI is shown in **Figure 2**.

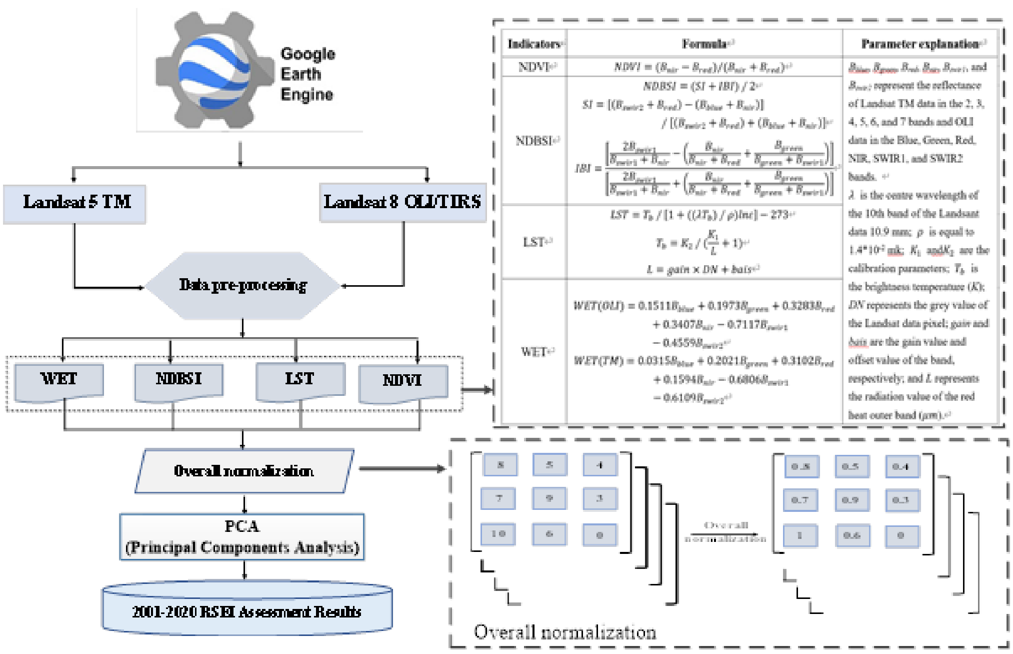

Figure 2. The calculation process of RSEI

After calculating the four ecological components based on remote sensing data, principal components analysis (PCA) is used to achieve multi-index synthesis to avoid the deviation of human subjective factors in the weight setting process [19]. Since the dimensions of the above four components are not uniform, it is necessary to normalize the above indexes, perform PCA operation, and construct RSEI with the first principal component (PC1). In addition, PC1 values need to be standardized again to facilitate horizontal comparison during the study period.

$$RSEI_0 = f(NDVI, NDBSI, WET, LST) \quad (1)$$

$$RSEI = \frac{RSEI_0 - RSEI_{0-min}}{RSEI_{0-max} - RSEI_{0-min}} \quad (2)$$

Equation 1 indicates that principal component analysis (PCA) is performed on the four indicators obtained by normalization, and the first principal component (PC1) is taken as $RSEI_0$. **Equation 2** indicates that the $RSEI_0$ obtained by the PCA is normalized to obtain the final RSEI.

3.2. Comprehensive nighttime light index (CNLI)

The CNLI index has been fully confirmed in the study by Zheng et al. that there is a significant correlation between the composite index of urbanization in China, which can allow the extraction of urbanization information for many years in a large area [20]. The comprehensive nighttime light index (CNLI) is defined as the product of the proportion of light area (LAP) and the average light intensity (MLI) in a certain area, and its formula is shown below.

$$CNLI = LAP \times MLI \quad (3)$$

$$LAP = Area_{light} / Area \quad (4)$$

$$MLI = \sum_{i=1}^{63} C_i \times DN_i \Big/ \sum_{i=1}^{63} C_i \times 63 \quad (5)$$

In **Equation 3–5**, $Area_{light}$ represents the area of the lighting area, and Area is the total area of the area; DN_i is the grey value of the light pixel, and C_i is the number of pixels whose light value is DN_i. It should be noted that according to the accuracy of NTL data, the 4 x 4 km grid was used as the research unit to quantify the CNLI of the study area, and then the natural breakpoint method was used to divide the CNLI into four grades according to the evaluation results.

3.3. Coupling coordination distance model

To reduce the dimension of the model function, this study uses a coupling coordination distance model based on the mapping of the function in the X-Y plane. At the same time, this study also takes advantage of the distance between the grid coordinate point and limit point (1,1) for further distinguishing [21]. Therefore, the coupling coordination distance D is defined as the sum of the distance between the urbanization-environment coordinate point and the diagonal and limit points. Given the range of RSEI and CNLI of the normalized grid unit is between 0 and 1, this study uses (0.5, 0.5) as the origin to divide the urbanization-environment coordinate points into four different quadrants. The formula is shown below.

$$D_i = |x_i - y_i| / \sqrt{2} + \sqrt{(x_i - 1)^2 + (y_i - 1)^2} \quad (6)$$

In **Equation 6**, x_i and y_i are the horizontal and vertical coordinates of the urbanization-environment coordinate points, namely the normalized CNLI index and RSEI index. D_i is the coupling coordination distance of point *i*, the smaller the D_i is, the higher the coupling coordination degree between the urbanization level and eco-environment condition of point *i* is.

4. Results

4.1. RSEI variation in the study area

With the help of the GEE cloud platform, this study quantitatively showed the RSEI of the study area from 2001 to 2020. The contribution rate of PC1 from 2001 to 2020 was 81.36% in 2001 and 82.55% in 2020, indicating that PC1 contains most of the features as shown in **Table 1**. This study has divided RSEI into three stages. In 2001, the high-value area was concentrated in the southwest, and the low-value area was distributed in the north and east, which is within the boundary of the study area. The overall RSEI in 2020 showed a slight decline. However, the eastern part of the study area, specifically the estuary of the Yellow River, remains relatively good. This area was also the key protected area of the Yellow River Delta (**Figure 3**).

Table 1. Characteristic value information of the PC1 each year in five-time points

Year	NDVI	WET	LST	NDBSI	Contribution rate (%)
2001	0.82	0.65	-0.14	-0.23	81.36
2020	0.92	0.66	-0.10	-0.24	82.55

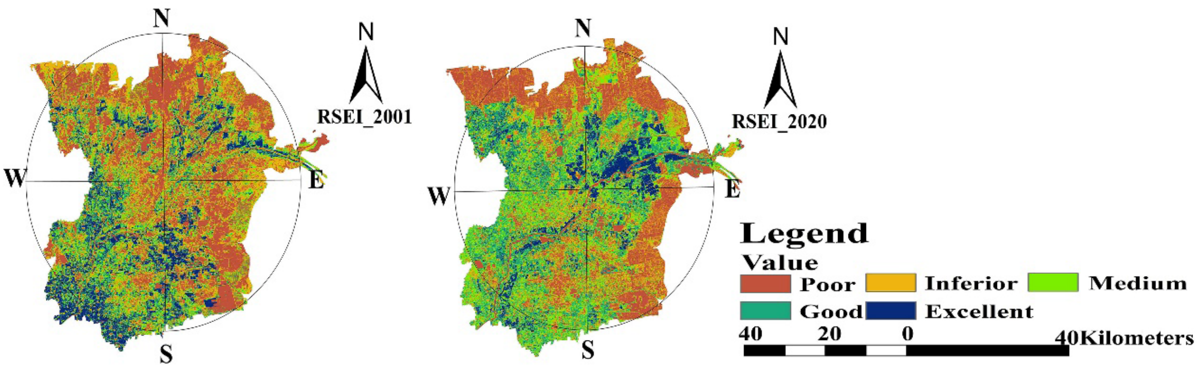

Figure 3. Spatial distribution of RSEI

4.2 Urbanization change in the study area

The CNLI in the study area varied greatly from 2001 to 2020 and had a slow upward trend over the past two decades, increasing by 0.1371. Among them, the average CNLI was 0.1011 (2001) and 0.2382 (2020). During the study period, the spatial distribution pattern of light pixel intensity exhibited a similar trend to the level of the CNLI, with a multi-center expansion. Notably, the southern part of the study area experienced the most significant increase in the CNLI as shown in **Figure 4**. Furthermore, this study also analyzed the area and proportion of each CNLI level from 2001 to 2020 (**Table 2**). The results indicate a significant decline in the area and proportion of the low level, with a decrease of 31.18% in 2020 compared to the proportion in 2001. On the other hand, there was a clear upward trend in the area and proportion of the inferior and high levels. Specifically, there was an increase of 15.45% in 2020 compared to the proportion of the inferior level in 2001 and an increase of 11.49% in 2020 compared to the proportion of the high level in 2001.

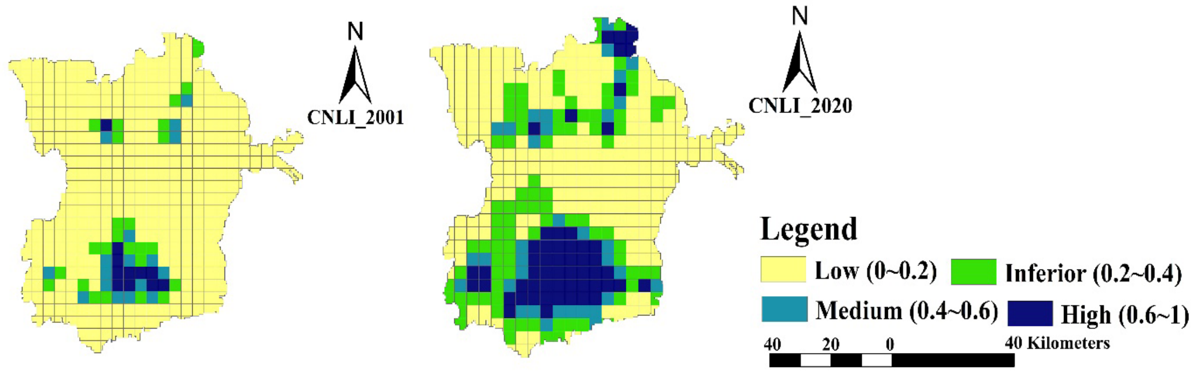

Figure 4. Spatial distribution of CNLI

Table 2. The change of CNLI grade from 2001 to 2020

Year	Low	Inferior	Medium	High
2001	86.09	6.60	4.44	2.87
2020	54.91	22.05	8.68	14.36

4.3. Coupling coordination analysis in the study area

The average value of the coordination degree (D_i) in the study area showed a downward trend from 2001 to 2020, with the average value of D_i being 1.3567 in 2001 and 1.2568 in 2020, which reflected the improvement of the overall coupling coordination between urbanization level and eco-environment in the study area to a certain extent. The low-value area of D_i in the study area showed an expanding trend from 2001 to 2020. Among them, the low-value area of D_i covered all the first quadrants from 2001 to 2020, but there were still some low-value areas of D_i distributed in the second and fourth quadrants. Secondly, the median area of D_i in the study area from 2001 to 2020 was mainly distributed around the low-value area, and the overall trend was to expand around. Compared with the low-value area of D_i, its median area coverage was larger, and more concentrated in the second and third quadrants. Finally, the high-value area of D_i in the study area showed a decreasing trend from 2001 to 2020, mainly distributed in the eastern and northern parts of the study area. The high-value area of D_i in 2001-2005 was more concentrated in the third quadrant, while the high-value area of D_i in 2010-2020 was more concentrated in the second quadrant. This indirectly showed that the urbanization level of the region was low, but the eco-environment quality was gradually improved (**Figure 5**).

4.4. Measures recommendations

The Yellow River Delta exhibits spatial differentiation in the coupling of urbanization and eco-environmental quality. Specifically, the coordination degree of the core area of urban development is higher than that of the marginal area. Consequently, distinct improvement measures must be implemented in various regions of the Yellow River Delta.

First, from the perspective of the high-value area of D_i, it has typical two-level characteristics, either in the area with a high eco-environment quality level or in the area with a relatively low eco-environment quality level. In addition, the region also contains key wetland protection areas. In summary, management decision-makers should strictly control the development of urbanization in the above-mentioned regions and implement ecological land protection policies, such as setting up an ecological control zone [22]. Secondly, from the perspective of low and medium-value areas of D_i, it is mainly located in and around the core area of urban development. In general, the level of social and economic development in the region is high, while the level of eco-environmental quality is at a medium level. Therefore, management decision-makers should focus on strengthening ecological restoration and improving green infrastructure construction in areas outside the central area. This will help to address local ecological and environmental problems and create a win-win situation between urbanization and the environment [11, 23].

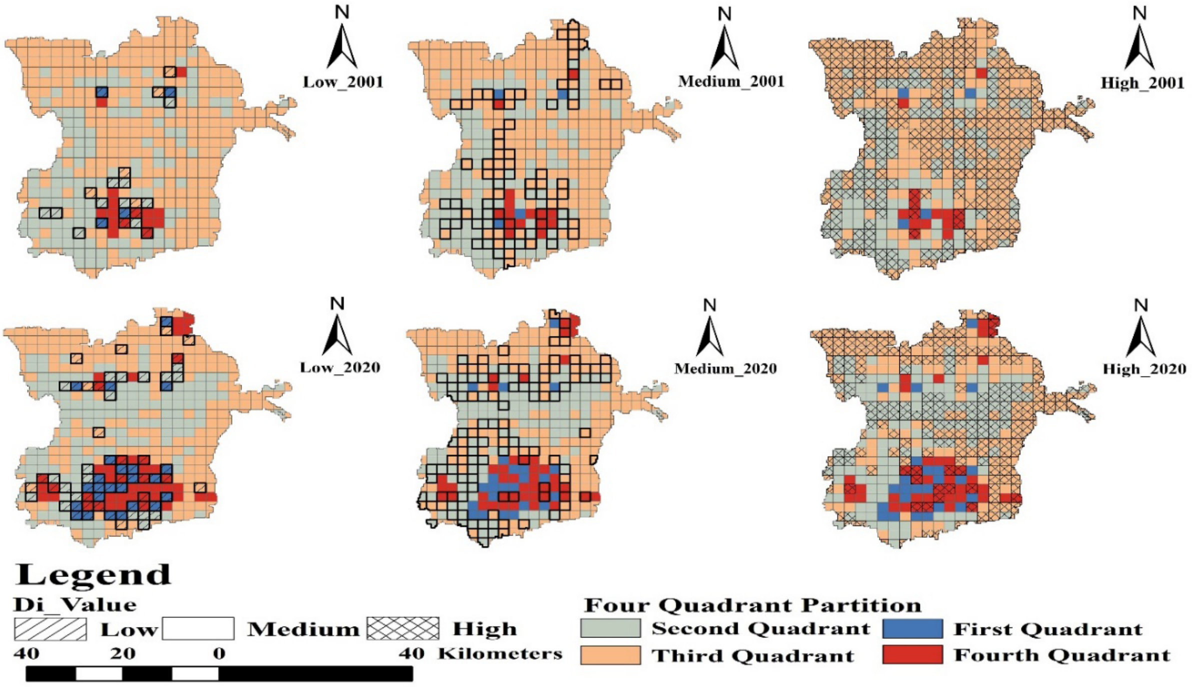

Figure 5. Spatial distribution of coordination degree

5. Conclusion

Based on the GEE cloud platform and ArcGIS, this paper constructs a coupling coordination distance model to analyze the urbanization and eco-environment coupling coordination of the region. The results show that the eco-environmental quality has shown an overall improvement trend, but the differences between regions are still significant. According to the spatial variation of RSEI, the RSEI level in the eastern part of the study area remained good and at a high level. From 2001 to 2020, the level of urbanization has increased significantly, but the regional differences are still significant. Meanwhile, the level of urbanization in the study area continued to expand outward. From 2001 to 2020, the coupling degree generally showed a downward trend, which reflected a certain extent that the urbanization development and eco-environment in the study area gradually developed to a good coupling and coordination stage.

Funding

This research was financially supported by the Innovation and Entrepreneurship Training Program for College Students, Qingdao University of Technology (S202310429348).

Disclosure statement

The authors declare no conflict of interest.

Author contributions

Study idea conceptualization: Lantian Li

Experimentation: Guirong Xiao, Jiaquan Liu, Qihang Li

Data analysis: Lantian Li

Study writing: Lantian Li

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