Dynamic Evaluation and Spatial Analysis of Ecological Environmental Quality in the Yellow River Delta

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Abstract: This study examines the spatiotemporal dynamics of ecological environment quality (EQ) in the Yellow River Delta (YRD), a vital economic region in Shandong Province, China, that has seen substantial ecological transformations due to accelerated development and population increase. The study utilizes remote sensing and geospatial technologies to develop an Ecological Quality Index (EQI), analyzing its temporal trends and spatial variations over the period from 2000 to 2020. Google Earth Engine (GEE) and Landsat TM/OLI satellite images were used to see at how EQ changed over time. The results shows that EQ has a V-shaped tendency, with the lowest point in 2000 (43.21% extremely low and 19.32% low) and the highest point in 2010 (10.57% very high and 46.72% high). There was a 11.45% growth in places with very high EQ and a 51.61% increase in regions with high EQ by 2020. However, there was a drop from 2010 to 2020, especially in the north and southwest. These findings show how important it is to balance economic growth with protecting the environment. They also give useful information to help safeguard the environment in the YRD.

Keywords: Ecological Quality (EQ); Yellow River Delta (YRD); Ecological Quality Index (EQI); Google Earth Engine (GEE); Landsat TM/OLI

1. Introduction

The natural environment has evolved into a significant barrier to the bearable progress of human civilization, which has been exacerbated by the growing difficulties brought about by the rise of climate change on a worldwide scale. As a consequence of this, educational institutions as well as political agencies are devoting a considerable amount of attention to these issues [1]. Over the course of the 1990s, China has executed a multitude of organic edifice initiatives. These programs include the establishment of national key environmental purpose zones as well as schemes that aim to transform agricultural land into grasslands and woodlands. Both the hasty expansion of the economy and the growing number of ecological and environmental problems served as the impetus for these projects. Nevertheless, in spite of these measures, the rapid pace of sprawl and automation continues to exacerbate the gap that exists between the preservation of the environment and the advancement of socioeconomic conditions.

For the purpose of ensuring ecological haven, promoting bearable progress, and improving human well-being, it is of the utmost rank to investigate the chronological and spatial oscillations in ecosystem eminence, as well as the factors that influence these changes. There has been a significant increase in the number of researchers focusing their attention on ecological environmental challenges. Some scientists are looking at changes in the ecological landscape of specific regions, while others are examining the impact of economic activities on social ecosystems. Several researchers, including Alexandrescu et al. [2] and Risteiu et al. [3] conducted research in Romania to examine the impact of mining contamination on social risks and demographic decline. Haq et al. [4] and Cretan et al. [5] conducted studies to examine the impact of foreign direct investment (FDI) on local ecosystems and urban development. Additionally, further research has examined how urban disadvantaged people in nations like Nigeria, Hungary, and the Philippines are affected by global climate change [6].

Quantitative investigations of regional ecological changes have utilized statistical techniques and operational research approaches [7]. These populations are living in urban areas. The analytic hierarchy process (AHP) [8] and principal component analysis (PCA) [9] are two methods that are frequently utilized in the process of developing ecological indices.

For the purpose of evaluating the ecological conditions of a particular region, the Chinese Ministry of Ecology and Environment has developed a significant environmental index (EI) by employing the analytic hierarchy process (AHP) and the entropy weight technique. [10] Taking into consideration the significant role that vegetation plays in the environmental system of the Earth, ecological indices can also be derived through the use of remote sensing or geographic information system (GIS) approaches. To monitor alterations in regional ecosystems, researchers have employed net primary productivity (NPP) [11], normalized difference vegetation index (NDVI) [12], enhanced vegetation index (EVI) [13], and remote sensing-based ecological indices (RSEI) [14]. In order to examine the spatiotemporal differences in ecological quality that occur within the Yellow River Basin (YRB) in China, Yang et al. created a Remote Sensing Ecological Index (RSEI) by employing principal component analysis. For the purpose of quantitatively evaluating ecosystem services and habitat quality, models such as InVEST and RUSLE have been deployed throughout a significant amount of time [15].

According to the findings of recent studies, the methods that are utilized to identify the factors that are responsible for ecological shifts may be divided into two basic classes: non-spatial deterioration models and spatial deterioration models. Stepwise deterioration [16], scenario analysis [17], unnatural ordination approaches [18], curve estimation methods [19], and ordinary least squares (OLS) [20] are all examples of methodologies that fall within the category of non-spatial regression. Methods such as geo-detector approaches [21], geologically biased deterioration [22], and areial lag models [23] are examples of techniques that fall within the category of spatial regression. Spatial regression models are especially beneficial as they accommodate spatial heterogeneity through the formulation of local regression equations [24], a method unattainable in non-spatial models. As a consequence of this, spatial deterioration models are increasingly being utilized in ecological examine. Zhang et al. utilized the geo-detector model to assess ecological vulnerability in the arid regions of northwest China, employing pointers such as soil quality, landscape, and nocturnal illumination data [25].

The YRD, a prominent river delta in China, has significantly boosted the economy of northern Shandong Province. Its distinctive geography, rich natural resources, and considerable potential for growth have drawn considerable attention, both domestically and globally. However, the region's development and construction have also certain growth to numerous ecological and environmental issues. These include the urban heat island effect [26], soil contamination [27], and heightened risks of disasters [28]. These challenges directly oppose the core ethics of ecological preservation and sustainable, environmentally friendly progress. Therefore, a thorough analysis of the spatial and temporal patterns and trends in ecological quality within the YRD is essential for advancing ecological conservation and sustainable development in the YRB and the delta region.

This research makes use of remote sensing and land survey data in order to investigate the development and distribution of ecological land, as well as the gravitational center in the YRD from the year 2000 to the year 2020. This is a study that is of significant importance for the preservation of the ecological environment of the region and for the sustainable development of the region. Furthermore, the research offers a significant illustration of the use of land use planning and ecological change in regional studies that are related to it.

2. Study Area and Data Sources

2.1 Study Area

The YRD, situated between coordinates 117°31' - 119°18'E and 36°55' - 38°16'N, is positioned within the silty fan region created by sedimentary deposits from the Yellow River's lower reach in Lijin County, Shandong Province. The delta covers around 6,783 square kilometers and is shaped like a fan, with Lijin County at its apex. It is delineated by the Tuhai River inlet to the north, the Xiaoqing River to the south, and encompasses Dongying City at its core. The delta exhibits a largely level topography, with an average elevation below 10 meters. Located in a mid-latitude region characterized by a warm temperate temperature, it has a semi-humid, continental precipitation environment, influenced by the Eurasian landmass and the Pacific Ocean. Figure 1 illustrates the geographical location of the study region.

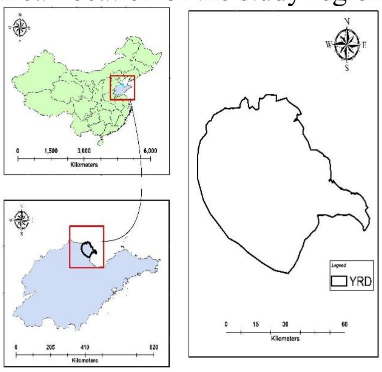
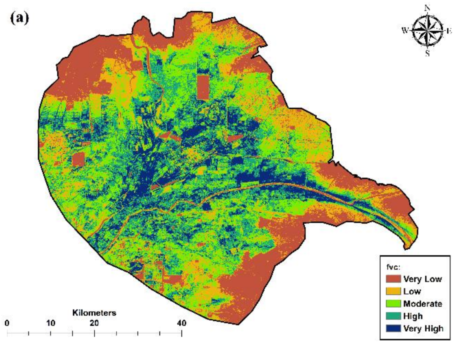


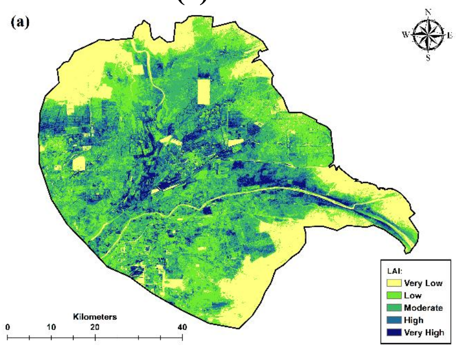
Figure 1. Map Depicting the Geographical Location of the Research Area

2.2 Data Source

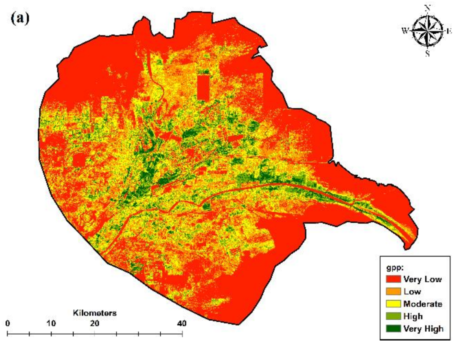
In this study, remote sensing imagery from Landsat 5 (TM) and Landsat 8 (OLI) for the years 2000, 2010, and 2020 were utilized as a remote sensing images in this study, land use and land cover changes (LULC) [29] and the data of fractional vegetation cover (FVC), leaf area index (LAI), and gross primary productivity (GPP) data were primary employed. The FVC, LAI and GPP data of the year 2000 are shown in Figure 2.



(a). FVC



(b). LAI



(c). GPP

Figure 2. FVC, LAI, and GPP Data of the YRD: (a). FVC, (b). LAI, (c). GPP

The EQI of YRD was calculated using the FVC, LAI, and GPP, which were acquired from the Chinese Academy of Sciences' Institute of Remote Sensing. In order to lessen the impact of seasonal variations and aquatic settings on the data processing results, the data duration was chosen to be June through August. The water bodies in the research region were completely submerged and removed using the annual permanent water body data, completely reducing their impact on EQI calculations.

3. Methods

3.1 Computation of the Ecological Quality Index (EQI)

According to the evaluation criteria established by the Ministry of Ecology and the Environment of China, the EQI reflects the overall state of the flora and ecosystems within a region. This study employed the comparative density of remote sensing ecological constraints, specifically FVC, LAI, and GPP, to calculate the EQI for the YRD. This facilitated the creation of the EQI. The FVC, LAI, and relative density of GPP in the YRD were assessed in accordance with the National Ecological Role Partitioning legislature established by the Ministry of Ecology and Environment of China. This assessment was conducted across four distinct vegetation types: farmland, shrubland, grassland, and forests. According to the data presented in Equation (1), the value range of apiece catalogue was normalized to a scale from 0 to 1.

$$RVI_{i,j,k} = \frac{F_{i,j,k}}{F_{maxi,j,k}} \quad (1)$$

In the i_{th} year, $RVI_{i,j,k}$ represents the comparative compactness of the k_{th} vegetation stricture in the j_{th} range; $F_{i,j,k}$ represents the ecological stricture worth of the k_{th} vegetation stricture in the j_{th} area; and $F_{maxi,j,k}$ indicates the supreme rate of the ecological limits for the k_{th} vegetation stricture in the j_{th} zone in the i_{th} year.

The procedure for determining the EQI is illustrated in Equation (2):

$$EQI_{i,j} = \frac{LAI_{i,j}+FVC_{i,j}+GPP_{i,j}}{3} \times 100 \quad (2)$$

$EQI_{i,j}$ shows how good the environment is in the j_{th} zone in the i_{th} year. $LAIi,j$ shows how dense the ecological leaf area index is in the j_{th} zone in the i_{th} year. $GPP_{i,j}$ shows how dense the total gross primary productivity of the ecosystem is in the i_{th} year and the j_{th} zone.

After computing the EQI, in line with the technical criteria for the evaluation and analysis of state ecological rank, the ecosystem's environmental quality was classified into five levels: very low, low, moderate, high, and very high, as depicted in Table 1.

Table 1. Eco-Environmental Eminence Grades

Level	Index
Very Low	EQI ≥0.76
Low	0.76>EQI ≥0.56
Moderate	0.56>EQI ≥0.36
High	0.36>EQI ≥0.21
Very High	EQI<0.21

3.2 Scrutiny of the Gravity Center of Ecological Environmental Quality

This study utilized the concept of the physical center of gravity to assess the spatial crusade features of ecosystem quality in the YRD, drawing on information from pertinent references. The focus of ecosystem quality is constantly changing because the quality of the ecosystem can get better or worse. By looking at how the gravity center of the quality of the ecosystem moves, you can learn a lot about how the ecological environment of the area has changed over time. This is how to figure it out:

$$X_t = \frac{\sum_{j=1}^{n} EQI_{tj}x_j}{\sum_{j=1}^{n} EQI_{tj}} \quad (3)$$

$$Y_t = \frac{\sum_{j=1}^{n} EQI_{tj}y_j}{\sum_{j=1}^{n} EQI_{tj}} \quad (4)$$

EQI_{ij} denotes the EQI of unit j at time t, while X_i and Y_j signify the geographical center positions of unit j, and X_t and Y_t indicate the dominant parameters of provincial bionetwork excellence at time t.

4. Results

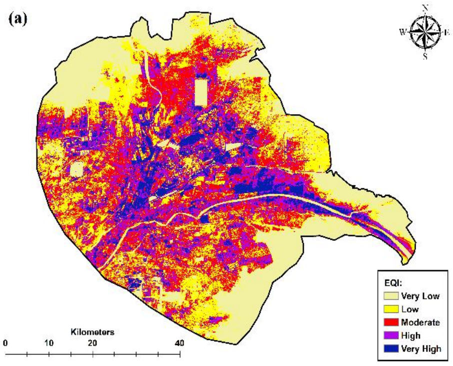
4.1 Spatial and Temporal Attributes of Ecological Excellence in YRD

To more effectively convey the spatio-temporal distribution features of eco-environmental excellence throughout the study range, the EQI values from 2000, 2010, and 2020 were categorized into five grades: very low, low, moderate, high, and very high. Figure 3 shows the annual breakdown of EQI levels in the YRD.

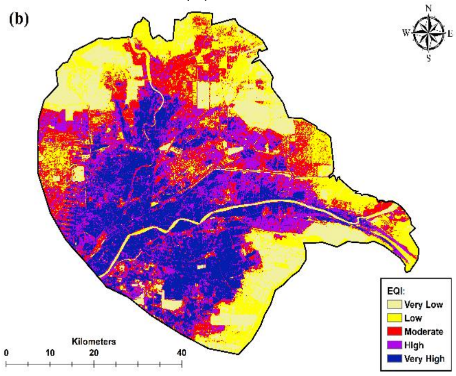
The areas very high and high eco-environmental quality are predominantly located along the YRB, with a distribution pattern resembling an inclined "Y". The areas very low and low ecological excellence are situated in the seaside regions of the YRD. The ecological quality progressively declines from the core of the YRD to its outskirts, with urban areas exhibiting two primary levels of ecological quality: very low and low.

Figure 3 and Table 2 Indicates the refined EQI data confirms a period of substantial ecological advancement between 2000 and 2010. The area characterized as “Very High” more than doubled, increasing from 9.91% to 23.86%. This reflects a robust recovery of the YRD biophysical functions. Simultaneously, the “Moderate” class decreased significantly as land transitioned into higher-quality categories. While other individual indicators showed fluctuations, the composite EQI demonstrates continued ecological resilience in the most recent decade. The combined area of “High” and “Very High” ecological status reached its highest peak in 2020, covering 41.92% of the delta. Although the “Very High” class saw a slight contraction from 2010, the “High” class expanded to 24.78%, maintaining a strong overall health baseline for the wetland system. The EQI provides a more holistic view of the delta by balancing structural changes (LAI/FVC) with functional ones (GPP). The relative stability of the “Very Low” and “Low” categories which consistently represent about 40% of the delta highlights that while restoration has been successful in core zones, a significant portion of the landscape remains vulnerable to salinity and hydrological stress.

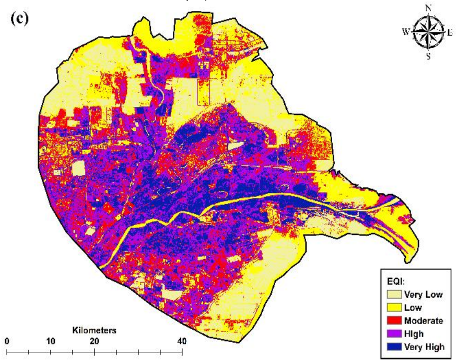
The refined EQI trajectory for the YRD shows a transition from a moderately healthy ecosystem in 2000 to a more productive and resilient system by 2020. The peak of ecological status occurred in 2010, followed by a stabilized high-quality state in 2020. These findings underscore the success of long-term conservation policies in the YRD while highlighting the areas that require ongoing management.



(a) 2000



(b) 2010



(c) 2020

Figure 3. Spatial Dispersal of Ecosystem Quality in YRD. (a) 2000; (b) 2010 (c). 2020

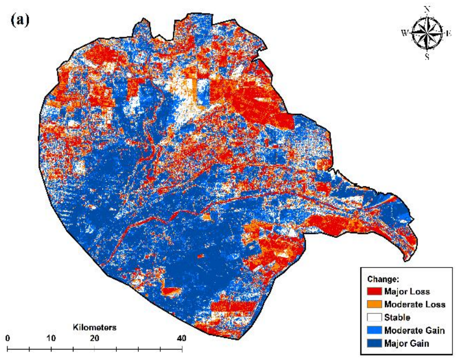
Table 2. Spatiotemporal Area Data for EQI

	YRD		
EQ Levels	2000	2010	2020
Very Low	17.35%	15.87%	17.82%
Low	24.36%	20.59%	21.63%
Moderate	30.07%	18.55%	18.62%
High	18.29%	21.11%	24.78%
Very High	9.91%	23.86%	17.13%

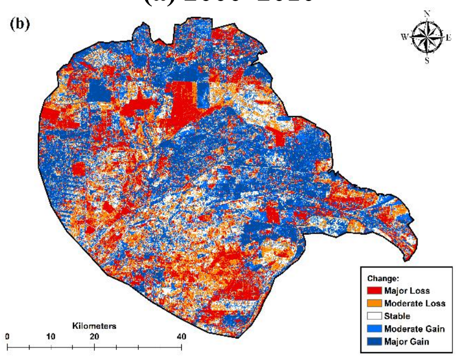
4.2 Analysis of the Fluctuation Pattern of EQI in the YRD Region

The fluctuation pattern of EQI in the YRD region from 2000 to 2020 are shown in the Figure 4. Over the course of the last twenty years, the EQI of the YRD has undergone a metamorphosis that can be described as a V-shaped wave. Between the years 2000 and 2010, there was a gradual improvement in the ecological quality of the delta as a whole. However, the ecological quality of the delta's northeastern region declined, while the southwestern region experienced an improvement.

Between the years 2010 and 2020, the ecological quality gradually deteriorated, notably in large portions of the delta's north-west and south-west sections. On the other hand, the rest of the region had a pattern that was a combination of deterioration and improvement. The overall ecological and environmental quality of the YRD shows a tendency of improvement between the years of 2010 and 2020. Through the proactive implementation of policies such as "Regulations of the People's Republic of China on Nature Reserves," "Wetland Protection Measures in Shandong Province," and "Ecological Protection and High-Quality Development of the YRD" over the course of the past two decades, local authorities have been able to successfully regulate the ecological environment and improve the eco-environmental quality of the YRD. This evolving trend was associated with the proactive execution of these policies.



(a) 2000–2010

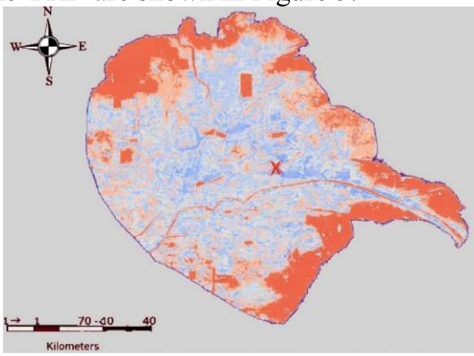


(b) 2010-2020

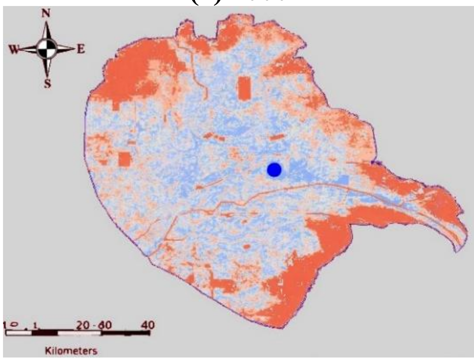
Figure 4. Ecological Environment Quality Change Map in YRD. (a) 2000-2010, (b) 2010-2020

4.3 Trajectory of the Gravity Center of Ecosystem Quality in YRD from 200 to 2020

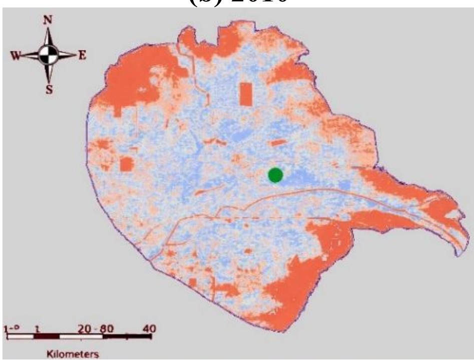
The calculated gravity center of the ecological environmental quality in 2000, 2010, and 2020 of the YRD are shown in Figure 5.



(a) 2000



(b) 2010



(c) 2020

Figure 5. Trajectory of the Gravity Center of EQ in YRD; (a). 2000; (b). 2010; (c). 2020

In 2000, the EQ of the YRD was comparatively less affected by urbanization and industry than in subsequent decades. The center of gravity was predominantly situated in the central region of the Delta, near the natural wetlands and the Yellow River, which remained largely unaffected by human intervention. This region, next to agricultural zones, indicated a balance between natural ecosystems and agricultural utilization, demonstrating a modest degree of ecological health. In 2010, the center of gravity had somewhat relocated towards the eastern region of the Delta, which had greater impact from industrial development and urban expansion. This transition signified that the ecological environment in the southern and western regions of the Delta commenced its degradation as a result of anthropogenic activity, with urbanized areas supplanting natural wetlands and woods. While in 2020, the center of gravity shifted northward, where conservation initiatives had enhanced ecological quality. The northern regions, abundant in wetlands and woodland fragments, increasingly contributed to the Delta's general ecological health, although urbanized areas continued to affect the center of gravity. These findings underscore the necessity of preserving conserved areas and fostering sustainable urban and industrial development to safeguard the ecological integrity of the YRD.

5. Conclusion

This research utilized remote sensing technology to do a thorough assessment of the ecological environmental quality (EQ) of the YRD in 2000, 2010, and 2020. The analysis employed the Ecological Environmental Quality Index (EQI) approach, integrating data from Landsat TM/OLI_TIRS, land use/land cover (LULC), Fractional Vegetation Cover (FVC), Leaf Area Index (LAI), and Gross Primary Productivity (GPP). The findings indicated significant regional variability in the EQ throughout the region. The northern and eastern coastal regions displayed diminished EQ values, whereas the western, southern, and select central areas exhibited comparatively elevated EQ. Temporal study revealed a pattern of decline, partial recovery, and subsequent degradation in ecological quality. In 2000, the general ecological quality (EQ) was low, however there was a significant increase in high-quality ecological regions by 2010. Nonetheless, this enhancement was succeeded by a notable deterioration in 2017, with a slight resurgence noted by 2020.

The examination of the Center of Gravity of Ecological Environmental Quality (GCEQ) for the YRD in 2000, 2010, and 2020 disclosed significant trends: In 2000, the Delta had a comparatively stable biological environment, with natural wetlands serving a vital function in ecosystem health. By 2010, the GCEQ had transitioned towards urban and industrial areas, indicating a deterioration in ecological quality. In 2020, a modest rebound was noted, ascribed to augmented conservation initiatives and superior management of wetlands and natural habitats. These findings highlight the essential necessity of safeguarding conservation areas and implementing sustainable urban and industrial development methods to protect the biological integrity of the YRD. Future policies must emphasize the enhancement of conservation projects in the northern and central regions, while simultaneously regulating urban expansion in the southern and eastern sectors of the Delta.

Acknowledgments

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