Pol. J. Environ. Stud. Vol. 31, No. 5 (2022), 4757-4765
DOI: *10.15244/pjoes/147295* ONLINE PUBLICATION DATE: 2022-08-02

Original Research

Integration of Multi-Source Remote Sensing Data for Spatial-Temporal Change Monitoring of Ecological Environment in the Yellow River Delta

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Received: 11 December 2021
Accepted: 11 March 2022

Abstract

Rapid and timely evaluation of ecological environment change is of great significance to the sustainable development of the region. Owing to climate change and more anthropological intervention, ecological environment is deteriorating in the Yellow River Delta High-Efficiency Ecological Economic Zone (YRDHEEZ). To evaluate ecological environment change of the YRDHEEZ, a comprehensive evaluation index (CEI) was built in this investigation, which integrated vegetation cover (VC), land surface temperature (LST) and fine particulate matter (PM2.5) concentration. The experimental results demonstrated that significant regional differences existed in the ecological environment of the YRDHEEZ from 2000 to 2018. The ecological environmental changes in most districts and counties are complex and diverse. More specifically, regions with improvement, moderate improvement and the unchanged ecological environment accounted for more than 70 % of the study area, which suggested that the ecological environment has improved. In order to further verify the validity of the CEI, a field survey was performed, and it found that the result of field survey corresponded with the CEI evaluation, which demonstrated the potential of multi-source remote sensing data to quickly monitor the change of ecological environment quality in the YRDHEEZ.

Keywords: ecological environment, remote sensing, comprehensive evaluation index, high-efficiency ecological economic zone in Yellow River Delta

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Introduction

In recent decades, with the rapid population growth, economic development, industrialization and urbanization, ecological environment is facing considerable pressure, such as the decline of vegetation coverage [1-3], soil pollution [4], air pollution [5, 6], urban heat island effect [7, 8], ecological environment damage and the reduction of animal and plant habitats [9, 10]. A series of ecological environment changes have attracted wide attention from government and academic. Ecological environment changes have an important impact on people's lives and health, and also restrict development of economy and society. Therefore, timely assessment of ecological environment changes is essential for regional sustainable development. Recently, urbanization in China has attached great importance to environmental protection, especially urban environmental protection. A series of environmental standards have been formulated to strengthen environmental governance and promote environmental improvement. Environmental monitoring and driving force analysis provide decision-making reference and data support for the coordinated the development of environment and economy.

Timely and accurate assessment of urban environmental changes is important for sustainable development of cities. A series of indicators have been developed to assess urban environmental changes, such as the theme-based sustainable framework developed by United Nations Commission on Sustainable Development, ecological footprint, sustainable development indicators, and Green city index. However, most of these indices are based on socio-economic census data or factual monitoring data, which have long data collection cycles and limited coverage, making it difficult to reflect the spatial and temporal heterogeneity of regional ecological environments. In view of the strong timeliness, wide coverage and abundant information of remote sensing data, it can be used as an important data source in the field of ecological environment and is increasingly used for regional ecological environment quality evaluation [11, 12]. Through numerous literature surveys, it can be found that the use of remote sensing data to monitor the ecological environment is more concentrated on air quality [13], water quality [14], soil pollution [15] and ecological environment monitoring [16, 17]. The factors affecting the environment are multifaceted, and there is an increasing number of studies which aim to evaluate and compare ecological environments in a comprehensive manner. Xu developed a remote sensing based ecological index using the greenness, wetness, dryness and heat obtained from remote sensing data, and found that the index can be used to quantitatively evaluate the ecological environment of the city [18-20]. Multiple parameters such as vegetation coverage, vegetation health index, land surface moisture, and surface temperature are selected to comprehensively evaluate the ecological environment and reveal the evolution of its temporal and spatial characteristics [21, 22]. The United Nations Commission on Sustainable Development has identified five major environmental themes: freshwater, land, atmosphere, biodiversity, and oceans, which is one of the most commonly used frameworks for assessing environmental conditions at national and regional scales. Based on this framework, He et al. [23] considered PM2.5 concentration, surface temperature, and vegetation cover to characterize air pollution, land cover, and biodiversity, respectively, in urban areas of China. The correlation of this index with other commonly used indicators was verified, and the correlation coefficient of this composite index with the ecological footprint was 0.86, and the correlation coefficients with electricity consumption and waste emissions were above 0.65. Therefore, it can be concluded that the CEI can effectively assess the environmental situation. The comprehensive evaluation index has achieved good application results in countries, urban agglomerations and rapidly urbanizing regions [24, 25].

The Yellow River Delta is the most extensive and well-preserved wetland ecosystem in the warm temperate zone of China, and is one of the most abundant coastal areas in eastern China. Human activities are increasing such as reservoir construction, oilfield development and aquaculture in the Yellow River Delta [26, 27]. Although the government has formulated various protection policies, the ecosystem is seriously disturbed and destroyed due to global climate change, socio-economic development and other factors. With the proposal of the national major strategy for the high-quality development of the protection areas in the Yellow River Basin, the change of ecosystem quality in the Yellow River Basin has attracted more and more attention [28]. Inspired by the research of Lu [24] and He [23, 29], this study used normalized difference vegetation index, land surface temperature and the fine particulate matter concentration data to construct a comprehensive evaluation index of the regional ecological environment, and analyze the changes of ecological environment quality from 2000 to 2018. A comprehensive evaluation the changes brought by the rapid development of the Yellow River Delta High-Efficiency Ecological Economic Zone (YRDHEEZ) provides an important basis for sustainable development.

The rest of the paper is organized as follows. Section 2 introduces the study area, dataset and processing. Section 3 describes the method of the comprehensive evaluation index. Section 4 analyzes and discusses the results, and the last section draws conclusions.

Materials and Methods

Study Area

There are 19 counties in the YRDHEEZ, including Hekou, Lijin, Kenli, Dongying, Guangrao, Wudi, Zhanhua, Yangxin, Huimin, Bincheng, Zouping, Boxing, Hanting, Shouguang, Changyi, Laoling, Qingyun, Gaoqing, Laizhou, which are adjacent to and have similar natural environment conditions (Fig. 1). The geographical range is 116°54′24″~120°18′24″E, 36°26′32″~38°16′09″N, with a total area of 2.65 km^2. The State Council approved the 'Development Plan for the Yellow River Delta High-Efficiency Ecological Economic Zone' in 2009, marking that the development of the Yellow River Delta has become a national strategy and an important part of the regional coordinated development strategy. After a long period of combined natural and human factors, the region has formed a unique ecological environment. Developing an efficient ecological economy and promoting the construction of ecological civilization bring opportunities for the comprehensive development, utilization of resources and sustainable development in the Yellow River Delta.

Data Sources and Preprocessing

Taking into account the availability of data, remote sensing data from 2000 to 2018 were selected to construct a comprehensive ecological environment assessment index for monitoring the changes in the ecological environment of the YRDHEEZ, including PM2.5 concentration, vegetation coverage, and land surface temperature. The details of the data used are as follows:

Fine particulate matter (PM2.5) concentration data was downloaded from the Atmosphere Composition Analysis Group of Dalhousie University [30] (http://fizz.phys.dal.ca/~atmos/martin/?page_id=140). The dataset uses MODIS, MISR and SeaWIFS instruments to estimate annual average PM2.5 concentration with 1km spatial resolution based on GEOS-Chem chemical model. The research employed the dataset from 2000 and 2018.

Normalized Difference Vegetation Index (NDVI) is a good indicator to reflect the vegetation status. The monthly vegetation index data product of MODIS data (MOD13A3) was used to calculate the vegetation coverage. The data were obtained on the official website of NASA (https://ladsweb.modaps.eosdis.nasa.gov/). The average annual NDVI was calculated from the monthly vegetation index data, and the vegetation coverage was calculated using the following formula.

$$VC_i = \frac{NDVI_i - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{1}$$

where VC_i is the vegetation coverage at pixel i, $NDVI_i$ is the NDVI value at pixel i, $NDVI_{soil}$ is the NDVI value of completely bare soil or no vegetation coverage area, and $NDVI_{veg}$ is the NDVI value of pure vegetation pixels. The pixel values corresponding to 1% and 99% cumulative probability of NDVI are taken as the values of $NDVI_{soil}$ and $NDVI_{veg}$, respectively [31].

Land Surface Temperature Data (LST) is a 8-day composite product of global MODIS LST/emissivity (MOD11A2) downloaded from National Aeronautics

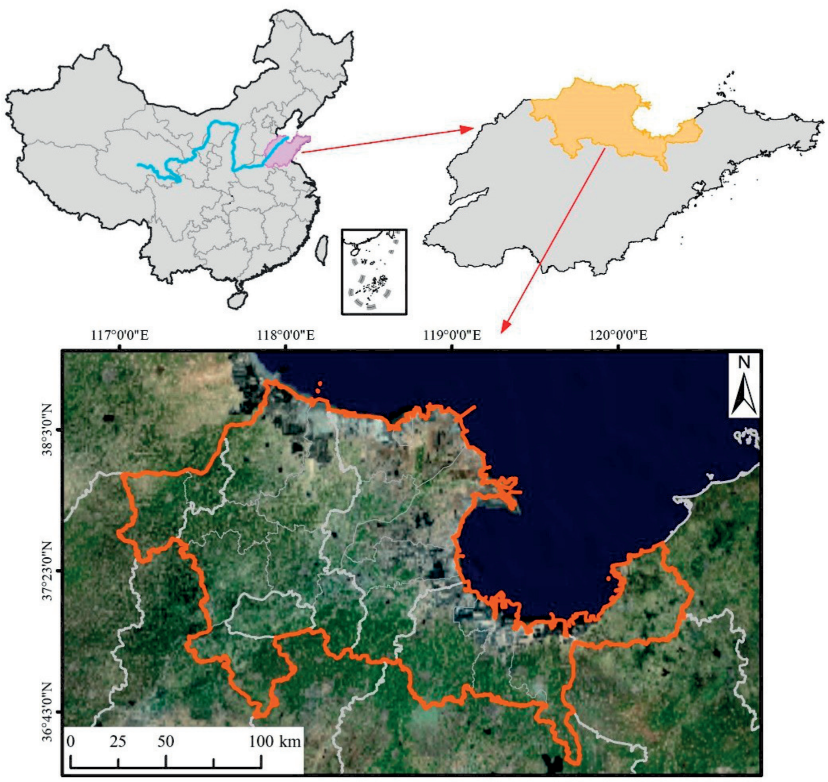

Fig. 1. Location of the Yellow River Delta.

and Space Administration (https://ladsweb.modaps.eosdis.nasa.gov/). Temperature has the characteristics of diurnal cycle change. Studies have shown that nighttime temperature is closely related to heat island intensity and climate warming [32]. The urban heat island intensity varies greatly by the time and season, characterized by significantly higher intensity at night than in the day [33, 34]. The nighttime temperature can better reflect the urban development, so the nighttime surface temperature of the dataset is used to calculate the annual average temperature.

All the data used above are converted to Albers projection with 1km spatial resolution.

Methods

Fine particulate matter (PM2.5) concentration, vegetation coverage and surface temperature are considered to be the key factors affecting the quality of the ecological environment. In order to comprehensively evaluate the quality of the ecological environment in the region, this paper constructs a comprehensive evaluation index (CEI) based on the above-mentioned three factors, and analyzes the environmental conditions using CEI, and tries to analyze the influencing factors.

Developing the CEI.

The CEI calculated the geometric average of PM2.5, VC and LST [23], which were calculated by the following formula:

$$CEI_i = \sqrt[3]{\left(\Delta PM_i + 1\right)\times\left(\Delta VC_i + 1\right)\times\left(\Delta LST_i + 1\right)} \quad (2)$$

where CEI_i is the environmental change at pixel i, and its range is 1-101. The larger the CEI value is, the more serious the environmental deterioration is. ΔPM_i, ΔVC_i and ΔLST_i represent the normalized changes in PM2.5 concentration, vegetation coverage and surface temperature changes at pixel i from 2000 to 2018, respectively.

ΔPM_i and ΔLST_i are computed using the following formula:

$$\Delta X_i = \frac{\left(X_i^{2018} - X_i^{2000}\right) - \min_X}{\max_X - \min_X}\times 100 \quad (3)$$

Where ΔX_i is the normalized changes in PM2.5 concentration or LST at pixel i. X_i^{2018} and X_i^{2000} are the values of PM2.5 concentration or LST at pixel i in 2018 and 2000, respectively; and min_X and max_X are the minimum and maximum values of PM2.5 concentration change or LST change, respectively.

ΔVC_i are computed using the following formula:

$$\Delta X_i = \frac{\max_X - \left(X_i^{2018} - X_i^{2000}\right)}{\max_X - \min_X}\times 100 \quad (4)$$

Where ΔX_i is the normalized changes in vegetation coverage change at pixel i; X_i^{2018} and X_i^{2000} are the values of vegetation coverage at pixel i in 2018 and 2000; min_X and max_X are the minimum and maximum vegetation coverage changes value.

Ecological Environment Change Assessment Based on CEI

According to the mean value and standard deviation of CEI values, the change of ecological environment quality from 2000 to 2018 is divided into five types: improvement, moderate improvement, unchanged, moderate deterioration and deterioration (Table 1).

Results and Discussion

Temporal and Spatial Variations of PM2.5, VC and LST

The variation results of PM2.5 concentration, vegetation coverage and surface temperature from 2000 to 2018 are shown in Fig. 2. As seen in the figure, PM2.5 concentrations increased in more than 85% of the areas, with the maximum increase reaching 16.03 $\mu g\cdot m^{-3}$. Only the coastal areas of the Yellow River estuary and Laizhou showed a decrease in PM2.5 concentrations. This is mainly due to the more inland emission sources and the slower diffusion and dilution effect of the atmosphere, forming a more serious air pollution.

The vegetation coverage of YRDHEEZ showed a positive trend of increase. The vegetation coverage in the central, Yellow River and its tributaries of the study area increased significantly, and the vegetation coverage in the southern and coastal areas of the study area decreased slightly. The increase of vegetation coverage is mainly manifested in the expansion of cultivated land and new added forest land. The decrease is mainly manifested in the southern urban construction areas of Zouping, Gaoqing, Boxing, Guangrao and Shouguang. This is attributed to the needs of development and construction, the increase of the impervious surface. The high level of soil salinization is not suitable for vegetation growth, resulting in a decrease in vegetation coverage in coastal areas, and the land use efficiency remains low. The fragmentation degree of vegetation coverage area in the whole region is significant.

There is a certain similarity between the change of vegetation coverage and land surface temperature, which is consistent with the conclusion that there is a certain correlation between LST and NDVI in previous studies [35, 36]. The LST of the southern region and the northern coastal region increased significantly in the YRDHEEZ. The expansion of construction land in Zouping, Boxing, Guangrao, Bincheng and other urban areas are mainly caused by the expansion of

Table 1. Classification criteria of environmental change types based on CEI.

Type	Ecological environment quality				
	Improvement	Moderate improvement	Unchanged	Moderate deterioration	Deterioration
Classification criteria	<μ – 1.5δ	μ – 1.5δ~μ – 0.5δ	μ – 0.5δ~μ + 0.5δ	μ + 0.5δ~μ + 1.5δ	>μ + 1.5δ
CEI	<31.358	31.358-38.851	38.851-46.345	46.345-53.838	>53.838

μ and δ represent the mean value and standard deviation of CEI of the environmental condition, respectively.

construction land. The impervious surface affects the heat divergence, resulting in an increase in surface temperature. In the northern Bohai coastal area, the heat absorbed by the surface cannot be released in time due to the aquaculture, salt industry, tourism and other development, which led to the increase of land surface temperature.

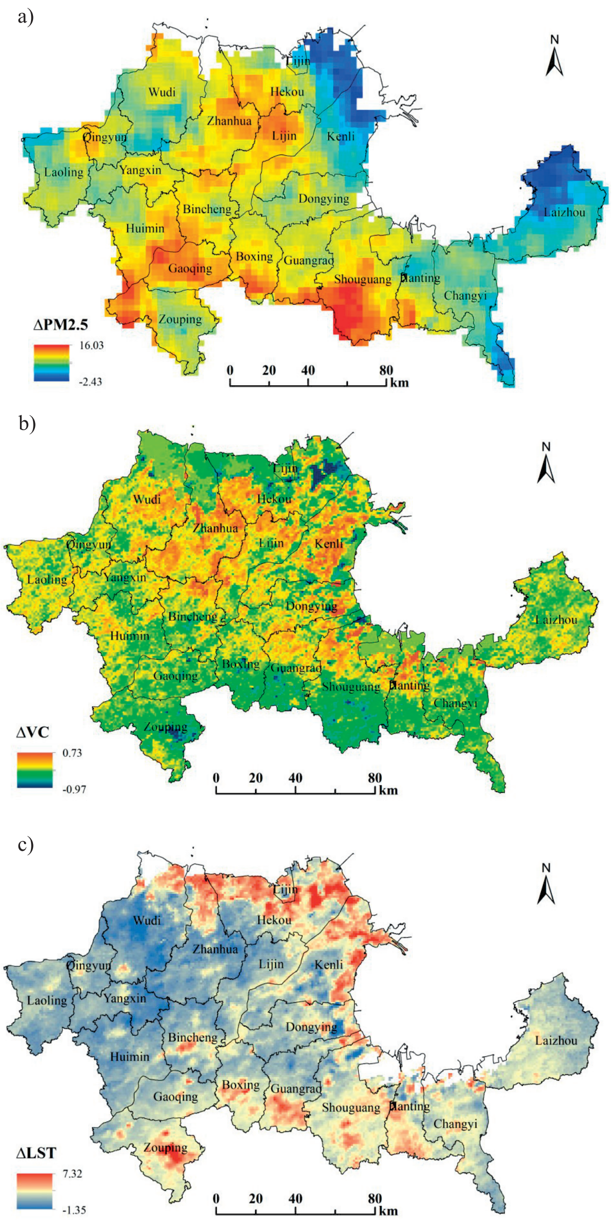

Fig. 2. Changes of PM2.5 a), VC b) and LST c) from 2000 to 2018.

Ecological Environment Quality Analysis of YRDHEEZ

According to the CEI, the standard deviations method is employed to divide the change of ecological environment quality into five grades. Then the area and the ratio of each grade are calculated (Table 2), and the changes in each category are discussed.

The results showed that the area of environmental deterioration and moderate deterioration is 6501km^2, accounting for 28.41% of the total area. The area of environmental improvement and moderate improvement is 7435 km^2, accounting for 32.50% of the total area. The area of ecological environment unchanged reached 8944 km^2, accounting for 39.09% (Table 2). On the whole, the proportion of regions which remain unchanged and improved has reached more than 70%, and the ecological environment changes generally show a better trend. The ecological environment change characteristics of YRDHEEZ from 2000 to 2018 have high spatial heterogeneity. As shown in Fig. 3, the deterioration of the ecological environment mainly occurs in the southern and northern coastal areas of the study area, which is roughly the same as the trend of LST and VC. Urban expansion and special geographical location have caused this environmental situation. The environmental conditions in the center part of the study area are better, which indicated that the environmental protection actions taken in the past two decades have been effective.

Ecological Environment Change in Counties

In order to explore the distribution trend of CEI in different regions, the Boxplot is used (Fig. 4). The ecological environment of each county in YRDHEEZ is quite different. The median and average values of CEI in each county are basically maintained between 40 and 50. The average and median values of Shouguang, Boxing, Gaoqing and Zouping are higher, and the ecological environment is deteriorating seriously. On the contrary, Laizhou, Wudi, Yangxin and Zhanhua are generally improved. The shorter the box is, the more similar the change is and the more concentrated the change is. The distance between quartile ranges

Table 2. The area and percentage of environmental quality changes from 2000 to 2018.

Type	Ecological environment quality				
	Improvement	Moderate improvement	Unchanged	Moderate deterioration	Deterioration
Area/km^2	1144	6291	8944	4596	1905
Percentage/%	5.00	27.50	39.09	20.09	8.32

and upper and lower limits values of CEI in Guangrao, Hanting, Hekou, Kenli and Shouguang is the largest. CEI changes greatly, indicating that the ecological environment changes greatly from 2000 to 2018, and the types of changes tend to be scattered and diverse. The ecological environment conditions in Huimin, Qingyun and other regions are relatively stable. The occurrence of outliers shows that there are high spatial

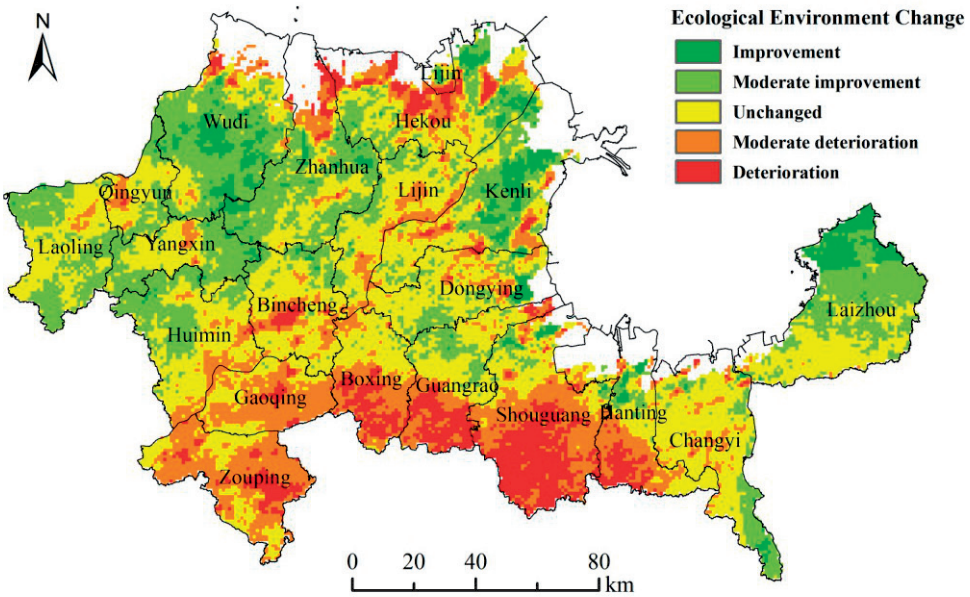

Fig. 3. Environment quality changes from 2000 to 2018 in YRDHEEZ.

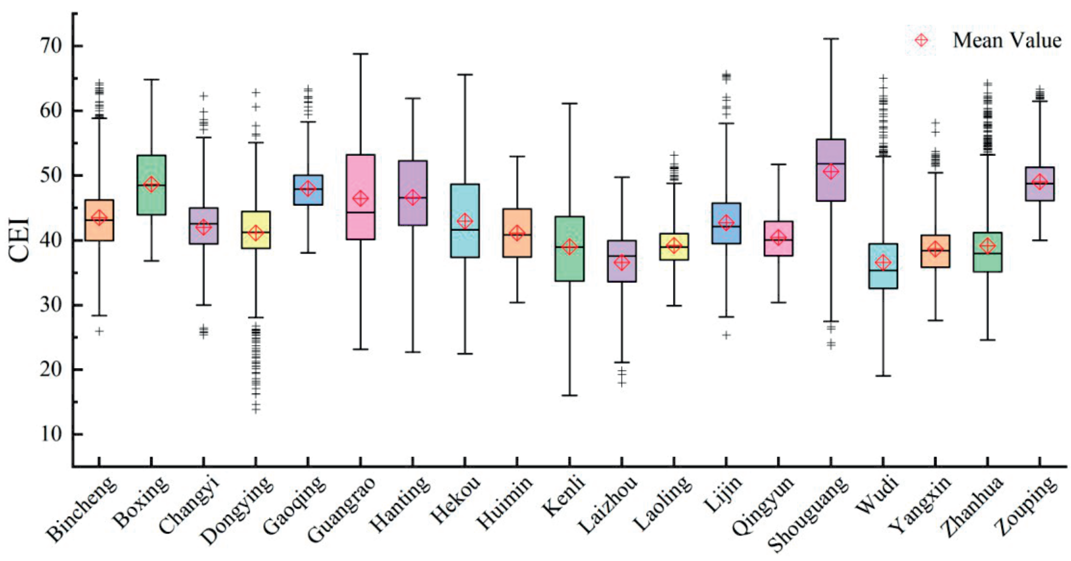

Fig. 4. CEI statistical results of 19 districts (counties).

Table 3. Correlation coefficients between variation of PM2.5 concentration, LST, VC and CEI.

	CEI	ΔPM2.5	Δ*LST*	Δ*VC*
CEI	1			
ΔPM2.5	0.52	1		
Δ*LST*	0.66	-0.07	1	
Δ*VC*	0.69	0.05	0.42	1

differences in the study area. Wudi, Zhanhua, Bincheng and Gaoqing have more abnormal high values, indicating that some areas in these areas have serious ecological environment deterioration. There are many abnormal low values in Dongying District, indicating that the ecological conditions of some regions have been significantly improved.

Correlation between PM2.5, LST, VC and CEI

In order to investigate the effectiveness of CEI and the causes of changes in the urban environment, we analyzed the correlation between ΔPM2.5, Δ*LST*, Δ*VC* and CEI (Table 3). The results showed that the correlation between three factors and CEI reached above 0.52. The correlation between Δ*VC* and CEI was the highest with a correlation coefficient of 0.69. This result indicates that all three factors play an important role in environmental change in the YRDHEEZ, with Δ*VC* having a greater influence than the other two. Therefore, it is necessary and meaningful to increase the vegetation cover and protect biodiversity. The correlation between ΔPM2.5 and Δ*LST*, Δ*VC* was extremely weak. The correlation between the change of LST and the change of VC is strong, which is consistent with the findings of other studies [37, 38].

Conclusions

In this paper, a comprehensive evaluation index based on multi-source remote sensing data was built, and was adopted to evaluated the ecological environment changes of the Yellow River Delta High-Efficiency Eco-Economic Zone in the past two decades. The main conclusions are as follows:

(1) PM2.5 concentrations increased from 2000 to 2018, with only slight decrease near the coastal zone. The vegetation coverage in the central region increased, and the southern built-up area and the northern coastal area decreased significantly. The change of land surface temperature was opposite to that of vegetation coverage. The land surface temperature in the central region decreased slightly, and the south and north of the study area increased significantly.

(2) According to the results of CEI, the sum of ecological environment improvement, moderate improvement and unchanged regions accounts for more than 70% of the YRDHEEZ, showing a trend of maintaining or improving. It proves that the environmental protection measures adopted in recent years have achieved results.

(3) The characteristics of environmental changes have spatial differences. Most districts and counties have experienced severe environmental changes. The environmental deterioration in Shouguang, Boxing, Gaoqing and Zouping is significant. Laizhou, Wudi, Yangxin and Zhanhua have improved significantly. Different regions should formulate corresponding policies to promote the efficient development of ecological environment and economy according to the local actual situation.

The research makes an effective attempt to assess the ecological environment change with the combination of multi-source remote sensing data, which provides insights into urban planning and management as well as ecological environment protection. In this study, only three factors are considered for evaluating ecological environment quality of the YRDHEEZ. However, ecological environment is likely to be subjected to other factors except the factors used in this study. In the future, new factors will be further involved for a more precise results of the evaluation of ecological environment.

Acknowledgments

This research was supported by National Natural Science Foundation of China (41877523).

Conflict of Interest

The authors declare no conflict of interest.

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