Ecological Indicators 160 (2024) 111835

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Characteristics and models of anthropogenic disturbances on islands from perspective of coastline: Extensive cases from Indian Ocean and mediterranean sea

Hao Li [a,b,e], Yuxin Zhang [a,b,c,d,*], Chao Fan [f], Xiyong Hou [b,c,d], Ling Zeng [e], Peng Guo [e]

[a] International Research Center of Big Data for Sustainable Development Goals, Beijing, China
[b] Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai Shandong 264003, China
[c] CAS Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai Shandong 264003, China
[d] Shandong Key Laboratory of Coastal Environmental Processes, Yantai Shandong 264003, China
[e] Shandong Agricultural University, Taian, China
[f] Zhejiang Ocean University, Zhoushan, China

ARTICLE INFO

Keywords:
Small Island
Anthropogenic disturbances
Coastline change
Coastal development and Utilization
Adaptation

ABSTRACT

The negative impacts of anthropogenic disturbances on the ecology of small island states or regions are important topics mentioned by United Nations' Sustainable Development Goals. This study used the coastline as an indicator to analyze four parameters (the annual variation rate of the artificial coastline length, the index of coastline utilization degree, the index of coastline type diversity, and the standard deviation ellipse of the latter two indicators) to study the changing characteristics of coastal development and utilization of over 13,000 islands, revealing the spatiotemporal evolution characteristics and patterns of human disturbance in island coastal zones. The results indicated that:(1) The spatial–temporal patterns of coastline length and structure undergone significant changes. The length of artificial coastline increased, while natural coastline decreased. The most pronounced change in the artificial coastline was the proliferation of aquaculture embankments, and the most drastic changes occurred in the coastal areas of Southeast Asia.(2) The intensity of coastal development and utilization, as well as the diversity of coastline types, showed an upward trend on the islands. (3) The centroid of coastline utilization degree and type diversity both shifted southeastward by 59.53 km and 931.05 km, respectively. (4) The anthropogenic disturbance patterns on the islands primarily included land reclamation and occupation of original wetland systems. Our study revealed the spatiotemporal characteristics and multiple scenario patterns of anthropogenic disturbance on islands at a large spatial scale from 1990 to 2020, and we quantitatively analyzed the relationship between anthropogenic disturbance factors and changes in the coastline of islands. Islands are currently facing significant pressures from development and conservation. This work is of great significance for the study of sustainable development and management of islands experiencing high-intensity human activities.

1. Introduction

Small island nations and regions are a focal point of the United Nations' Sustainable Development Goals (Van Beynen et al., 2018; Hume et al., 2021). Due to their relatively underdeveloped economies, many small island nations often sacrifice natural resources in exchange for economic development. It is noteworthy that the development and utilization of coastal zones and marine resources are key pathways for their economic growth (Lee et al., 2014; Hassanali, 2017; Sarathchandra et al., 2018). Due to increasing human activities, such as large-scale land reclamation for urban expansion, construction of ports and aquaculture ponds, the ecological pressure on island ecosystems is becoming increasingly severe. Moreover, anthropogenic disturbances have a profound and often irreversible impact on island ecosystems (Nguyen et al., 2016). This issue has garnered global attention on a widespread scale (Nicholls and Cazenave, 2010; Sahoo and Bhaskaran, 2018; Lapointe

* Corresponding author at: Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai Shandong 264003, China.
E-mail address: yxzhang@yic.ac.cn (Y. Zhang).

https://doi.org/10.1016/j.ecolind.2024.111835
Received 19 December 2023; Received in revised form 23 February 2024; Accepted 29 February 2024
Available online 6 March 2024

et al., 2020; Zhang and Hou, 2020).

The impacts of anthropogenic disturbances on island ecosystems are characterized by complexity and diversity. For instance, urbanization and land development can directly alter coastal landscapes, leading to the destruction of habitats and ecological connectivity, resulting in the loss of biodiversity, and the discharge of wastewater (Duan et al., 2016; Chouhan et al., 2017). The excessive logging of mangrove forests for the construction of aquaculture ponds not only directly leads to the loss of wetland ecosystems and their ecological functions but also exacerbates the risk of storm surge disasters faced by islands (Thomas et al., 2017; Wei et al., 2021; Das et al., 2023). Furthermore, port construction results in the hardening of coastlines, altering the sediment transport patterns in nearshore waters and disrupting the biodiversity of benthic organisms in the vicinity (Dauvin et al., 2006; Davis et al., 2022; Chen et al., 2023a). The degradation of island ecosystems can potentially lead to further issues such as biodiversity loss, habitat destruction, water pollution, coastal erosion, and increased risks of sea-level rise. However, research on the mechanisms of anthropogenic disturbances in island ecosystems is currently limited, with a particular lack of studies at large spatial scales.

On the other hand, particularly for small island nations, there is a relatively low level of education and knowledge which limit island residents awareness of the negative impacts of various types of anthropogenic disturbances on their ecosystems. In the pursuit of resource development, they may neglect to implement necessary mitigation measures, which can potentially lead to a vicious cycle of degradation in island ecosystems (Katircioğlu, 2014; Lapointe et al., 2020). Therefore, it is crucial to collect basic data and implement sustainable development strategies and management measures for the residents of island communities.

Overall, the impact mechanisms of anthropogenic disturbances on islands are a widely studied field (Delgado et al., 2017). Current research on the effects of anthropogenic disturbances on islands primarily focuses on land use, species invasion, human-induced landscape patterns, nearshore water quality, and biodiversity. These studies aimed to investigate the changes in ecosystem services, ecosystem diversity, ecological vulnerability, biological homogenization, and the evolution of ecosystem health in island ecosystems (Shen et al., 2016; Iacarella et al., 2018; Adyasari et al., 2021; Chen et al., 2023b). Xie et al. (2021) developed an adjusted assessment system for ecosystem service values (AESV) based on land use and ecological vulnerability. This system provided a scientific basis for the management of island ecosystems undergoing land use changes. Chi et al. (2020) established an evaluation model for the impact of human activities on island ecosystems, from perspectives of damage to the natural ecosystem and support for the social ecosystem. This model served as a solid reference for sustainable development in island regions. Coccia et al. (2022) investigated the response of invertebrates in coastal wetlands in Chile to anthropogenic disturbances, extreme events, and key environmental factors using measures of size diversity and traditional community diversity. These findings contributed to the development of scientific strategies for the conservation of wetland invertebrates.

However, current research in this field has mainly focused on individual or a few islands, and there is a lack of understanding of human activities on large sample islands at a large spatial scale. This hinders the systematic study of the characteristics and patterns of human disturbances in complex island environments. Additionally, due to the geomorphological and locational characteristics of islands, island residents are mostly concentrated in coastal areas, similar to mainland regions. The coastline is one of the most typical geographical elements for studying the theory of human-environment relationships and coordinated development in the context of land-sea integration (Vousdoukas et al., 2020; Cai et al., 2022; Yan et al., 2023). Therefore, the development and utilization of coastlines serve as good indicators of human activities in coastal areas. However, there is currently a significant lack of research on the characteristics of coastline development and utilization in large sample islands, and this knowledge gap needs to be addressed.

This study took the coastline as its research subject, and investigated the characteristics and patterns of human disturbances in the coastal zones of islands at a large spatial scale in Southeast Asian archipelagos, the Indian Ocean, and the Mediterranean. The main objective of this study was to address a scientific question: how to study the characteristics and patterns of anthropogenic disturbances in the coastal zones of island environments from a coastline perspective. Therefore, the research content and objectives of this study were as follows: (1) Using remote sensing and geographic information system (GIS) techniques, calculate indices such as coastline utilization degree, coastline type diversity, and coastline artificialization rate to reflect the characteristics and patterns of anthropogenic disturbances in the coastal zones of islands. (2) Visualize the spatial patterns of anthropogenic disturbances and their development trends using grid-based method, natural break method, and standard deviation ellipse method. (3) Utilize the DPSR (Driving-Pressure-State-Response) framework to reveal the response patterns of islands to anthropogenic disturbances. These indices will enable us to analyze the spatial patterns and development trends of anthropogenic disturbances in island coastal zones, and to reveal the impacts of different types of human activities on coastal ecosystem. The research not only established a solid foundation for preserving and overseeing island ecosystems, but also advocated for the sustainable use of resources and the environment, while promoting socio-economic growth in island regions.

2. Material and methods

2.1. Study region

The study area extends from Southeast Asia to the Cape of Good Hope in Africa, and from the Mediterranean Sea to a longitude range of 6° W to 140° E and a latitude range of 35° S to 45° N (Fig. 1). It spans across the three major plates of Eurasia, India, and Africa, encompassing the Pacific Ocean, Indian Ocean, and Mediterranean Sea. Considering the visualization effect of the research results and the differences in projection coordinate systems, the study area was divided into four subregions for the quantitative analysis of coastal development and utilization index and type diversity index: (1) Southeast Asia - Indochina Peninsula region. (2) South Asia, West Asia and Maldives region. (3) Red Sea-Mediterranean region. (4) East African coast region.

The Southeast Asia-Indochina region encompasses islands in the coastal waters of Southeast Asia, including the Indonesian archipelago and the Philippine archipelago. The majority of the region has a tropical rainforest climate, characterized by high temperatures and abundant rainfall throughout the year. The terrain is predominantly plains and hilly mountains, with numerous rivers. The tourism industry, aquaculture, and foreign trade are the mainstay industries in this region.

In the South Asia region, the majority of the area has a tropical monsoon climate with significant spatial and temporal variations in precipitation. The terrain is characterized by mountains, plateaus, and plains. Agriculture is the main economic source of South Asia. The West Asia region is mostly tropical desert areas, with desert and semi-desert landscapes. The main economic industries in this region are the petroleum industry, transportation industry, and livestock farming. The Maldives and its surrounding islands have a flat terrain and belong to a tropical marine climate. The tourism industry and shipping industry are the main economic pillars of the Maldives.

The Red Sea region has a tropical desert climate, characterized by high temperatures and aridity throughout the year, with scarce precipitation.The Mediterranean region is mostly characterized by a Mediterranean climate, with significant differences in precipitation between winter and summer. The terrain is predominantly mountainous, with plains and plateaus along the coast. The islands and coastlines in this region are mostly mountainous and have a relatively low level of

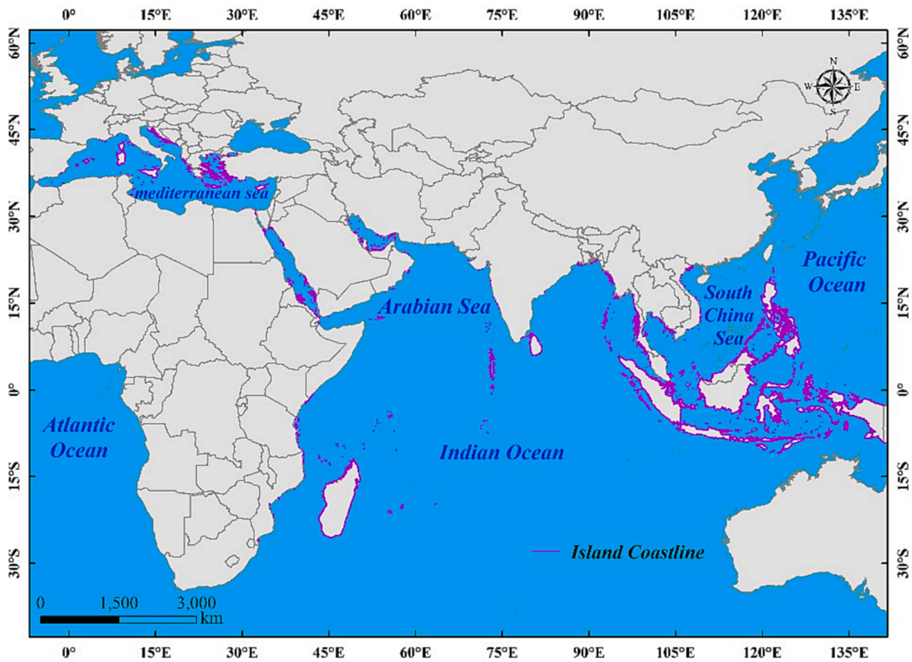


Fig. 1. The study area.

development. The main economic pillars are fishing, tourism, and salt production.

The East Coast of Africa region includes islands such as Madagascar, the Seychelles, and Mauritius. The region has a variety of climate types, but most areas experience high temperatures and distinct wet and dry seasons. The terrain is mainly composed of plateaus, mountains, and plains. The economic level in this region is relatively low, with agriculture, fishing, tourism, and export processing industries being the main drivers of development.

2.2. Coastline data

The extraction and dynamic monitoring of coastlines using high-resolution, long-term, and readily available land remote sensing images have become the mainstream approach for coastline monitoring (Choung and Jo, 2016; Abu Zed et al., 2018; Sun et al., 2023). In this study, more than 3500 scenes of Landsat TM/ETM+/OLI remote sensing images with a resolution of 30 m were used (download in United States Geological Survey, USGS). The availability of imagery for the Maldives archipelago in 1990 was limited, rendering it inaccessible for analysis.

The fluctuating tides and irregular storm surges make it challenging to determine the exact position of the coastline. The mean high tide line (MHTL), due to its advantages of easy identification and high stability in remote sensing imagery, has been widely applied in coastal monitoring and management (Hou et al., 2014; Hou et al., 2016; Zhang and Hou, 2020). It partially mitigates the influence of tides and serves as a reliable reference for coastline determination. Its utilization in coastal management practices facilitates precise analysis and decision-making. Therefore, in this study, MHTL was adopted as a proxy for the coastline. Through field investigations and on-site measurements of the coastal zones and islands in mainland China, an image feature library for visual interpretation of different types of coastlines was established, as shown in Table 1. The detailed process of coastline interpretation can be referred to in previous studies (Zhang and Hou, 2020; Zhang et al., 2021).

2.3. Uncertainty in coastline position

In this study, an accuracy analysis was conducted using a feature-based evaluation method. Specifically, the vectorized coastline data was used to generate sample points at regular intervals. These sample points were then imported into the Google Earth platform, where their positions were adjusted to align more closely with the location of the mean high tide line, using high-resolution remote sensing imagery as a background. The adjusted sample points were defined as reference points. The actual error was calculated as the Euclidean distance between the sample points and their corresponding reference points. The "theoretical maximum allowable error (MPE)" of the coastline data was determined based on the mathematical relationship between the uncertainty of the coastline position and the image resolution (Yi et al., 2013; Hou et al., 2014). Finally, the accuracy of the coastline extraction was assessed by comparing the MPE with the average error, as shown in equations (1)-(3).

$$\eta = \frac{\sum_{i=1}^{n}\sqrt{(X_i - x_i)^2 + (Y_i - y_i)^2}}{n} \# \tag{1}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(d_i - \eta)^2}{n}} \# \tag{2}$$

$$P = \frac{2\sqrt{2}}{3} \times \alpha \# \tag{3}$$

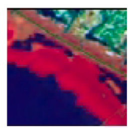
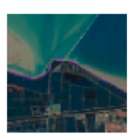
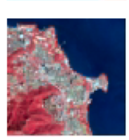
where (X_i, Y_i) is the coordinates of the sample points, (x_i, y_i) is the coordinates of the reference points, η represents the average error of the sample, σ indicates the population standard deviation of the error values, d_i is the actual error values, and n is the number of samples. P represents the theoretical maximum allowable error, and α indicates the image resolution.

The maximum allowable error for interpreting the coastline from a 30-meter resolution remote sensing image is 28.28 m. In our study area, we selected 1694 sample points and calculated their average error to be 11.24 m with a standard error of 22.54 m. Therefore, the accuracy meets the experimental requirements.

2.4. Methodology

The anthropogenic disturbance characteristics of coastal islands are

Table 1
Coastline interpretation flag library.

First Level	Second Level	Characteristics	Interpretive flag
Natural Coastline	Rocky Coastline	It is mostly distributed in alternating areas between headlands and bays, and is composed of hard rock.	
	Sandy Coastline	Often located at the top of the beach, The brightness of the beach surface is high.	
	Silty Coastline	There is a significant difference in vegetation density on both sides of the coastline, which is located on the silty coast.	
	Biogenic Coastline	The coastline is covered with mangrove shores, reed shores, coral reefs, etc., distributed near the estuary of the tide Beach or coastal marsh area.	
Artificial Coastline	Groin and Jetty	Groin: low wall used to prevent wave erosion and regulate the flow of water along the coast.Jetty: A seawall facing the shore to keep out the waves.	
	Harbor and Wharf	Coastline has a regular shape and extends more seawall.	
	Reclamation	The sea wall is under construction around the sea embankment.	
	Aquaculture dike	Dikes built for aquaculture.	
	Salt pan dike	This shoreline is used for saline-alkali drying and reclamation of dikes, and is rectangular in shape and distributed in patches.	
	Traffic dike	A man-made dam used for transportation.	
	Urban Coast	Coastline is mainly distributed in construction development zones such as cities, towns and coastal development zones.	

quantified using four indicators: the annual variation rate of the artificial coastline length, the index of coastal utilization degree, the index of coastal line type diversity, and the standard deviation ellipse of the latter two indicators. The specific research route is shown in Fig. 2.

2.4.1. Coastline length change

Annual variation rate of the coastline length reflects the intensity of coastline length changes over a certain period and is one of the standards for reflecting the spatiotemporal variation characteristics of the coastline (Li et al., 2022). In addition, this ratio can avoid errors caused by the length of the study unit and different study periods, as shown in equation (4).

$$ICLI_{ij} = \frac{L_j - L_i}{(j-i) \times L_i} \times 100\%\# \tag{4}$$

where $ICLI_{ij}$ represents the annual variation rate of the coastline length, L_i and L_j indicate the coastline lengths in the starting year and ending year, respectively. A positive value of $ICLI_{ij}$ indicates an increase in coastline length, while a negative value indicates a decrease. The magnitude of $ICLI_{ij}$ reflects the extent of coastline length change. A larger absolute value indicates a more pronounced variation in coastline length.

2.4.2. Coastline type diversity

The Index of Coastline Type Diversity (ICTD) reflects the human disturbance to the coastline from the perspective of the types or methods of coastal development and utilization (Li et al., 2023). This index is also influenced by the types and lengths of the coastline. It ranges from 0 to 1, as shown in Equation (5).

$$ICTD = 1 - \frac{\sum_{i=1}^{n} L_i^2}{\left(\sum_{i=1}^{n} L_i\right)^2}\# \tag{5}$$

where n represents the total number of coastline types, and L_i represents the length of the i-th coastline type. A higher value of $ICTD$, closer to 1, indicates a greater diversity of coastal development and utilization types, with similar lengths for each coastline type.

2.4.3. Coastline utilization degree

The Index of Coastline Utilization Degree (ICUD) quantifies the impact intensity of human development and utilization activities on the coastline. The utilization degree is influenced by the length and type of the coastline, with different intensity factors assigned to different coastline types, as shown in Equation (6). The determination of intensity factors is primarily based on field investigations combined with expert knowledge, and their values range from 1 to 4, as shown in Table 2.

$$ICUD = \sum_{i=1}^{n} A_i \times Q_i \times 100\%\# \tag{6}$$

where n is the total number of coastline types, A_i is the length of the i-th coastline type, and Q_i is the development intensity factor of the i-th coastline type. A larger $ICUD$ indicates more intense human development and utilization activities in the region.

2.4.4. Analysis unit

Due to the widespread and scattered distribution of islands in this study, the analysis of human disturbance spatiotemporal characteristics is challenging. Therefore, we utilized a 30 × 30 km grid created using ArcGIS software as the analytical unit for this study. We calculated the length of coastline, coastline artificialization rate, ICUD, and ICTD within each grid. The natural breaks method is an iterative process that compares the sum of squared differences between each observation within a class and the class mean. This method reveals inherent grouping and pattern characteristics in the data, effectively grouping similar values and maximizing the differences between classes (Jenks, 1967; Lu et al., 2021). Using the natural break method, we classified the intensity of coastal development and the diversity of development types into five categories: low value, slight value, moderate value, slight high value, and high value, as shown in Table 3.

2.4.5. Standard deviational ellipse

The Standard Deviational Ellipse (SDE) spatial statistical method provides a relatively accurate representation of the spatial distribution

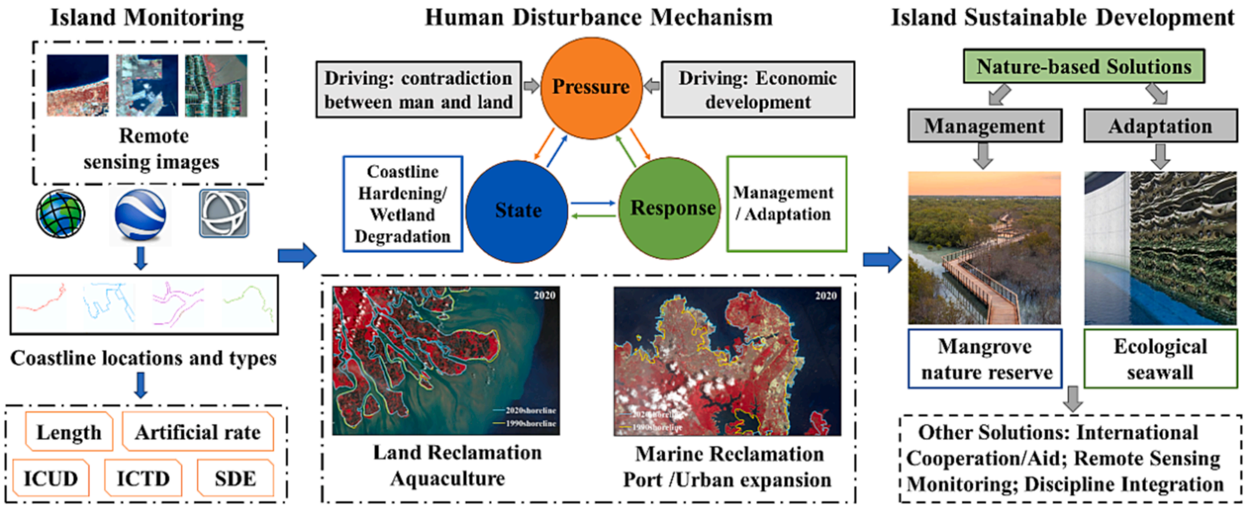


Fig. 2. Research route.

Table 2
Human action intensity index of each type of shoreline.

Coastline Type	Natural Coastline	Groin and Jetty	Harbor and Wharf	Reclamation
Intensity factor	1	4	4	4
Coastline Type	Aquaculture dike	Salt pan dike	Traffic dike	Urban Coast
Intensity factor	3	3	4	4

characteristics of geographic features. The SDE method quantitatively describes the central features, directional features, and spatial morphology of geographic feature distribution from a global spatial perspective, based on the spatial location and structure of the study object. It effectively captures the spatiotemporal characteristics of geographic features (Li Deren and Hanruo, 2017). The parameters of the Standard Deviational Ellipse primarily include the centroid, azimuth, and lengths of the major and minor axes of the ellipse. The calculation formulas for these parameters are shown in equations (7)-(10).

$$\overline{X}_w = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \overline{Y}_w = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \tag{7}$$

$$\tan\alpha = \frac{\left(\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 \widetilde{y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 \widetilde{y}_i^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 \widetilde{y}_i^2}}{2\sum_{i=1}^{n} w_i^2 \widetilde{x}_i \widetilde{y}_i} \tag{8}$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} (w_i \widetilde{x}_i cos\alpha - w_i \widetilde{y}_i sin\alpha)^2}{\sum_{i=1}^{n} {w_i}^2}} \# \tag{9}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} (w_i \widetilde{x}_i sin\alpha - w_i \widetilde{y}_i cos\alpha)^2}{\sum_{i=1}^{n} {w_i}^2}} \# \tag{10}$$

where (x_i, y_i) represents spatial positions of the study objects, w_i denotes the corresponding weights, $(\widetilde{x}_i, \widetilde{y}_i)$ indicates coordinate deviations of the spatial positions of each study object to the centroid $(\overline{X}_w, \overline{Y}_w)$. α represents the azimuth of SDE, and x and y are the x and y axis lengths of SDE, respectively.

Table 3
Classification of indices.

Index	Value	Grade division
ICUD	0 ≤ ICUD < 61	Low
	61 ≤ ICUD < 109	Slight Low
	109 ≤ ICUD < 287	Moderate
	287 ≤ ICUD < 486	Slight high
	486 ≤ ICUD < 870	High
ICTD	0 ≤ ICTD < 0.1	Low
	0.1 ≤ ICTD < 0.2	Slight low
	0.2 ≤ ICTD < 0.4	Moderate
	0.4 ≤ ICTD < 0.6	Slight high
	0.6 ≤ ICTD < 1.0	High

3. Results

3.1. *Spatiotemporal variation of island coastline length and structure*

This study extracted a total of 12,737 islands in 1990, 13,542 islands in 2000, 13,589 islands in 2010, and 13,629 islands in 2020. The length of the natural coastline decreased by 3516 km between 1990 and 2020, while the length of the artificial coastline increased by 7075 km. The annual growth rates of the artificial coastline length were 5.08 %, 4.18 %, and 2.53 % during the periods of 1990–2000, 2000–2010, and 2010–2020, respectively. The specific changes in the length of the artificial coastline in different regions are shown in Table 4. The coastal resources of the Philippines and Indonesia are abundant. Over the past 30 years, significant developments have been observed in their aquaculture industry, port transportation sector, and urbanization processes (Mcsherry et al., 2023; Lei et al., 2023). As a result, the artificial coastline was primarily concentrated in the southwestern part of Luzon Island, the northeastern and southeastern parts of Kalimantan Island,

Table 4
Length of artificial coastline by region and year from 1990 to 2020.

Region	Artificial coastline length(km)			
	1990	2000	2010	2020
Philippine Islands	1351	1872	1866	2135
Islands of Indonesia	1947	3301	5511	7161
Offshore southeast Asia	153	303	415	596
South and West Asia	169	182	375	471
The Red Sea	16	35	59	59
The Mediterranean Sea	560	612	700	751
East coast of Africa	15	34	51	62
Maldives Islands	/	14	29	51

and the northern part of Java Island.

The lengths of various types of artificial coastlines in the study area have shown a consistent upward trend over the years, as depicted in Fig. 3. The most significant increase was observed in aquaculture embankments, which have grown 3474 km over a period of 30 years. The lengths of urban coastlines, port coastlines, and reclamation coastlines also experienced noticeable growth, with increases of 885 km, 845 km, and 730 km, respectively. Despite the increasing lengths of various types of artificial coastlines, the annual change rate of their length has significant time difference. For instance, the rate of change for port dock coastlines reached its peak at 4.8 % during the period of 2000–2010. The rates of change for salt pan coastlines, reclamation coastlines, and urban coastlines all reached their peaks during the period of 1990–2000.

The changes in various types of artificial coastlines also exhibit significant spatial variations. From 1990 to 2020, the port dock coastlines in the coastal areas of the Indochinese Peninsula, South Asia, the Mediterranean, and the Maldives experienced notable increases, with increments of 122 km, 109 km, 101 km, and 11 km, respectively. In the Philippines and the Red Sea, the urban coastlines and reclamation coastlines had the highest increments, with values of 245 km and 20 km, respectively. The aquaculture coastlines in Indonesia and the East Coast of Africa showed the most prominent growth, with increments of 3191 km and 16 km, respectively.

3.2. Spatiotemporal variation in the degree of coastline utilization

The sum of island coastlines utilization degree index in the entire study area increased from 206,934 in 1990 to 227,513 in 2020. Among them, the grid cells with an intensity index classified as “moderate” (109–287) experienced the largest increase, accounting for approximately 50 % of the total number of changing grid cells. This indicates that human disturbances in the study area are primarily characterized by moderate development and utilization activities. The spatial distribution of utilization intensity in the four sub-regions from 1990 to 2020 is shown in Figs. 4-7, with corresponding statistical data presented in Tables 5-6.

The main types of grid cells in terms of utilization degree in Southeast Asian archipelagos from 1990 to 2020 were low-value and slight low-value grid cells. The changes in utilization intensity in Southeast Asian archipelagos were characterized by a decrease in low-value grid cells and an increase in moderate-value grid cells. The regions where moderate-value grid cells increased were mainly located in the southeastern part of Sumatra Island, the eastern part of Java Island, and the southeastern part of Sulawesi Island (Fig. 4). The regions where high-value grid cells increased were mainly located in the eastern part of Sumatra Island, the northeastern and southeastern parts of Borneo Island.

The grid cells of utilization degree in the South and West Asia islands were mainly characterized by low-value and slight low-value grid cells (Fig. 5). Moderate-value grid cells were primarily distributed in the western part of the Persian Gulf, the western and northern parts of the Sri Lanka archipelago. The changes in utilization intensity in South and West Asia were characterized by an increase in low-value and moderate-value grid cells. The region with an increase in low-value grid cells was located in the southeastern part of the Persian Gulf. The regions with an increase in moderate-value grid cells were located in the southeastern and southwestern parts of the Persian Gulf.

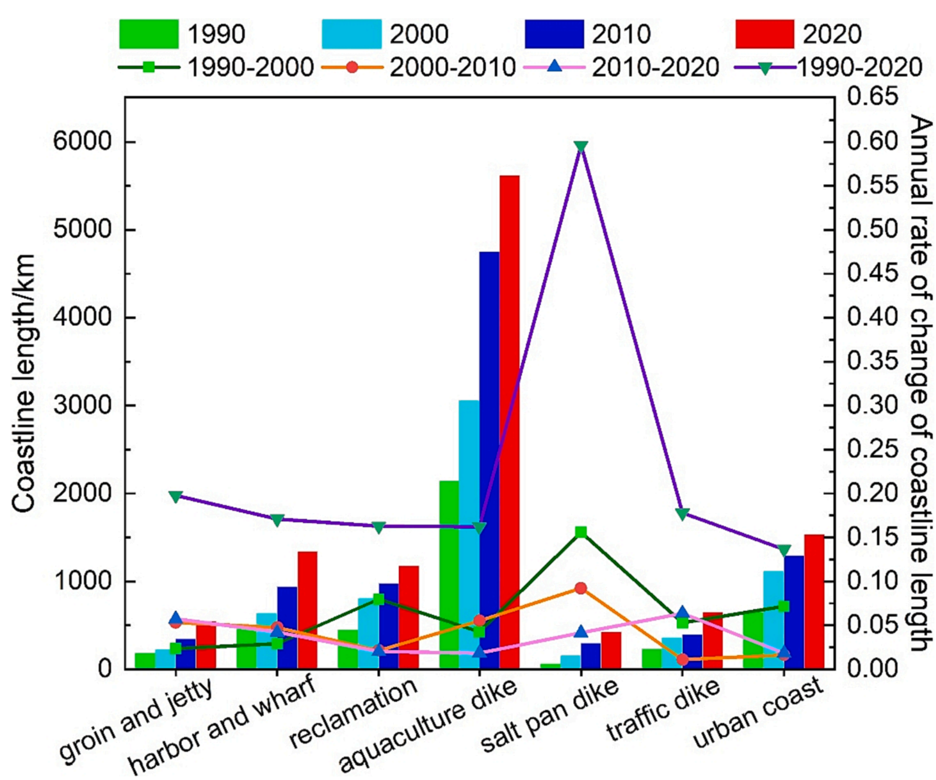


Fig. 3. Length and annual change rate of various artificial coastlines.

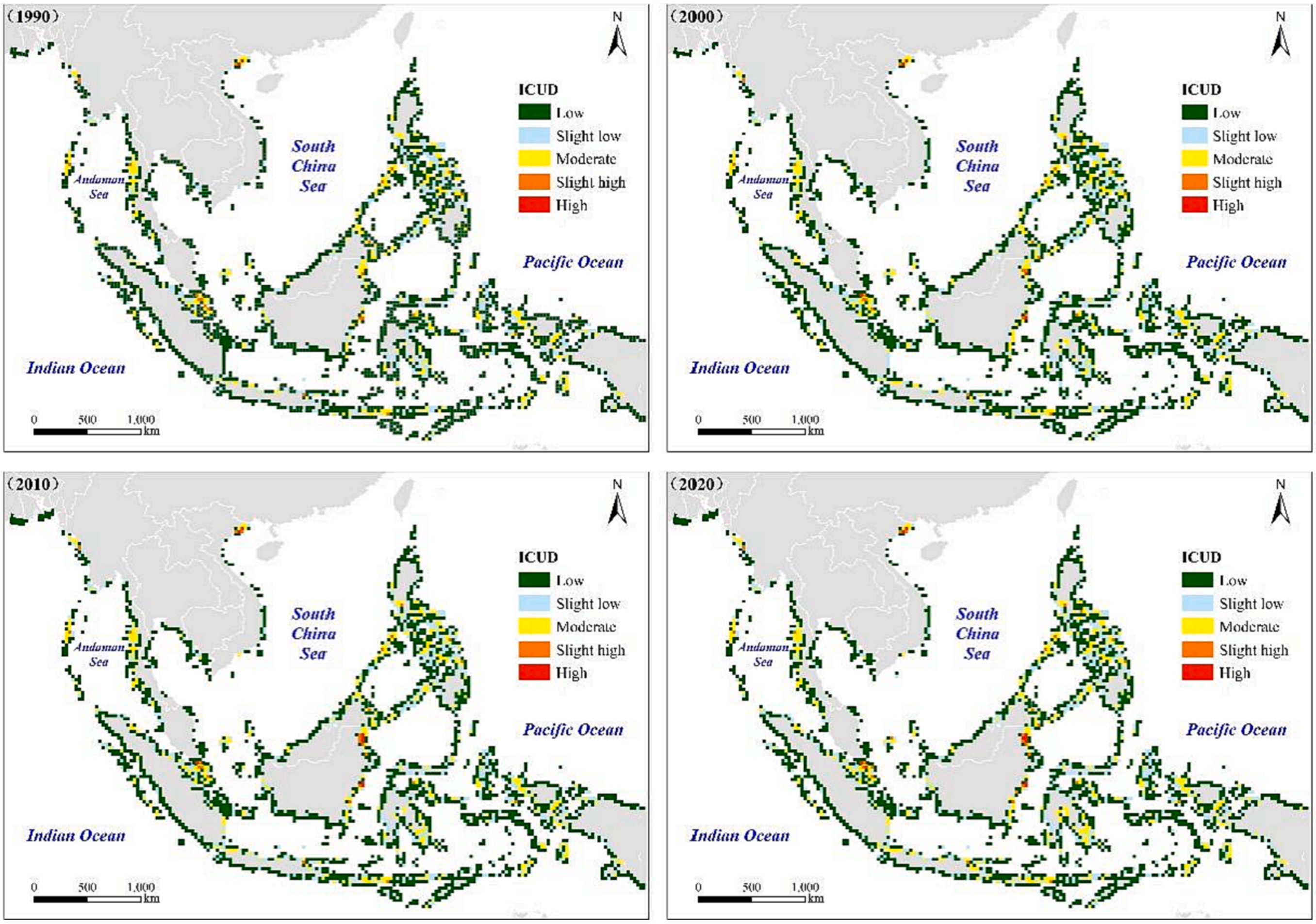


Fig. 4. Distribution of ICUD in Southeast Asia - Indochina Peninsula from 1990 to 2020.

The utilization degree grids of the Red Sea and Mediterranean Sea islands were primarily characterized by low-value, slight low-value, and moderate-value grid cells, predominantly distributed in the northern, eastern, western parts of the Mediterranean Sea, and the southeastern part of the Red Sea (Fig. 6). The changes in utilization intensity were characterized by an increase in low-value and moderate-value grid cells, as well as a decrease in slight low-value grid cells. Specifically, the regions with an increase in moderate-value grid cells were located in the southeastern part of the Red Sea and the northwestern part of the Mediterranean Sea. The regions with an increase in low-value grid cells were located in the northwestern part of the Mediterranean Sea and the southeastern part of the Red Sea.

The grid cells of utilization degree along the East Coast of Africa were primarily characterized by low-value and moderate-value grid cells (Fig. 7). The moderate-value grid cells were predominantly concentrated in the northern part of Madagascar Island. The utilization intensity have remained relatively stable over the past 30 years, with a predominant increase in low-value grid cells. The region with an increase in low-value grid cells were located in the northwestern part of the Mozambique Channel.

The utilization degree of the islands in the study area were characterized by the standard deviation ellipse offset, as shown in Fig. 8. From 1990 to 2020, the utilization degree formed a distribution pattern of "northwest-southeast", with the centroid moving approximately 2 km southeastward on average each year. The azimuth angle also deviated $4'$ towards the southeast, and the ellipse area contracted approximately 60,000 km^2 annually in the northwest-southeast direction. These findings strongly indicated that Southeast Asia played a strong role in the evolution of spatial pattern of island development and utilization intensity in the study area.

3.3. Characteristics of coastline type diversity

The sum of the coastline type diversity index in the study area increased from 102 in 1990 to 222 in 2020. Among them, the grid cells classified as "low value" (0–0.1) showed the most significant decrease. The most significant changes in the number of coastline type diversity grids were low, moderate and high value grid cells. The spatiotemporal evolution of coastline type diversity from 1990 to 2020 is illustrated in Figs. 9-12, and the corresponding statistical data can be found in Tables 7-8.

The grid cells with low values dominate the coastline type diversity in the Southeast Asian islands. The grid cells with moderate and high values were mainly distributed in the northern part of Sumatra Island, the northeastern part of Borneo Island, the southwestern part of Sulawesi Island, and the southeastern part of the Philippine Islands (Fig. 9). The changes in coastline type diversity were primarily characterized by a decrease in low-value grid cells and an increase in other types of grid cells. The regions with the largest increase in high-value grid cells were the northeastern part of Borneo Island, the southeastern part of Java Island, and the northwestern part of Sulawesi Island. Additionally, there were significant temporal differences in the increase of development and utilization type diversity. The periods with the most significant increase in low-value, medium-value, and high-value grid cells were 1990–2000, 2000–2010, and 2010–2020, respectively.

From 2000 to 2020, the grid cells with medium value of coastline type diversity in South and West Asia islands were mainly distributed in the eastern, southeastern, and northwestern parts of the Persian Gulf,

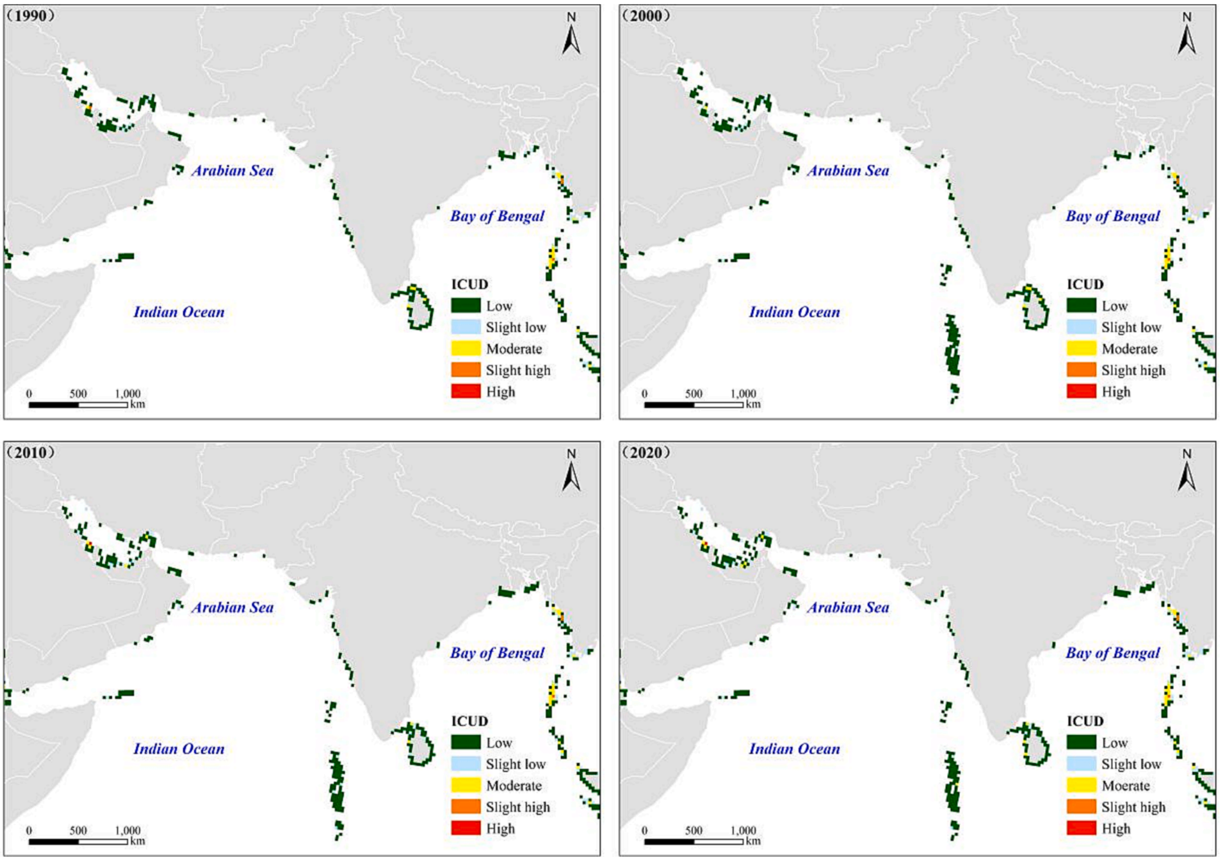


Fig. 5. Distribution of ICUD in South Asia, West Asia and Maldives from 1990 to 2020.

while the grid cells with slight high value were concentrated in the western and southeastern parts of the Persian Gulf, with the high-value grid cells observed in the western region (Fig. 10). The changes in shoreline type diversity grid cells were characterized by a decrease in low-value grid cells and an increase in moderate-value grid cells. The regions with the most significant increase in moderate-value grid cells were primarily located in the southeastern and northwestern parts of the Persian Gulf, with the most notable increase occurring during the period from 2000 to 2010.

Low-value, moderate-value, and medium-value are the main types of coastline type diversity grid cells in the Red Sea and Mediterranean Sea islands over a period of 30 years. The low-value grid cells were densely distributed in the eastern and northern parts of the Red Sea and Mediterranean Sea (Fig. 11). The moderate-value grid cells were mainly found in the northwestern part of the Mediterranean Sea, while the medium-value grid cells were predominantly located in the northwestern part of the Mediterranean Sea. The changes in coastline type diversity grid cells were characterized by a decrease in low-value grid cells and an increase in moderate-value grid cells. The regions with the most significant increase in moderate-value grid cells were the western and northeastern parts of the Mediterranean Sea, with the most notable increase occurring during the period from 1990 to 2000.

The coastline type diversity along the East Coast of Africa were predominantly characterized by low-value and moderate-value grid cells (Fig. 12). Over a period of 30 years, the increase in moderate-value and medium-value grid cells represented the main trend in the variation of coastline utilization type diversity. The region with an increase in medium-value grid cells were the northwestern part of Madagascar, with the most significant increase occurring during the period from 2000 to 2010. The region with an increase in low-value grid cells were the northeastern part of Madagascar. The area where the lower value grid cells added were northeast Madagascar.

The long axes of the standard deviation ellipses for coastline type diversity in the study area from 1990 to 2020 exhibited a northwest-southeast orientation, while the short axes showed a southwest-northeast orientation (Fig. 13). This indicated that the diversity of shoreline in the northwest - southeast direction increased more significantly than that in the southwest - northeast direction in the study area during the past 30 years. Furthermore, the magnitude of change in the long axis was significantly higher than that of the short axis. Additionally, the centroid of the ellipses moved an average of approximately 31 km per year in the southeast direction, and the area of the ellipses contracts by an average of approximately 150,000 km^2 per year in the southeast-northwest direction. This information revealed the fact that Southeast Asia were the region with the most complex pattern of anthropogenic disturbance.

4. Discussion

4.1. Spatiotemporal difference of anthropogenic disturbance in islands

There are significant spatial variations in anthropogenic disturbance on islands, which are evident at multiple spatial scales. At a large spatial scale, the Southeast Asian archipelago exhibited the most pronounced anthropogenic disturbance. For instance, over the past thirty years, extensive mangrove forests have been cleared and large-scale land reclamation has been carried out in Indonesia to facilitate the development of aquaculture and port transportation industries (Fig. 14). In contrast, the islands in the Mediterranean and along the East Coast of Africa experienced relatively less anthropogenic disturbance, largely due to the influence of their topography and geomorphology (Crossett and Metz, 2017). At the island level, there were significant variations in anthropogenic disturbance within islands due to natural factors such as topography, climate, and precipitation. The western coast of Sumatra

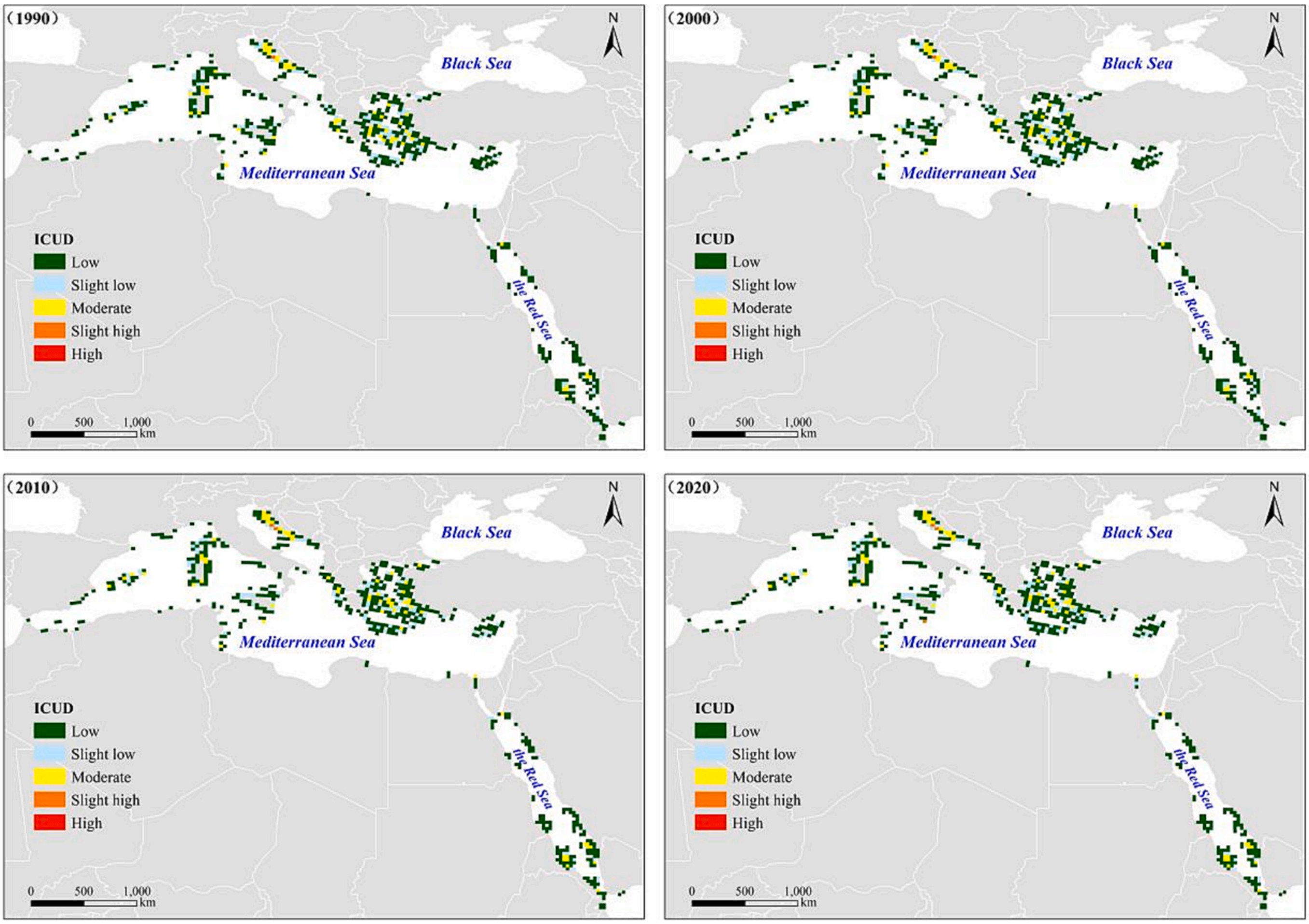


Fig. 6. Distribution of ICUD in the Red Sea and Mediterranean Sea from 1990 to 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Island was dominated by rocky mountain ranges, while the eastern part has flat terrain with extensive wetlands, resulting in higher levels of anthropogenic disturbance in the eastern region compared to the western region. The southwestern part of Sri Lanka, which was the center of economic gravity and had higher annual rainfall than other parts of the country, was more suitable for human habitation. Consequently, human-induced disturbances in this region were expected to be significantly higher than in other parts of the island (Malmgren et al., 2003; Dahanayake and Wickramasinghe, 2022). Furthermore, driven by island resources and economic development activities, there are significant spatial variations in anthropogenic disturbance on islands (Chi et al., 2018; Kurniawan et al., 2019). For instance, the eastern coast of Kalimantan Island in Indonesia and the western coast of the Borneo Bay were characterized by a concentration of aquaculture coastlines, while the northern and eastern coasts of Java Island exhibited a higher concentration of port and urban coastlines.

Similarly, there are significant temporal variations in anthropogenic disturbance on islands. South Asia, the Red Sea, and the Mediterranean witnessed large-scale port and dock construction between 2000 and 2010, resulting in the highest variability in anthropogenic disturbance intensity during this period compared to others. Likewise, between 2010 and 2020, Southeast Asia experienced a significant increase in port and dock construction as well as aquaculture expansion, leading to the highest anthropogenic disturbance intensity over the past decade. On the other hand, the East Coast of Africa experienced the largest increase in anthropogenic disturbance intensity between 1990 and 2000, primarily due to extensive land reclamation activities.

4.2. Models of anthropogenic disturbance in islands

There were two main patterns of anthropogenic disturbance on islands, namely land reclamation and in situ wetland reclamation. Additionally, to explain the response of islands to anthropogenic disturbance, the Driver-Pressure-State-Response (DPSR) framework was introduced, as shown in Fig. 15.

4.2.1. Land reclamation driven by human-land conflicts

The conflict between urban expansion and land conservation is driven by the limited area, unique geographical location, and isolation from the mainland of islands (Cao et al., 2021). In the past few decades, the land resources of island nations have been unable to meet the rapidly increasing demand for urban development (Tay et al., 2018). At the same time, residents of some small islands faced severe challenges from extreme natural disasters such as sea-level rise, storm surges, and global climate change (Bellard et al., 2014; Rovere et al., 2018). These facts have given rise to the first pattern of anthropogenic disturbances, characterized by the accelerated process of land reclamation by conflicts between human and land, as shown in Fig. 15. Notably, Singapore reclaimed a total area of 114 km^2 between 1975 and 2010 (Zhang et al., 2017).

Land reclamation to meet the land demand for urban development has undeniably passive consequences. The construction of land reclamation leads to coastal hardening, which alters nearshore hydrodynamic processes, hinders sediment deposition, and exacerbates the spread of marine species, thereby disrupting the balance of nearshore ecosystems (Scherner et al., 2013; Floerl et al., 2021). Furthermore, the

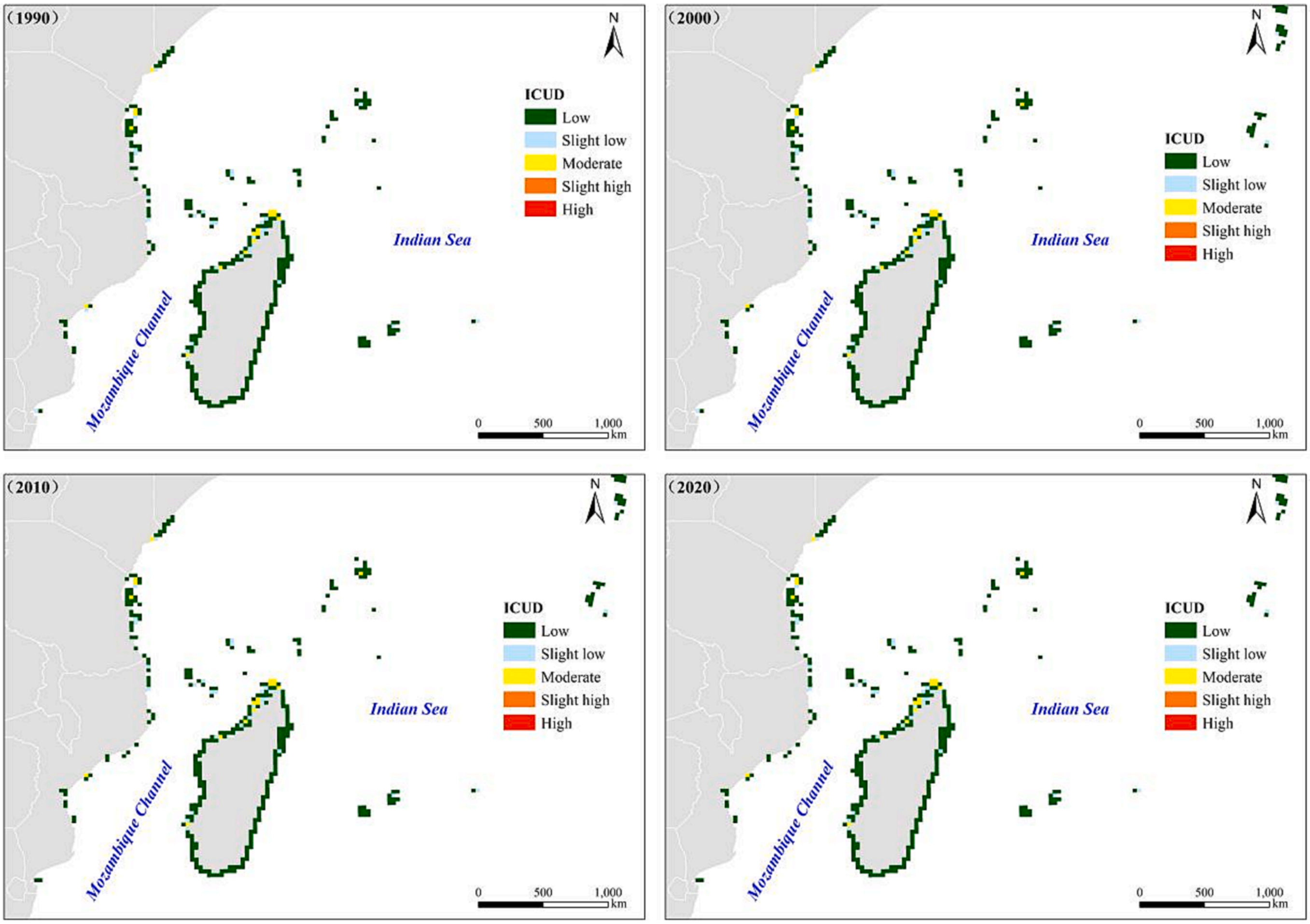


Fig. 7. Distribution of ICUD in the East coast of Africa from 1990 to 2020.

Table 5
Sum of coastline utilization degree index in four regions from 1990 to 2020.

Region	Sum of coastline utilization degree index			
	1990	2000	2010	2020
Southeast Asia - Indochina Peninsula	160,116	165,451	170,840	176,450
South Asia, West Asia and Maldives[aa]	5725	7733	8529	9030
the Red Sea and Mediterranean Sea	28,236	28,455	28,843	29,071
East coast of Africa	12,857	12,900	12,931	12,962

[aa] Maldives was excluded in 1990

urban expansion driven by land reclamation intensifies the high-intensity anthropogenic disturbance activities on islands. The significant variation in the intensity of island development and utilization in this study is primarily attributed to the construction of large-scale port terminals.

4.2.2. Economy-driven in situ wetland reclamation

The limited resources and market capacity of islands have shaped a unique economic development model. This development model relies primarily on the tourism industry, aquaculture, and port transportation to drive economic growth (Ali et al., 2015; Tovar et al., 2015; Lapointe et al., 2021). Among them, in contrast to the development of port transportation through land reclamation, the in-situ occupation of mangrove wetlands for aquaculture development incurs lower costs. Therefore, some islands with abundant mangrove resources prioritize the in-situ clearance of mangroves for aquaculture development (Malik et al., 2017; Tinh et al., 2022), which represents the second major anthropogenic disturbance pattern identified in our study, as shown in

Table 6
Grid changes of coastline utilization degree in four regions from 1990 to 2020.

Region	Grade division	Grid number			
		1990	2000	2010	2020
Southeast Asia - Indochina Peninsula	Low	2041	2014	1994	1965
	Slight low	547	552	555	554
	Moderate	333	350	366	391
	Slight high	22	25	27	30
	High	2	5	8	10
South Asia, West Asia and Maldives[b]	Low	188	283	289	293
	Slight low	13	18	23	21
	Moderate	5	5	6	9
	Slight high	1	0	0	0
	High	0	0	1	1
the Red Sea and Mediterranean Sea	Low	488	487	495	495
	Slight low	105	105	97	98
	Moderate	60	61	65	64
	Slight high	1	1	2	3
	High	0	0	0	0
East coast of Africa	Low	307	309	315	316
	Slight low	34	32	31	31
	Moderate	17	18	18	18
	Slight high	0	0	0	0
	High	0	0	0	0

[b] Maldives was excluded in 1990

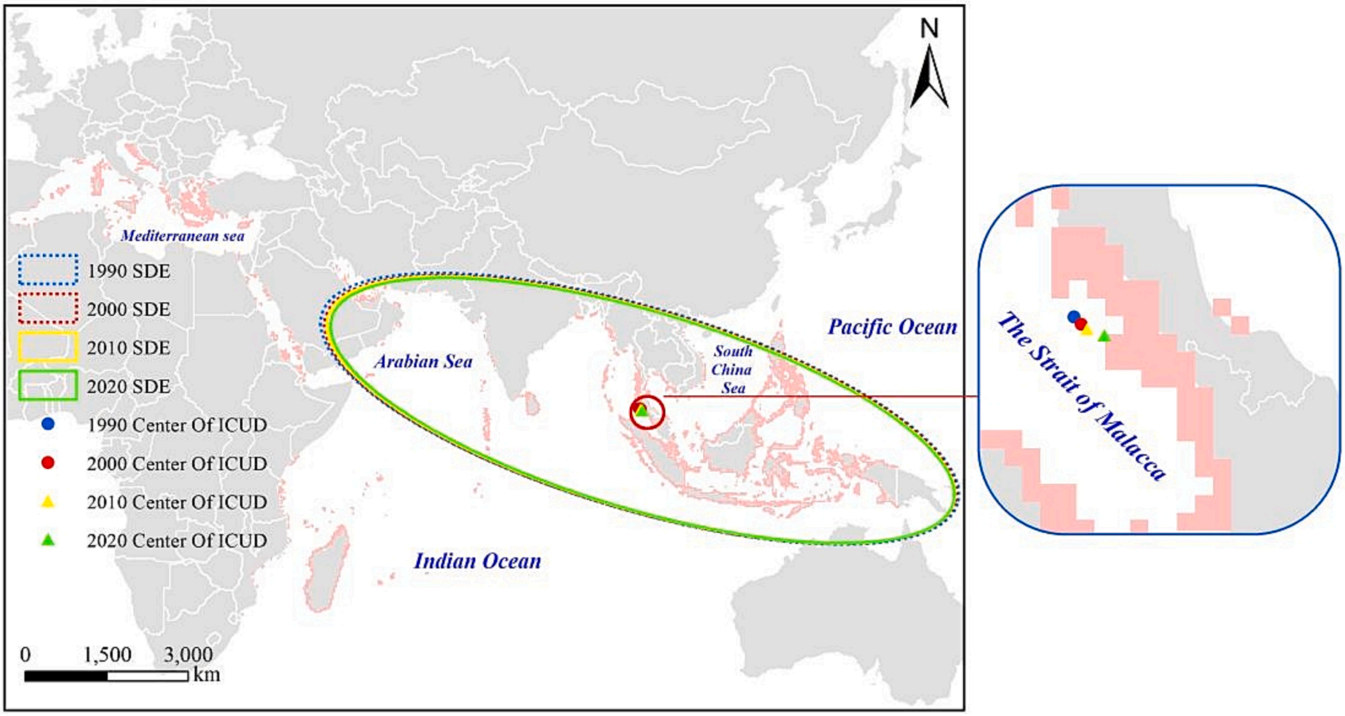


Fig. 8. Spatial distribution of geometric center of gravity of coastline utilization degree in the study area from 1990 to 2020.

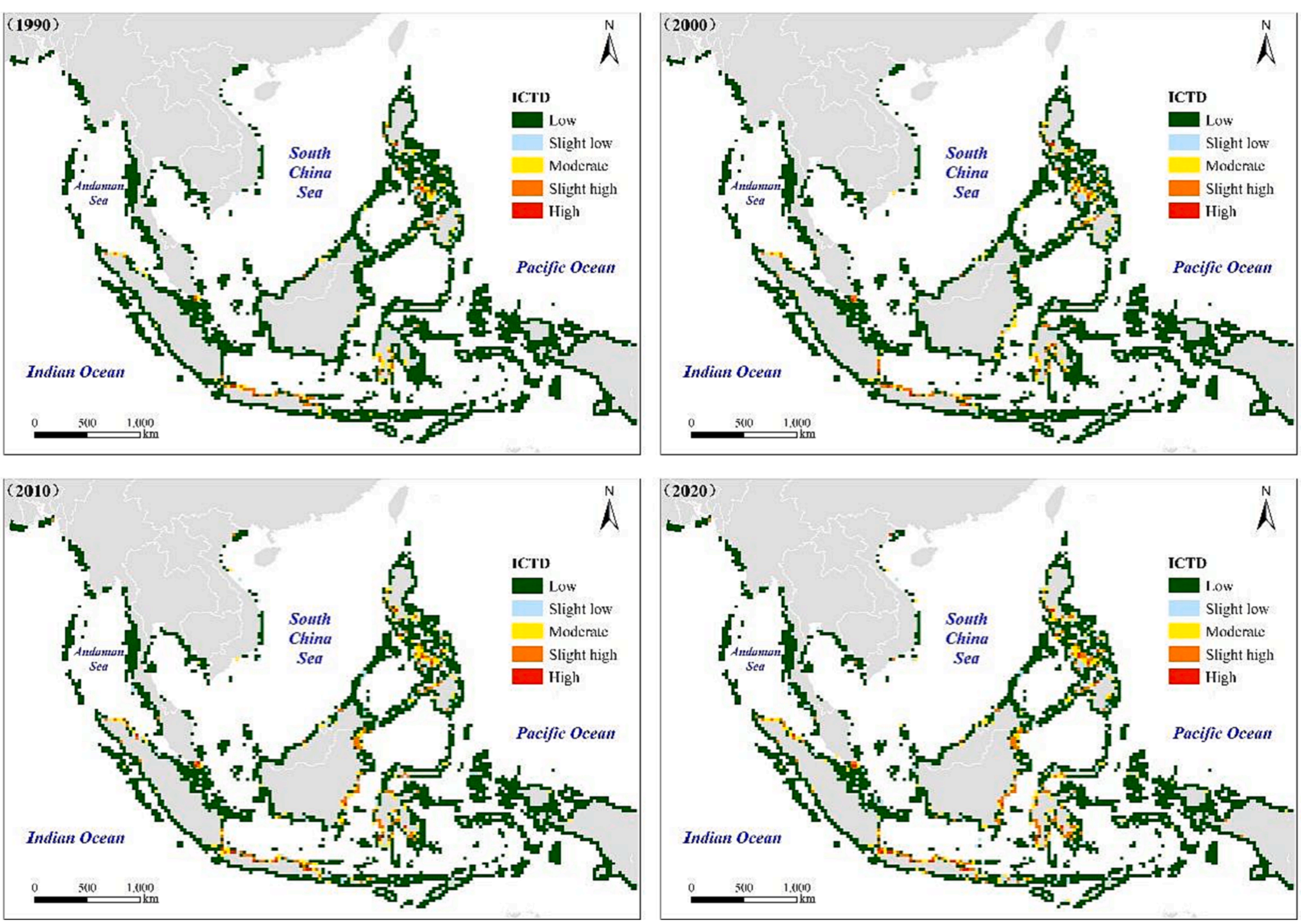


Fig. 9. Distribution of ICTD in Southeast Asia - Indochina Peninsula from 1990 to 2020.

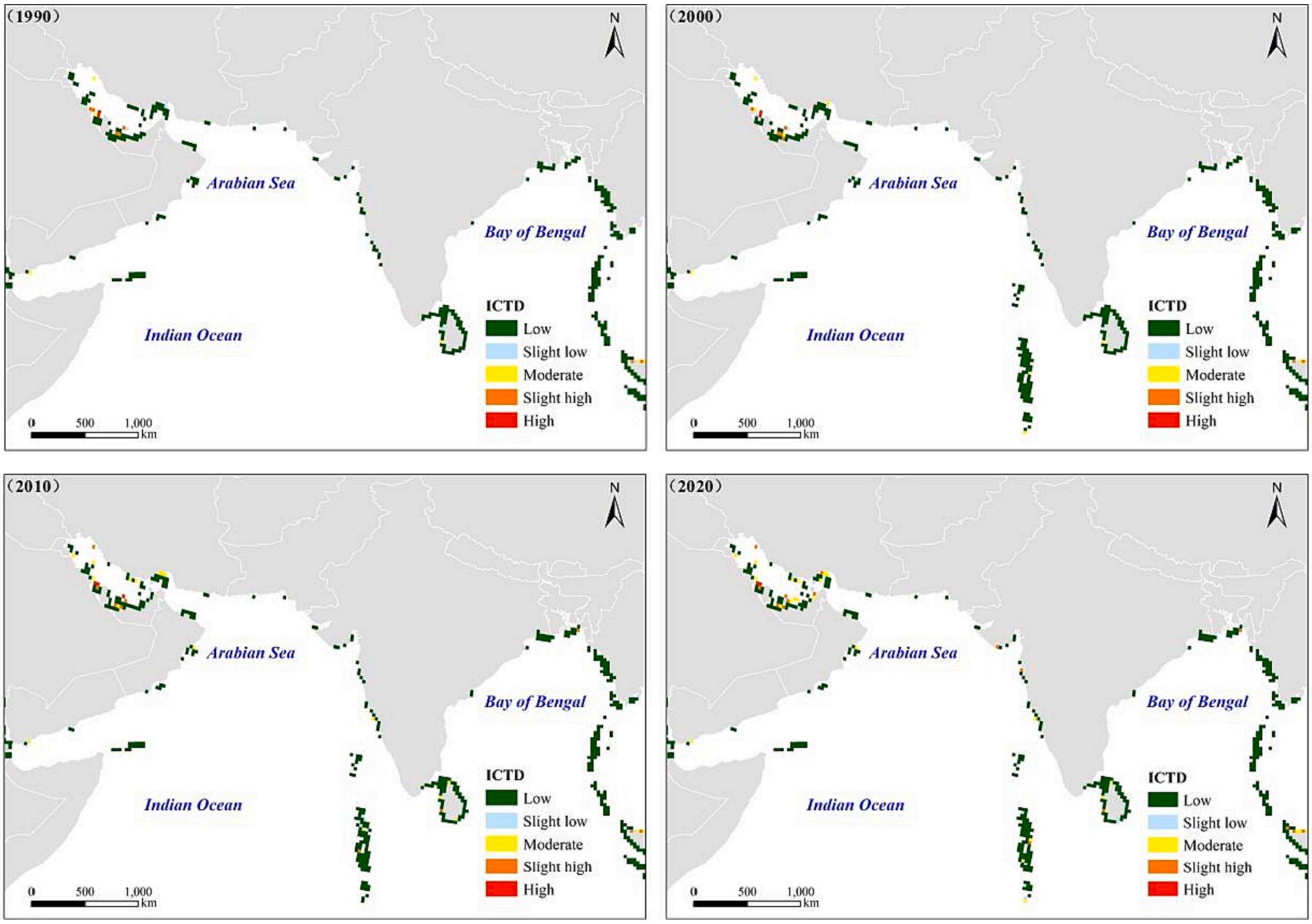


Fig. 10. Distribution of ICTD in South Asia, West Asia and Maldives from 1990 to 2020.

Fig. 16. Based on the global mangrove dataset by Xiao et al (2021), we calculated that the mangrove wetland area in Southeast Asia decreased from 650,000 ha in 2000 to 470,000 ha in 2015. Accordingly, our data results indicate that the aquaculture coastline in Southeast Asia experienced a significant increase, expanding from 2,118 km in 1990 to 5,553 km in 2020. The large-scale occupation of wetlands for aquaculture development can generate substantial economic benefits, but its impact on nearshore benthic environments and biodiversity is subject to scrutiny (Apine et al., 2023; Fang et al., 2023).

Coastal wetlands possess functions such as erosion resistance, water conservation, and biodiversity maintenance (Taillardat et al., 2018; Trégarot et al., 2021). However, the approach of economy development based on wetland occupation has led to the degradation of wetland ecosystems and the compression of nearshore ecological space. For instance, the felling of mangroves for the construction of aquaculture ponds directly results in the loss of wetland ecosystems and their functions (Thomas et al., 2019). Additionally, coastal aquaculture reduces the input of nearshore sediments and generates a significant amount of aquaculture waste, which can contribute to frequent occurrences of coastal erosion, groundwater pollution, and soil salinization (Van Wesenbeeck et al., 2015; Dauda et al., 2019; Tan et al., 2023).

In addition, the series of issues resulting from the aforementioned two patterns (states) will alter the anthropogenic disturbance (pressure) in the form of coastal resource utilization type replacement. In summary, both of the aforementioned anthropogenic disturbance patterns can alleviate the conflicts between human and the land and promote social and economic development. However, they are not environmentally friendly in terms of their impact on ecosystems. Therefore, the local government needs to weigh the advantages and disadvantages when formulating policies to alleviate the contradiction between human and land and promote the sustainable development of islands.

4.2.3. Relationship between anthropogenic disturbance factors and changes of coastlines in islands

The above discussion qualitatively analyzes the impact of anthropogenic disturbance factors on the coastal line and ecological environment of islands. However, compared to qualitative analysis, quantitative analysis of the relationship between anthropogenic disturbance factors and island coastal line changes can further assist decision-makers in assessing and predicting the risks of coastal line changes in islands. This can help in formulating effective protection strategies for islands (Li et al., 2021; Huang et al., 2023). Moreover, population, urban area, and nearshore aquaculture are considered as the main anthropogenic factors driving coastal line changes (Zhang et al., 2021). Therefore, to reveal the quantitative relationship between anthropogenic disturbance factors and coastal line changes, we chosen two disturbance factors (population and urban area) and three coastal line change parameters (ICUD, ICTD, and artificial coastline length) for regression analysis. Considering coastal line characteristics, island area, and the number of central cities on the islands, we selected two regions (Java Island and Luzon Island). A 30 km buffer zone was created for these two areas to represent the coastal zone. Based on the urban boundary data (Li et al., 2020) and the global population of raster data (https://ghslsys.jrc.ec.europa.eu/download.php? ds = pop), we extracted the urban area and population of these two coastal zones from 1990 to 2020, and conducted regression analysis with the parameters of coastline change.

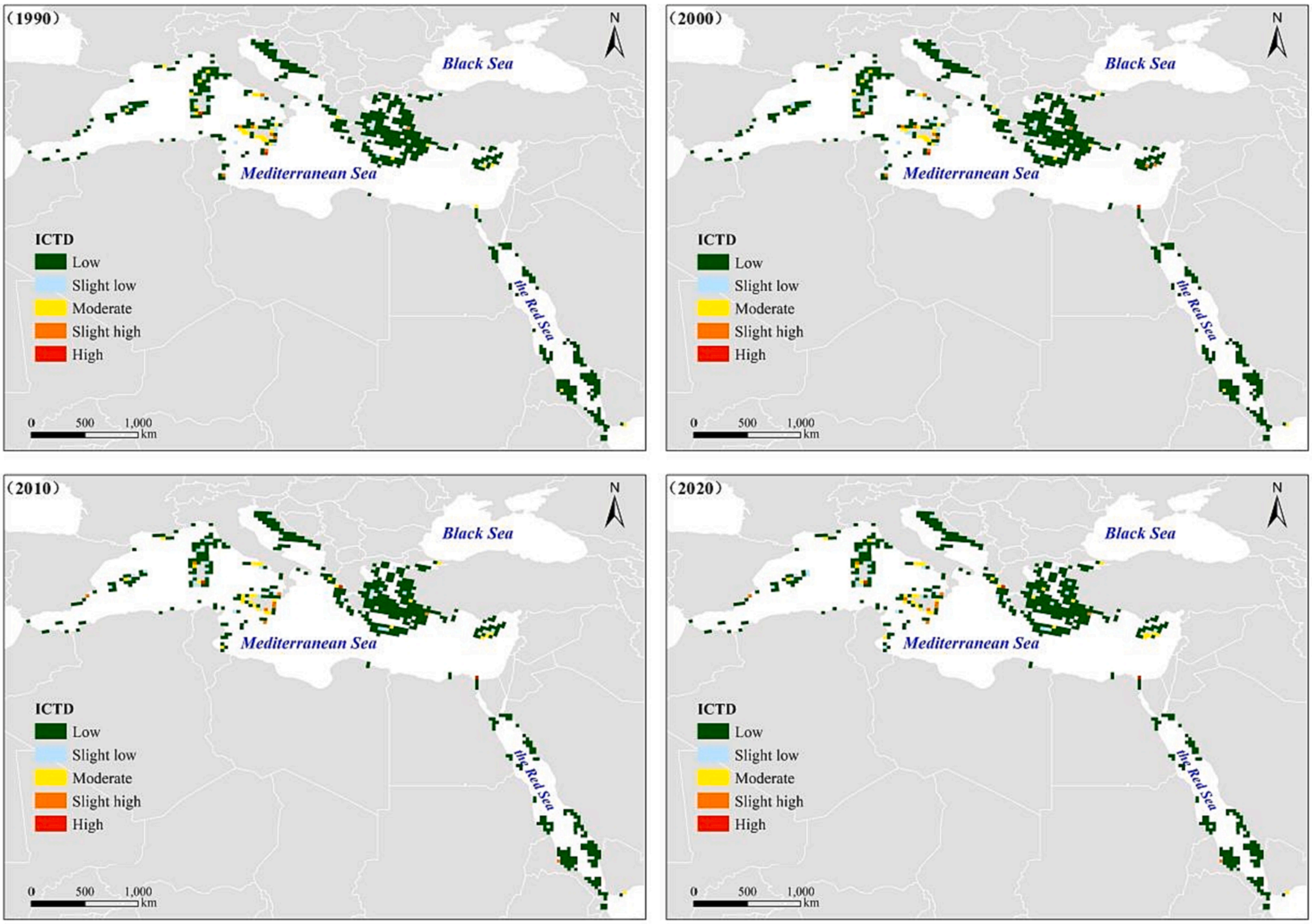


Fig. 11. Distribution of ICTD in the Red Sea and Mediterranean Sea from 1990 to 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The results indicated a significant positive correlation between the population and urban area of the two regions and the parameters of shoreline change (Fig. 17). The coefficient of determination (R^2) was greater than 0.85, suggesting a strong relationship between these variables. This finding supported the conclusion that the migration and expansion of population to coastal zones, as well as the extension of cities towards the sea, were important factors contributing to significant changes in the coastlines of islands.

4.3. Islands adapt to human disturbance

The adaptation of islands to anthropogenic disturbances is crucial for achieving island sustainable development. In 2008, the International Union for Conservation of Nature (IUCN) proposed "Nature-based Solutions (NbS)" as an approach to address global climate change, enhance global biodiversity, and promote sustainable development of human societies (Cohen-Shacham et al., 2016). NbS employs ecologically friendly approaches to restore ecosystems, mitigate natural disasters, and preserve biodiversity, thereby promoting sustainable development (Faivre et al., 2017; Moraes et al., 2022). NbS has proven to be effective in disaster resilience, water resource protection, and integrated coastal zone management on islands (Cotton et al., 2022; Lee et al., 2022; Crisman and Winters, 2023). Therefore, NbS serves as effective means for island adaptation to anthropogenic disturbances.

Restoring mangroves can provide favorable habitats for island organisms, mitigate wave erosion, and alleviate the negative impacts of anthropogenic disturbances (Lennon and Sealey, 2022; Zhang et al., 2023), making it the most direct and effective approach for island adaptation to anthropogenic disturbances. The mangrove ecosystems on islands are rapidly degrading under the dual pressures of anthropogenic deforestation and extreme natural disasters (Akbar et al., 2017; Pham et al., 2018). In response, local governments can establish mangrove nature reserves through legislation to facilitate effective restoration of mangroves. Additionally, the cultivation method of complementary nutrient components in the ecological niche of mangrove, algae, fish and other aquatic animals and plants can make full use of nutrients in seawater and promote the virtuous cycle of mangrove protection and aquaculture (Chopin et al., 2012). Bangladesh implemented this approach and was expected to restore a quarter of the degraded mangroves within the next 30 years (Ahmed et al., 2017).

By developing ecologically friendly ecological seawalls (MacArthur et al., 2019; Kosová et al., 2023), it is possible to restore the balance of land-sea material exchange and revive coastal ecosystems on islands. The existing seawalls on islands maintain coastal stability but suffer from poor ecological functionality, susceptibility to material corrosion and aging, and high maintenance costs (Naylor et al., 2011; Suedel et al., 2022). The development of eco-seawalls that can maintain coastal stability and biodiversity can reduce the damage to nearshore marine habitats caused by coastal defense structures (Salauddin et al., 2021; Suedel et al., 2022). However, island nations often face technological and economic limitations, and they can rely on international assistance or collaborative research and development for eco-seawalls. MacArthur et al. (2019) developed a novel type of seawall that enhances surface biodiversity and prolongs the lifespan of the seawall by increasing the

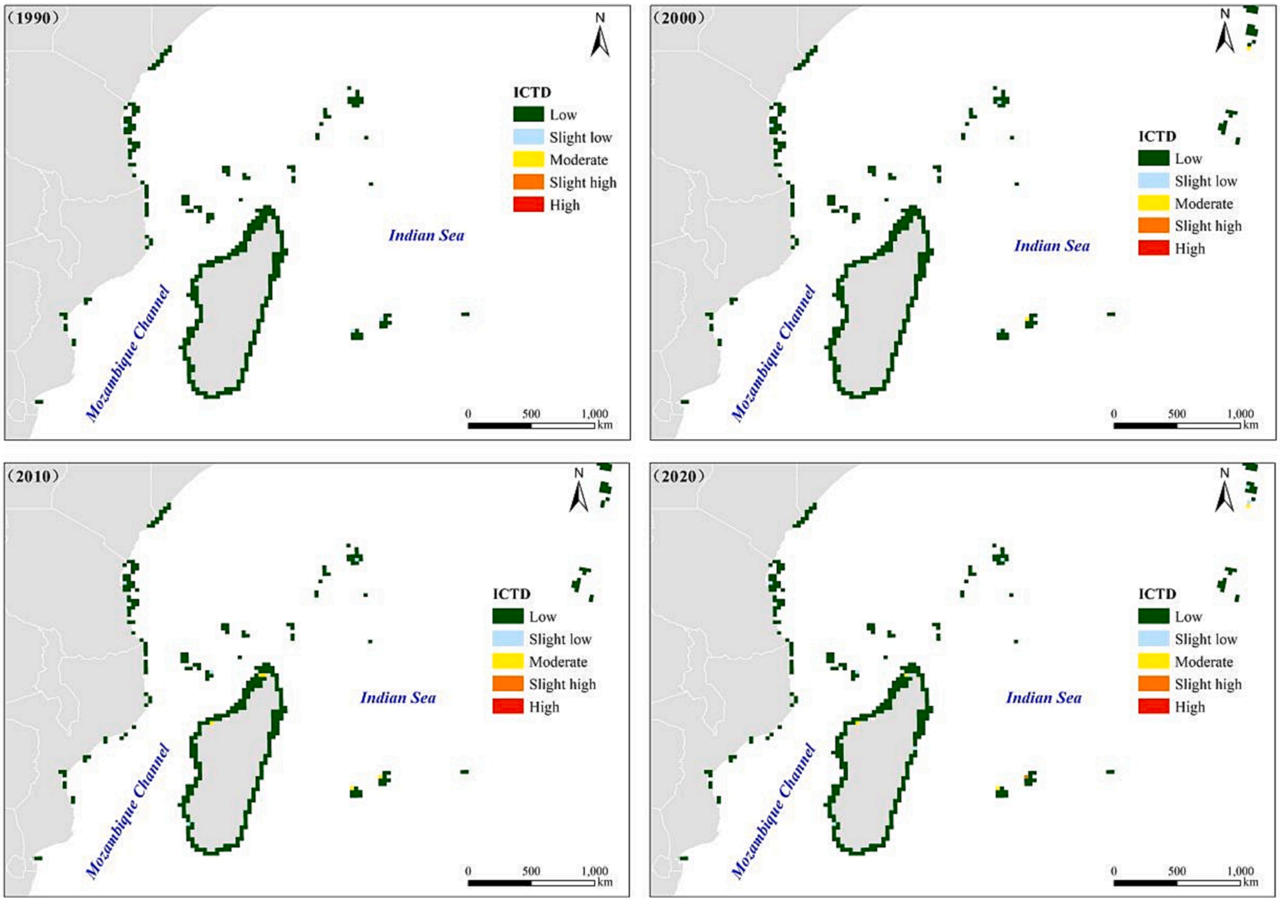


Fig. 12. Distribution of ICTD in the East coast of Africa from 1990 to 2020.

Table 7
Sum of coastline type diversity index in four regions from 1990 to 2020.

Region	Sum of coastline type diversity index			
	1990	2000	2010	2020
Southeast Asia - Indochina Peninsula	75	108	140	177
South Asia, West Asia and Maldives[c]	6/	8	13	17
the Red Sea and Mediterranean Sea	20	21	23	25
East coast of Africa	1	1	2	3

[c] Maldives was excluded in 1990

Table 8
Grid changes of coastline type diversity in four regions from 1990 to 2020.

Region	Grade division	Grid number			
		1990	2000	2010	2020
Southeast Asia - Indochina Peninsula	Low	2729	2640	2563	2464
	Slight low	69	108	127	152
	Moderate	80	99	128	158
	Slight high	58	84	110	146
	High	9	15	22	30
South Asia, West Asia and Maldives[d]	Low	192	284	284	275
	Slight low	4	7	8	13
	Moderate	4	8	16	21
	Slight high	5	5	8	13
	High	2	2	3	2
the Red Sea and Mediterranean Sea	Low	593	588	592	585
	Slight low	22	29	28	31
	Moderate	29	24	27	31
	Slight high	8	10	9	10
	High	2	3	3	3
East coast of Africa	Low	355	354	355	355
	Slight low	3	4	4	6
	Moderate	0	1	5	3
	Slight high	0	0	0	1
	High	0	0	0	0

[d] Maldives was excluded in 1990

complexity of its surface structure.

However, the unregulated expansion of land reclamation is often constrained through policy measures. As one of the countries with the largest land reclamation areas in the world, China has implemented punitive measures for exceeding the prescribed limits on land reclamation activities through the “Management Measures for Land Reclamation Plans” issued in 2011 (referred to as the “Measures”), effectively curbing the expansion of land reclamation activities (Liu et al., 2018). Simultaneously, the “Measures” combined with the Three Major Engineering Projects (the “South Red and North Willow” ecological project, the “Blue Bay” remediation project, and the “Ecological Island and Reef” restoration project) further restrict the scale and rate of land reclamation activities.

4.4. Strength and weakness in this study

In this study, we constructed a large-scale, multi-temporal dataset of island coastlines and quantitatively analyzed the spatiotemporal characteristics of anthropogenic disturbances from the perspective of island coastlines. We summarized two patterns of anthropogenic disturbances on islands and discussed the adaptive strategies of islands to these disturbances. On one hand, this study filled the data gap in the research area, and on the other hand, it contributes to the dynamic monitoring of anthropogenic disturbances on a substantial number of islands, providing a scientific basis for the sustainable protection and

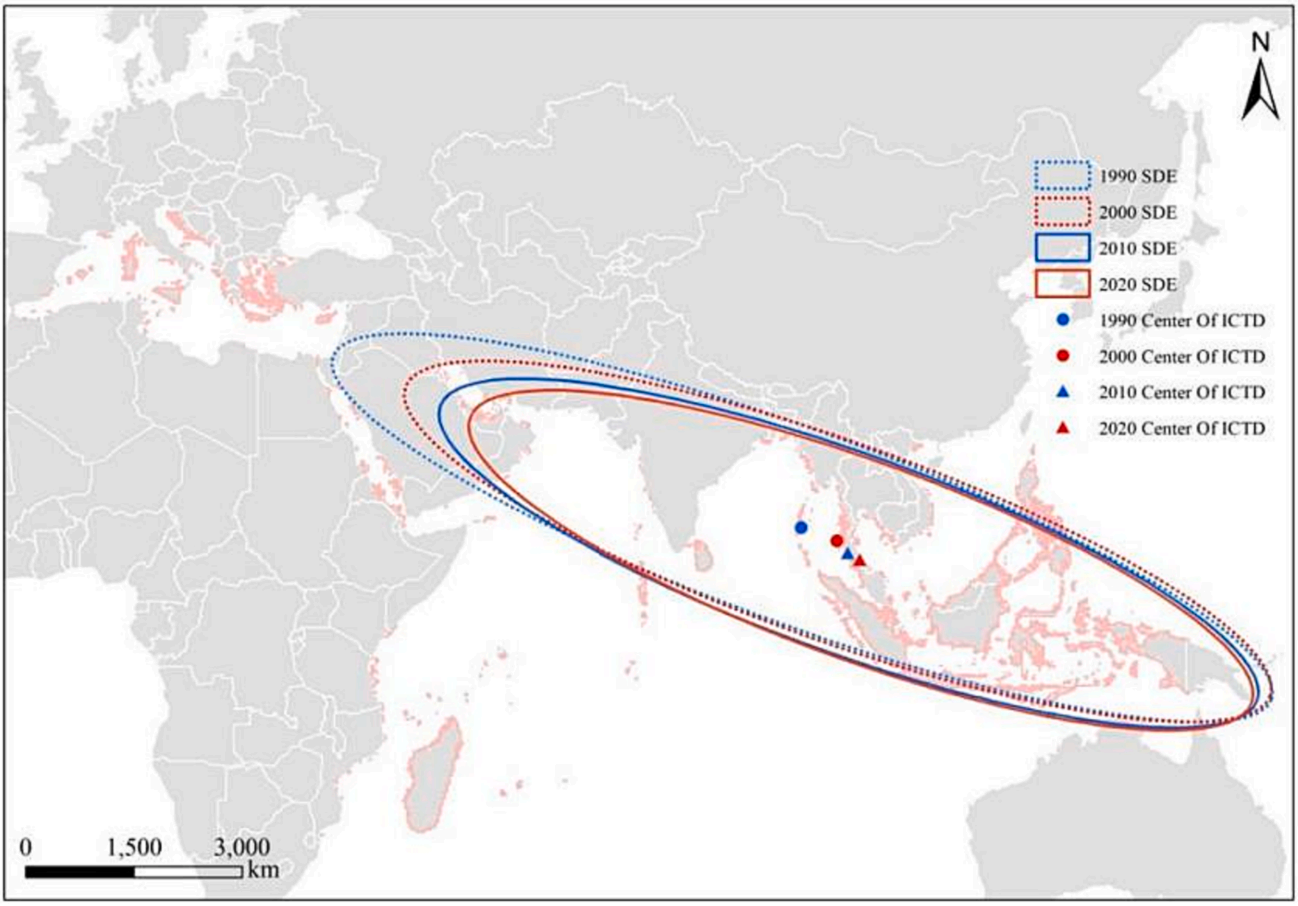


Fig. 13. Spatial distribution of geometric center of gravity of coastline type diversity in the study area from 1990 to 2020.

management of island resources.

The limitations of this study are twofold. Firstly, the long time series may mask the variations in anthropogenic disturbance characteristics in certain regions. Secondly, analyzing the anthropogenic disturbances of entire islands solely from the perspective of coastlines may not provide a comprehensive understanding, particularly for larger islands, as coastlines primarily reflect the characteristics of coastal areas.

The study of anthropogenic disturbances on islands is a complex

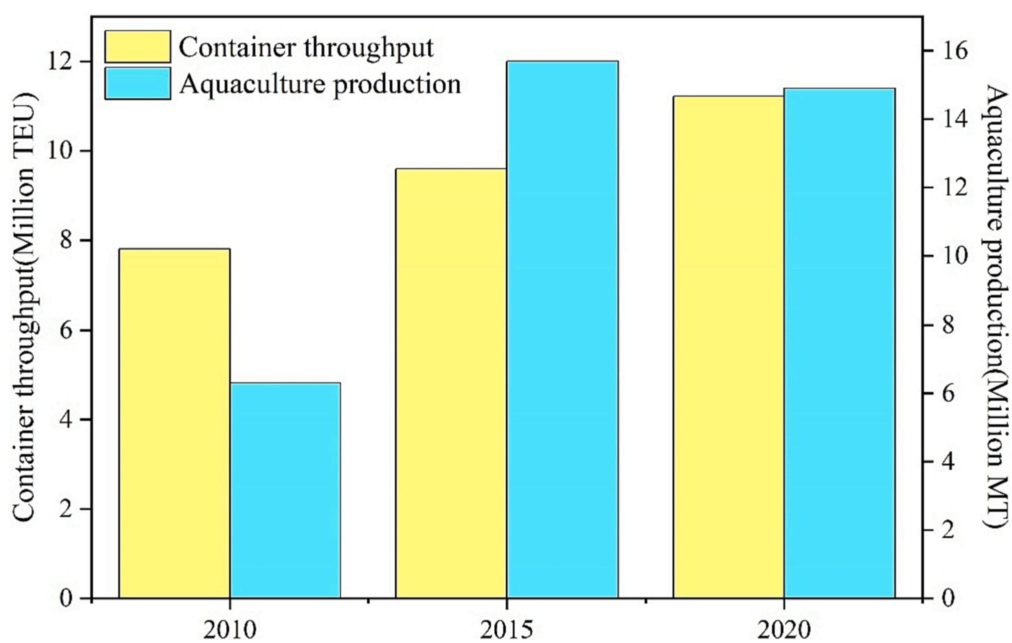


Fig. 14. Indonesia's Port Container Throughput and Aquaculture Production, 2010–2020.

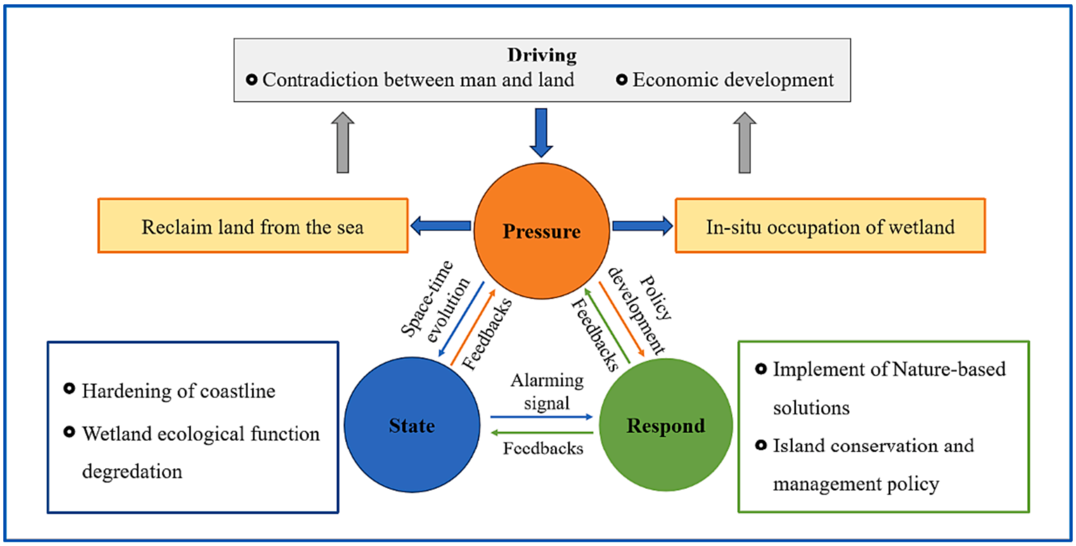


Fig. 15. A DPSR framework used to reflect the response mechanisms of islands to anthropogenic disturbances.

issue that involves multiple disciplines. In future research, we will focus on interdisciplinary integration to explore the mechanisms of anthropogenic disturbances on islands from multiple perspectives and levels.

5. Conclusion

Based on remote sensing images from 1990 to 2020, we established a dataset of island coastlines in Indian Ocean and mediterranean sea through visual interpretation. Subsequently, four indicators (ICLI, ICTD, ICUD and the SDE of the latter two) were analyzed based on the coastline dataset to measure the spatiotemporal evolution characteristics and patterns of anthropogenic disturbances on islands. We found that the artificial coastline in the study area increased by 7074 km over the course of 30 years, with aquaculture enclosures being the main

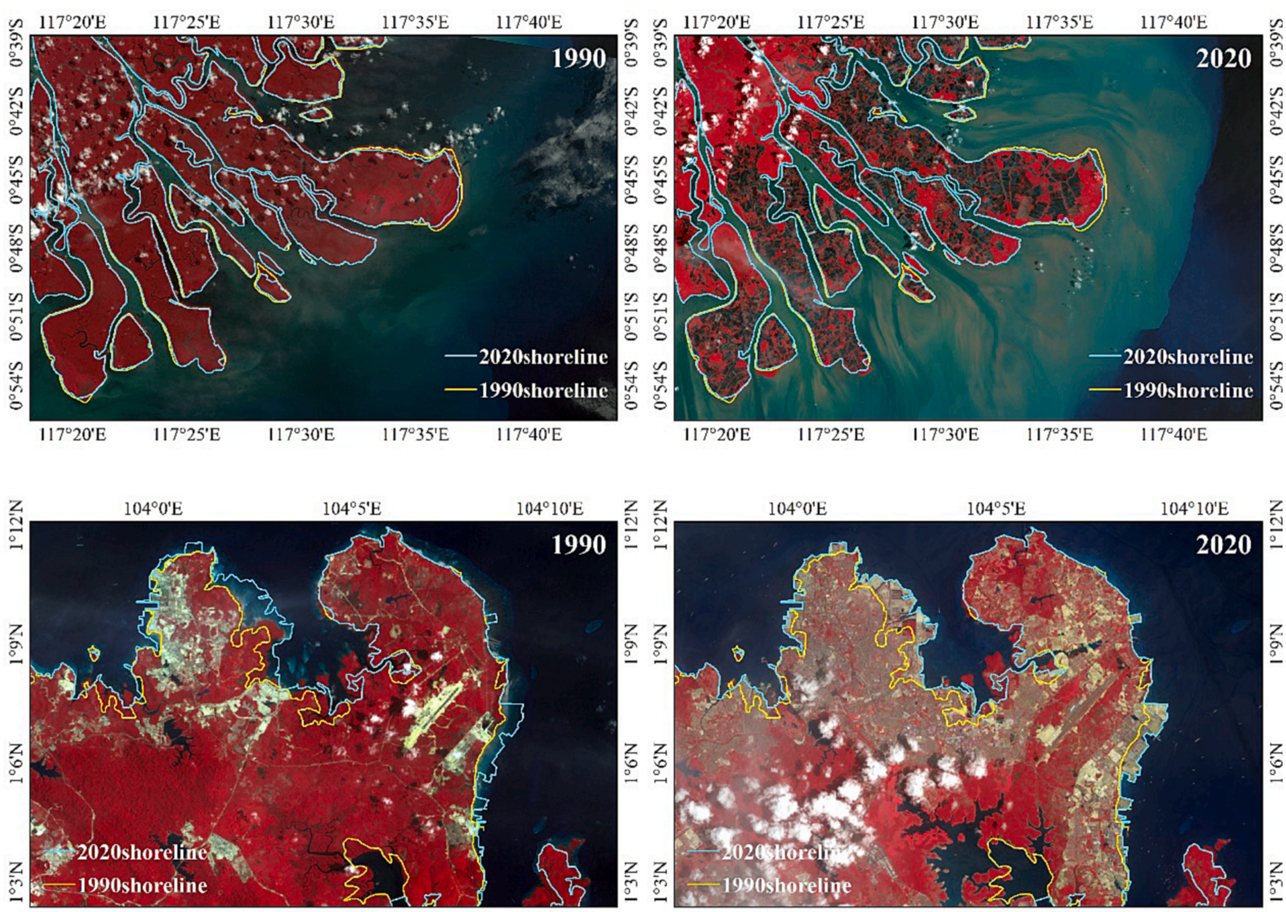


Fig. 16. Images of changes in sea and land patterns in Pawnee Bay and Singapore Strait.

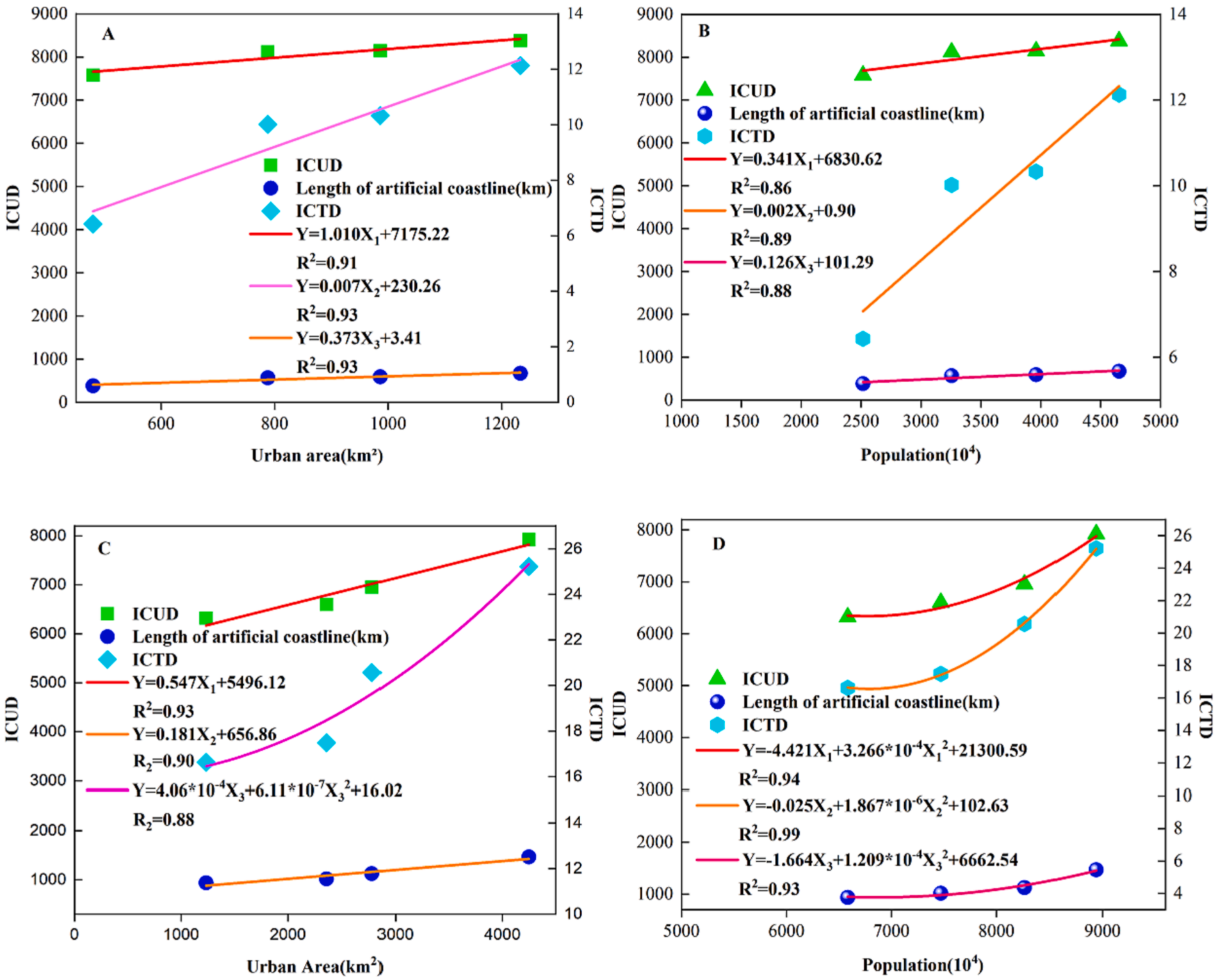


Fig. 17. Regression analysis of human disturbance factors and coastline change parameters. (Note: figures A-B show the results of regression analysis for Luzon, figures C-D show the results of regression analysis for Java Island. X_1 represents ICUD, X_2 indicates Length of artificial coastline, X_3 is ICTD.).

contributor. Moreover, both the intensity of coastal line utilization and the diversity of coastal line types showed a significant upward trend. Their respective centroids have shifted towards the Southeast Asia region, with a displacement of 59.53 km and 931.05 km, respectively. It is worth noting that these phenomena are primarily caused by two modes of development: land reclamation-driven construction resulting from the conflict between human activities and the occupation of wetlands-driven economic development. Additionally, we discussed the response patterns of islands to anthropogenic disturbances, the potential links between anthropogenic disturbance factors and island coastlines, as well as management and conservation strategies for islands under rapid anthropogenic disturbances.

Our research findings have practical implications for the sustainable development of islands. Firstly, we have filled the gap in large-scale, long-term series datasets of island coastlines. Secondly, analyzing anthropogenic disturbances on islands from a coastal perspective provides an intuitive and efficient approach. Lastly, by integrating data on population, impermeable surface area, urban expansion, and other factors, we can better explore the patterns and driving forces of anthropogenic disturbances on islands, thereby providing effective strategies for their management and conservation.

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.

CRediT authorship contribution statement

Hao Li: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yuxin Zhang:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Chao Fan:** Writing – review & editing. **Xiyong Hou:** Writing – review & editing, Funding acquisition. **Ling Zeng:** Formal analysis. **Peng Guo:** Writing – review & editing.

Declaration of 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.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Director Fund of the International Research Center of Big Data for Sustainable Development Goals (Grant No. CBAS2022DF019), Shandong Provincial Natural Science Foundation (Grant No. ZR2022QD072), and National Natural Science Foundation of China (Grant No. 42176221).We would like to express thanks for the constructive comments from the editor and anonymous referees.

References

Abu Zed, A.A.A., Soliman, M.R., Yassin, A.A., 2018. Evaluation of using satellite image in detecting long term shoreline change along el-Arish coastal zone, Egypt. Alex. Eng. J. 57 (4), 2687–2702.

Adyasari, D., Pratama, M.A., Teguh, N.A., et al., 2021. Anthropogenic impact on indonesian coastal water and ecosystems: current status and future opportunities. Mar. Pollut. Bull. 171, 112689.

Ahmed, N., Bunting, S.W., Glaser, M., et al., 2017. Can greening of aquaculture sequester blue carbon? Ambio 46, 468–477.

Akbar, A.A., Sartohadi, J., Djohan, T.S., et al., 2017. The role of breakwaters on the rehabilitation of coastal and mangrove forests in West Kalimantan, Indonesia. Ocean Coast. Manag. 138, 50–59.

Ali, V., Cullen, R., Toland, J., 2015. ICTs and tourism in small island developing states: the case of the Maldives. J. Glob. Inf. Technol. Manag. 18 (4), 250–270.

Apine, E., Ramappa, P., Bhatta, R., et al., 2023. Challenges and opportunities in achieving sustainable mud crab aquaculture in tropical coastal regions. Ocean Coast. Manag. 242, 106711.

Bellard, C., Leclerc, C., Courchamp, F., 2014. Impact of sea level rise on the 10 insular biodiversity hotspots. Glob. Ecol. Biogeogr. 23 (2), 203–212.

Cai, H., Li, C., Luan, X., et al., 2022. Analysis of the spatiotemporal evolution of the coastline of Jiaozhou Bay and its driving factors. Ocean Coast. Manag. 226, 106246.

Cao, W., Zhou, Y., Li, R., et al., 2021. Monitoring long-term annual urban expansion (1986–2017) in the largest archipelago of China. Sci. Total Environ. 776, 146015.

Chen, C., Liang, J., Yang, G., et al., 2023a. Spatio-temporal distribution of harmful algal blooms and their correlations with marine hydrological elements in offshore areas, China. Ocean Coast. Manag. 238, 106554.

Chen, C., Yang, X., Jiang, S., et al., 2023b. Mapping and spatiotemporal dynamics of land-use and land-cover change based on the Google earth engine cloud platform from landsat imagery: a case study of Zhoushan Island China. Heliyon 9 (9).

Chi, Y., Shi, H., Zheng, W., et al., 2018. Archipelagic landscape patterns and their ecological effects in multiple scales. Ocean Coast. Manag. 152, 120–134.

Chi, Y., Zhang, Z., Xie, Z., et al., 2020. How human activities influence the island ecosystem through damaging the natural ecosystem and supporting the social ecosystem? J. Clean. Prod. 248, 119203.

Chopin, T., Cooper, J.A., Reid, G., et al., 2012. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4 (4), 209–220.

Chouhan, H.A., Parthasarathy, D., Pattanaik, S., 2017. Urban development, environmental vulnerability and CRZ violations in India: impacts on fishing communities and sustainability implications in Mumbai coast. Environ. Dev. Sustain. 19, 971–985.

Choung, Y.J., Jo, M.H., 2016. Shoreline change assessment for various types of coasts using multi-temporal landsat imagery of the east coast of South Korea. Remote Sensing Letters 7 (1), 91–100.

Coccia, C., Contreras-López, M., Farina, J.M., et al., 2022. Comparison of taxonomic and size-based approaches to determine the effects of environment and disturbance on invertebrate communities in coastal Chile. Ecol. Ind. 143, 109356.

Cohen-Shacham E, Walters G, Janzen C, et al. Nature-based solutions to address global societal challenges[J]. IUCN: Gland, Switzerland, 2016, 97: 2016-2036.

Cotton, I., Forster, J., Lorenzoni, I., et al., 2022. Understanding perceived effectiveness of a novel coastal management project: the case of the bacton-Walcott sandscaing scheme, UK. Front. Mar. Sci. 9, 1028819.

Crisman, T.L., Winters, Z.S., 2023. Caribbean small island developing states must incorporate water quality and quantity in adaptive management of the water-energy-food nexus. Frontiers in environmental. Science.

Crossett, C.C., Metz, N.D., 2017. A climatological study of extreme cold surges along the african highlands. J. Appl. Meteorol. Climatol. 56 (6), 1731–1738.

Dahanayake, H.D., Wickramasinghe, D., 2022. Impacts of floods on Colombo during two decades: looking back and thinking forward. Progress in Physical Geography: Earth and Environment 46 (5), 697–715.

Das, A., Choudhury, K.M., Choudhury, A.K., 2023. An assessment of mangrove vegetation changes in reference to cyclone impacted climatic alterations at land–ocean interface of indian Sundarbans with application of remote sensing–based analytical tools. Environ. Sci. Pollut. Res. 30 (38), 89311–89335.

Dauda, A.B., Ajadi, A., Tola-Fabunmi, A.S., et al., 2019. Waste production in aquaculture: sources, components and managements in different culture systems. Aquaculture and Fisheries 4 (3), 81–88.

Dauvin, J.C., Desroy, N., Janson, A.L., et al., 2006. Recent changes in estuarine benthic and suprabenthic communities resulting from the development of harbour infrastructure. Mar. Pollut. Bull. 53 (1–4), 80–90.

Davis, A.R., Broad, A., Small, M., et al., 2022. Mapping of benthic ecosystems: key to improving the management and sustainability of anchoring practices for ocean-going vessels. Cont. Shelf Res. 247, 104834.

Delgado, J.D., Riera, R., Rodriguez, R.A., et al., 2017. A reappraisal of the role of humans in the biotic disturbance of islands. Environ. Conserv. 44 (4), 371–380.

Duan, H., Zhang, H., Huang, Q., et al., 2016. Characterization and environmental impact analysis of sea land reclamation activities in China. Ocean Coast. Manag. 130, 128–137.

Faivre, N., Fritz, M., Freitas, T., et al., 2017. Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518.

Fang, G., Yu, H., Zhang, Y., et al., 2023. Diversities and shifts of microbial communities associated with farmed oysters (Crassostrea gigas) and their surrounding environments in Laoshan Bay marine ranching, China. Microorganisms 11 (5), 1167.

Floerl, O., Atalah, J., Bugnot, A.B., et al., 2021. A global model to forecast coastal hardening and mitigate associated socioecological risks. Nat. Sustainability 4 (12), 1060–1067.

Hassanali, K., 2017. Challenges in mainstreaming climate change into productive coastal sectors in a Small Island state-the case of Trinidad and Tobago. Ocean Coast. Manag. 142, 136–142.

Hou, X.Y., Wu, T., Wang, Y.D., et al., 2014. Extraction and accuracy evaluation of multi-temporal coastlines of mainland China since 1940s. Mar. Sci 38, 66–73.

Hou, X.Y., Wu, T., Hou, W., et al., 2016. Characteristics of coastline changes in mainland China since the early 1940s. Sci. China Earth Sci. 59, 1791–1802.

Huang, L., Zhao, C., Jiao, C., et al., 2023. Quantitative analysis of rapid siltation and erosion caused coastline evolution in the coastal mudflat areas of Jiangsu. Water 15 (9), 1679.

Hume, A., Leape, J., Oleson, K.L.L., et al., 2021. Towards an ocean-based large ocean states country classification. Mar. Policy 134, 104766.

Iacarella, J.C., Adamczyk, E., Bowen, D., et al., 2018. Anthropogenic disturbance homogenizes seagrass fish communities. Glob. Chang. Biol. 24 (5), 1904–1918.

Jenks, G.F., 1967. The data model concept in statistical mapping. International Yearbook of Cartography 7, 186–190.

Katircioğlu, S.T., 2014. Estimating higher education induced energy consumption: the case of northern Cyprus. Energy 66, 831–838.

Kosová, E., James, K., MacArthur, M., et al., 2023. The BioGeo ecotile: improving biodiversity on coastal defences using a multiscale, multispecies eco-engineering design. Ecol. Eng. 188, 106881.

Kurniawan, F., Adrianto, L., Bengen, D.G., et al., 2019. The social-ecological status of small islands: an evaluation of island tourism destination management in Indonesia. Tour. Manag. Perspect. 31, 136–144.

Lapointe, M., Gurney, G.G., Cumming, G.S., 2020. Urbanization alters ecosystem service preferences in a Small Island developing State. Ecosyst. Serv. 43, 101109.

Lapointe, D., Renaud, L., Blanchard, M.E., 2021. Tourism adaptation to coastal risks: a socio-spatial analysis of the Magdalen Islands in Québec, Canada. Water 13 (17), 2410.

Lee, S., Hall, G., Trench, C., 2022. The role of nature-based solutions in disaster resilience in coastal Jamaica: current and potential applications for 'building back better'. Disasters 46, S78–S100.

Lee, M.T., Wu, C.C., Ho, C.H., et al., 2014. Towards marine spatial planning in southern Taiwan. Sustainability 6 (12), 8466–8484.

Lei, L., Ozturk, I., Murshed, M., et al., 2023. Environmental innovations, energy innovations, governance, and environmental sustainability: evidence from south and southeast asian countries. Resour. Policy 82, 103556.

Lennon, E., Sealey, K.S., 2022. Characterizing nearshore fish assemblages from intact and altered mangrove shorelines in Biscayne Bay, Florida, United States. Front. Mar. Sci. 9, 894663.

Li Deren, Y.U., Hanruo, LI.X., 2017. The Spatial-Temporal Pattern Analysis of City Development in Countries along the Belt and Road Initiative Based on Nighttime Light Data 42, 711–720.

Li, X., Gong, P., Zhou, Y., et al., 2020. Mapping global urban boundaries from the global artificial impervious area (GAIA) data. Environ. Res. Lett. 15 (9), 094044.

Li, X., Yan, H., Yang, Y., et al., 2022. Spatiotemporal coastline variations in the Pearl River estuary and the relationship with multiple human disturbances. Front. Mar. Sci. 9, 1032105.

Li, K., Zhang, L., Chen, B., et al., 2023. Analysis of China's coastline changes during 1990–2020. Remote Sens. (Basel) 15 (4), 981.

Li, C., Zhu, L., Dai, Z., et al., 2021. Study on spatiotemporal evolution of the Yellow River Delta coastline from 1976 to 2020. Remote Sens. (Basel) 13 (23), 4789.

Liu, L., Xu, W., Yue, Q., et al., 2018. Problems and countermeasures of coastline protection and utilization in China. Ocean Coast. Manag. 153, 124–130.

Lu, Y., He, T., Xu, X., et al., 2021. Investigation the robustness of standard classification methods for defining urban heat islands. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 14, 11386–11394.

MacArthur, M., Naylor, L.A., Hansom, J.D., et al., 2019. Maximising the ecological value of hard coastal structures using textured formliners. Ecol. Eng. 142, 100002.

Malik, A., Mertz, O., Fensholt, R., 2017. Mangrove forest decline: consequences for livelihoods and environment in South Sulawesi. Reg. Environ. Chang. 17, 157–169.

Malmgren, B.A., Hulugalla, R., Hayashi, Y., et al., 2003. Precipitation trends in Sri Lanka since the 1870s and relationships to el niño–southern oscillation. Int. J. Climatol. 23 (10), 1235–1252.

McSherry, M., Davis, R.P., Andradi-Brown, D.A., et al., 2023. Integrated mangrove aquaculture: the sustainable choice for mangroves and aquaculture? Frontiers in Forests and Global Change 6, 1094306.

Moraes, R.P.L., Reguero, B.G., Mazarrasa, I., et al., 2022. Nature-based solutions in coastal and estuarine areas of Europe. Front. Environ. Sci. 10, 829526.

Naylor, L.A., Venn, O., Coombes, M.A., et al., 2011. Including Ecological Enhancements in the Planning, Design and Construction of Hard Coastal Structures: A Process Guide 66, 110461)..

Nguyen, T.T.X., Bonetti, J., Rogers, K., et al., 2016. Indicator-based assessment of climate-change impacts on coasts: a review of concepts, methodological approaches and vulnerability indices. Ocean Coast. Manag. 123, 18–43.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328 (5985), 1517–1520.

Pham, T.D., Kaida, N., Yoshino, K., et al., 2018. Willingness to pay for mangrove restoration in the context of climate change in the cat Ba biosphere reserve, Vietnam. Ocean Coast. Manag. 163, 269–277.

Rovere, A., Khanna, P., Bianchi, C.N., et al., 2018. Submerged reef terraces in the maldivian archipelago (Indian Ocean). Geomorphology 317, 218–232.

Sahoo, B., Bhaskaran, P.K., 2018. Multi-hazard risk assessment of coastal vulnerability from tropical cyclones–a GIS based approach for the Odisha coast. J. Environ. Manage. 206, 1166–1178.

Salauddin, M., O'Sullivan, J.J., Abolfathi, S., et al., 2021. Eco-engineering of seawalls—an opportunity for enhanced climate resilience from increased topographic complexity. Front. Mar. Sci. 8, 674630.

Sarathchandra, C., Kambach, S., Ariyarathna, S.C., et al., 2018. Significance of mangrove biodiversity conservation in fishery production and living conditions of coastal communities in Sri Lanka. Diversity 10 (2), 20.

Scherner, F., Horta, P.A., de Oliveira, E.C., et al., 2013. Coastal urbanization leads to remarkable seaweed species loss and community shifts along the SW Atlantic. Mar. Pollut. Bull. 76 (1–2), 106–115.

Shen, C., Shi, H., Zheng, W., et al., 2016. Spatial heterogeneity of ecosystem health and its sensitivity to pressure in the waters of nearshore archipelago. Ecol. Ind. 61, 822–832.

Suedel, B.C., Calabria, J., Bilskie, M.V., et al., 2022. Engineering coastal structures to centrally embrace biodiversity. J. Environ. Manage. 323, 116138.

Sun, W., Chen, C., Liu, W., et al., 2023. Coastline extraction using remote sensing: a review. Giscience & Remote Sensing 60 (1), 2243671.

Taillardat, P., Friess, D.A., Lupascu, M., 2018. Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. Biol. Lett. 14 (10), 20180251.

Tan, S.Y., Sethupathi, S., Leong, K.H., et al., 2023. Challenges and opportunities in sustaining aquaculture industry in Malaysia. Aquac. Int. 1–31.

Tay, J.Y., Wong, S.K., Chou, L.M., Todd, P.A., 2018. Land reclamation and the consequent loss of marine habitats around the Ayer Islands, Singapore. Nature in Singapore 11, 1–5.

Thomas, L.R., Clavelle, T., Klinger, D.H., et al., 2019. The ecological and economic potential for offshore mariculture in the Caribbean. Nat. Sustainability 2 (1), 62–70.

Thomas, N., Lucas, R., Bunting, P., et al., 2017. Distribution and drivers of global mangrove forest change, 1996–2010. PLoS One 12 (6), e0179302.

Tinh, P.H., MacKenzie, R.A., Hung, T.D., et al., 2022. Distribution and drivers of Vietnam mangrove deforestation from 1995 to 2019. Mitig. Adapt. Strat. Glob. Chang. 27 (4), 29.

Tovar, B., Hernández, R., Rodríguez-Déniz, H., 2015. Container port competitiveness and connectivity: the Canary Islands main ports case. Transp. Policy 38, 40–51.

Trégarot, E., Caillaud, A., Cornet, C.C., et al., 2021. Mangrove ecological services at the forefront of coastal change in the french overseas territories. Sci. Total Environ. 763, 143004.

Van Beynen, P., Akiwumi, F.A., Van Beynen, K., 2018. A sustainability index for small island developing states. Int J Sust Dev World 25 (2), 99–116.

Van Wesenbeeck, B.K., Balke, T., Van Eijk, P., et al., 2015. Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty. Ocean Coast. Manag. 116, 466–469.

Vousdoukas, M.I., Mentaschi, L., Hinkel, J., et al., 2020. Economic motivation for raising coastal flood defenses in Europe. Nat. Commun. 11 (1), 2119.

Wei, S., Lin, Y., Wan, L., et al., 2021. Developing a grid-based association rules mining approach to quantify the impacts of urbanization on the spatial extent of mangroves in China. Int. J. Appl. Earth Obs. Geoinf. 102, 102431.

Xiao Han, Su Fenzhen, Fu Dongjie, Yu Hao, Ju Chengyuan, Pan Tingting, Kang Lu. 10-M GLOBAL MANGROVE CLASSIFICATION PRODUCTS OF 2018-2020 BASED ON BIG DATA. V1. Science Data Bank. http://www.doi.org/10.11922/sciencedb.01019. (2021-08-12).

Xie, Z., Li, X., Chi, Y., et al., 2021. Ecosystem service value decreases more rapidly under the dual pressures of land use change and ecological vulnerability: a case study in Zhujiajian Island[J]. Ocean Coast. Manag. 201, 105493.

Yan, F., Wang, X., Huang, C., et al., 2023. Sea reclamation in mainland China: process, pattern, and Management. Land Use Policy 127, 106555.

Yi, G., Wang Hui, Su Fenzhen, et al., 2013. Spatial and temporal of continental coastline of China recent three decades. Acta Oceanlogica Sinica (in Chinese) 35 (6), 31–42.

Zhang, R., Chen, Y., Lei, J., et al., 2023. Experimental investigation of wave attenuation by mangrove forests with submerged canopies. Coast. Eng. 186, 104403.

Zhang, Y., Hou, X., 2020. Characteristics of coastline changes on Southeast Asia Islands from 2000 to 2015. Remote Sens. (Basel) 12 (3), 519.

Zhang, Y., Li, D., Fan, C., et al., 2021. Southeast Asia island coastline changes and driving forces from 1990 to 2015. Ocean Coast. Manag. 215, 105967.

Zhang, J., Su, F., Ding, Z., 2017. Sea reclamation status of countries around the South China Sea from 1975 to 2010. Sustainability 9 (6), 878.