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Spatiotemporal pattern of landscape ecological sensitivity in coastal zone in the last 30 years: an empirical study of Shandong Peninsula, China

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Abstract

The global population and social economy are highly concentrated in the coastal zone. This region is being subjected to rapid human development. The coastal zone is located at the intersection of marine and terrestrial ecosystems in an ecologically complex environment. Hence, its original landscape patterns have undergone substantial alterations. The present study used a comprehensive framework to evaluate landscape ecological condition and sensitivity indices based on landscape composition, configuration, and function in the coastal zone of the Shandong Peninsula over the past 30 years. Eight evaluation units between 100 m and 10 km were employed to understand the Vulnerability scale effects of landscape ecological condition and sensitivity along the scale change. Between 1990 and 2020, the ecological condition and sensitivity of the coastal zone of Shandong Peninsula initially decreased and then gradually increased. The total evaluation demonstrated a trend of initial decrease and subsequent increase with evaluation scale. It was determined that 1 km was the optimal scale for landscape ecological sensitivity evaluation. The present research indicated that the evaluation of landscape ecological condition and sensitivity provides a technical reference for optimizing spatial development patterns in the coastal zones of Shandong Peninsula as well as other regions.

Keywords Landscape ecological sensitivity · Landscape pattern · Coastal zone · Scale · Shandong peninsula

Introduction

The coastal zone constitutes only 18% of the total global surface area but bears ~ 70% of the world's population, ~ 65% of all large cities, a vast GDP, and 90% of the halobios. It is of great significance in regulating the global ecosystem, promoting human society development and supporting the flow of ecosystem material and energy (Du et al. 2007; Luo 2016; Hatje et al. 2020). Ecological ecotone in the coastal zone is representative around the world, which is affected by both terrestrial and marine ecosystems (Zhang et al. 2015; Suo et al. 2016; Anderson et al. 2022). The continuous expansion of the artificial landscape has led to the destruction of the original ecosystem. Rapid urbanization process and agricultural development have led to serious landscape fragmentation in coastal zone. In addition, the coastal zone is often threatened by natural disasters such as typhoons, storm surges and sea-level rise (Young et al. 2019), and the natural ecological functions are constantly degraded, including seawater eutrophication problems, shrinking of coastal wetland and secondary salinization of coastal soil (Cao and Wong 2007; Gao et al. 2014; Costanza et al. 2021). Therefore, studies of the coastal zone can disclose variations in the coastal ecosystem and facilitate spatial planning.

Ecological sensitivity refers to the ability of an ecosystem to adapt to internal changes and external disturbances, including the internal evolution of natural ecosystems,

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material and energy exchange with adjacent ecosystems, and interference from human activities (Fossile et al. 2021). Environmental problems, including human development, utilization activities, invasive species and other disturbances may create negative ecological sensitivity. For this reason, ecological sensitivity has also become an important indicator of ecosystem evaluation, and has been widely used in many fields, such as ecological service value (Peng et al. 2021), major function-oriented zoning (Fan 2015; Duan et al. 2021), land cover and land use (Wang and Bian 2011; Bai and Guo 2021), desertification (Guo et al. 2020) and soil erosion (Cui, et al. 2022). The landscape pattern comprises the quantity, area and spatial distribution of ecosystem type (Yohannes et al. 2021), is influenced by a combination of natural and artificial factors, and profoundly influences and alters the ecosystem structure, process and function (Chen et al. 2013; Chi et al. 2020). Therefore, a landscape ecological sensitivity evaluation framework was established based on the landscape pattern and applied to coastal zones. It is conducive to accurately understand the intensity of human activities and changes of ecosystem while facing human activities and natural disturbances.

Landscape ecological sensitivity was proposed by D. Brunsden and J. B. Thornes in 1979 and it was originally applied to geomorphology (Brunsden and Thornes 1979). Landscape ecological sensitivity was subsequently developed by numerous scholars and may be defined as the "spatiotemporal changes in landscape systems in response to internal and external interference." (Thomas 2001). Temporal-scale variations in landscape ecological sensitivity represent the change of landscape in the internal landscape pattern at various times as well as the time-dependent independent events induced by external interference, which is essentially a variable that changes with time. Spatial-scale variations in landscape ecological sensitivity indicate the changes in the composition and configuration of the landscape as well as the spatial heterogeneity of the ecological sensitivity in the whole region. Since the concept was first proposed, subsequent have endeavored to elucidate the relationship between geological and geomorphic change and landscape ecological sensitivity (Hansom 2001; Knox 2001). Shi et al. (2017) assessed the landscape ecological sensitivity of Yulin City, Shaanxi Province through natural and artificial factors; Chi et al. (2019) constructed LECI (landscape ecological condition index) and LESI (landscape ecological sensitivity index) to evaluate landscape ecological condition and landscape ecological sensitivity in Chongming Island, which is a typical estuarine alluvial island highly effected by artificial activities; Peng et al. (2021) analyzed the landscape ecological sensitivity of Three Gorges Reservoir region by the means of LECI. Although above studies have achieved good results, there are still deficiencies in the following three aspects: (1) Study area selection. Most studies have focused on the spatial and temporal changes within a specific geographical unit, such as watersheds, nature reserves, islands (Shi et al. 2017; Peng et al. 2021), etc. The internal ecological structure of these geographical entities is relatively homogeneous and the ecosystem is comparatively enclosed, and it is difficult to reflect the spatial changes of various landscape patterns. (2) Evaluation scale. Current studies usually focus on a single evaluation scale, failing to reveal the impact of research results caused by the change of scale. Scale issue has always been the key research topic of landscape ecologists, and it is also one of the core issues of landscape ecology (Wu 2004; Zhang 2006; Chen et al. 2014a, b). (3) Comprehensive analysis of landscape pattern. At present, many studies used the landscape indices to analyze the landscape pattern, landscape function and landscape sensitivity, but the comprehensive evaluation combined with the composition, configuration and function of the landscape pattern is rarely be seen.

The evaluation framework was constructed using various landscape and remote sensing indices derived from open-source data. Landscape composition, configuration and function are three important part of landscape pattern, they describe the complexity and structure of landscape. This evaluation framework comprehensively reflects the spatiotemporal characteristics of the coastal zone landscape pattern and provides multiple countermeasures and suggestions for coastal zone ecosystem conservation. Open-source landscape data and remote sensing images were used and were applicable to empirical studies in different regions. The previously proposed landscape ecological sensitivity models were only applied in small-scale studies. It was uncertain how well they would perform under large-scale, complex surface conditions and in regions with high anthropogenic activity and spatiotemporal heterogeneity. Therefore, we enhanced the evaluation model so that it could be successfully applied to the large-scale study areas and the complex geological and geomorphic conditions and changes in the Shandong Peninsula coastal zone. The present study endeavored to answer the following questions: (1) How do the landscape ecological condition and sensitivity indices apply in compound areas with large spatial variability and highly heterogeneous land surface characteristics? (2) How do these indices vary along a 100-m–10-km spatial scale? Based on spatiotemporal scales, the present study evaluated the landscape ecological condition and sensitivity indices of the Shandong Peninsula between 1990 and 2020. It also considered data redundancy, key information retention, and other issues to determine the most appropriate evaluation scale.

Material and methods

Study area

The study area is the whole coastal zone of Shandong Peninsula, China, which borders the Bohai Sea in the north and the Yellow Sea in the east (Fig. 1). The study area encompasses twenty-seven counties in seven cities, namely Rizhao, Qingdao, Weihai, Yantai, Weifang, Dongying and Binzhou. The northern part is the alluvial plain formed by the sediment accumulation of the Yellow River. Offshore mariculture, salt field reclamation and port construction have encroached on the original natural coastline, resulting in dramatic shoreline changes. The Shandong Peninsula has gently rolling hills, and its coastline is mainly sandy and bedrock. Due to the coastal reclamation, urban construction and aquaculture activities in this area, the original coastline has been seriously damaged. In response to the reforms of China, the marine economy, including marine fisheries, marine biomedicine, and other industries, has rapidly developed in the Shandong Peninsula coastal zone over the past thirty years. The total marine economy of the northern marine economic circle led by Shandong Province account for 29.2% of Chinese marine economy in 2020 (Department of Marine Strategic Planning and Economy Ministry of Natural Resources, P. R. China 2022). However, transformation of the original ecological environment follows economic development. Intense human activities have led to serious damage to the original animal and plant habitats and soil environment in the region. Strong landscape fragmentation has hindered the original ecological functions and energy flow process. During the "The thirteenth Five-Year plan", China put forward the coastal zone ecological restoration strategy. In 2017, the original State Oceanic Administration published coastline protection and utilization measures and management practices. The national marine functional zoning also standardized land development and utilization of coastal areas in terms of territorial spatial planning, protected the existing coastal ecological environment through proper planning and development, and repairs and renovates the coasts with low utilization rate and serious degradation of ecological functions.

Therefore, choosing the coastal zone of Shandong Peninsula, where the economic and ecological environment are changing rapidly, as the research area, has representative significance for exploring the changes of landscape ecological sensitivity in the past 30 years from 1990 to 2020.

Data resource

Landscape data

The landscape type data we derived in this paper were gathered from Globe Land (http://www.globallandcover.com/) 30 m × 30 m resolution land use data in 2000, 2010 and 2020 (Chen et al. 2014a, b). A combination of machine and manual visual interpretation was used to obtain the landscape type data in 1990. In order to ensure the continuity of the data, Landsat data with the same resolution of 30 m × 30 m was selected to obtain landscape type data. Finally, four periods of landscape type data from 1990 to 2020 were obtained.

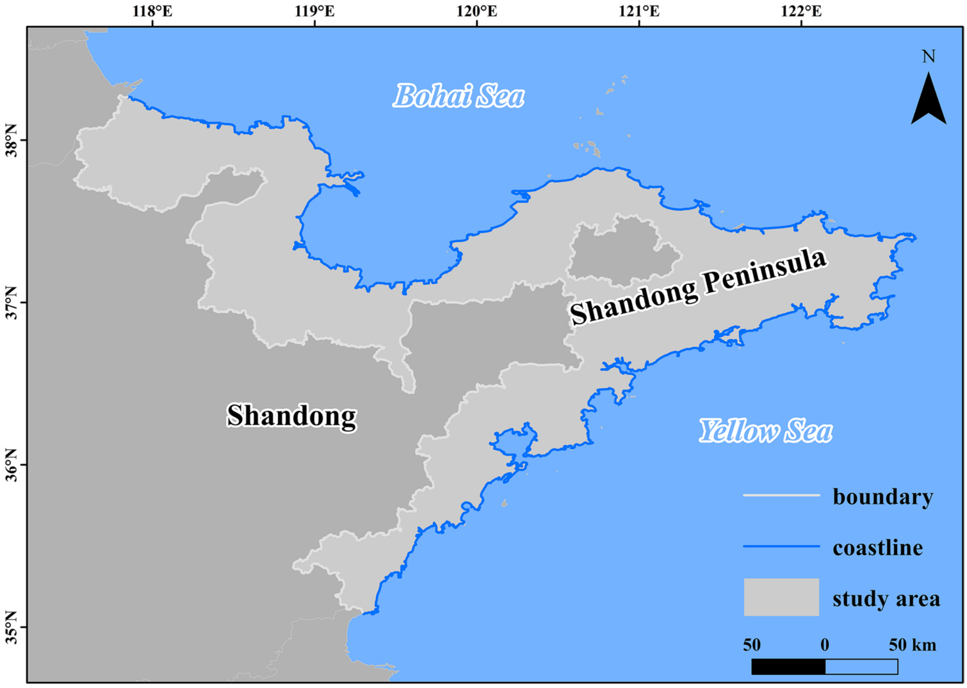


Fig. 1 Location of the study area

Remote sensing data

Cloudless multispectral remote sensing data of Landsat 5 in 1990, 2000 and 2010 and Landsat 8 in 2020 within the study area were obtained from USGS (http://www.usgs.gov) (Figs. 2 and 3). Landsat 5 was launched in 1984, have 7 bands in TM sensor. Landsat 8 was launched in 2013, its' OLI sensor have 9 bands. Both satellites can provide remote sensing data that fulfill this reearch. Selected images were acquired at the end of May and the start of June each year (Table. 1). This sampling strategy attenuated the impact of seasonal changes and facilitated the acquisition of cloud-free, high-quality images. ENVI and ArcGIS 10 were used to preprocess (clip, geometrically correct, radiometrically calibrate, and atmospherically correct) the Landsat images. The output served as the basic data source for the subsequent steps.

Landscape ecological condition index

Landscape composition, configuration and function are three vital components of the landscape pattern (Martin et al. 2016). Based on the research results, several factors were selected to represent three components. Factor selection should ensure that landscape composition, configuration and function can be fully represented. The factors must be easy to calculate and include data sources and calculation methods so that they can be adapted for application in large-scale research areas (Appendix Table 6).

Landscape composition Landscape composition includes the number and area of each landscape type having important impacts on ecological processes such as forest regeneration, species flow, and biodiversity (Perez-Cardenas et al. 2021). Here, the number of landscape types (NL), human interference index (HII), human assistance index (HAI) and vegetation coverage (VC) were selected to represent the landscape composition.

Landscape configuration Landscape configuration indicates the spatial distributions of landscape patches. As human activity alters original ecosystems, landscape fragmentation becomes the general trend in landscape configuration. It lowers the ecosystem service value, habitat quality, and species abundance and diversity (Ramalho et al. 2014; Wang et al. 2014; Mikolajczyk et al. 2021). Therefore, several landscape indices were selected to quantify the landscape configuration. The indices depicted landscape configuration, were reasonably practicable (Willemen et al. 2008; De Groot et al. 2010), and included number of patch (NP), total edge (TE), Shannon-Weiner index (SWI) and landscape isolation index (LII).

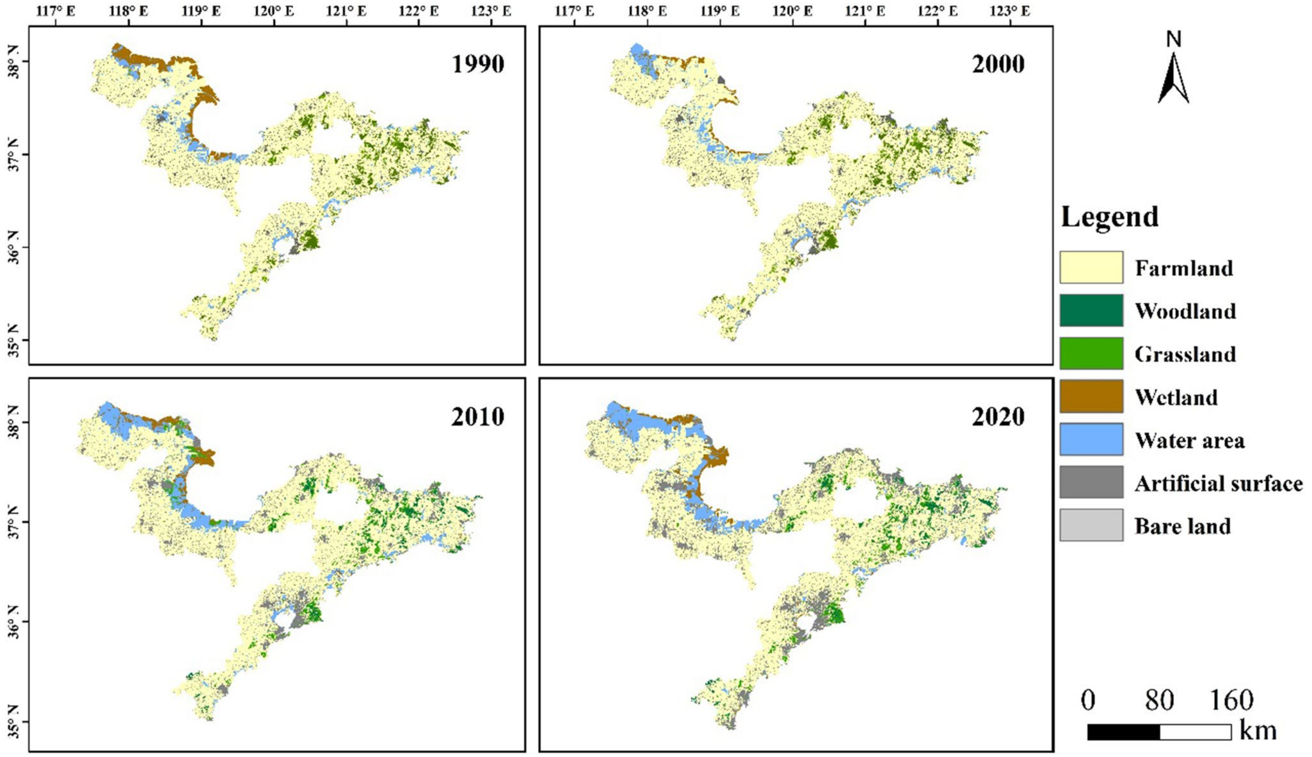


Fig. 2 Land use data during 1990 to 2020

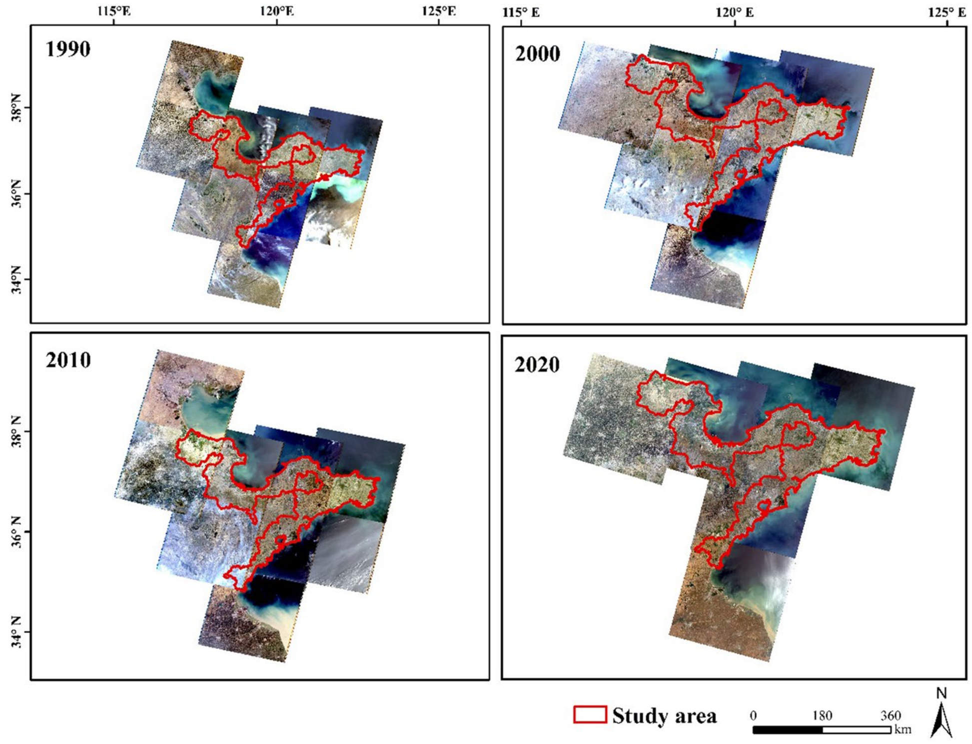


Fig. 3 Landsat images during 1990 to 2020

Landscape function Landscape function is the capacity of the landscape to furnish ecological services and products for human society, including food for humans and habitats for wild animals and plants (Willemen et al. 2008; De Groot et al. 2010; Oehri et al. 2020). The selected landscape function evaluation factors included certain remote sensing indices such as normalized difference vegetation index (NDVI), normalized difference built-up and bare soil index (NDBSI), soil salinity index (SSI) and distance to visual landscape (DVI).

Table 1 Landsat images information

WRS PATH	WRS ROW	Date	WRS PATH	WRS ROW	Date
1990			2000		
119	34	1990/6/2	119	34	2000/6/13
119	35	1990/6/2	119	35	2000/6/13
120	34	1990/5/24	120	34	1999/6/2
120	35	1990/5/25	120	35	2002/5/25
120	36	1992/5/29	120	36	2000/5/19
121	34	1990/6/16	121	34	1998/5/5
121	35	1990/6/16	121	35	2000/4/8
122	33	1992/5/27	122	34	2000/5/17
122	34	1991/5/10			
2010			2020		
119	34	2009/6/6	119	34	2019/5/1
119	35	2009/6/22	120	34	2020/5/9
120	34	2010/5/15	120	35	2020/5/10
120	35	2009/6/13	120	36	2018/6/6
120	36	2010/4/13	121	34	2020/5/26
121	33	1992/5/27	122	34	2018/5/3
121	34	2009/6/4			
121	35	2009/6/5			

The evaluation factors of landscape composition, configuration and function were obtained. According to the different functions they provide, we divided those factors into positive ones and negative ones and standardized. Positive factors include HAI, VC and NDVI, and their values increased with landscape ecological condition. The negative factors included all other evaluation factors. Their values decreased with declining landscape ecological condition. To attenuate the influences of outliers, 5% and 95% were taken as the upper and lower limits, respectively, of the data for each year. Standardization was calculated as shown in Eq. 1:

$$I_f = \begin{Bmatrix} \dfrac{V_x - V_{\min}}{V_{\max} - V_{\min}} \\ \\ \dfrac{V_{\max} - V_x}{V_{\max} - V_{\min}} \end{Bmatrix} \tag{1}$$

where, I_f is the result of all evaluation factors after standardization, and V is the specific value of each evaluation factor. If I_f is greater than 1, the value is 1; if I_f is less than 0, the value is 0. Positive factors use first equation, negative equation use another one. For the three aspects of landscape sensitivity evaluation, namely landscape composition, landscape configuration and landscape function, were homogenized, and the calculation formula is as follows:

$$\mathrm{R}_i = \frac{1}{n}\sum I_f \tag{2}$$

where R_i represents three aspects of landscape sensitivity, namely, landscape composition, configuration and function.

In this paper, LECI (landscape ecological condition index) was used to express the landscape ecological condition. The formula is as follows:

$$\mathrm{LECI} = \sqrt{[w\mathrm{R}_1 + (1-w)\mathrm{R}_2] \times \mathrm{R}_3} \tag{3}$$

where R_1, R_2 and R_3 reference landscape composition, configuration and function, namely; *w* is weight index. In order to reach the balance between landscape composition and configuration, *w* was set as 0.5 (Chi et al. 2019).

Landscape ecological sensitivity index

Landscape sensitivity is a characteristic quantity that changes with time due to the interference of internal changes and external factors in the ecosystem (Wu 2019). Therefore, LESI were established (landscape ecological sensitivity index) to represent the changes of landscape ecological sensitivity in three periods, namely 1990–2000, 2000–2010 and 2010–2020. The formula is as follows:

$$LESI = \frac{10 \times (LECI_{en} - LECI_{be})}{Y_{en} - Y_{be}} \tag{4}$$

where LECI_{en} and LECI_{be} represent LECI in begin and end of the year in the time period, Y_{en} and Y_{be} refer to end and start year in the time period.

Scale effect of landscape ecological condition and sensitivity

The scales of landscape ecology include phenomenon or intrinsic scale, observation scale and evaluation or simulation scale. The scale change discussed in this paper was evaluation scale, which is essential to dig and analyze more information within the ecosystem more accurately (Zhang 2006; Haddad et al. 2015). In this paper, it represents the size of the evaluation unit. Therefore, with the help of fishnet data in ArcGIS spatial analysis, different landscape ecological sensitivity evaluation units were used in this paper, which were 100 m, 200 m, 400 m, 800 m, 1 km, 2 km, 5 km and 10 km, namely. These evaluation units were selected based on the information contained in the evaluation unit such as data redundancy, the basic data used in the present work, and the area of the study region. By steadily increasing the evaluation units, changes in the landscape ecological condition and sensitivity of the study area were analyzed along the scale gradient.

Results

LECI spatial and temporal characteristic

The LECI values for the Shandong Peninsula coastal zone between 1990 and 2020 were calculated based on the land use data and the preprocessed remote sensing data combined with the evaluation index system (Table 2). The overall situation in the region over the past thirty years has demonstrated the unbalanced spatial heterogeneity

Table 2 LECIs in the four years

Scale	Year			
	1990	2000	2010	2020
10 km	0.5428	0.5169	0.5056	0.5411
5 km	0.5322	0.5219	0.4977	0.5284
2 km	0.5292	0.5306	0.5032	0.5259
1 km	0.5345	0.5395	0.5126	0.5321
800 m	0.5483	0.5624	0.5293	0.5356
400 m	0.5489	0.5632	0.5345	0.5436
200 m	0.5618	0.5801	0.5589	0.5567
100 m	0.5782	0.5758	0.5757	0.5850

of the distribution of the landscape ecological condition there. Between 1990 and 2010, rapid urbanization, agricultural and industrial development have caused LECI to decline in the Shandong Peninsula coastal zone. Nevertheless, the concerted efforts of regulatory bodies towards ecological environment restoration have significantly improved LECI as of 2020. Thus, ecological protection has dramatically ameliorated the ecological conditions of the entire coastal zone.

In each year, the LECI initially fell and then rose as the evaluation unit decrease from 10 km to 100 m. The maximum LECI occured at 100 m in each year except 2000. The main reason is that with the decrease of evaluation scale, the impact of surrounding patches on each evaluation unit decreases, which can more accurately reflect the landscape ecological condition within the evaluation unit, improve the gap of LECI between different landscape types, so as to have a higher LECI value (Fig. 4).

The spatial LECI distributions are shown in Fig. 5. In 1990, high LECI areas were distributed in the eastern hilly region while the low-LECI areas included the Yellow River Delta and its surrounding plain. By 2000, urbanization effect began to appear and low LECI areas were mainly distributed in artificial surface and surrounding big cities. The high LECI areas were scattered mainly in Yellow River Delta and on gently rolling hills. By 2010, the low LECI areas continued to increase, and the high LECI areas (0.8–1) were virtually nonexistent, and the landscape and LECI were seriously fragmentized. Because of a series of ecosystem protection projects, in 2020, high LECI areas were mainly distributed in Yellow River Delta and its north area. Constantly increase of wetland area and protection projects were the main reason.

LESI spatial and temporal characteristic

The LESI is presented in Fig. 6. The evaluation periods were 1990–2000, 2000–2010, and 2010–2020. The landscape ecological sensitivity was poor (< 0 at all evaluation scales) between 2000 and 2010, good between 1990 and 2000, and excellent between 2010 and 2020. The differentiation scales for the other two periods showed that the LESI decreased with increasing evaluation scale.

Based on the calculation results, the LESIs were divided into five grades, namely lower than -0.2, -0.2 to -0.05, -0.05 to 0.05, 0.05 to 0.2 and higher than 0.2, corresponding to the five conditions of very negative, negative, general, positive and very positive landscape ecological sensitivity, respectively (Fig. 7). Between 1990 and 2000, China was still in the early stage of reform and opening up. Urbanization and industrialization were vigorously expanding, but their development was

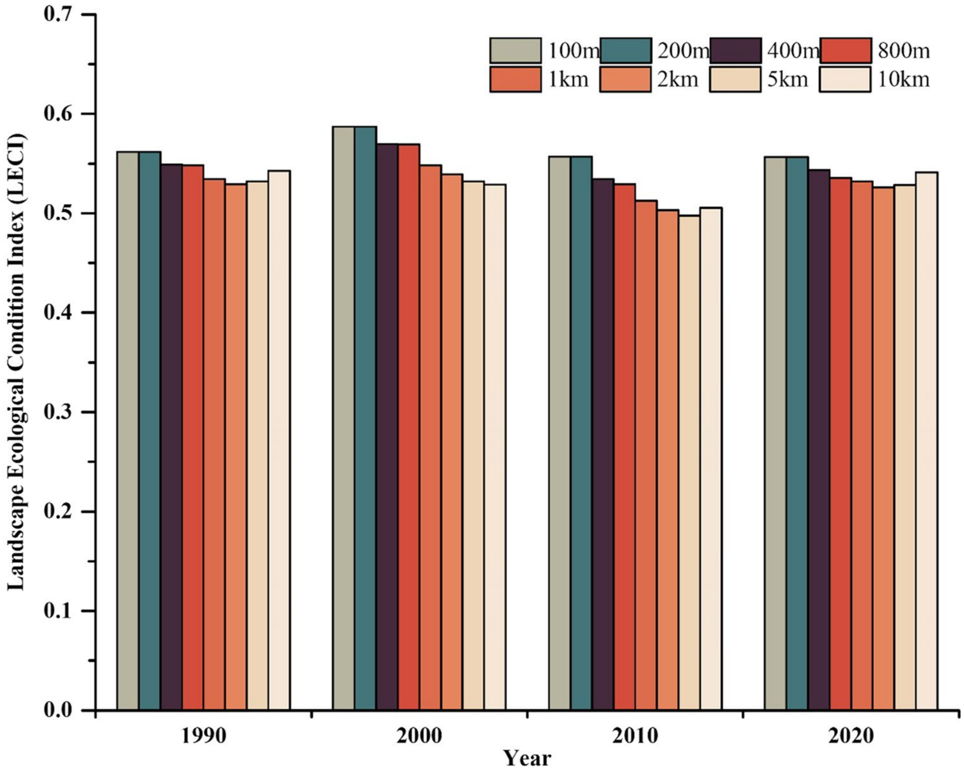
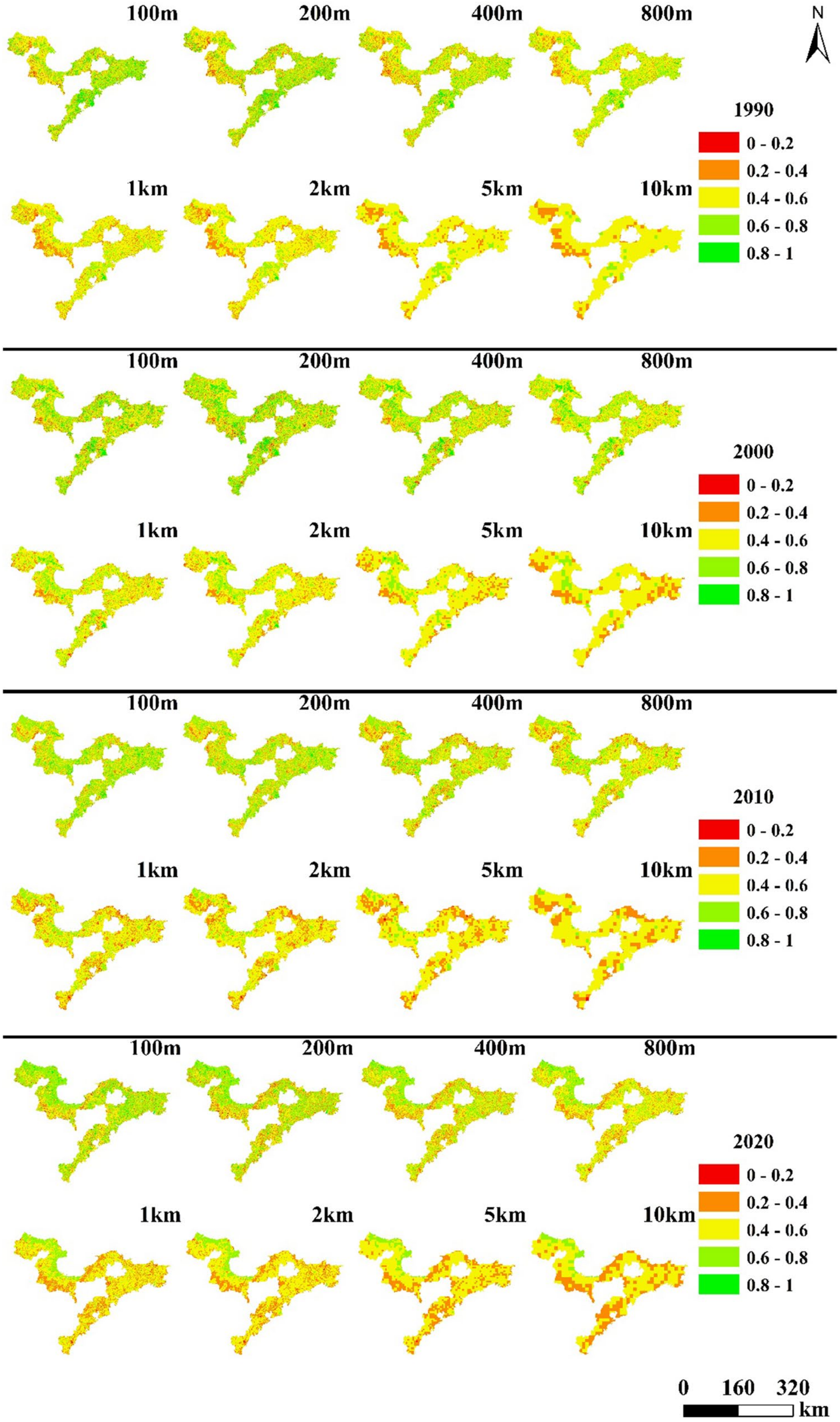


Fig. 4 LECIs in the four years at different scale

Fig. 5 LECIs spatial distribution in Shandong coastal area



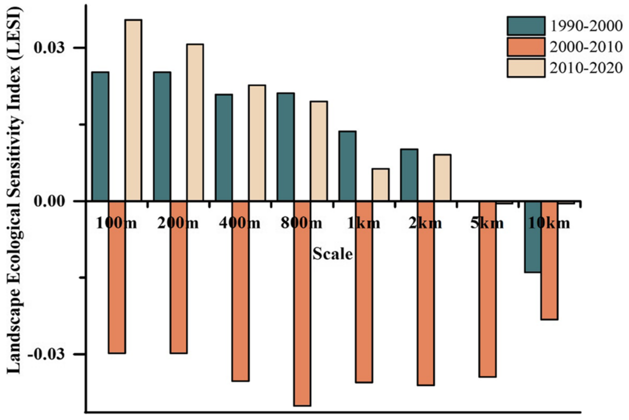
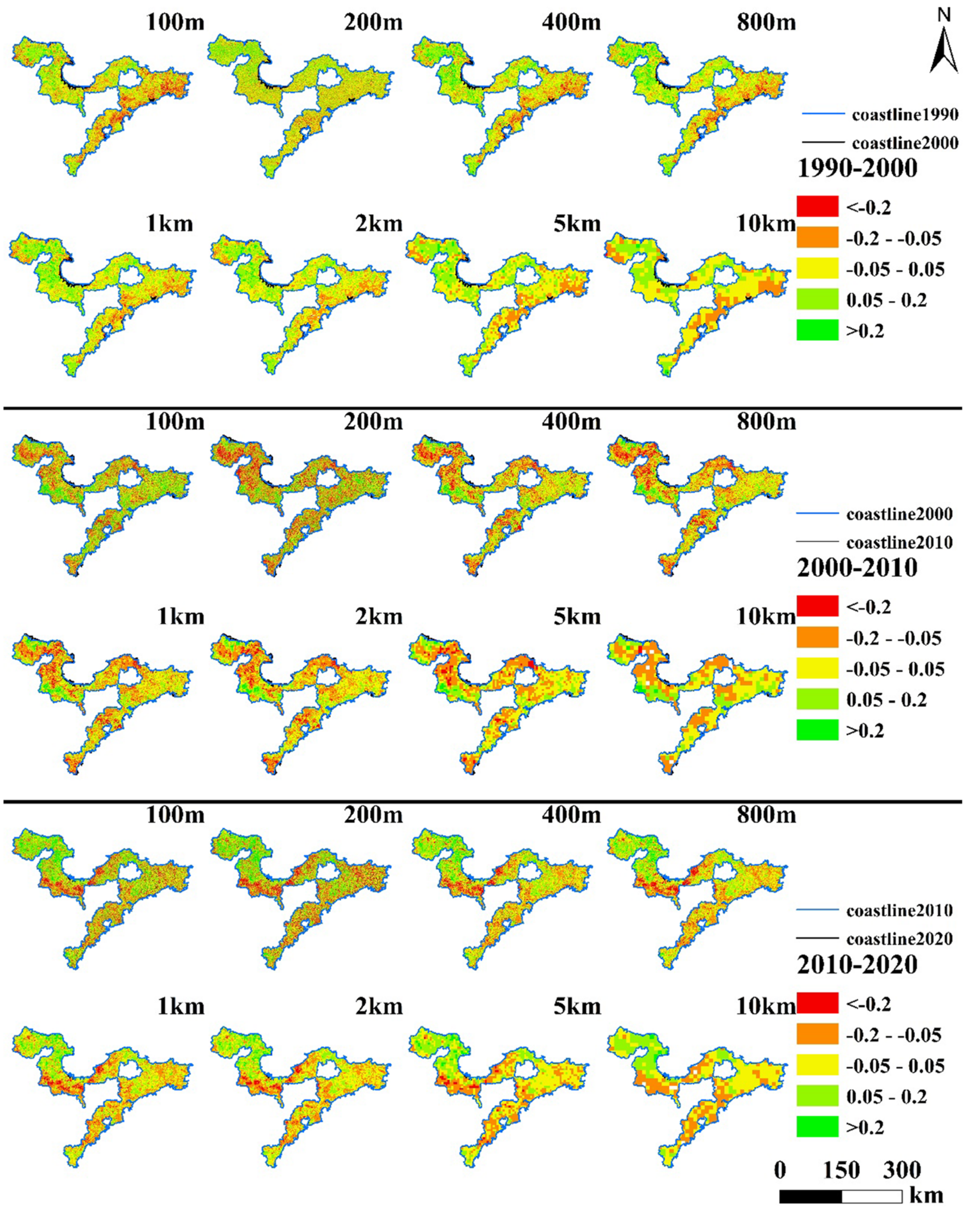


Fig. 6 LESIs in the four years at different scale

disorganized. However, at this period, the driving and radiating effects of big cities were not yet evident, and infrastructure construction and urban development were relatively primitive. For these reasons, the human activity in this period did not markedly alter the surface landscape violently. As there are marked differences in geography and openness between Shandong Peninsula and southeast of Shandong, there is an imbalance between the development between the east and the west. Therefore, the ecological sensitivity of the eastern coastal zone was significantly lower than that of the western coastal zone. Between 2000 and 2010, Shandong Province underwent rapid economic development. In 1999, the government of Shandong Province issued the decision on further accelerating the construction of small towns. Rapid

Fig. 7 LESIs spatial distribution in Shandong coastal area



urbanization construction has led to the quick changes in the landscape of the coastal zone, and the reclamation of the coastline has also entered a period of rapid expansion. In the region, salt fields and aquaculture developed during the 1980s and there was a relatively stable, dormant development period during the 1990s. Coastline transformation was intensified in the 2000s. As of 2002, regulatory agencies restrained aquaculture and industrial development on the coastlines of China. Town and port construction became the principal direction of natural coastline transformation. Nevertheless, high-intensity development has destroyed natural landscapes and original coastlines. Drastic surface changes in the region between 2000 and 2010 decreased landscape ecological sensitivity to its lowest point in nearly 30 years. After 2010, ecological problems associated with high-intensity development began to appear and sensitized the public to the need for ecological protection. Functional zoning policies issued in 2011 activated environmental restoration in ecologically sensitive areas and helped establish and conserve the ecological security of China. Coastal zones and wetlands are important parts of the coastal ecosystem and have received increasing attention from regulatory agencies. The former State Oceanic Administration launched coastal zone renovation, restoration, and protection initiatives in 2010 and optimized the landscape pattern to improve coastal ecosystem quality. The Yellow River Delta and the coastal areas of Laizhou Bay have poor ecological environmental sensitivity but have undergone vital key remediation and restoration work. A wetland vegetation restoration project proposed during the “Thirteenth Five-Year Plan” period restored the original landscape pattern and ecological functions of these environmentally sensitive areas via the installation of secondary vegetation, protective levees, upstream water transfer, and so on. These measures significantly enhanced the landscape ecological sensitivity of the region. Nevertheless, the eastern Shandong Peninsula and most of its adjacent plains continue to have poor landscape ecological sensitivity because of ongoing economic activity and urban construction in these areas.

Discussion

Main effect factor of LECI and LESI

Correlation coefficients were used to analyze the relationship among LECI, LESI and various evaluation factors at various scales in the study area (Tables 3 and 4). For the entire study area, the correlation between LECI and R3 was relatively strong as the landscape function has comparatively greater weight in LECI and LESI calculation. The landscape function was the synthesis of landscape composition and configuration, representing the services provided by the ecosystem and affected by the latter two. The overall correlation coefficient revealed an initial decrease and a subsequent increase in the expansion of the evaluation unit along the scale change. The correlation analysis results of LESI with LECI and other evaluation factors disclosed that LECI was more relevant to LESI than other indices. Furthermore, the absolute values of the

Table 3 The correlation coefficient between LECI and re1, re2 and re3 in different scale

LECI	Scale	re1	re2	re3	LECI	Scale	re1	re2	re3
1990	100 m	0.462	0.560	0.746	2010	100 m	0.481	0.527	0.765
	200 m	0.530	0.592	0.709		200 m	0.550	0.575	0.717
	400 m	0.647	0.624	0.648		400 m	0.730	0.569	0.699
	800 m	0.510	0.502	0.692		800 m	0.662	0.467	0.731
	1 km	0.498	0.631	0.712		1 km	0.645	0.595	0.707
	2 km	0.004	0.006	0.721		2 km	0.606	0.581	0.707
	5 km	0.408	0.628	0.730		5 km	0.594	0.627	0.684
	10 km	0.387	0.678	0.759		10 km	0.561	0.711	0.662
2000	100 m	0.489	0.569	0.744	2020	100 m	0.775	0.687	0.672
	200 m	0.593	0.599	0.703		200 m	0.666	0.701	0.616
	400 m	0.706	0.612	0.664		400 m	0.781	0.693	0.660
	800 m	0.618	0.512	0.695		800 m	0.733	0.639	0.686
	1 km	0.486	0.613	0.687		1 km	0.614	0.735	0.837
	2 km	0.430	0.597	0.684		2 km	0.588	0.719	0.853
	5 km	0.384	0.647	0.688		5 km	0.613	0.745	0.895
	10 km	0.379	0.731	0.689		10 km	0.635	0.786	0.931

Table 4 The correlation coefficient between LECI and re1, re2 and re3 in different scale

LECI		LESI							
Scale		1990–2000							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
1990	re1	–0.051	–0.062	0.011	0.050	–0.230	–0.010	0.002	0.026
	re2	–0.074	–0.071	–0.115	–0.074	–0.176	0.001	–0.166	–0.149
	re3	–0.471	–0.425	–0.415	–0.435	–0.463	–0.480	–0.536	–0.597
	LECI	–0.426	–0.379	–0.351	–0.378	–0.432	–0.440	–0.496	–0.472
2000	re1	0.062	0.171	0.263	0.298	0.321	0.351	0.312	0.250
	re2	0.090	0.124	0.102	0.120	0.020	0.038	0.010	–0.230
	re3	0.455	0.448	0.402	0.394	0.257	0.239	0.222	0.173
	LECI	0.419	0.456	0.420	0.462	0.292	0.292	0.235	0.147
Scale		2000–2010							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
2000	re1	–0.171	–0.231	–0.253	–0.196	–0.199	–0.160	–0.117	–0.137
	re2	–0.234	–0.233	–0.271	–0.246	–0.195	–0.170	–0.143	–0.118
	re3	–0.386	–0.409	–0.382	0.377	–0.332	–0.330	–0.381	–0.407
	LECI	–0.470	–0.499	–0.499	–0.499	–0.424	–0.410	–0.392	–0.363
2010	re1	0.165	0.144	0.162	0.163	0.184	0.182	0.149	0.084
	re2	0.251	0.231	0.231	0.194	0.206	0.168	0.131	0.105
	re3	0.442	0.391	0.356	0.402	0.403	0.451	0.514	0.548
	LECI	0.533	0.470	0.437	0.476	0.455	0.468	0.417	0.435
Scale		2010–2020							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
2010	re1	–0.133	–0.130	–0.145	–0.057	0.021	0.080	0.218	0.347
	re2	–0.195	–0.162	–0.092	0.009	0.201	0.269	0.370	0.440
	re3	–0.576	–0.563	–0.544	–0.582	–0.412	–0.440	–0.428	–0.341
	LECI	–0.598	–0.557	–0.479	–0.467	–0.158	–0.120	0.003	0.164
2020	re1	0.206	0.225	0.208	0.187	0.219	0.216	0.315	0.437
	re2	0.292	0.292	0.366	0.376	0.496	0.484	0.512	0.546
	re3	0.272	0.278	0.309	0.347	0.543	0.479	0.663	0.747
	LECI	0.423	0.424	0.451	0.488	0.620	0.640	0.700	0.760

correlation coefficients for all evaluate factor decreased with the expansion of the evaluation unit, showing a more obvious change of scale effect. To a certain extent, the landscape function can represent the spatiotemporal characteristics of the landscape condition, and the data source of the landscape function is more stable and can be easily acquired, and the calculation method is clear and sophisticate. Therefore, the long-term spatiotemporal change monitoring in the future, the landscape function indices can be used as a more economical and low-cost method.

Human activity affects regional ecological function by changing surface characteristics. This phenomenon is especially true for the Shandong Peninsula coastal zone. The correlations of the four evaluation factors of landscape function, namely NDVI, NDBSI, SSI and DVI, with LESI were analyzed (Table 5). The NDBSI, which measures the degree of land drought, has the highest correlation in most evaluation scales. It is comprehensive and representative as it integrates several remote sensing indices including NDBI, SAVI, MNDWI, and SSI and analyzes and evaluates natural and artificial features such as cities, soils, and water bodies. NDVI and SSI represent vegetation and soil salinity, respectively, and reflect the important role of landscape function in landscape ecological sensitivity evaluation. DVI assesses the impact of natural ecosystem on human society, represents only a fraction of the services that natural landscape provides. For this reason, its correlation coefficient was low.

Scale effect

With the increase of the evaluation scale, the LECI and LESI basically show a downward trend, indicating that the evaluation results of landscape ecological condition and landscape

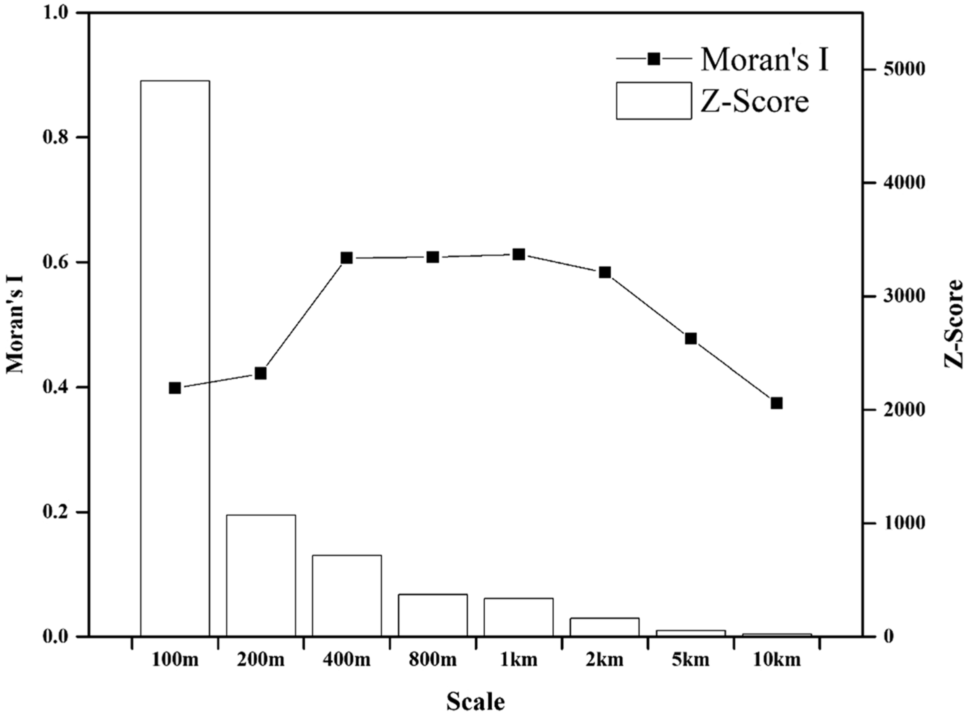
Table 5 The correlation coefficient between landscape function indices and LESI in different scale

LECI		LESI							
Year	Landscape Function Index	1990–2000							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
1990	DVI	–0.029	–0.049	–0.071	–0.071	–0.184	–0.192	–0.239	–0.270
	NDVI	0.046	0.006	–0.204	–0.200	0.260	0.330	0.066	0.068
	NDBSI	–0.036	–0.014	–0.280	–0.285	–0.302	–0.317	–0.343	–0.377
	SSI	–0.012	0.046	–0.402	–0.429	–0.368	–0.372	–0.375	–0.385
2000	DVI	–0.060	–0.025	0.041	0.041	–0.055	–0.064	–0.111	–0.161
	NDVI	0.018	–0.011	0.237	0.220	0.323	0.318	0.319	0.299
	NDBSI	–0.035	–0.007	0.400	0.386	0.377	0.355	0.376	0.380
	SSI	–0.012	–0.011	0.240	0.230	0.190	–0.207	–0.241	–0.259
Year	Landscape Function Index	2000–2010							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
2000	DVI	0.010	0.030	–0.060	–0.054	–0.049	–0.050	–0.047	–0.049
	NDVI	0.035	0.231	–0.221	–0.208	–0.191	–0.180	–0.139	–0.097
	NDBSI	–0.131	–0.247	–0.358	–0.362	–0.336	–0.335	–0.374	–0.356
	SSI	0.029	0.020	–0.232	–0.214	0.015	0.024	0.021	–0.025
2010	DVI	0.156	0.029	0.093	0.105	0.120	0.126	0.144	0.125
	NDVI	–0.012	0.013	0.134	0.137	0.056	0.065	0.093	0.106
	NDBSI	–0.165	0.010	0.311	0.341	0.331	0.369	0.381	0.388
	SSI	0.030	0.016	0.274	0.315	0.151	0.148	0.102	0.061
Year	Landscape Function Index	2010–2020							
		100 m	200 m	400 m	800 m	1 km	2 km	5 km	10 km
2010	DVI	0.071	0.073	0.075	0.084	0.255	0.267	0.361	0.497
	NDVI	0.275	–0.120	–0.508	–0.530	–0.660	–0.679	–0.744	–0.799
	NDBSI	0.652	0.630	–0.510	–0.535	–0.617	–0.640	–0.677	–0.709
	SSI	–0.262	–0.121	–0.297	–0.316	0.343	0.371	0.481	0.594
2020	DVI	0.339	0.320	0.250	0.275	0.429	0.456	0.530	0.636
	NDVI	0.128	0.129	–0.108	–0.120	–0.453	–0.474	–0.551	–0.644
	NDBSI	0.235	0.247	0.221	0.246	0.521	0.547	0.624	0.703
	SSI	0.196	0.142	0.190	0.213	0.478	0.502	0.581	0.662

ecological sensitivity continue to deteriorate on a large evaluate scale, which is roughly the same as the research results of Chi et al. (2019). Meanwhile, we used 100 m × 100 m, 200 m × 200 m, 400 m × 400 m, 800 m × 800 m, 1 km × 1 km, 2 km × 2 km, 5 km × 5 km and 10 km × 10 km, which can more clearly reflect its change process and provide more options for the best evaluation scale.

Prior research focused on spatial landscape patterns but not the impact of the scale effect on changes in landscape pattern. Applying the optimal scale for landscape pattern and ecological sensitivity evaluations accurately reflects the landscape ecological condition and fully mines and utilizes the research data. It also provides a reference for selecting the appropriate scales for spatial land planning and ecological restoration. The minimum evaluation unit was set to 100 m × 100 m. As the Landsat image resolution used in this research was 30 m × 30 m, the minimum evaluation unit can make full use of remote sensing data. However, the evaluation unit is too small to fully reflect the real situation within the unit. Taking the total edge (TE) index as an example, a patch larger than 10000 m^2 (take 100 m × 100 m evaluation units for example) may have very complex boundaries at the edge. However, because the evaluation unit was too small, if the evaluation unit is located inside a landscape patch, TE might be low; but if the evaluation unit is located at the edge of a patch, TE might be high. Therefore, although the small evaluation unit can obtain a higher LECI and LESI, there is still deviation. The coastal zone of Shandong Peninsula is a typical area with agriculture as the matrix landscape type. In the contiguous agricultural area, the landscape composition and landscape configuration were barely change. Too small evaluation unit will lead to too much redundant data, resulting in

Fig. 8 Moran's I and Z-Score of LESI in different analysis scales



the extension of the calculation and analysis process. The evaluation unit is too large (e.g., 5 km × 5 km and 10 km × 10 km) will result in too much information in the same evaluation unit, which is similar to the mixed pixels in multi-spectral remote sensing images, covering part of the original information, resulting in the deviation of the evaluation results.

Moran's I was introduced to analyze the scale effect. In this study, each evaluation unit is associated with the ones surrounding it. Moran's I is a geostatistical variable that quantify spatial element structure, characteristics, and connectivity. It can detect the correlations and connections structure between a geographic variable and its surrounding variables in two dimensional. Theoretically, the larger the evaluation unit is, the more complex the landscape pattern inside and around it. In theory, the landscape pattern within and without an evaluation unit increases and Moran's I decreases with the size of the evaluation unit. Therefore, Moran's I was used to carry out quantitative analysis of scale effect. The analysis results showed (Fig. 8) that LESI is greater than 0 on all research scales, indicating that it presents a positive state. With the increase of research scales, Moran's I showed a trend of first rising, changes slowly at 400 m to 1 km, and then falling. The maximum value appeared at 1 km, and the changes on both sides were relatively intense. The Z-score showed a decreasing trend, indicating that the aggregation mode of LESI was the most obvious in the range of 400 m to 1 km.

Therefore, to select the best scale, we should not only consider the accuracy of the evaluation results, but also consider the data redundancy, the convenience of the calculation and the applicability of the final results. Average correlation coefficients between LECI and LESI along the evaluation scales change from 100 m to 10 km were 0.307, 0.313, 0.338, 0.339, 0.348, 0.307, 0.362 and 0.379, respectively. Therefore, considering the above factors, 1 km scale was selected as the best evaluation scale, because its moderate scale size will cause least deviation of the evaluation results, and it meets the needs of research and practical application in terms of data redundancy and calculation convenience.

Suggestions for coastal zone ecological protection

After thirty years of development, urbanization is now rapidly growing in the Shandong Peninsula coastal zone. Occupation of cultivated lands by urban construction was the major land use change there. Moreover, the urbanization rate has exceeded the population growth rate. The appropriation of cultivated land and intensive coastline development and utilization have caused landscape fragmentation which has destroyed the original coastal zone ecological network system in Shandong Peninsula. Continuous declines in landscape connectivity and function are the main reasons for the deterioration in landscape ecological sensitivity in Shandong Peninsula. Seawater intrusion, storm surges, and soil salinization rendered

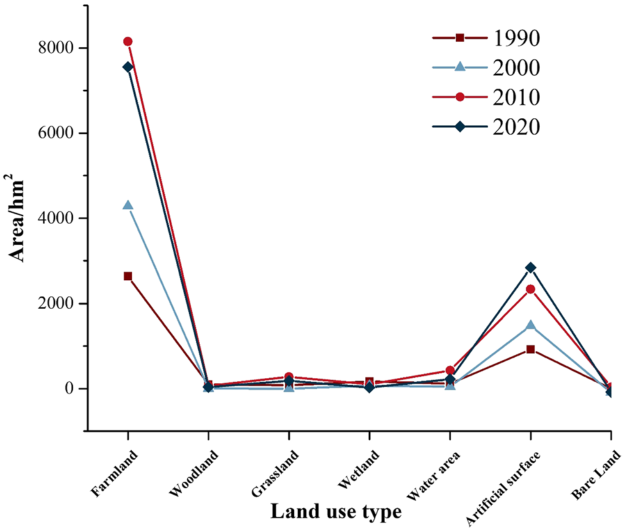


Fig. 9 Area of landscape ecological sensitivity in 4 years(hm^2)

the ecological environment of the coastal zone easy to damage and difficult to repair. The present study identified the areas in the Shandong Peninsula coastal zone with high LESI over the past thirty years. Areas with LECI < 0.5 and LESI < 0 per year were deemed to have poor landscape ecological sensitivity in each period. Cultivated land and artificial surfaces had the largest proportions of ecologically sensitive areas. Cultivated land occupied the largest proportion and had the fastest growth rate until 2020. Artificial surfaces showed a constant growth trend. The foregoing phenomena were consistent with the fact that most landscapes in Shandong Peninsula consist of cultivated land and artificial surfaces, and these are the most strongly affected by human activity (Fig. 9).

Therefore, based on the development status of the coastal zone in Shandong Peninsula, we proposed several strategies to restore coast ecosystem: (1) As urbanization and its radiation effect are largely responsible for landscape fragmentation in the region, development should be restricted, urban construction land should be limited, and land resources should be intensively utilized and land use structure should be optimized in areas with low ecological sensitivity. (2) Urban construction and population increase have reduced the water flow of the original river network, degraded its structure and function, and lost the original ecological function. Through urban waterway restoration and water source protection, the water flow of the original river network can be restored, the connectivity of hydrological network can be improved, the material and energy flow between different landscapes can be increased, and the landscape connectivity can be improved. (3) A combination of artificial and natural restoration measures can solve the problems of soil secondary salinization in coastal areas and soil heavy metal pollution in industrialized and mining areas. The evaluation results show that restoration measure in Yellow River Delta has improve LECI and LESI significantly. Moreover, agricultural product yield and quality can be ameliorated. (4) Reasonable planning for the construction of the urban green space and the ecological corridor could improve the connectivity of urban ecological network and mitigate the damage that urban expansion has caused to the original ecological network.

Conclusion

In the present work, the evaluation of landscape ecological sensitivity was conducted in Shandong coastal region. Our study solved the following questions: (1) Optimized landscape ecological sensitivity evaluation framework was assessed in a highly complex coastal area. (2) Scale effects of LECI and LESI were analyzed, the 1 km evaluation unit was proved to be the ideal spatial evaluation scale.

The evaluation results of LECI and LESI showed that, the LECI initially slightly decreased from 1990 to 2010, and then increased from 2010 to 2020. LESI also showed a "high-low–high" trend. In 2000–2010, LESI was in the worst condition due to the intense human activities. In 2010–2020, the Yellow River Delta and its surroundings had an obviously high LESI. Hence, effective ecological restoration projects can substantially improve the condition of the ecosystem. Landscape function indices, namely NDVI, NDBSI, SSI and DVI, have better correlation coefficient with LECI and LESI. Due to the reliable calculation method and continuous remote sensing data sources, landscape function indices have evolved into a more convenient and practical way in the long-time ecosystem monitor. Changes in the evaluation scale disclosed that both LECI and LESI initially decreased and then increased. Based on the evaluation accuracy, data redundancy, convenience of calculation, and applicability of the final results, 1 km was selected as the optimal evaluation scale. Several improvement strategies were proposed for landscape ecological sensitivity on the basis of the evaluation results and the optimal evaluation scale.

Appendix

Table 6 Evaluation factors

Evaluation indices		Equation	Description
Landscape composition	NL	—	Number of landscape type;
	HII	$\mathrm{HII} = \frac{\sum ANLA_i \times IC_i}{TA}$	Proportion of negative landscape type;
	HAI	$\mathrm{HAI} = \frac{\sum APLA_i \times IC_i}{TA}$	Proportion of positive landscape type;
	VC	$\mathrm{VC} = \frac{\sum \mathrm{VLA_i}}{\mathrm{TA}}$	Area of vegetation landscape in evaluation unit;
Landscape configuration	NP	—	Number of patches;
	TE	—	Length of patch;
	SWI	$\mathrm{SWI} = -\sum \left[\frac{LA_i}{TA} \times Ln\left(\frac{LA_i}{TA} \right) \right]$	Diversity of landscape;
	LII	$\mathrm{LII} = \sum \left(0.5 \times \sqrt{\frac{\mathrm{LN_i}}{\mathrm{TA}}} \times \frac{\mathrm{TA}}{\mathrm{LA_i}} \right)$	Isolation of patch
Landscape function	NDVI	$NDVI = \frac{B5-B4}{B5+B4}$	Vegetation growth situation and distribution;
	NDBSI	$NDBSI = \frac{IBI+BSI}{2}$	Soil and water conservation capacity and soil drought status;
		$\mathrm{IBI} = \frac{2\times B6/(B6+B5)-[B5/(B5+B4)+B3/(B3+B6)]}{2\times B6/(B6+B5)+[B5/(B5+B4)+B3/(B3+B6)]}$	
		$\mathrm{BSI} = \frac{(B6+B4)-(B5+B2)}{(B6+B4)+(B5+B2)}$	
	SSI	$SSI = \sqrt{B2 \times B4}$	Soil salt content and soil quality;
	DVI	—	Proximity of various natural landscapes to human activities

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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