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Spatiotemporal Evolution of Production–Living–Ecological Land and Its Eco-Environmental Response in China's Coastal Zone

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Abstract: High-intensity human activities have caused dramatic transformations of land function in China's coastal zone, putting enormous pressure on the region's ecological environment. It is urgent to fully understand the spatiotemporal evolution of the land-use function in the coastal zone to promote sustainable development. Therefore, based on CNLUCC data for 2000, 2010, and 2020, this study quantitatively explored the spatiotemporal evolution of production–living–ecological land (PLEL) and its eco-environmental response in China's coastal zone by using multiple land-use analysis methods, gradient analysis, and the eco-environmental quality index. The results showed that over the past 20 years, the production land (PL) continued to decrease, whereas the living land (LL) and blue ecological land (BEL) increased. In the vertical direction, PL and the ecological land (EL) dominated in the northern and the southern coastal zone, respectively. In the horizontal direction, with increasing distance from the coastline, the green ecological land (GEL) increased, whereas it was the opposite for BEL. The transformations of PLEL were high and low frequency in the north and south, respectively. From 2000 to 2020, the eco-environmental quality of China's coastal zone slightly degraded, with conditions that were "excellent in the south and poor in the north". The eco-environmental qualities of each sub-coastal zone gradually improved with increasing distance from the coastline. The main transformation types that led to eco-environmental improvement and degradation were from other production lands (OPL) to blue ecological land (BEL) and BEL to OPL, respectively. The findings will guide PLEL planning, eco-environmental protection, and science-based land usage.

Keywords: production–living–ecological land; spatiotemporal evolution; eco-environmental response; China's coastal zone

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1. Introduction

Coastal zones provide essential resources for human social activities and play a significant role in regulating the climate, protecting biodiversity, alleviating the pressure of human–land conflict, and controlling floods. While having an important ecosystem service function, the ecological environment is also extremely fragile and vulnerable to climate change and human activities [1–3]. Along with the drastic changes in land-use, increased human activities have resulted in coastal erosion, coastal wetland shrinkage, coastal environmental pollution, and the aggravation of coastal ecological problems [4–6]. Therefore, the research on the evolution of land function in coastal zones is significant to ensure coastal protection and ecological health.

Previous studies have mostly emphasized on the spatiotemporal variations in land-use types in the coastal zones [7–9], but the transformation of land function patterns still needs to be sufficiently analyzed. Particularly, the impact of changes in land function on the ecological environment requires further research. In 2005, Chen and Shi classified land space into production–living–ecological land (PLEL) based on the main function of the land [10]. In 2012, the Communist Party of China proposed the goals and principles of land space optimization from the perspective of PLEL [11]. The production land (PL) includes industrial zones, urban production land predominantly used to develop mineral resources, and agricultural production land (APL) for grain crops. The main function of PL is to provide industrial, agricultural, and related service products. Living land (LL) mainly includes urban construction areas for residential purposes, rural settlements, and other areas for living functions. The main function of LL is to meet the daily needs of people. Ecological land (EL) comprises natural areas such as rivers, lakes, and forests and also includes a few artificially constructed areas, such as artificial forests. In addition, it includes natural lands, such as sandy land, bare land, and beaches [12,13].

At present, much research has been carried out concerning PLEL, most of which focuses on the basic concept [14,15], classification schemes [16,17], type identification [18–20], coordination analysis [5,21,22], and its spatiotemporal evolution [23–25]. In terms of spatial scale, provinces, cities, counties, and urban agglomerations have received more attention. The continuous spatiotemporal changes in PLEL have not been sufficiently examined over long periods in large regions, especially in coastal zones, where land-use changes can be drastic, making it difficult to reflect the complete process of the spatial functional changes in coastal zones. Moreover, due to different economic development strategies and ecological spatial control measures in various regions, there may be some spatial differences in the scale, the development speed, the transformation intensity, and the evolution of hotspots in PLEL across large regions [26,27]. This differentiation in the different gradients could guide managers to formulate more scientific and reasonable regional territorial spatial planning. However, the spatiotemporal evolutionary differentiation of PLEL in coastal zones has hitherto received limited attention. In particular, the spatial aggregation characteristics of the development and degradation of PLEL have yet to be thoroughly analyzed. Gradient analysis divides the study area into gradient zones according to a specific rule. By counting the distribution of study objects in each gradient zone, the differentiation pattern of study objects in the gradient direction is explored [28]. Therefore, this study used gradient analysis to investigate the spatial and temporal evolution of PLEL along the coastal zone in both vertical and horizontal directions.

The existing research has shown that land-use transformation has greatly affected the eco-environmental quality [29–33]. However, current research has focused chiefly on the spatial identification and change characteristics analysis of PLEL, ignoring the impact of the transformation of PLEL on the ecological environment in coastal zones [13]. Moreover, due to the fragility of their ecosystem and the complexity of external interference, coastal zones have frequent ecological and environmental problems [34]. Therefore, from the perspective of PLEL, an in-depth analysis of the responses to land-use transformation on the environment in coastal zones should be further implemented and expanded. The typical methods weighing the ecological responses are ecosystem service value, remote sensing ecological index, landscape ecological risk index, and eco-environmental quality index (EI). Among them, due to its simplicity and accuracy, the EI method has been widely recognized and applied [35,36]. The authoritative experts in the research field assign EI values to each land use type through the expert evaluation method, considering the impact of each land use on the ecological environment, such as hydrology, climate, soil, atmosphere, biodiversity, etc. The range of the values is 0–1, with high values representing good ecological quality. The method explores the regional eco-environmental quality based on the EI value and area ratio of each land use type in the statistical unit [37,38]. The ecological impact rate of land use change reflects the impact of land use changes on eco-environmental improvement or degradation by calculating the change values of EI in the land use transfer areas. These two methods can reflect the eco-environmental quality status of different land types and clarify the main land use transformations that cause changes in the overall eco-environmental quality of the region [39–41]. Given the broad application of this method in China [42–44], this study adopted the EI and the ecological impact rate of PLEL change (EIR) to explore the eco-environmental response to PLEL transformation comprehensively.

According to statistics, China's coastal zone accounts for approximately 13.5% of the land area, contains 43% of the country's population, and makes up 57% of the GDP. The coastal zone has become the economic belt with the highest economic density, strongest comprehensive strength, and the largest strategic support in China [45]. However, the acceleration of urbanization and population aggregation, as well as the increase in production activities, have significantly pressured the ecological environment of the coastal zone. Therefore, in the current critical period involving the strategic transformation of China's territorial spatial planning, a comprehensive description and assessment of the spatiotemporal changes and the eco-environmental responses to PLEL in the coastal zone are vital for understanding the evolutionary process of China's territorial spatial functions in the coastal zone, coordinating the development of PLEL on land and sea, and optimizing territorial space management. Within this context, taking China's coastal zone as the study area, this study was conducted to (1) realize a thorough characterization of the spatiotemporal evolution of PLEL in the past 20 years; (2) reveal whether there were clear spatial differentiations following different gradients (horizontal and vertical) regarding PLEL; and (3) employ the environmental analysis method to discover the eco-environmental responses to the transformation of PLEL.

2. Materials and Methods

2.1. Study Area

The study area contained all coastal prefecture-level cities in mainland China, as well as four inland cities very close to the sea: Anshan, Linyi, Shaoxing, and Yulin; in addition, the islands of Hainan and Taiwan were within the study area (Figure 1). The South China Sea islands were not included in the study area because of their small sizes. To better study the spatial differentiation of PLEL evolution, according to the actual situation of land use in China's coastal zone and common intervals [28], the coastal zone within 50 km from the coastline was divided into 5 horizontal gradient zones at 10 km intervals. In the vertical direction, based on factors such as topography, climate, economy, and culture, the coastal zone was divided into 4 longitudinal subzones from north to south: the Bohai Sea (BS) coastal zone, the Yellow Sea (YS) coastal zone, the East China Sea (ECS) coastal zone, and the South China Sea (SCS) coastal zone.

Numerous studies have shown that land use in China's coastal zone has changed dramatically over the past 20 years. Di et al. indicated that the intensity of land use increased from 2000 to 2010 [46]. Du et al. found that urban land expanded rapidly at an annual growth rate of nearly 5% from 2000 to 2020 [47]. Although 41.03% of China's coastal cities have grown at high intensity in the last 20 years, the proportion of urban impervious surface has decreased, whereas that of urban green space has increased. In 2020, urban impervious surface and green space in the coastal zone accounted for 63.70% and 26.72% of the urban land area, respectively [48]. In addition to urban land, coastal wetlands also changed very frequently. From 2000 to 2010, the conversion of cropland and wetlands to construction land and natural coastal wetlands to artificial wetlands were the dominant changes in the Bohai Sea coastal zone [49]. In addition, sea reclamation has expanded the proportion of China's artificial coastline. Since 1980, the artificial coastline has increased nearly 3 times. The new land was mainly used for aquaculture, ports, and farming [50]. Considering the frequent land use changes in China's coastal zone, this study was of great practical importance to investigate the characteristics of PLEL transformation in this region.

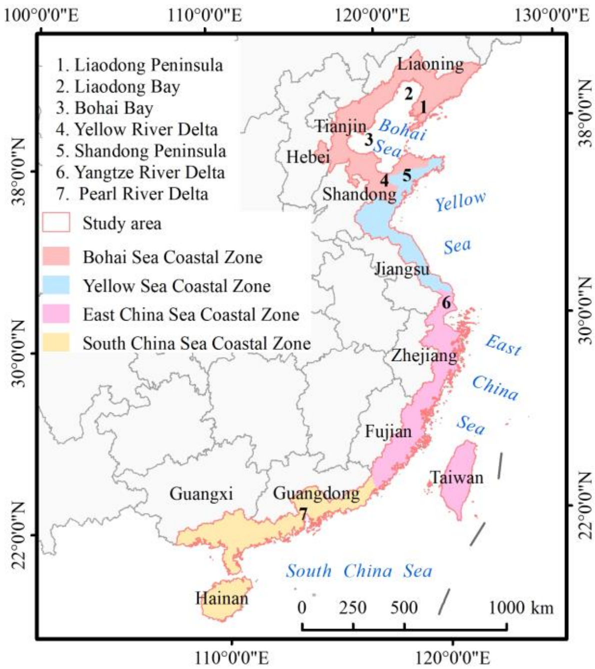


Figure 1. The location of the study area.

2.2. Data Sources

This study used CNLUCC data from 2000, 2010, and 2020. The data were developed by the Chinese Academy of Sciences at a 30 m spatial resolution (http://www.resdc.cn (accessed on 16 September 2022)). The Landsat TM/ETM images were used for interpretation. Using geoscientific knowledge and visual interpretation via the human–computer interaction, data producers characterized 6 primary and 25 secondary land-use categories. Its reasonable classification system has become one of China's most commonly used land-use classification systems. To ensure the quality and consistency of CNLUCC during each period, data corrections were made by field verification using UAV images and field survey data [51]. The overall accuracy of the primary and secondary categories was greater than 93% and 90% [52], respectively, which fulfilled the accuracy requirements of this study.

2.3. Methods

The process flow of this study was presented in Figure 2. First, according to the predominant function of the land, CNLUCC data were reclassified to PLEL. Then, the degree of single land function change (LF) and land use transfer matrix were used to explore the evolution pattern of the quantity of PLEL. Specifically, the change rates of PLEL from 2000 to 2010, from 2010 to 2020, and from 2000 to 2020 were characterized by LF. The land use transfer matrix reflected the transfer amount between the two types of PLEL. For the spatial change pattern of PLEL, the geo-informational graphic was used to generate the transformation map of PLEL from 2000 to 2010 and from 2010 to 2020, which could reveal the similarities and differences in the spatial distribution of PLEL transformation. The differentiation characteristics of the PLEL in horizontal and vertical gradients were shown according to the shoreline buffers and the north–south coastal zones, respectively, i.e., the proportions of each type of PLEL in 5 shoreline buffers and 4 sub-coastal zones were counted separately, and their spatial and temporal variation characteristics were studied. The spatial correlation of the changes in PLEL from 2000 to 2020 was analyzed using Getis-Ord Gi* to identify aggregation areas of the increases and decreases in PLEL, which could reveal trends in the development and degradation of each type of PLEL. Finally, the eco-environmental responses to the transformation of PLEL were evaluated by EI and EIR. The research unit of the environmental situation was set at 5 km $\times$ 5 km in this study, considering the expression effect and calculation efficiency. By calculating the EI values of each statistical unit in the horizontal and vertical gradient zones, the spatial distribution characteristics of eco-environmental quality in the study area at different gradients were demonstrated. EIR values were calculated during the periods of 2000–2010 and 2010–2020 to explore further the positive (EIR > 0) or negative (EIR < 0) impact of the transformation of PLEL on the eco-environment, thus specifying the relationship between the improvement or deterioration of the eco-environmental quality and the PLEL change.

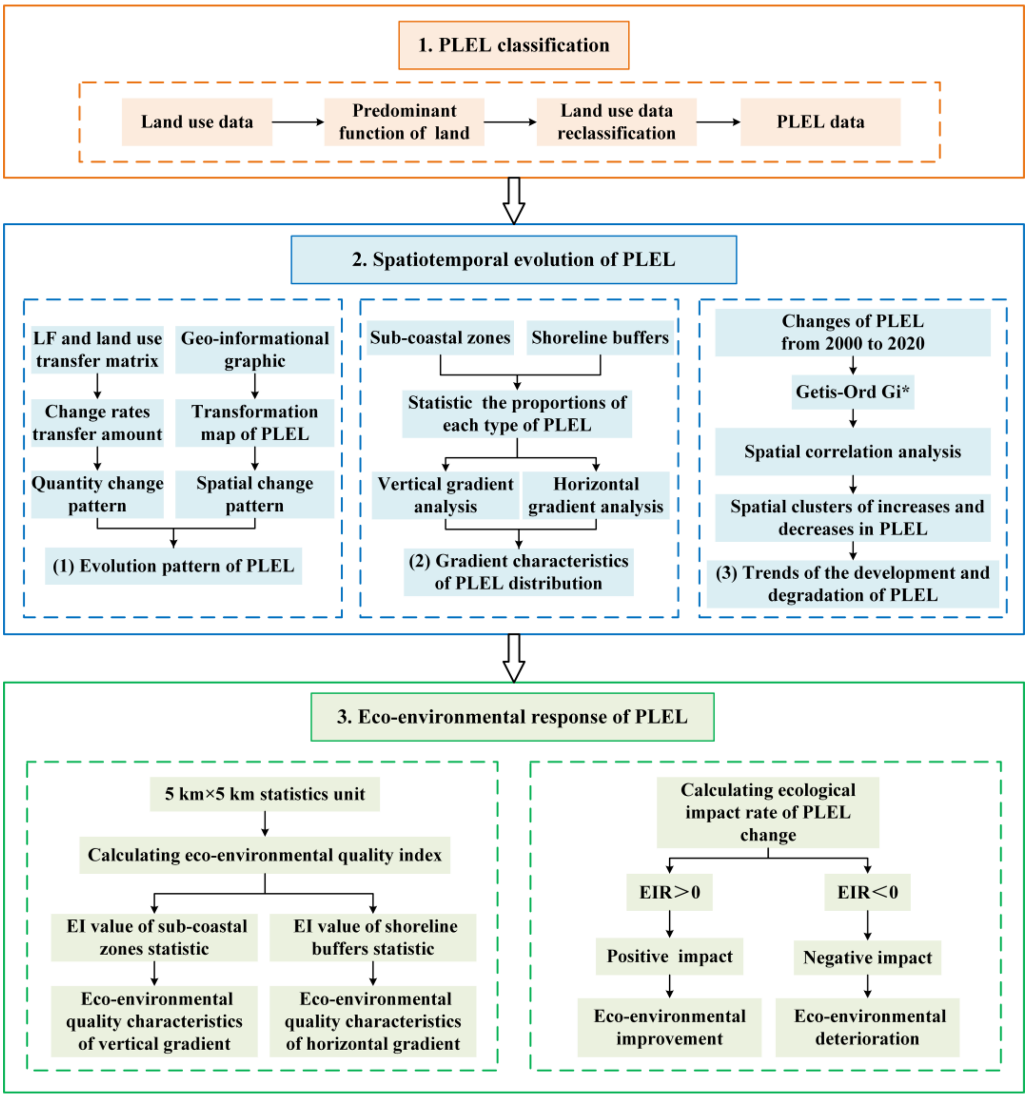


Figure 2. The workflow of this study.

2.3.1. Classification of Predominant Function of Land

A land-use type often has multiple functions, but there is generally one predominant function in terms of the primary purpose of human use of the land. For example, paddy fields not only provide food for humans, but they also have important ecological functions, such as maintaining soil fertility, preventing floods and droughts, conserving water, and improving wetland function. They have both productive and ecological functions but are primarily used for production; thus, this study classified them as PL based on their predominant function. Based on fully identifying the predominant land-use function and drawing on existing research [35,36,53,54], this study established the association between the secondary land-use type and PLEL. The third-level PLEL was gradually merged into the first- and second-level PLEL. For example, APL and other production lands (OPL) were the third-level PLEL. The APL included paddy fields and dry farmland; the OPL included other construction lands, such as industrial, mining, and transportation. APL and OPL formed PL in the first-level PLEL.

Drawing on the EI values of secondary land-use types, as introduced by Li et al. [35] and referring to the research results of many experts and scholars [32,55,56], the EI value of PLEL was assigned using an area-weighted method, taking into account the actual condition in coastal areas. Firstly, the EI values of the second- and third-level PLEL were calculated by an area-weighted method, according to the EI values and areas of the secondary classes of land use. Then, the average values of EI in 2000, 2010, and 2020 were calculated as the final EI values of PLEL. The classification of the predominant land function and its corresponding EI values are shown in Table 1.

Table 1. Classification of predominant land function and its corresponding eco-environmental quality index.

Predominant Land Function			**EI**	**Land Use (EI)**
First-Level	**Second-Level**	**Third-Level**		
Production land	-	Agricultural production land	0.28	Paddy field (0.25), dry farmland (0.3)
		Other production lands	0.15	Other construction lands such as industrial, mining, and transportation (0.15)
Ecological land	Green ecological land	Forest ecological land	0.83	Forest (0.95), shrubland (0.65), sparse forest land (0.45), other forest lands (0.4)
		Grassland ecological land	0.60	High-(0.75), medium-(0.45), and low-coverage grassland (0.2)
	White ecological land	-	0.08	Bare land (0.05), sandy land (0.01), Gobi (0.01), saline land (0.05), marshland (0.65), barren rocky land (0.01), other unused lands (0.01)
	Blue ecological land	-	0.73	Rivers (0.55), lakes (0.75), ponds (0.55), permanent ice and snow (0.9), tidal flats (0.45), beach lands (0.55)
Living land	-	-	0.20	Urban land (0.20), rural residential land (0.20)

2.3.2. Degree of Single Land Function Change

The LF reflected the quantitative changes in land function over a specific period [57]. We used this method to explore the similarities and differences in the change rates of PLEL during different periods, and its calculation formula was as follows:

$$LF = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

where LF is the degree of single land function change (%); U_a and U_b represent the area of PLEL at the initial and final stages of the study, respectively (km^2); and T is the monitoring period.

2.3.3. Spatial Correlation Analysis

Getis–Ord Gi* is a local autocorrelation index that could indicate the spatial heterogeneity of the distribution of study objects. In order to reveal the strengthening or weakening trends in the land function from 2000 to 2020, this study explored the statistically significant hotspots and cold-spots of the aggregation areas of the development and degradation of PLEL, according to the following formula:

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} x_j - \overline{X} \sum_{j=1}^{n} W_{ij}}{S \sqrt{\frac{n \sum_{j=1}^{n} W_{ij} - \left(\sum_{j=1}^{n} W_{ij}\right)^2}{n-1}}} \tag{2}$$

where X_j is the attribute value of unit *j*; W_{ij} represents the spatial weight between unit *i* and unit *j*; *n* is the total number of statistical units; *S* is the standard deviation of the attributes of *n* units; and $\overline{X}$ is the average of the attributes of the *n* units.

2.3.4. Eco-Environmental Response

1. Eco-environmental Quality Index

This study quantitatively reflected the ecological situation by calculating the EI values of the PLEL in a statistical unit [58]. The formula used was the following:

$$EI = \sum_{i=1}^{N} \frac{A_{ki}}{A_k} R_i \tag{3}$$

where *EI* means the eco-environmental quality index, A_{ki} means the area of the *i*th type of PLEL, A_k means the area of statistical unit, R_i means the *EI* of the *i*th PLEL, and *N* means the amount of PLEL types.

2. Analysis of the Characteristics of Eco-Environmental Quality

To understand the status of eco-environmental quality in the whole coastal zone, we categorized the EI values of each year into 5 grades according to the regularity of their natural transitions [13,35,42,48], and the grades from lowest to highest were as follows: low-quality area ($EI \leq 0.16$), lower-quality area ($0.16 < EI \leq 0.40$), moderate-quality area ($0.40 < EI \leq 0.54$), higher-quality area ($0.54 < EI \leq 0.68$), and high-quality area ($EI > 0.68$).

3. The Ecological Impact Rate of Production–Living–Ecological Land Change

The EIR could further isolate the types of PLEL changes that improved or deteriorated the eco-environment, thus guiding our exploration of the leading factors causing environmental changes [59]. The formula used was the following:

$$EIR = (EI_t - EI_0)LA/TA \tag{4}$$

where *EIR* represents the ecological impact rate of PLEL change; EI_t and EI_0 are *EI* values of a particular PLEL category at the end and beginning of the study, respectively; *LA* represents the area of the changed PLEL category; and *TA* represents the overall area of the study area.

3. Results

3.1. Distribution of PLEL

As shown in Figure 3, the distribution of PLEL from 2000 to 2020 was essentially the same. PL was primarily located in the northern coastal zones (the BS and YS zones). The green ecological land (GEL) was primarily in the ECS and SCS coastal zones and in the northeastern part of the YS coastal zone. The white ecological land (WEL) had a small area and was scattered inland of the coastal zone. The blue ecological land (BEL) was primarily found in Bohai Bay (BHB) and the southern coastal zone of the YS. The pattern of LL showed "large dispersion and small aggregation".

According to the pie charts in Figure 3, the proportions of each PLEL type over three years were similar, and the proportions from large to small were observed for GEL, PL, LL, BEL, and WEL. From 2000 to 2020, the proportion of PL gradually shrank from 44.03% to 41.57%. In contrast, LL expanded from 6.39% to 9.47%. Compared to the previous two types, the proportion of EL showed little change.

3.2. Evolution Pattern of PLEL

The dynamic degree of PLEL in the coastal zone during 2000–2020 was calculated using Formula (1), and the results are shown in Table 2. Except for the LL and BEL, all other types showed a shrinkage. The most dramatic decrease in WEL between 2000 and 2010 was accompanied by a significant increase in LL, which could be explained by the rapid economic development and urban expansion during this period. GEL had the smallest dynamic degree among the five lands, reflecting the policies concerning the conservation of forest–grass land. In terms of inter-year variation, there was a large increase in LL and a large decrease in PL and GEL. The change in PL in the first decade was much smaller than in the second decade, and the opposite was true for the other PLEL types.

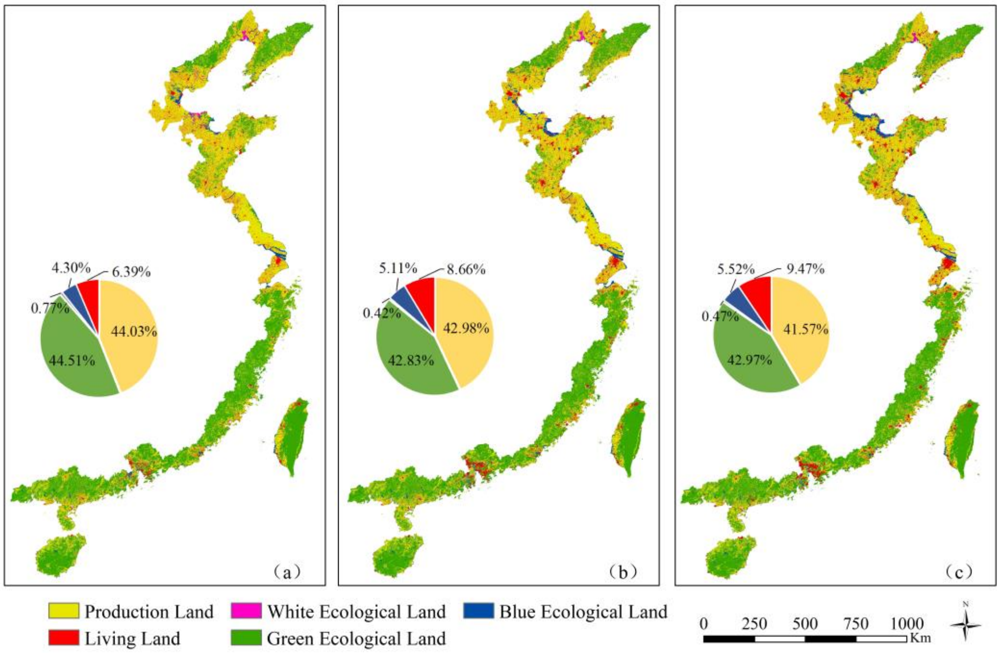


Figure 3. The distribution of PLEL in China's coastal zone in (**a**) 2000, (**b**) 2010, and (**c**) 2020.

Table 2. Inter-year variation and dynamic degree of PLEL from 2000 to 2020.

	2000–2010		2010–2020		2000–2020	
	Inter-Year Variation (km^2)	Dynamic Degree (%)	Inter-Year Variation (km^2)	Dynamic Degree (%)	Inter-Year Variation (km^2)	Dynamic Degree (%)
Production Land	−4798.30	−0.21	−7154.39	−0.32	−11,952.69	−0.26
Green Ecological Land	−8065.85	−0.35	865.17	0.04	−7200.68	−0.16
White Ecological Land	−1803.70	−4.50	254.35	1.16	−1549.35	−1.94
Blue Ecological Land	4251.65	1.91	2190.68	0.83	6442.33	1.44
Living Land	11,908.11	3.59	4235.79	0.94	16,143.90	2.43

Figure 4 shows that the transformations of PLEL during each period were highly similar, and the sizes of the transferred out in descending order were observed for PL, GEL, LL, BEL, and WEL, respectively. The largest transferred-in area during each period was for the LL type, consistent with the evidence that LL had expanded dramatically. For the transformation of PL, the areas transformed into LL during each period were the largest, followed by GEL. This indicated that a large amount of PL had been occupied during urban expansion, and the occupied areas in the former decade were more than twice those in the latter decade. Meanwhile, the national measures of returning arable land to forest and grassland transformed PL into GEL, with a total conversion of 9200 km^2 over the past 20 years. There was also a transformation from GEL to PL during various periods, which resulted in the largest decrease in GEL, indicating that some areas were still developing production by occupying forests and grasslands. From 2000 to 2020, the net conversion from GEL to PL was 4590 km^2. BEL was primarily transformed into PL, GEL, and LL, and the LL was primarily transformed into PL and GEL. Transformations from WEL were the smallest among all transformation types, only 2750 km^2, and the transformations to WEL were 1180 km^2.

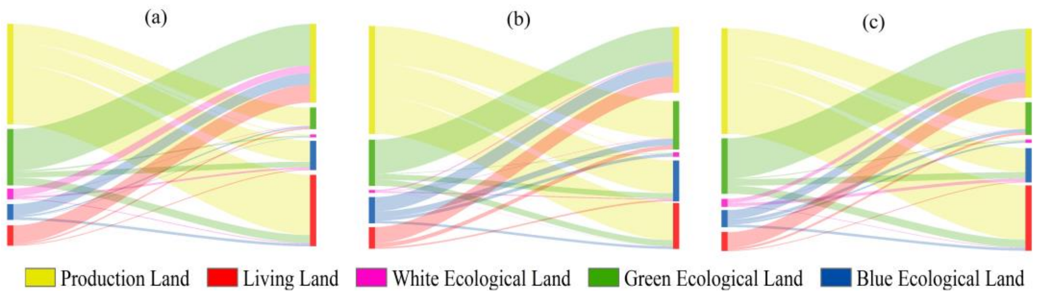


Figure 4. Transformations of PLEL during (**a**) 2000–2010, (**b**) 2010–2020, and (**c**) 2000–2020.

As shown in Figure 5, the transformations in PLEL in 2000–2010 and 2010–2020 were fragmented. The areas transformed into LL were primarily distributed around the city, and the increase in LL from 2000 to 2010 was significantly more than that from 2010 to 2020. From 2000 to 2010, the most dramatic transformations were found in the Yellow River Delta (YRD) coastal zone and the Pearl River Delta (PRD). As shown in the yellow box in Figure 5a, a large area of PL in the YRD coastal zone was transformed into BEL. In 2001, the General Office of the State Council approved the adjustment scheme of the functional area of the YRD Nature Reserve to improve the conservation of the ecological environment of wetlands. Based on the changes mentioned above, the protection measures achieved remarkable results. In addition, a large amount of WEL was converted to PL and BEL, and some GEL was converted to other types of PLEL in this region. As shown in the blue box area in Figure 5a, massive PL in the PRD was transformed into BEL. Moreover, there was a large amount of PL and BEL converted into LL in this region, indicating that urban expansion in that period was primarily by encroaching on arable land and reclamation projects. The boxed area of Figure 5b demonstrated that large-scale conversion of PL to BEL occurred from 2010 to 2020, reflecting the continuous strengthening of wetland protection measures.

3.3. Gradient Characteristics of PLEL Distribution

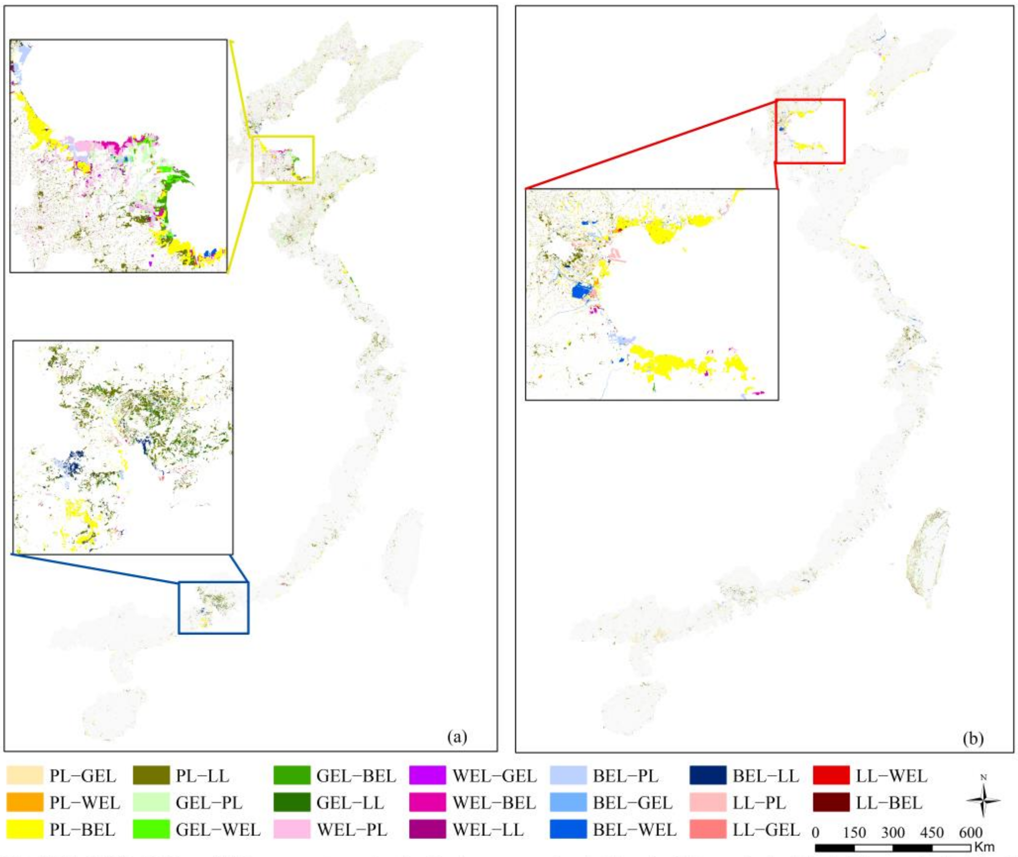
3.3.1. Characteristics of Vertical Gradient

In the vertical direction, the proportion of PLEL in each sub-coastal zone of China had clear differences (Figure 6). From north to south, PL first increased and then decreased. Among the sub-coastal zones, the YS coastal zone had the largest share of PL, followed by the BS coastal zone. Contrary to the vertical change characteristics of PL, the percentage of GEL first decreased and then increased, accounting for more than 58% in the ECS and the SCS coastal zones and only approximately 12% in the YS coastal zone. The proportions of white and blue ecological lands in each sub-coastal zone were small, and the LL in the BS and YS coastal zones was higher than that in the ECS and SCS coastal zones. In general, the distribution of PLEL in China's coastal zone showed vertical patterns of "PL in the north and EL in the south".

Regarding changes in PLEL percentages for each sub-coastal zone, PL continuously decreased from 2000 to 2020, whereas LL had the opposite trend. BEL showed an increasing trend in each sub-coastal zone, and the increase in the northern coastal areas (the BS and YS zones) was larger than that in the southern coastal areas (the ECS and SCS zones). The change in WEL showed no evident regularity. Factors such as economic growth, population agglomeration, and urban expansion have led to the constant occupation of EL by PL and LL. In particular, the decreasing trend in GEL in the northern coastal zone was apparent, indicating the urgency of implementing EL control measures.

3.3.2. Characteristics of Horizontal Gradient

Figure 7 shows that the spatial patterns of PLEL in China's coastal zone during different periods were similar in the horizontal direction. Within 20 km from the coast, PL accounted for the highest proportion of over 40% each year, followed by GEL, accounting for more than 30%. Within the 20–50 km offshore range, the proportion of GEL exceeded that of PL and became the dominant type. LL of coastal areas (10–50 km) exceeded BEL and became the third category in area proportion, indicating that the urban expansion in inland areas (10–50 km) was drastic, and the urban development in coastal areas (0–10 km) advanced in parallel with the coastal protection.



PL, GEL, WEL, BEL, and LL represent production land, green ecological land, white ecological land, blue ecological land, and living land, respectively.

Figure 5. Transformation map of PLEL during (**a**) 2000–2010 and (**b**) 2010–2020.

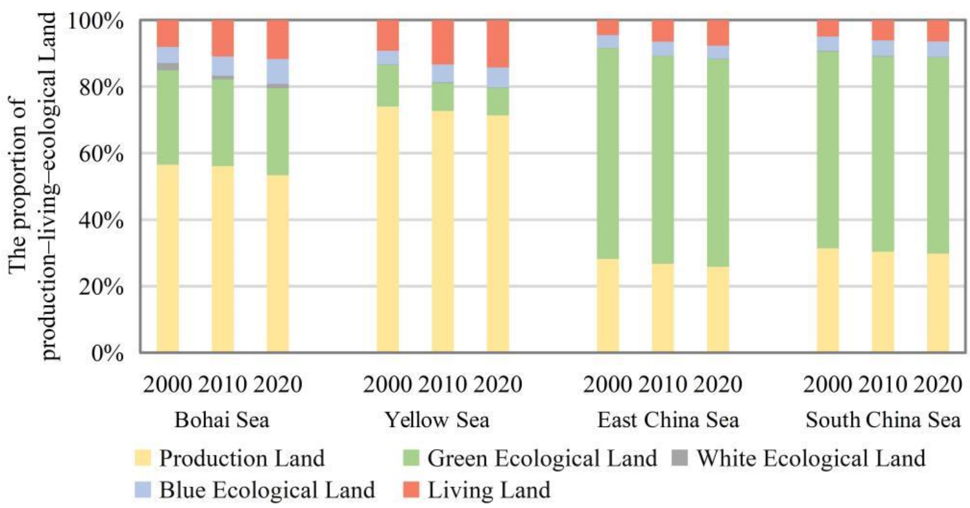


Figure 6. Proportion of PLEL in each sub-coastal zone of China during different periods.

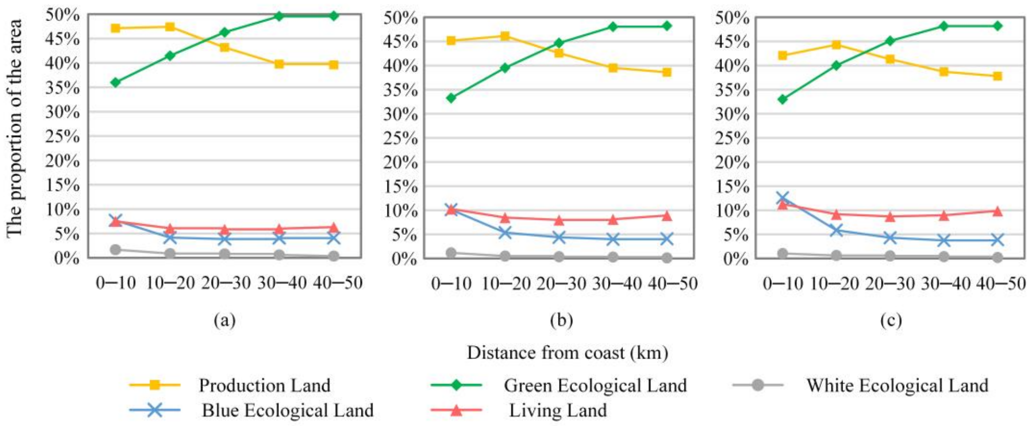


Figure 7. Changes in PLEL in China's coastal zone according to the distance from the coast in (**a**) 2000, (**b**) 2010, and (**c**) 2020.

The change in PLEL in the distance from the coast was consistent across different periods. The proportion of PL increased within 0–20 km from the coastline and then reduced as the distance from the coast increased. The proportion of GEL was positively correlated with the distance from the coast, and its proportion increased rapidly in the range of 0–40 km as the distance from the coast increased. The changing trend in BEL was opposite to that of GEL, i.e., the more inland it became, the smaller the proportion of BEL. The proportion decreased rapidly in the 10–20 km range from the coast and then slowed down, gradually maintaining at approximately 4%. The LL first shrank and then slowly expanded, and the area obviously decreased within 10–20 km away from the coast, which could have been related to the increase in PL and GEL in the same region. The area proportion of WEL in each offshore area during each period was less than 1.17%, and the changes were not evident. In short, the nearshore area (0–10 km) was primarily the PL and LL, whereas inland GEL gradually increased. Therefore, regarding the utilization of coastal zones, ecological protection should be strengthened to minimize the influence of human activity on the ocean.

3.4. Hotspot Analysis of Development and Degradation of PLEL

The hotspots of inflow and outflow of PLEL were analyzed to reflect their development and degradation. Hotspot analysis indicated that the increases in PL transformation from 2000 to 2020 were largely concentrated in the northern coastal plain, and PL increases in Liaodong Peninsula, BHB, Shandong Peninsula, and the western part of Taiwan showed significant aggregation (Figure 8). However, the increase in PL transformation in the coastal areas of Jiangsu, the eastern part of Taiwan, and south of Hainan presented significant cold-spot aggregation, indicating that these areas were not prone to conversion into PL. The high-incidence areas of GEL inflow were aggregated in Liaodong Bay, the southern region of Guangxi, and the coastal areas of Taiwan. Increases in GEL transformation in BHB coastal areas and most coastal areas in Jiangsu showed significant low-value aggregation. The increase in WEL transformation showed a significant high-value aggregation in BHB coastal area and Shanghai, whereas the spatial distribution characteristics were not significant in other regions. The transformation into BEL was aggregated in the coastal areas of BHB, Jiangsu, and the PRD. The aggregation areas of LL development were aggregated in the BS coastal zone, YS coastal zone, and the PRD. In general, it manifested as high-value aggregation on the northern coast and low-value aggregation on the southern coast, indicating that the northern region was prone to transform into LL.

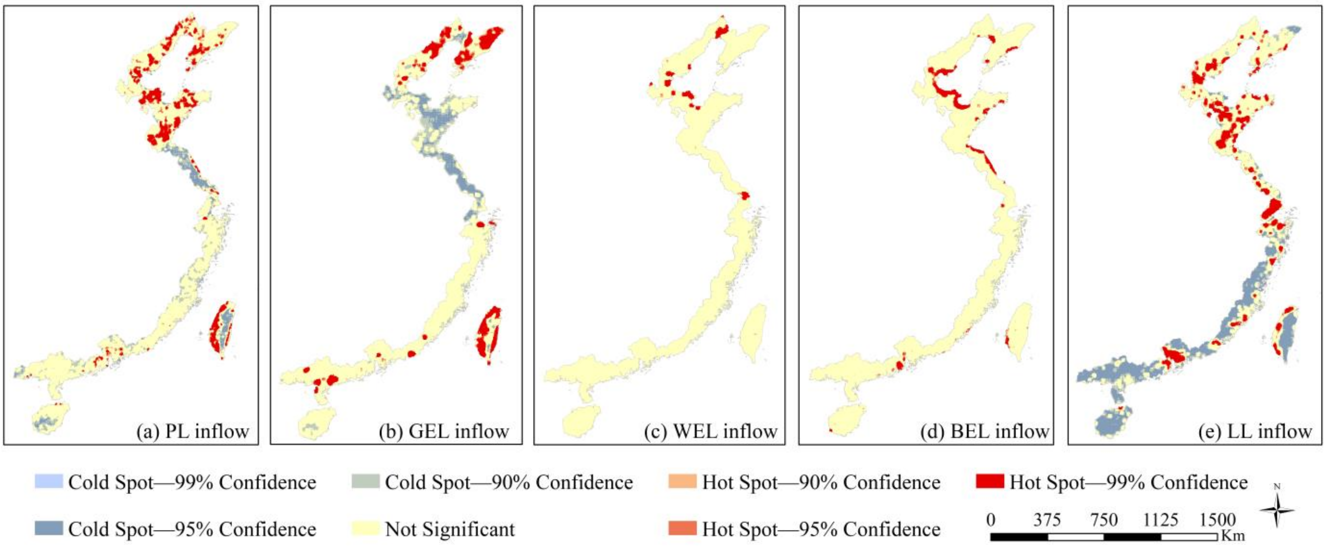


Figure 8. Spatial correlation analysis of the inflow of (**a**) production land, (**b**) green ecological land, (**c**) white ecological land, (**d**) blue ecological land, and (**e**) living land.

The outflow of the PL was similar to that of the inflow of the LL (Figure 9). The high-value agglomerations were dispersed and widespread, and the high incidence of PL loss on the northern coast was significantly larger than on the southern coast. The significant aggregation areas of GEL degradation were primarily located along the southern coast of YS. The Liaodong Peninsula, Shandong Peninsula, and the western Taiwan coastal zones were characterized by significant hotspots of GEL loss. The loss of WEL was aggregated in the coastal areas of BHB, whereas the loss in other areas was not significant. The loss of BEL was primarily distributed in BHB, Yangtze River Delta, and PRD. The high-incidence areas of LL loss were primarily aggregated in the BHB, Shandong Peninsula, western Taiwan, and PRD. The loss of LL on the northern coast was far more than that on the southern coast.

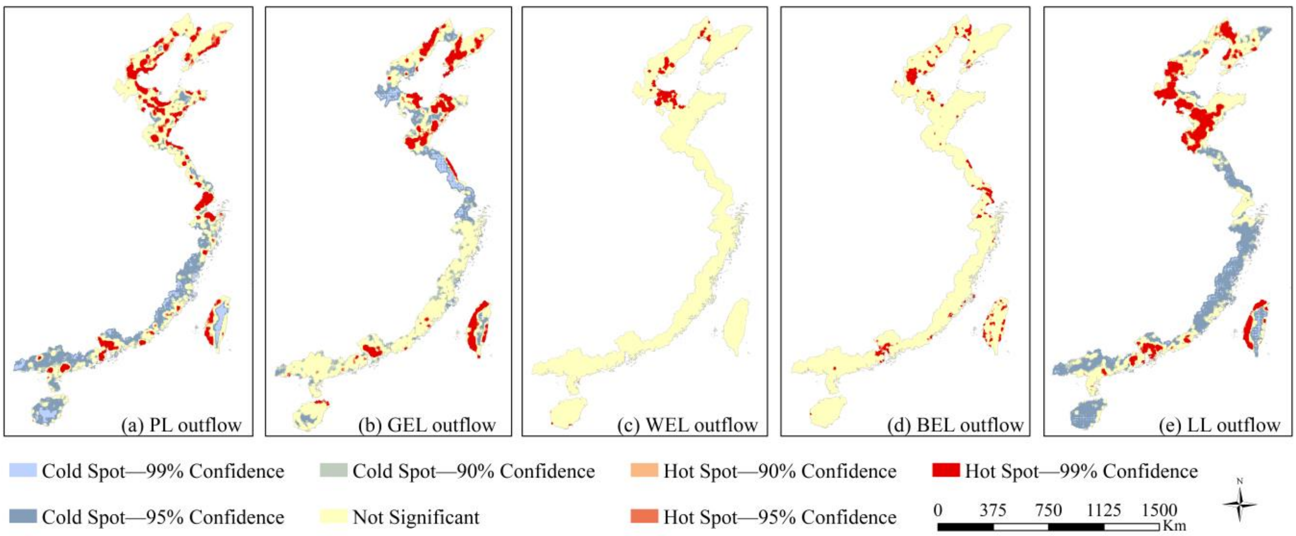


Figure 9. Spatial correlation analysis of the outflow of (**a**) production land, (**b**) green ecological land, (**c**) white ecological land, (**d**) blue ecological land, and (**e**) living land.

In general, the spatial transformations of PLEL in the northern coastal area were more frequent than in the southern coastal area; thus, the changes in land use on the northern coast were more frequent. In addition, we found that the high-incidence areas of PL loss were greater than those of its development. This could have been due to the economic structural transformation and urban expansion encroaching on cultivated land, which aggravated the loss of PL. Some intersections in the high-incidence areas of GEL development and degradation were aggregated in the coastal areas of Liaodong Bay and Taiwan. These areas showed evident changes in GEL due to the influence of governmental policies and the environment. By contrast, most areas of the Jiangsu coastal zone showed significant cold spots, indicating less fluctuation in GEL in these areas. The high-incidence areas of WEL transformation were relatively small, and most areas showed insignificant spatial distribution characteristics. The development and degradation of BEL intersected at hotspots in the BHB and the PRD, indicating that BEL was frequently exchanged with other land types in these areas. The regional distributions of most hot- and cold-spots in the development and degradation of LL were similar. This showed that there were significantly higher incidences of LL spatial transformation, which were primarily distributed in the densely populated BHB, the YS coast, the Yangtze River Delta, and the PRD.

3.5. Eco-Environmental Response Analysis

3.5.1. Eco-Environmental Quality Index Analysis

For a complete understanding of the eco-environmental qualities of the study area, the change patterns were analyzed based on vertical and horizontal gradients. As illustrated in Figure 10a, the eco-environmental quality of China's coastal zone has experienced a slight degradation trend over the past 20 years. From north to south, the EI values first reduced and then increased, and the quality of the YS coastal zone was the worst. Overall, the quality of the southern coast was better than that of the northern coast. In 2010, the difference in the EI between the SCS coastal zone and the YS coastal zone was the largest; the former was 0.29 higher than the latter.

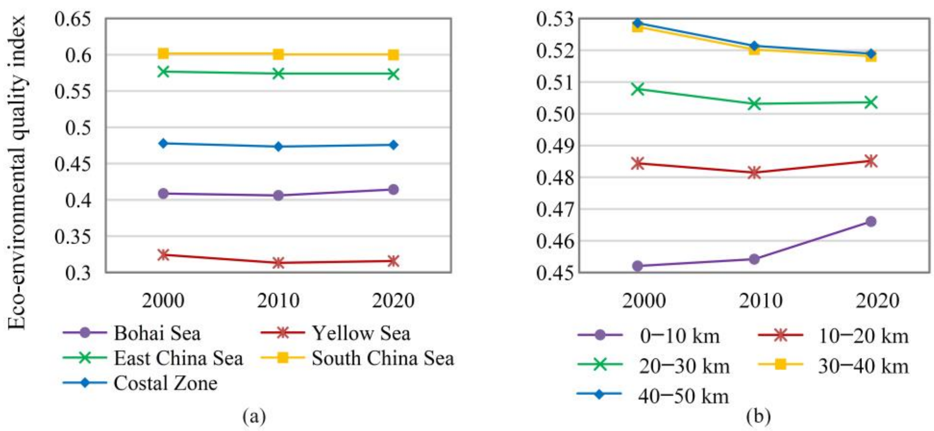


Figure 10. Eco-environmental quality index of China's coastal zone in (**a**) vertical gradient and (**b**) horizontal gradient from 2000 to 2020.

As illustrated in Figure 10b, regarding the horizontal gradient, the EI value of each coastal zone exhibited a clear regularity. The quality of the coastal zone was gradually optimized as the distance from the shoreline increased. This could have primarily been related to the high intensity of development in the offshore area, causing a large encroachment of LL and PL on EL. From 2000 to 2020, the EI values of areas within 30–50 km, 10–30 km, and 10 km from the coastline continued to decrease, decreased and then increased, and continued to increase, respectively. It indicated that the eco-environmental qualities in the areas near the coastline were improving, whereas those in the inland areas were not.

3.5.2. Spatial Characteristics of Eco-Environment Quality

As illustrated in Figure 11, the distribution of eco-environmental qualities in China's coastal zone varied significantly. The large contiguous lower-quality areas appeared in the BS and YS coastal zones. The eco-environmental qualities of the coastal zones in most areas of Hainan and Taiwan were relatively high, and other high-quality areas were scattered among the coastal zones of ECS, SCS, and the inland area of the Liaodong Bay Peninsula. From 2000 to 2020, the distribution of the eco-environmental qualities in China's coastal zones changed slightly, with low-quality areas on the northern coast and high-quality areas on the southern coast.

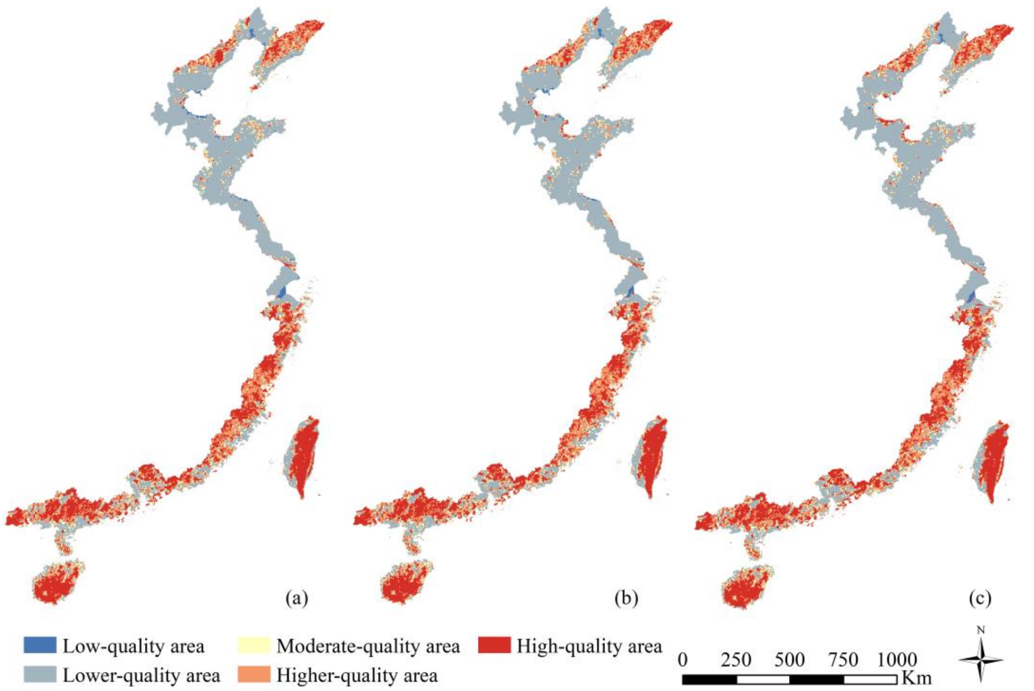


Figure 11. Spatial distribution of eco-environmental qualities of China's coastal zone in (**a**) 2000, (**b**) 2010, and (**c**) 2020.

3.5.3. Ecological Impact Rate of PLEL Transformation

As shown in Table 3, during the 2000–2010 and 2010–2020 periods, the top two impact rates of optimizing the ecological quality were the transformation from OPL to BEL and APL to forest ecological land (FEL). The former was the transformation type with the largest impact during the two periods, accounting for 53.12% and 63.37%, respectively, indicating that the governmental policy of protecting wetlands and marine areas had greatly improved the ecological qualities of the coastal zones. The transformation from APL to BEL, or FEL, improved ecological and environmental qualities over the past 20 years. Furthermore, the transformation from PL or grassland ecological land (GLEL) to BEL or FEL greatly improved the ecological quality.

The structural transformations of PLEL that caused ecological degradation during the two periods were primarily the transformations from BEL to OPL, from GLEL to APL, from APL to LL, and from BEL to WEL. In general, the transfer from EL to LL and PL greatly reduced the eco-environmental qualities. Particularly, the loss of GLEL, BEL, and FEL with high EI values caused a remarkable negative effect on the ecological environment. Additionally, the internal transformation of EL also led to some degradation of the ecological and environmental qualities, such as the transformation from BEL to GLEL or WEL and the transformation from GLEL to WEL. Therefore, in ecological and environmental management, we should not only prevent the loss of EL but also monitor the local deterioration within EL.

Table 3. Major transformations and impact rates of PLEL on the ecological quality of China's coastal zone during different periods.

Eco-Environmental Change	2000–2010			2010–2020		
	Transformation Model	EIR	(%)	Transformation Model	EIR	(%)
Eco-Environment Improvement	OPL→BEL	0.012050	53.12	OPL→BEL	0.030563	67.37
	APL→BEL	0.002889	12.74	APL→FEL	0.008495	18.73
	WEL→BEL	0.002020	8.90	APL→BEL	0.001512	3.33
	APL→FEL	0.002004	8.84	APL→GLEL	0.001268	2.79
	GLEL→FEL	0.001028	4.53	GLEL→FEL	0.000717	1.58
	GLEL→BEL	0.000767	3.38	WEL→BEL	0.000667	1.47
	Total	0.020758	91.51	Total	0.043221	95.27
Eco-Environment Deterioration	GLEL→APL	−0.005273	19.07	BEL→OPL	−0.003818	21.99
	APL→LL	−0.005089	18.40	BEL→WEL	−0.003533	20.35
	BEL→OPL	−0.003548	12.83	BEL→APL	−0.001706	9.82
	FEL→APL	−0.002961	10.71	FEL→OPL	−0.001387	7.99
	BEL→APL	−0.002071	7.49	APL→LL	−0.001346	7.75
	FEL→LL	−0.001327	4.80	APL→OPL	−0.001270	7.31
	APL→OPL	−0.001315	4.75	FEL→APL	−0.001191	6.86
	BEL→LL	−0.001127	4.07	FEL→LL	−0.000705	4.06
	FEL→OPL	−0.001118	4.04	BEL→LL	−0.000585	3.37
	GLEL→WEL	−0.000867	3.14	BEL→GLEL	−0.000333	1.92
	Total	−0.024696	89.30	Total	−0.015875	91.43

Note: APL, OPL, BEL, FEL, GLEL, LL, and WEL represent agricultural production land, other production lands, blue ecological land, forest ecological land, grassland ecological land, living land, and white ecological land, respectively.

4. Discussion

4.1. The Accuracy of PLEL Classification

Currently, the existing identification approaches for PLEL are land-use data consolidation, index measurement, and social-perception data classification. The differences in cognitive perspectives and theoretical foundations, the indicator system's diverse characteristics, and the accessibility of multi-source data make the latter two methods difficult to apply widely [60]. As land-use data consolidation was widely used and better suited to studies concerning large regions, we chose this method to classify PLEL.

The accuracy of the land-use data and the fineness of its categories directly affected the accuracy of PLEL. However, most land-use data are classified using only the spectral and textural information present in remote sensing images and could not, therefore, reflect the social and economic attributes generated by human activities, resulting in classification errors in PLEL [61]. For example, some artificial buildings are PL, such as factories, warehousing, and logistics, whereas others are LL intended for residential uses, such as homes and restaurants, but it is difficult to distinguish their types using only remote sensing images. As a result, some land-use data classified all buildings as urban land and did not carefully distinguish between PL, such as factories, and LL, such as residential areas. If such land-use data were used to classify PLEL, some industrial production land could be omitted.

In this study, the CNLUCC dataset was selected to avoid these errors. In contrast to the traditional land-use classification data, the producers of the CNLUCC dataset had developed a land-use classification system with detailed categories, integrated expert experience and geoscientific knowledge in the classification process, and they referred to other auxiliary data as well, such as topographic, vegetation, and land-use planning maps, and so on. The other construction lands in its secondary category included industrial, mining, and transportation, which easily delineated PL and LL areas and avoided any misclassification. The quality control of the CNLUCC and its remote sensing interpretation strictly observed the following standards: (1) the accurate rates of arable land, as well as urban and rural settlements, were not less than 95%; (2) the accurate rates of grassland, forest land, and water were not less than 90%; and (3) the accurate rate of unused land was not less than 85%. Therefore, in terms of both the accuracy and granularity of the classification system, the CNLUCC dataset is high-quality data for classifying PLEL and has been widely used for PLEL research [13]. This study could obtain the PLEL data that fulfilled the accuracy requirement at a macro-scale based on the CNLUCC dataset. Therefore, the results of the transfer area, inter-year variation, dynamic degree, and the ecological impact rate measured by PLEL data have a high degree of confidence. However, this method had some limitations when reflecting the multi-functional properties of land. Usually, the land has composite characteristics, i.e., mixed lands such as living-production land and production-ecological land. The single model of ecological, production, and living land cannot capture the coupled interaction characteristics of the land. However, very few studies have considered multi-functional land use in coastal areas, which should be the focus of future research.

4.2. Issues Involved in the Eco-Environmental Response of PLEL

Over the past 20 years, the distribution and the eco-environmental response of PLEL in China's coastal zone have had evident gradient characteristics caused by governmental policies, nature, and other factors. The northern coastal zone, with low terrain and fertile soil, is situated on the Northeast Plain and the North China Plain. It is an essential industrial and agricultural production base for food, vegetables, and coal in China; therefore, its main PLEL type was PL. The distribution of GEL in the north was less than that in the south, consistent with the latitudinal zonal distribution of the vegetation in China. Affected by heat and precipitation, the vegetation in the southern low-latitude areas grows densely and extensively; thus, the distribution of GEL was higher in this region. Coastal areas have superior geographic locations, convenient transportation, and large population densities, and these areas have been affected by the governmental open-cities and coastal open-area economic policies; thus, they have incomparable advantages over inland areas in terms of their economic foundation, technological infrastructure, and capital allocation. Therefore, based on the horizontal gradient, coastal human activities were more intensive, and the distributions of PL and LL were broader than those in inland areas. Affected by the distribution of PLEL, the qualities of the ecological environment indicated that the southern coastal zone was better than the northern coastal zone, and the inland region was better than the coastal region. Therefore, the coordination of regional land development, arable protection, and ecological and environmental construction should be emphasized to optimize resource allocation and protect the ecological environment in coastal areas.

The coastal areas are affected by the interaction between land and ocean systems. Therefore, the marine ecological environment may be damaged by land changes. According to the hotspot analysis in Section 3.4 and the China Marine Ecological Environment Bulletin in 2020, we found that there was a high correlation between the sea area corresponding to the hotspot area of LL development and poor seawater, indicating that the high intensity of human activities not only affected the land ecological environment but also had negative effects on the adjacent seawater.

Additionally, the China Marine Ecological Environment Bulletin emphasized that in 2000 and 2010, the four major sea areas, in descending order of pollution, were the ECS, BS, SCS, and YS. The BS and YS areas that did not meet first-class seawater quality standards increased yearly, whereas those of the ECS and SCS decreased yearly. The water quality of the ECS and BS was poor during the early years of the study, which could have been influenced by the implementation of the governmental foreign economic opening policy. During this period, the economy developed rapidly, forming an open economic coastal zone, and the exploitation degree in this region was continuously strengthened. Land reclamation projects destroyed the coastal zone ecosystem and increased marine pollution. The water quality of the ECS over the past 20 years was poor among the four major sea areas, whereas, in Section 3.3.1, we showed that EL in the ECS coastal zone was far larger than that in the BS and YS, which indicated that the factors causing the degradation of the marine ecosystems were diverse. Considering only the patterns of PLEL could not fully explain the changes in the marine ecological environment. Therefore, further studies about the comprehensive eco-environmental response of sea and land during the development of coastal zones should be conducted to guide the reasonable layout of land function.

4.3. Issues Involved in the Application of PLEL Evolution Research

Although LF has been widely used in land use change studies, it is unable to capture changes between two PLELs with different locations and attributes but the same amount. Therefore, this study adopted multiple methods to reveal the differentiation pattern of PLEL evolution in China's coastal zone at different periods. The land use transfer matrix was used to capture the quantitative transfer between the two PLELs, the spatial distribution of the transition between the two PLELs was depicted by the geo-informational graphic, and the hot spot analysis was used to identify the aggregation areas of PLEL development or degradation. However, none of these studies addressed the intensity characteristics. It has been shown that intensity analysis can monitor the intensity of transfer between land use categories at different time points [12]; thus, it is necessary to carry out investigations on PLEL intensity analysis in future studies. In addition, PLEL transitions are differentially influenced by natural resources, regional development orientation, infrastructure, and transportation; thus, further research on PLEL evolution impact mechanisms is needed.

5. Conclusions

This study combined various analysis methods to investigate the spatiotemporal evolution and the gradient effects of PLEL in China's coastal zone. In addition, the eco-environmental response to the PLEL transformation was discussed. The main findings were the following:

(1) There were evident regional distinctions in the spatial distribution of PLEL. PL and BEL were mostly distributed in the northern coastal zone, GEL was mostly distributed in the southern coastal zone, and LL was scattered.

(2) Regarding dynamic evolution, PL consistently decreased, whereas LL and BEL increased, and EL showed a slightly shrinking trend. The transformation of PLEL in the northern coastal areas was more frequent. The new LL and GEL were primarily converted from PL, and the new PL was primarily converted from GEL.

(3) In the vertical direction, the PLEL scales of each sub-coastal zone in China had evident differences. From north to south, PL first expanded and then shrank, whereas GEL was the opposite. In the horizontal direction, the nearshore areas (0–10 km) were primarily PL and LL. As the distance from the coastline increased, GEL and BEL increased and decreased, respectively.

(4) From 2000 to 2020, the eco-environmental quality slightly degraded, showing that the south was superior to the north. It was positively correlated with the distance from the coastline. The transformations from OPL to BEL and from BEL to OPL were the main conversions to improve and reduce the eco-environmental quality, respectively.

In short, we suggest that the northern coastal zone and offshore areas should strengthen EL restoration, whereas the southern coastal zone and inland areas need to improve the efficiency of PL and LL utilization, thus advancing the sustainable use of territorial regions in China's coastal zone.

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