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Title: Assessing the Ecological Impacts of Coastal Reclamation: An Integrated Index System

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Conflict of interest declaration

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Assessing the ecological impacts of coastal reclamation: An integrated index system

Abstract

Coastal land reclamation has been practiced widely to accommodate rapid economic growth and urbanization. However, the exploitation of coastal wetlands also imposes ecological risks and jeopardizes ecological security in many countries. There is a need to assess the overall effects of coastal reclamation. We developed a conceptual framework to assess the ecological impacts of coastal land reclamation in three dimensions: land quantity, ecological environment, and land quality. An integrated index system was constructed accordingly and tested by using data from Cixi, a coastal city in eastern China. Our index system generated rich information to assess the impacts of reclamation on added land area, landscape ecological risk, and cropland soil quality. The results showed that coastal reclamation played an important role in maintaining the balance of the supply and demand of land resources during urbanization in the study area. However, its adverse ecological effects were also evidenced. Coastal reclamation not only increased the landscape disturbance and ecological risk but also significantly decreased the overall cropland soil quality. The city's original reclamation-driven development strategy is unable to meet the updated requirements of "quantity-quality-ecological balance" for cropland protection. Our index system can help land use policymakers monitor the ecological effects of coastal reclamation. The knowledge gained has major policy implications for sustainable land use management in coastal areas.

Keywords: Land reclamation; Remote sensing; Landscape ecological risk; Soil quality; Cropland protection

1 Introduction

Historically, coastal areas attract business activities due to their access to transport networks and fertile lands. Consequently, it is commonplace that land demand outstrips land supply in coastal areas, and the gap has been further widened as a result of the rapid urbanization process across the world (Lazzari et al., 2019). Facing this challenge, coastal cities increasingly rely on ocean sprawl as a key strategy to meet land demand. Reclamation of coastal wetlands has also emerged as an important method for increasing human living and production space (Zhang et al., 2020b; Wang et al., 2014). Many countries, including the Netherlands, Japan, Italy, Portugal, Singapore, Korea, and Saudi Arabia, have expanded their land area through reclamation projects. These land reclamation projects played a significant role in promoting local industrial and agricultural development, as well as urban construction (Sousa et al., 2020; Fokker et al., 2019; Sengupta et al., 2018). However, large-scale reclamation also gives rise to ecological issues such as habitat fragmentation, soil degradation, and biodiversity loss, resulting in serious ecological security risks (Barbier, 2019; Sun et al., 2017). The reclaimed area has further developed into an ecologically fragile area disturbed by human activities and may suffer long-term negative effects from irrational land use management such as inefficient use, idle waste, and even soil pollution (Yang et al., 2017; Tian et al., 2016). Despite many studies on coastal land reclamation, it is still unclear how the net effect of coastal land reclamation should be determined.

This study addresses this research question by proposing an integrated index system to assess the ecological effects of coastal land reclamation activities. The coastal land reclamation process is long, and its effect is long lasting. Therefore, an index is necessary to track the effect over time. We included three dimensions, i.e., land quantity, ecological environment, and land quality, in the proposed index system to account for the complexity of the land reclamation process. Three subindices, i.e., the added cropland area index (ACA), landscape ecological risk index (ERI), and soil quality index (SQI), were developed accordingly. A weighting system was used to compose the final Integrated Benefits Index (IBI), which measures the overall effects of coastal land reclamation. The system is designed in such a way that policymakers can incorporate local priorities by adjusting the weighting among the three dimensions.

We tested the proposed index system by using data from a typical coastal city in China. Cixi City, our study area, has been acquiring land along its coastline for decades, and the local areas have undergone significant changes through this process. Our empirical analysis shows clear evidence of both the benefits and the costs of coastal reclamation in this city. By comparing remote sensing images, we observed that coastal reclamation expanded rapidly by 393.71 km^2 from 1985 to 2020, equivalent to 42% of the original land area. The coastal landscape presented a gradual evolution from natural wetlands to artificial landscapes dominated by cropland, built-up land, and mariculture. Coastal reclamation played an important role in maintaining the balance of land resources during urbanization. Meantime, land reclamation had negative ecological impacts on ecological security. From 1985 to 2020, the landscape ecological risk in Cixi City increased from low-medium to medium-high levels, while the overall soil quality index of cropland dropped from 2.50 to 2.38.

We also found that the city’s coastal land reclamation outcomes can only be considered satisfactory in the old regime when economic growth was the first priority. Significant land use policy changes are needed to meet the central government’s new requirements of striking a balance between economic growth and sustainable development. The empirical analysis demonstrates the flexibility and tractability of our conceptual model and the proposed index system. It is an effective and efficient tool to measure the effects of coastal land reclamation from a land use policy perspective.

The rest of the paper is organized as follows. The second section gives the conceptual model, followed by the description of the index system in Section 3. Section 4 provides details of the empirical strategies. The findings are presented and discussed in Section 5. Section 6 concludes.

2 Conceptual model

Existing studies have identified several important aspects of assessing the impacts of land reclamation activities on coastal ecosystems. Most of these studies investigated these aspects individually in isolation. We designed a conceptual model to bring these studies into one unified framework, as shown in Figure 1. The conceptual framework consists of five dimensions, namely, landscape/land use change, soil properties, biodiversity, ecosystem services, and ecological risks. We surveyed the literature to determine the factors to be included in each of these five dimensions.

First, reclamation activities transform coastal landscape/land use patterns from natural ecosystems to artificial ones. This process affects the quantity of different types of land in and around the reclaimed areas. For example, since the end of the 19th century, nearly 2000 ha of wetlands were converted to anthropic environments due to coastal wetland reclamation in Ria Formosa, Portugal. However, this process led to a 20% natural area reduction in the same area (Sousa et al., 2020). Similar effects are observed in other parts of the world (Murray et al., 2019) and especially in China (Hu et al., 2021; Zhang et al., 2020b). Therefore, it is an important aspect of coastal reclamation impacts to be considered in our conceptual model.

Second, wetland soils' physical, chemical, and biological properties are altered by the conversion, which leads to changes in soil quality. We measured changes in soil quality based on their physical, chemical, and biological properties. Evidence shows that soil physical and chemical properties can be affected by coastal land reclamation, both in the short term and in the long term (Li and Zhang, 2021; Xu et al., 2021; Xie et al., 2019; Cui et al., 2012). The impacts of coastal reclamation on biological properties, such as bacterial diversity and macrofaunal communities, have also been identified in many studies (Ge et al., 2021; Hua et al., 2017). Therefore, we included these three groups of indicators in the conceptual framework to capture the effects of coastal reclamation on soil quality.

Third, conversion alters coastal biodiversity due to the different habits of wetlands and terrestrial areas. We focused on the diversity of plants, animals, and microbial communities in this dimension. Researchers have documented significant impacts of coastal reclamation on mangroves in Indonesia and China (Slamet et al., 2020; Sun et al., 2015). The habitat choice and migration pattern of birds are also affected by coastal reclamation activities (Sun et al., 2016). The negative effect of coastal reclamation on animal species number and diversity is alarming (Yang et al., 2016). There has also been growing concern regarding the shifts in soil bacterial and fungal communities in areas affected by coastal reclamation (Yang et al., 2021; Kim et al., 2019). Therefore, these are important aspects to be considered when assessing the impacts of coastal reclamation on biodiversity.

Fourth, land use change is a primary driver of ecosystem service loss. Therefore, land conversion during coastal reclamation affects the provision, regulation, and cultural services of the coastal ecosystem. Following the practice in the ecosystem services literature, we consider provision, regulation, and cultural service in the conceptual model. Specifically, a positive relationship is identified between reclamation activity intensity and material production (Liu et al., 2020b; Yang et al., 2017); while coastal land reclamation tends to reduce the ecosystem services of coastal wetlands in terms of water regulation, carbon storage and soil retention (Tian et al., 2021; Yu et al., 2021; Li et al., 2017), as well as aesthetic and recreational services to affected areas (Wang et al., 2010). We include all three aspects in the conceptual model to capture the complex relationship between coastal land reclamation and ecosystem services.

Finally, the changes in biodiversity and ecosystem services have an impact on the ecological security of coastal ecosystems and ultimately impose ecological risks. As this poses a significant threat to the sustainability of both the urban and natural environments in affected areas, extensive studies have been conducted in this stream of research. Empirical investigations show that coastal reclamation increases ecological risks primarily through soil pollution (Lu et al., 2020; Zhao et al., 2016), eutrophication (Qiao et al., 2017; Li et al., 2014), and biological invasion (Granse et al., 2021; Wang et al., 2017). The effects of these changes manifest themselves in terms of landscape disturbance (Wu et al., 2022; Zhou et al., 2018), and landscape vulnerability (Wang et al., 2021c; Zhang et al., 2015). Taking stock of findings in the literature, we focused on landscape disturbance and landscape vulnerability to construct a landscape ecological risk index to capture the ecological effect of coastal land reclamation.

The effects through these five channels do not work in isolation; one aspect of the ecological effects of reclamation can affect the others due to their interdependency and nonlinear interactions. For example, intensive land use changes can cause landscape fragmentation and biodiversity loss, thereby compromising coastal ecosystem services, which in turn could increase landscape ecological risks. By considering these five dimensions in one unified framework, our theoretical model has the advantage of isolating the net effect of each dimension when studying the complex relationship between land reclamation and coastal ecosystems. We considered these dimensions as the channels through which land reclamation activities affect coastal ecosystems. The effects are further classified into three categories, land quantity, land quality, and ecological outcomes, because these are the three most important metrics in China's land use policies (Zhou et al., 2021; Liu et al., 2019).

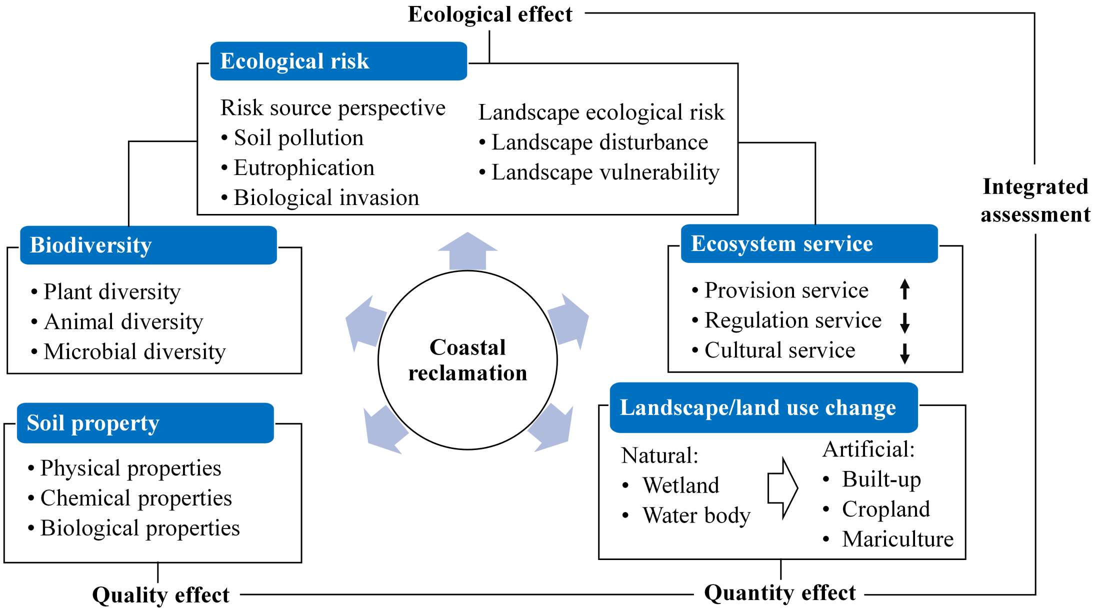

Fig. 1 Conceptualization of an integrated coastal reclamation assessment model

3 An integrated index system for land reclamation assessment

Based on the conceptual model in Figure 1, we further developed an integrated index system to assess the ecological effects of coastal reclamation (see Figure 2). We developed measurements for each of the three types of effects. The data source, objects of measurement, and indicators of each effect are given in the second column of Figure 2. Specifically, the index system consists of a quantity indicator that monitors the amount of cropland areas added by the reclamation process, a quality indicator that measures soil quality in the reclamation areas, and an ecology indicator that gauges the overall ecological impacts of coastal reclamation processes. Finally, an integrated benefit index of coastal reclamation is created to quantify the trade-off between the gain of added cropland and the cost of increased ecological risks and decreased soil quality. This integrated index system allows us to assess the overall effect of land reclamation systematically and comprehensively. The methods to construct the three indicators and the integrated benefit index are outlined below.

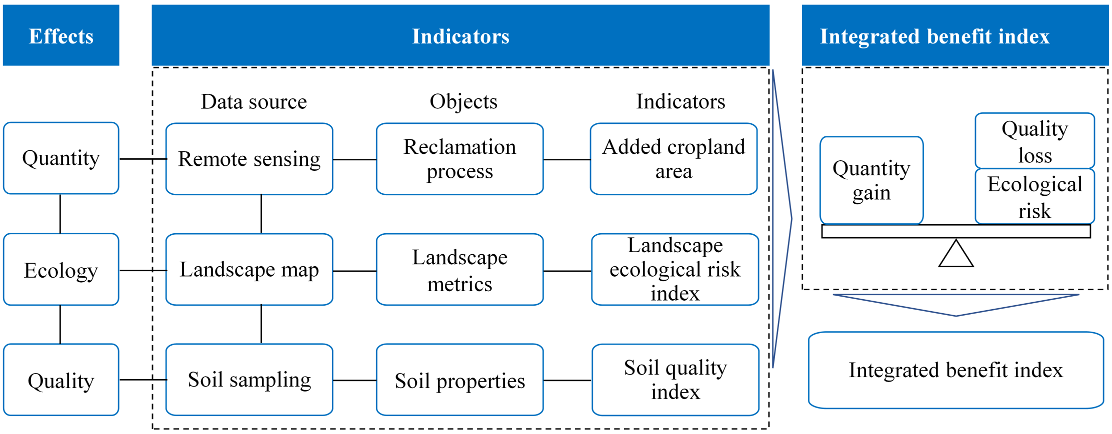

Fig. 2 An integrated index system for coastal reclamation assessment

3.1 Land quantity indicator: added cropland area (ACA)

We used remote sensing images to track the coastal reclamation expansion. This is an effective way to measure cropland areas added to the affected areas and therefore to be used as a reliable indicator of the quantity of land added by the coastal reclamation process. It is a common practice to use remote sensing images to quantify changes in land quantity in coastal reclamation studies. For example, Lin et al. (2019) explored the spatiotemporal changes in paddy field area in Hangzhou Bay using three periods of Landsat data; time-series Landsat imagery was used to map wetland changes within a reclaimed area in Shanghai in Wu et al. (2018); and a large-scale study of the total amount of increased cultivated land in China from 1979 to 2014 also used remote sensing images such as Landsat, SPOT, ZY-2 and ZY-3 (Meng et al., 2017). Our land quantity indicator, denoted ACA hereafter, is constructed according to these existing practices.

3.2 Ecology indicator: landscape ecological risk index (ERI)

In the land use policy domain, researchers use two methods to assess the ecological risk caused by land use changes: an ecological risk evaluation system based on the relation between risk source and receptor exposure, or landscape pattern metrics that reflect the landscape ecological risks brought by land use changes. Coastal reclamation has an extensive impact on the landscape pattern and leads to wide changes in the coastal area. Meanwhile, the specific risk sources and receptors in reclamation are difficult to identify. Therefore, the landscape pattern metrics method is more suitable for assessing the ecological risks caused by coastal reclamation. According to the landscape ecological risk assessment (LERA) framework, a landscape made up of various local ecosystems is the ideal scale for examining how human activities affect the environment. Landscape dynamics can characterize comprehensive ecological risks from various stressors and offer a method for mitigating ecological risk based on landscape pattern optimization (Liao et al., 2020). This approach has been employed in numerous studies in coastal areas to date (Ai et al., 2022; Zhang et al., 2020a), but has not been used to investigate the ecological impacts of coastal reclamation.

Based on the LERA framework, we develop a landscape ecological risk index (ERI) to capture two important dimensions of coastal reclamation impacts: "ecological loss" and "risk probability." "Ecological loss" is measured by a disturbance degree index (D_i) and a vulnerability index (V_i). D_i represents the level of landscape disturbance brought on by human activities and natural changes. V_i reflects the ability of landscape components to maintain stable ecological structure and function. "Risk probability" is estimated based on the area of each landscape type and reflects the contribution of each landscape type to the overall landscape risk. The formula of ERI is as follows.

$$ERI_k = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} \times D_i \times V_i \tag{1}$$

where ERI_k is the landscape ecological risk index of unit k, k is the assessment unit, i is landscape type, n is the total number of landscape components, A_{ki} is the area of land use type i in unit k, A_k is the area of unit k, D_i is the landscape disturbance index of type i, and V_i is the landscape vulnerability index. The higher the ERI value is, the higher the ecological risk.

Following the approach in Ai et al. (2022) and Ran et al. (2022), we construct landscape fragmentation (LF_i), separation (LS_i), and dominance (LD_i) indices to calculate D_i. LF_i describes the degree of fragmentation of landscape components, which reflects how humans have altered coastal ecosystems. High levels of landscape fragmentation have been linked to ecological risks such as habitat loss, biodiversity loss, and ecosystem degradation, according to earlier studies. LS_i represents the level of isolation or segregation between landscape patches. Given that external disturbances harm the connectivity of the landscape, its high value reflects how these disturbances affect the structure of coastal ecological networks. LD_i denotes the extent to which a particular type predominates the landscape in the landscape structure. These three indices were calculated by Fragstats 4.2 software, using the following formulas.

$$D_i = aLF_i + bLS_i + cLD_i \tag{2}$$

$$LF_i = n_i / A_i \tag{3}$$

$$LS_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A}} \tag{4}$$

$$LD_i = \frac{Q_i + M_i}{4} + \frac{L_i}{2} \tag{5}$$

where LF_i, LS_i, and LD_i are the landscape fragmentation, separation, and dominance indices of landscape type i, respectively; a, b, and c represent the weights of LF_i, LS_i, and LD_i and take the values of 0.5, 0.3, and 0.2 respectively, based on previous studies and expert opinions (Zhang et al., 2020a). n_i is the number of patches of landscape type i, Q_i is the ratio of units of landscape type i to the total units, M_i is the ratio of the number of patches of landscape type i to the total number of patches, and L_i is the ratio of the area of landscape type i to the total area.

Finally, V_i, the landscape vulnerability index in Equation (1), is a comprehensive measure of the sensitivity and resistance of landscape components. It reflects the expected loss or damage to landscape components caused by external disturbance (Karimian et al., 2022; Rani et al., 2018). Different ecosystems have different sensitivities to external disturbances and abilities to resist external disturbances. We ranked the landscape vulnerability index of each of the n landscape types in descending order (i.e., higher index numbers represent lower vulnerability). The index numbers are normalized before entering Equation (1).

3.3 Land quality indicator: soil quality index (SQI)

The calculation of the soil quality index involves three steps. First, soil quality indicators were selected based on the assessment’s goals. The selection of soil quality indicators frequently changes depending on the study’s objectives. Climate, topography, soil characteristics, and management techniques are typically limiting factors for cropland soil quality (Lehmann et al., 2020; Bünemann et al., 2018). Second, raw indicator values are converted into scores by using either expert judgement (e.g., the Delphi method as used in Liu et al. (2020a)) or statistical methods. Finally, indicator scores are converted into an index by using a weighted linear combination method (Qiu et al., 2017).

3.4 An integrated coastal reclamation effects index (IBI)

Based on three indicators in terms of ACA, LERI, and SQI, the integrated coastal reclamation effects index (IBI hereafter) is created to assess the integrated benefit of coastal reclamation. The formula of IBI is as follows.

$$IBI_i = \alpha ACA_i^* + \beta ERI_i^* + \gamma SQI_i^* \qquad (6)$$

where ACA_i^*, ERI_i^*, and SQI_i^* are the normalized scores of the added cropland area, landscape ecological risk index, and soil quality index in year i, respectively. α, β, and γ represent the weights of ACA_i^*, $LERI_i^*$, and SQI_i^*, respectively. The values of IBI range between zero and one, with larger values indicating greater benefits from coastal reclamation. By setting the values of α, β, and γ, policymakers can set the priorities or balances among the three components and assess the impacts of coastal reclamation accordingly. For example, in the empirical investigation parts of the study, we calculated the value of IBI under three scenarios, i.e., balanced development (α=1/3, β=1/3, and γ=1/3), socioeconomic development (α=3/5, β=1/5, and γ=1/5), and ecological priority (α=1/5, β=3/5, and γ=1/5).

4 Empirical Implementation

To demonstrate the capacity and flexibility of the proposed index system, we use a typical coastal city in China in the empirical analysis part of this study. The scale of coastal reclamation in China is much larger than that in other countries (Murray et al., 2019). All of China’s coastal provinces and cities have undergone extensive land reclamation since the 1950s due to land scarcity brought on by explosive economic growth and urbanization (Wang et al., 2014). Between 1979 and 2014 alone, the total area of land reclamation was 11,163 km^2 in China (Meng et al., 2017), equivalent to ten times the size of Hong Kong. It demonstrated how the central government's emphasis on land reclamation was continuously strengthened by sorting out relevant laws and regulations on the management of land reclamation (Table 1). There have been two sizable waves of coastal reclamation overall. The first was to reclaim cropland and practice mariculture, focusing on agricultural growth. It was the stage in which the state actively promoted reclamation in an effort to address the nation's food shortage (Miao and Xue, 2021). There were no specific laws to control land use practices in coastal areas. The second wave started when the Land Management Law in 1998 first proposed the policy of "to achieve cropland requisition-compensation balance" (CRCB), which required the local government to ensure that if cropland is converted into construction, the same amount of cropland needs to be developed (Liu et al., 2017). The CRCB policy triggered ocean sprawl in coastal areas (Liu and Li, 2020). The coastal reclamation projects have grown over the subsequent two decades, contributing significantly to the stabilization of cropland areas during urbanization. However, since it was proposed in 1998, the CRCB policy has gone through three stages: "quantitative balance," "quantity-quality balance," and "quantity-quality-ecological balance" (Liu et al., 2019). Whether the reclamation-driven development model can still adapt to the revised CRCB policy is up for debate. More seriously, the overexploitation of coastal wetlands is viewed as a threat to ecological security in China, which contradicts China's advancement towards ecological civilization (Zhang et al., 2020b). To this end, the central government has successively issued a series of policies to restrict coastal reclamation, including the strictest reclamation regulations implemented in 2018 that stopped approving any new land reclamation projects. The fever for land reclamation quickly subsided, and a new stage of coastal land use emerged (Wang et al., 2021b). The scale of coastal land reclamation and the pace of policy changes make China a good test ground for our conceptual model.

Table 1 Relevant laws and regulations on coastal reclamation management in China.

Year	Laws and regulations	Key function
1982	Marine Environmental Protection Law of the People's Republic of China	Proposing reclamation is a part of coastal and marine engineering
2001	Sea Area Use Management Law of the People's Republic of China	Stipulating the approval authority of reclamation
2003	Outline of China's Marine Economic Development Plan	Proposing the goal of building a strong marine economy
2006	Opinions on Enforcing Management of Sea Use for Regional Construction	Proposing strict review of regional construction sea use planning and dynamic monitoring of regional construction sea use
2009	Island Protection Law of the People's Republic of China	Restricting engineering construction that alters the coastline
2009	Notice on Intensifying Management of Land Reclamation Plans	Rectifying and normalizing enclosing and reclamation order and enforcing implementation of enclosing and reclamation plan
2016	Measures for the Control of Sea Reclamation	Controlling the adverse impact of reclamation activities on the marine ecological environment
2018	Notice on Strengthening the Protection of Coastal Wetlands and the Strict Control of Reclamation	The annual quota of reclamation is cancelled. Approval of new reclamation projects is stopped except for major national strategic projects. Historical illegal reclamation projects are required to be prosecuted.
2019	Notice on Further Clarifying the Requirements for Handling Issues Left over from the History of Reclamation	Standardizing work procedures and requirements for dealing with the problems left over from the history of reclamation
2021	Coast Guard Law of the People's Republic of China	Stipulating the coast guard's task in supervision and inspection of illegal reclamation

4.1 Study area

We selected Cixi, a coastal city in eastern China, as our study area. Cixi City, with a total area of 1361 km² and a population of 1.83 million, is situated on the south of the Yangtze River Delta (Fig. 3). Tidal flat wetlands and flat terrain dominate northern Cixi City, while hilly areas can be found in the south. The area has a subtropical monsoon climate, characterized by a mean annual temperature of 16 ℃ and average annual precipitation of 1381 mm. Cixi City is an economically important part of the Yangtze

River Delta in China. Its GDP soared from 1.04 billion RMB (1 RMB ≈ 0.14 USD) in 1985 to 200.83 billion RMB in 2020. However, the per capita land area is only 0.08 ha or about one-tenth of the national average (0.68 ha). To meet the soaring demand for land resources, Cixi City has rapidly increased coastal reclamation in recent decades. This has led to drastic changes in land use/cover patterns as well as acute conflicts between human activities and ecological conservation (Cao et al., 2020). Therefore, Cixi City can be regarded as a typical case of coastal reclamation in China's rapidly developing regions.

The study area can be divided into two regions: the reclaimed area and the inland area. The coastlines in 1985 and 2020 were used to determine the inner and outer baselines, respectively. The land area in 1985 was classified as inland, and the region enclosed by the inner and outer baselines was defined as the reclaimed area.

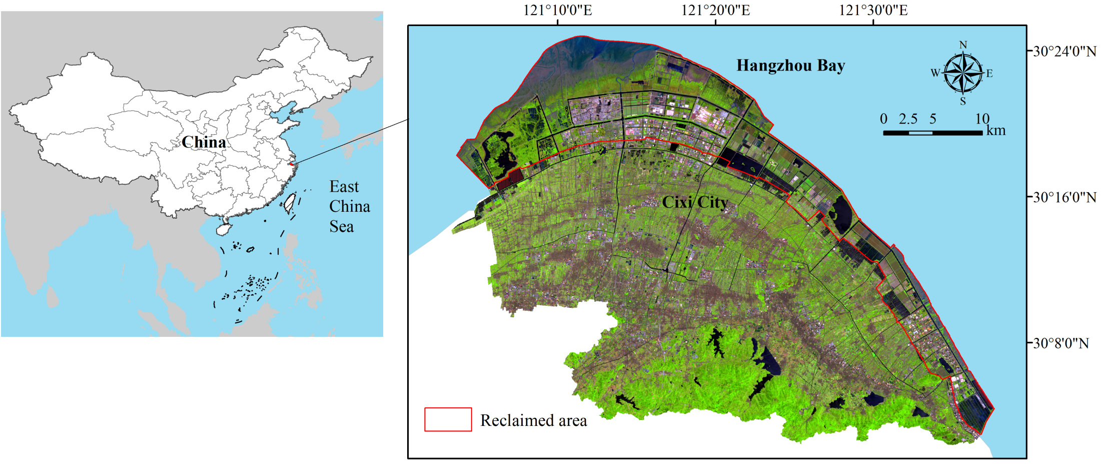

Fig. 3 Location of Cixi City, China. (2020, May; Landsat 8; 6,5,4).

4.2 Data collection and processing

Cloud-free Landsat images (path, 118; row, 39) in 1985, 1995, 2005, 2010, 2015, and 2020 were downloaded from the United States Geological Survey (USGS) Center for Earth Resources Observation and Science (http://glovis.usgs.gov/). All images were visually interpreted by qualified experts after standard preprocessing. Seven landscape types were interpreted in light of coastal land use/cover patterns, including built-up, cropland, mariculture, mudflat, orchard, water body, and woodland. Accuracy assessment was carried out by following the approach recommended by Su et al. (2014). Specifically, we first interpreted the 2020 landscape map and assessed its accuracy with 100 sample points obtained from the field survey as well as 100 sample points from Google Earth in 2020. The landscape information for the other years was then retroactively updated using the 2020 landscape map as a reference. Accuracy assessment for the other years was facilitated by historical aerial photos from the Zhejiang Administration of Surveying Mapping and Geoinformation as well as high-resolution images (e.g., Quickbird, and SPOT). The above techniques were successful in creating the reference landscape maps for the years 1985 to 2020, as shown in Table 2.

Table 2 Accuracy statistics of the interpreted landscape maps.

	1985	1995	2005	2010	2015	2020
Overall accuracy (%)	93.5	91.0	92.5	89.5	89.5	92.0
Kappa index	0.91	0.88	0.90	0.86	0.86	0.89

4.3 Landscape ecological risk assessment

Using the Create Fishnet tool in ArcGIS 10.4, a grid with 1224 assessment units (1 km × 1 km) covering the entire area of Cixi City was produced based on the average patch size of the landscape maps. The ERI was then determined for each grid unit in 1985, 1995, 2005, 2010, 2015, and 2020 using a landscape pattern-based methodology.

Following Ran et al. (2022) and Chen et al. (2020), we ranked the landscape vulnerability index of each landscape type in the study area, where 7 is the most vulnerable and 1 is the least vulnerable. The coastal wetlands are typical ecologically fragile areas. They have the highest vulnerability and sensitivity in the study area, so the vulnerability assigned to mudflats was 7. Coastal water bodies are susceptible to land use/cover change due to environmental changes and human activities such as agriculture, offshore aquaculture, and fishing; consequently, values of 6 and 5 were given to water bodies and mariculture, respectively. Cropland can quickly be occupied by construction. However, considering the state’s strict implementation of cropland protection policies, a value of 4 was assigned to cropland. The orchard and woodland values in the study area were 3 and 2, respectively, due to the small areas and change rates of orchard and woodland, as well as the orchard's higher level of human disturbance. The built-up area is the most stable category, despite its rapid growth. When a landscape is transformed into a built-up area, the likelihood of further changes is low. Consequently, a value of 1 was assigned. After the normalization method using linear scaling equations, the vulnerability values of the seven landscape types were as follows: mudflat = 0.2500, water body = 0.2143, mariculture = 0.1786, cropland = 0.1429, orchard = 0.1071, woodland = 0.0714, and built-up = 0.0357.

4.4 Soil quality index

We focused on soil physics, nutrient properties, and crop yield to assess the primary productivity of cropland. Cixi City is situated on a coastal plain with a level and low-lying topography. The climate and topographic conditions are fairly uniform in the study area, and the cropland management practices also tend to follow a similar pattern. Therefore, soil properties are the main factors in assessing and comparing soil quality, and the assessment's goals are focused on soil physics and nutrient properties.

Six common indicators with the highest frequency in related studies (Deng et al., 2011) were chosen for soil quality assessment, as summarized in Table 3. We combined the Delphi method with expert score ranking to determine the scale and weight of each variable concerning its contributions to soil productivity. The highest weight was given to the soil texture indicator because it influences many other soil physical and chemical properties as well as the availability of certain soil nutrients for crop growth. The SQI was then created by combining different variables using a weighted linear combination method (Qiu et al., 2017).

Table 3 Assessment system for the soil quality index.

Indicator	Score				Weight (%)
	1	2	3	4	
Texture	Heavy clay/sand	Light clay/sand clay	Clay loam/sand loam	Loam	25
OM (organic matter, %)	<1.5	1.5-2.5	2.5-3.5	>3.5	20
pH	>7.8	<5.5	5.5-6.5/7.5-7.8	6.5-7.5	10
TN (total nitrogen, %)	<0.08	0.08-0.12	0.12-0.15	>0.15	15
AP (available phosphorus, mg/kg)	<15	15-30	30-40	>40	15
AK (available potassium, mg/kg)	<50	50-80	80-100	>100	15

5 Empirical findings

5.1 Coastal reclamation and landscape changes

From 1985 to 2020, a total of 393.71 km^2 of coastal wetlands were reclaimed in Cixi City, equivalent to 42% of the original land area, with an average annual reclamation of 11.25 km^2(Fig. 4). The entire process could be divided into three periods: before 1995, from 1995 to 2015, and after 2015. The reclamation intensities of the three periods were 1.01, 11.48, and -1.29 km^2·year^{-1}, respectively. Extensive reclamation occurred in the two decades from 1995 to 2015, but it has since ceased, and even a small portion of the reclaimed land has been converted back to wetlands.

The dominant landscape types of coastal wetlands in 1985 included shallow water and mudflats, and most of the area was converted into cropland, built-up land, and mariculture in 2020 (Fig. 5). Water bodies acted as major exporters, leading to the highest net loss in the area (265.63 km^2), while mudflats displayed a trend of first increasing and then decreasing (Fig. 6). Cixi City's coastal landscape generally presented a gradual transition from natural wetlands to artificial landscapes. Meanwhile, the inland areas showed a typical urbanization pattern in which constructed lands expanded (71.03 to 310.14 km^2) at the expense of croplands (608.49 to 414.50 km^2) from 1985 to 2020. However, the total amount of cropland in Cixi City remained largely stable after 2010 due to land reclamation. Since 1985, the added cropland area in the reclaimed area in 1995, 2005, 2010, 2015, and 2020 was 9.31, 57.77, 57.46, 81.70, and 90.78 km^2, respectively.

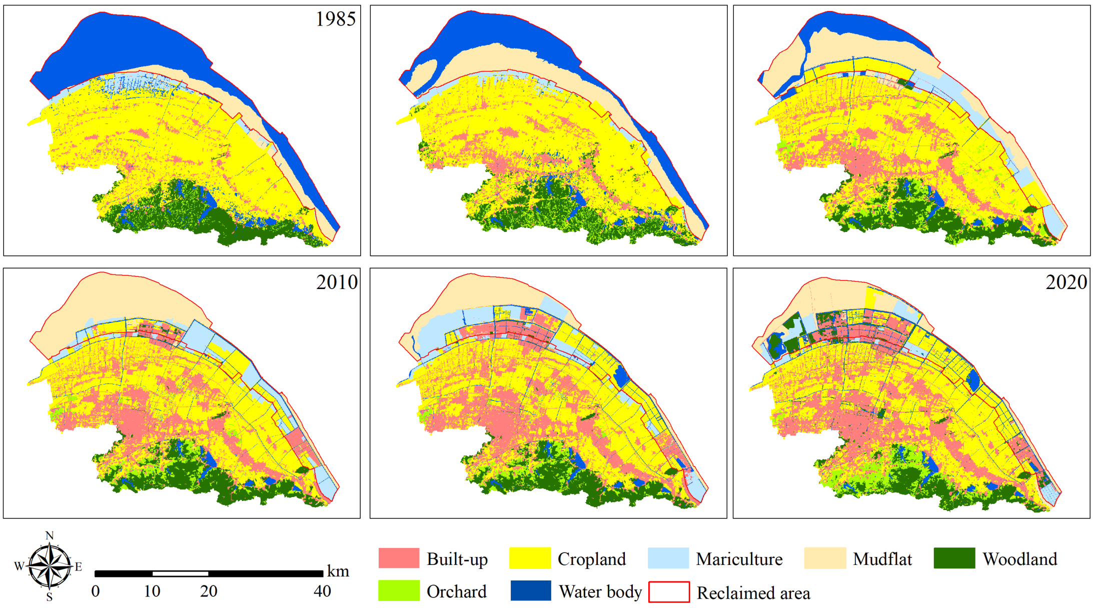

Fig. 4 Landscape maps from 1985 to 2020

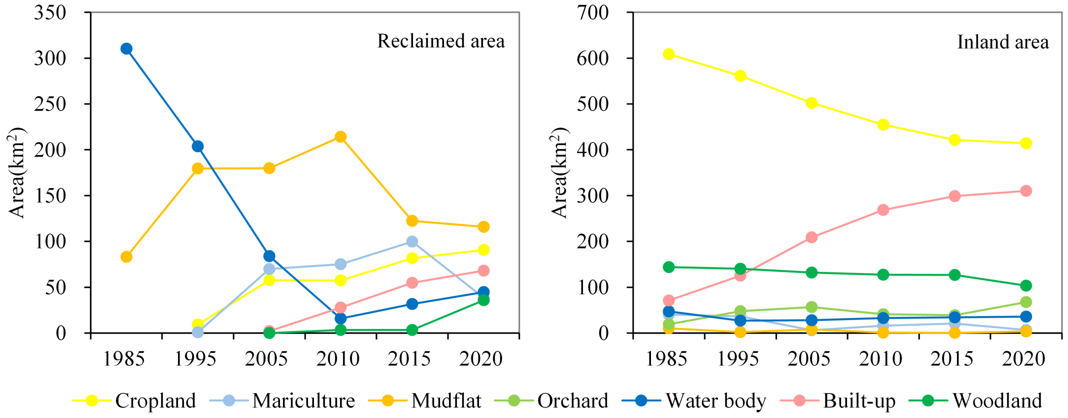

Fig. 5 Areal changes in landscape categories from 1985 to 2020

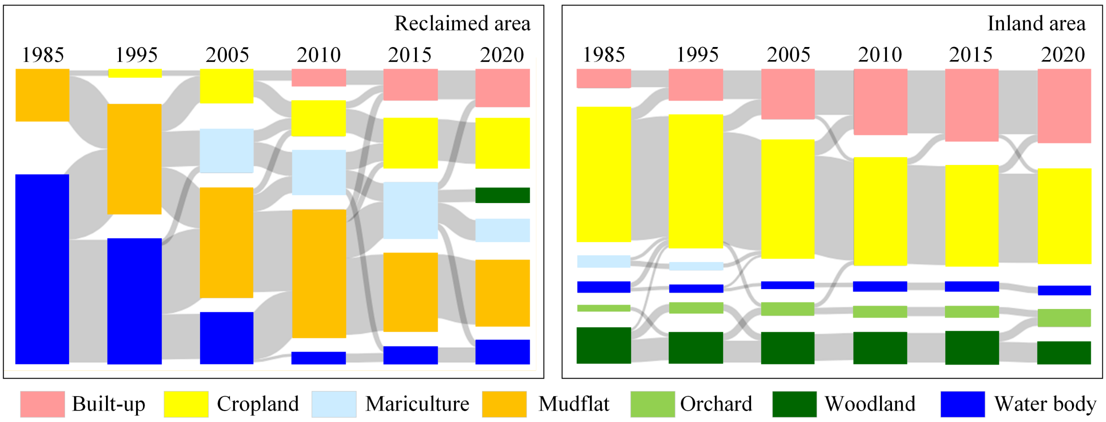

Fig. 6 Evolution of landscapes from 1985 to 2020.

Note: The length of the colored rectangle represents the area of the various landscape types. The grey band connecting the two rectangles denotes the conversion in various landscape types

5.2 Landscape ecological risk changes

The average ERI values of Cixi City in 1985, 1995, 2005, 2010, 2015, and 2020 were 0.1625, 0.1746, 0.1645, 0.1839, 0.1889, and 0.2075, respectively. The ecological risk in Cixi City stabilized at a relatively low level from 1985 to 2005 and then increased sharply. The natural breaks classification of ERI resulted in five levels: low (0.0477, 0.0951], medium-low (0.0951, 0.1409], medium (0.1409, 0.1997], medium-high (0.1997, 0.3271], and high (0.3271, 0.7862]. The ecological risk structure of Cixi City shifted from being dominated by low and medium to medium and high levels between 1985 and 2020. The expansion of the red and orange grids serves as evidence of this change (Fig. 6). The number of high-risk and medium-high-risk units increased by 113 (176.6%) and 151 (88.3%), respectively.

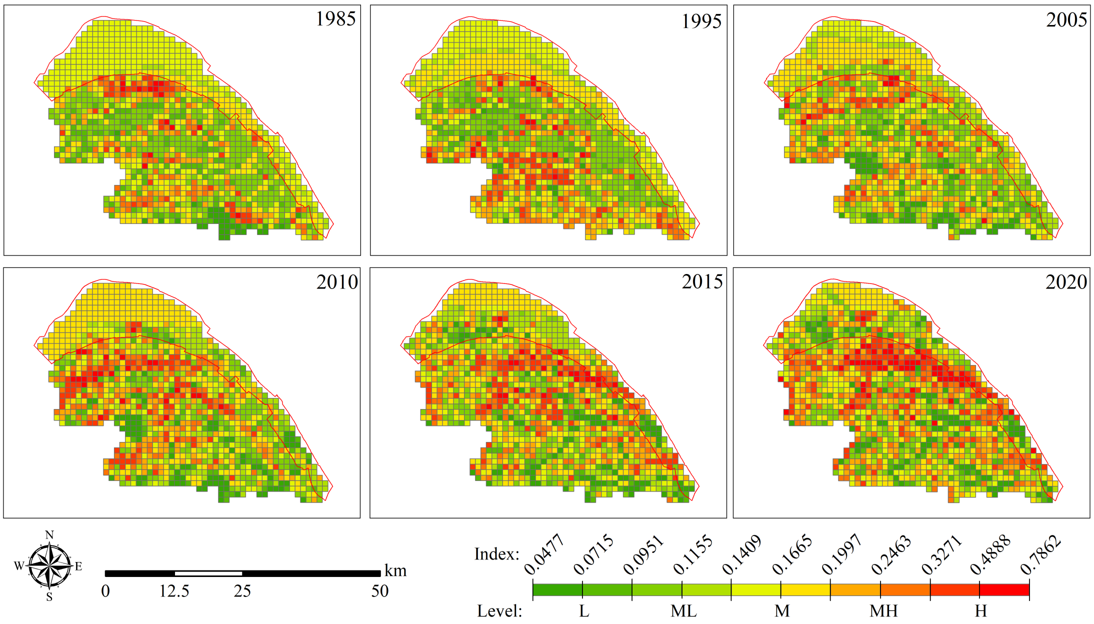

Fig. 7 Maps of landscape ecological risk levels from 1985 to 2020.

Note: L (low), ML (medium-low), M (medium), MH (medium-high), and H (high).

The landscape ecological risk in Cixi City varied significantly across space in 1985 (Fig. 7). Nearly the entire reclaimed area was made up of medium-low-risk areas. The low-risk areas were widely dispersed in the southern hilly areas and central cropland, while the high-risk and medium-high-risk areas were primarily concentrated in the northern inland area with a small amount scattered in the central. Over time, the composition and distribution of ERI in the reclaimed areas gradually became more fragmented and dispersed. High-risk areas spread outward, accounting for the inland area from 7.2% in 1985 to 17.9% in 2020 and began to emerge in the reclaimed areas (5.6% of the reclaimed area). In comparison to reclaimed areas, the ERI average values and growth rates in inland areas were significantly higher (Fig. 8).

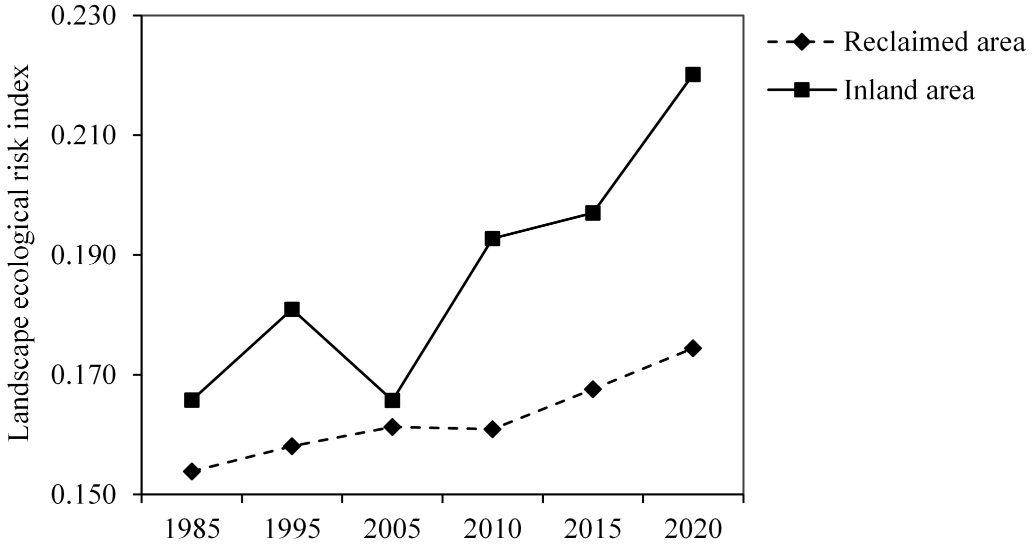

Fig. 8 Average ERI changes from 1985 to 2020.

5.3 Cropland soil quality changes

Data on six soil quality indicators were collected through soil sampling, including 310 soil samples from cropland across Cixi City in 2020 (Fig. 9a). Each soil sample's SQI was calculated separately, and a spatial distribution map of the SQI was generated using ordinary kriging interpolation in ArcGIS 10.4.

The impacts of coastal reclamation on cropland soil quality are striking, according to Fig. 9. Based on the findings of the overlay analysis of the 1985 and 2020 landscape maps (Fig. 9a), the majority of cropland gains (i.e., areas highlighted in blue in Fig. 9a) came from coastal reclamation, and all cropland losses (i.e., areas highlighted in pink in Fig. 9a) occurred in the inland area. The SQI distribution map further showed that Cixi City's cropland soil quality was primarily spatially distributed as being high in the south and low in the north (Fig. 9b). As a result, the soil quality of added cropland was significantly lower than that of the lost cropland (i.e., the average SQI values were 2.20 versus 2.57). The overall cropland soil quality in Cixi City also worsened as a result of coastal reclamation, with the average SQI falling from 2.50 in 1985 to 2.38 in 2020.

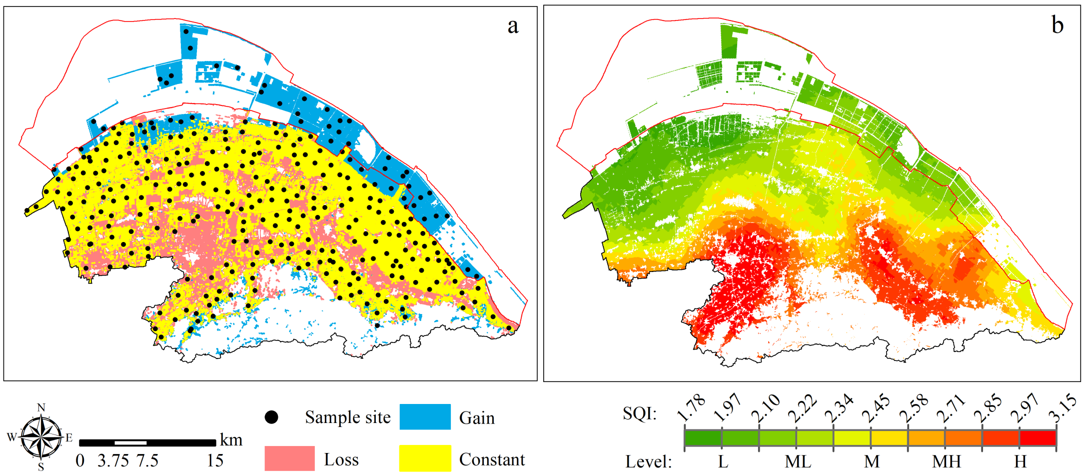

Fig. 9 Maps of cropland changes from 1985 to 2020, soil sample sites in 2020 (a), and soil quality levels (b).

5.4 Integrated benefit index changes

In Fig. 10a, we contracted the movement of ACA, ERI, and SQI over time. It is evident that the gain of cropland in the reclaimed area came at the expense of the soil quality of cropland and ecological security throughout the entire area of Cixi City. The sharp drop in the SQI between 2010 and 2020 is concerning, as by its own, the drop largely offsets the gain from cropland supply from coastal reclamation. This is a demonstration of our index system's ability to support granular analysis of the impacts of coastal reclamation to support targeted policymaking.

To further demonstrate the flexibility and capacity of the proposed integrated benefit index system, we calculate the value of IBI under three scenarios, i.e., balanced development (α=1/3, β=1/3, and γ=1/3, denoted BD), socioeconomic development (α=3/5, β=1/5, and γ=1/5, denoted SD), and ecological priority (α=1/5, β=3/5, and γ=1/5, denoted EP). The assessment outcomes for IBI in Cixi City varied greatly under the three different scenarios, as shown in Fig. 10b. The SD scenario complied with the requirements of China's earlier stage of development, which was focused on economic expansion. Under the SD scenario, the IBI overall maintained a steady growth of 50%, from 0.4 in 1985 to 0.6 in 2020. However, under the BD scenario which reflected the perspective of quantity-quality-ecological balanced protection, the IBI displayed a diametrically opposed downwards trend. It demonstrated how historical pursuits of economic growth have significantly worsened local ecological conditions and even resulted in an irreparable loss of net benefit. In addition, under the more aggressive EP scenario for ecological conservation, the IBI fell by 75% between 1985 and 2020. From the perspective of ecological priority, coastal reclamation implemented by Cixi City was a failed development strategy whose gains did not compensate for the losses.

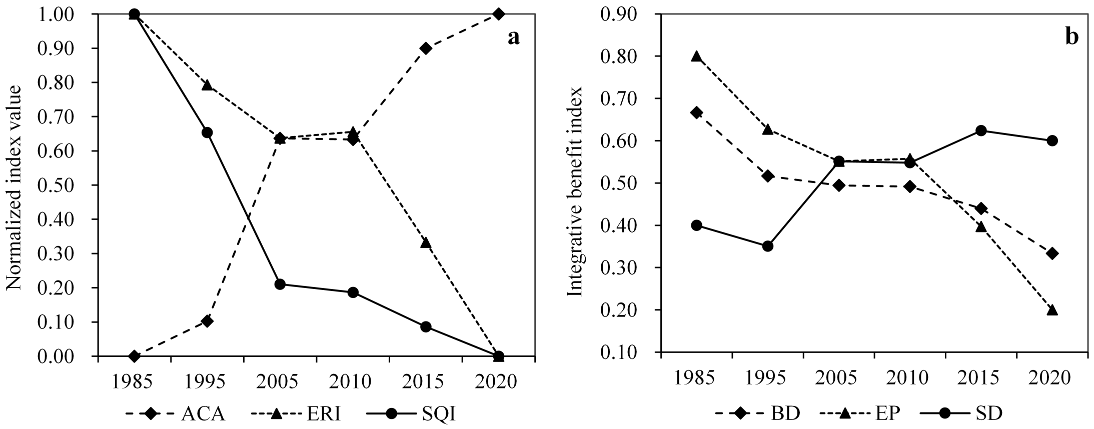

Fig. 10 Normalized index values of ACA, LERI, and SQI (a) and IBI (b) changes from 1985 to 2020.
Note: balanced development (BD), socioeconomic development (SD), ecological priority (EP).

6 Discussions and policy implications

6.1 Process of coastal reclamation

Our study found clear evidence of the benefits of the ocean sprawl strategy, including supplying the additional land needed to accommodate local population growth, urban development, and economic growth. Cixi is one of the most economically advanced cities in China due to its advantageous location at Hangzhou Bay and abundant sediment accumulation that helped the city to form and grow. Between 1985 and 2020, Cixi significantly increased its original area by nearly 41.8 percent. Coastal wetlands were reduced by 59.2%, but cropland and built-up land were added, making up 23.1 and 17.3 percent of the total reclaimed area, respectively. As a result, Cixi City's cropland distribution changed from the inland to the reclamation area, and the gravity center of the entire cropland moved 4.6 kilometers northwest towards the sea. This trend corresponds to ocean sprawl in coastal cities around the world. Research revealed that direct human activities such as aquaculture, agriculture, coastal development, and construction were responsible for 39 percent of the global loss of coastal wetlands over the previous two decades (Murray et al., 2022). Other nearby cities in the Hangzhou Bay Area also frequently engaged in land reclamation, with an average annual reclamation of 25.04 km^2 between 1985 and 2015 (Qiu et al., 2021).

The reclamation process in Cixi City can be divided into three periods according to reclamation intensities. Before 1995, the Qiantang River's natural sand deposition created a sizable tidal mudflat at the estuary of Hangzhou Bay. At that time, human intervention was minimal. Later, with the support of authorities, emerging large-scale coastal reclamation projects have had a dramatic impact on coastal ecosystems and landscapes (Li et al., 2020). By visualizing the pattern of land use changes in Cixi, our analysis demonstrated that coastal reclamation played an important role in maintaining the balance of land resources during urbanization. This is achieved by producing additional land areas for agriculture, construction, and mariculture, which eased the pressure of cropland loss in the inland area. Consequently, inland areas showed a pattern of urbanization at the expense of cropland, while cropland occupied mariculture, water bodies, and woodland to partly compensate for the loss of food production. This phenomenon was widespread in China's urbanization because historical towns and cities were frequently constructed on agricultural land and urban sprawl tended to occur close to existing settlements.

Our analysis also suggested that the reclaimed area has gone through a distinctive landscape change path along the water body, mudflat, mariculture, cropland, and built-up. One of the primary forces behind this development may be the economic benefits per unit area (Qiu et al., 2021). After 2015, the rate of land reclamation from coastal mudflats slowed considerably, and there was even a trend towards converting part of the mariculture back to ecological wetlands and natural water bodies (Wang et al., 2021b). Since then, coastal reclamation and land use have advanced to the stage of being a priority for ecological conservation. Such findings were in line with earlier studies that identified periodic coastal reclamation as the main force behind neighborhood urbanization and economic growth (Liu and Li, 2020; Meng et al., 2017).

6.2 Ecological impact of coastal reclamation

Many researchers have claimed that the impact of coastal land use/cover changes from natural to artificial was the most obvious aspect of the ecological effects of coastal reclamation (Lin et al., 2019; Sun et al., 2016). Our index system revealed that ongoing coastal reclamation has caused long-term detrimental ecological losses. Using Cixi as an example, we show that landscape ecological risks increased significantly in both the reclaimed and inland areas in Cixi, especially after extensive reclamation projects were completed. This result is consistent with earlier studies suggesting that reclamation harmed the stability of coastal ecosystems (Yu et al., 2021). The interaction of seaward urbanization and the loss of coastal wetlands will have severe squeezing effects on coastal zones and weaken the ecosystem services provided by coastal wetlands (Wu et al., 2022).

In terms of the landscape, reclamation expansion would largely result in landscape fragmentation, isolation, and irregularity, all of which have been shown to have a significant impact on a variety of ecological processes and functions (Ju et al., 2021). Our study revealed that the ERI and the landscape disturbance index both showed similar upwards trends, leading to the conclusion that anthropogenic disturbances brought on by coastal reclamation would induce potential ecological risks. Notably, ecological security in the inland area has not improved at the expense of rising ecological risks in reclamation areas. The overall ecological risk in Cixi City showed an upwards trend, indicating a continuous decline in ecological security across the entire region.

Reclaiming coastal wetlands for cropland can significantly alter the soil environment (Xie et al., 2020). In the early stages of reclamation, high salinity in wetland soil is a significant limiting factor for soil quality, as it directly lowers soil microbial activity and vegetation cover, prevents the accumulation of organic matter, and raises soil pH (Ge et al., 2021). Another important consideration is the soil texture, as cropland quality is severely constrained by wetland soils' high sand content and low clay content (Wang et al., 2021a). Some researchers even hold that the soil quality of reclaimed land can remain stable after more than 300 years of human improvement and use of the soil (Zhang et al., 2022). Our findings are consistent with the literature. The cropland soil quality in the reclamation area was significantly lower than that in the inland area via soil sampling and soil quality index evaluation. The overall cropland soil quality in Cixi City exhibited a downwards trend, illuminating a persistent decline in cropland production services at the level of the entire region. These results demonstrated that coastal reclamation does have detrimental ecological effects on cropland soil quality and landscape ecological risks.

6.3 Recommendations on land conservation policy

The reclamation process in Cixi City exhibited a staged feature, which was consistent with the evolution of national reclamation management policies from support to strict control. The first stage of reclamation activities (from the 1950s to the mid-1990s) was for agricultural production, with negligible socioeconomic benefits and limited impact on the ecological environment. Later, the CRCB policy was adopted as a national strategy for cropland protection. However, at that time, China's urbanization was beginning to speed up. Coastal areas typically experienced land shortages due to the demands of local urban development, economic prosperity, and construction, as well as the need to maintain the total amount of cropland proposed by the central government. Local governments had to adopt aggressive ocean strategies to add more land by a massive expansion of reclamation as a result of these priority conflicts. The ecological environment in coastal areas has also suffered significant harm at the same time, with wetland degradation issues standing out in particular. To accomplish this, the central government has issued a succession of policy directives that limit coastal reclamation. Particularly in 2018, China issued the strictest coastal land reclamation regulations and stopped approving any new land reclamation projects. As part of the strategy for ecological civilization, coastal reclamation has moved into the third stage of prioritizing coastal ecological protection.

Due to its rapid socioeconomic development, Cixi City was characterized by tensions and contradictions in its land management. The CRCB policy made coastal reclamation one of the key strategies for easing the tension between expanding construction and shrinking agricultural land. As a result, Cixi City's total cropland quantity remained largely stable after 2010. This result means that coastal reclamation has achieved its established goal and has become a driver for local development. However, the goal of CRCB policy has also undergone significant reforms, evolving from the initial quantitative balance to the current "three-in-one" of quantity, quality, and ecology for cropland protection.

Our analysis shows that the city’s reclamation-driven development strategy was unable to meet the updated CRCB policy requirements for soil quality and ecological security. The three scenarios in Section 5.4 are carefully designed to mirror the CRCB policies in the three stages mentioned above. The overall effects of land reclamation are positive only in the old regime, i.e., the first stage when increasing land supply for urban development is the priority. However, the benefits of coastal reclamation dropped sharply when assessed against the new policies, i.e., ecological risk and soil quality carry more weight. Our analysis suggests that the Cixi government should implement sustainable land use policies for coastal reclamation to achieve synergies between economic prosperity and ecological security. For example, land consolidation initiatives can be used to enhance the reclaimed cropland's soil quality and functional value. In addition, financial subsidies can be provided for coastal wetland restoration to compensate for stakeholders’ income loss. Potential financial resources include ecological compensation from industrial enterprises and tourism revenue from wetland parks in reclaimed areas.

7 Conclusions

This research proposes an integrated index system to assess the ecological consequences associated with the land reclamation process. Focusing on land use changes in affected areas and leveraging existing studies, we constructed a conceptual framework that covers land supply quantity, ecological environment, and soil quality. An integrated index system is developed based on the conceptual model and tested by using data from a typical coastal city in China.

Our study contributes to the literature in two ways. First, the conceptual model provides a comprehensive and systematic approach to assess the ecological impacts of coastal land reclamation. The index system helps land use policymakers identify the essential indicators to monitor the ecological effects of coastal reclamation. It is flexible in terms of the dimensions to be included in the framework, as well as the weighting to be assigned to each component. The validity and reliability of the model are established from a sound analysis of existing studies. Therefore, the study added an important analytical framework to policymakers' and researchers' toolboxes.

Second, the empirical findings from Cixi City are not only evidence of the tractability of our theoretical model, but also important new evidence from a key player in the global campaign for sustainable development. Our multidimensional index system shows how much ecological risk has been rising and soil quality has been deteriorating as a result of coastal land reclamation in Cixi City. The negative impacts on the city's ecological environment cannot be offset by the gain from land area increases. As Cixi is a typical coastal city in China, empirical findings from this city can be used to estimate the ecological impacts of land reclamation in cities with similar features but without required data for index construction. Therefore, the study also adds value to the literature at the empirical front.

Future studies could improve this research in multiple ways. First, the empirical investigation part of the study could be expanded to cover other coastal cities where land reclamation was practiced. Our model required a wide range of land quality indicators and remote sensing images to construct the indices. These data might not be available for all cities. However, technological advances and local economic development will eventually make the construction of a nationwide index system feasible. The results will be a 'full picture' of the ecological consequences of coastal reclamation, monitored over time and along the entire coastline. It will be a powerful policymaking tool to monitor and manage coastal ecological environments.

Second, the calculation of the ecological risk index and soil quality index relies heavily on qualitative assessment (e.g., the scoring process). When multiple cities are included in the system mentioned above, it is important to maintain the consistency and reliability of the index number calculation. This can be achieved in two ways: through the use of either more quantitative data or the same team for all cities.

Finally, the interaction between socioeconomic factors, the ecological environment and coastal reclamation is complex. In our conceptual framework, the effect on economic development is indirectly captured although the measurement of land quantity. Specifically, there is an implicit assumption that land reclamation helps economic development by increasing the supply of land. Socioeconomic factors are not included in the model directly for the sake of parsimony because the focus of our analysis is on the ecological effects of land reclamation. Future studies might improve our work by connecting our index system with measurements of other aspects of the local economy.

References

Ai, J., Yu, K., Zeng, Z., Yang, L., Liu, Y., Liu, J., 2022. Assessing the dynamic landscape ecological risk and its driving forces in an island city based on optimal spatial scales: Haitan Island, China. Ecol Indic 137, 108771.

Barbier, E.B., 2019. Chapter 27 - The Value of Coastal Wetland Ecosystem Services, in: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Hopkinson, C.S. (Eds.), Coastal Wetlands. Elsevier, pp. 947-964.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – A critical review. Soil Biol. Biochem. 120, 105-125.

Cao, Y., Li, G., Tian, Y., Fang, X., Li, Y., Tan, Y., 2020. Linking ecosystem services trade-offs, bundles and hotspot identification with cropland management in the coastal Hangzhou Bay area of China. Land Use Policy 97, 104689.

Chen, J., Dong, B., Li, H., Zhang, S., Peng, L., Fang, L., Zhang, C., Li, S., 2020. Study on landscape ecological risk assessment of Hooded Crane breeding and overwintering habitat. Environ Res 187, 109649.

Cui, J., Liu, C., Li, Z., Wang, L., Chen, X., Ye, Z., Fang, C., 2012. Long-term changes in topsoil chemical properties under centuries of cultivation after reclamation of coastal wetlands in the Yangtze Estuary, China. Soil and Tillage Research 123, 50-60.

Deng, J., Qiu, L., Wang, K., Yang, H., Shi, Y., 2011. An integrated analysis of urbanization-triggered cropland loss trajectory and implications for sustainable land management. Cities 28, 127-137.

Fokker, P.A., Gunnink, J.L., Koster, K., de Lange, G., 2019. Disentangling and Parameterizing Shallow Sources of Subsidence: Application to a Reclaimed Coastal Area, Flevoland, the Netherlands. JGR Earth Surface 124, 1099-1117.

Ge, B., Yang, R., Yang, L., Jiang, S., Tang, B., 2021. Changes in soil macrofaunal communities along soil age gradient under centuries of cultivation after coastal reclamation. Catena 200, 105170.

Granse, D., Suchrow, S., Jensen, K., 2021. Long-term invasion dynamics of Spartina increase vegetation diversity and geomorphological resistance of salt marshes against sea level rise. Biol Invasions 23, 871-883.

Hu, T., Fan, J., Hou, H., Li, Y., Li, Y., Huang, K., 2021. Long-term monitoring and evaluation of land development in a reclamation area under rapid urbanization: A case-study in Qiantang New District, China. Land Degrad Dev 32, 3259-3271.

Hua, J., Feng, Y., Jiang, Q., Bao, X., Yin, Y., 2017. Shift of bacterial community structure along different coastal reclamation histories in Jiangsu, Eastern China. Sci Rep-Uk 7, 10096.

Ju, H., Niu, C., Zhang, S., Jiang, W., Zhang, Z., Zhang, X., Yang, Z., Cui, Y., 2021. Spatiotemporal patterns and modifiable areal unit problems of the landscape ecological risk in coastal areas: A case study of the Shandong Peninsula, China. J Clean Prod 310, 127522.

Karimian, H., Zou, W., Chen, Y., Xia, J., Wang, Z., 2022. Landscape ecological risk assessment and driving factor analysis in Dongjiang river watershed. Chemosphere 307, 135835.

Kim, K., Samaddar, S., Chatterjee, P., Krishnamoorthy, R., Jeon, S., Sa, T., 2019. Structural and functional responses of microbial community with respect to salinity levels in a coastal reclamation land. Appl Soil Ecol 137, 96-105.

Lazzari, N., Becerro, M.A., Sanabria-Fernandez, J.A., Martín-López, B., 2019. Spatial characterization of coastal marine social-ecological systems: Insights for integrated management. Environ Sci Policy 92, 56-65.

Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment.

Li, F., Ding, D., Chen, Z., Chen, H., Shen, T., Wu, Q., Zhang, C., 2020. Change of sea reclamation and the sea-use management policy system in China. Mar. Policy 115, 103861.

Li, J., Pu, L., Zhu, M., Zhang, J., Li, P., Dai, X., Xu, Y., Liu, L., 2014. Evolution of soil properties following reclamation in coastal areas: A review. Geoderma 226-227, 130-139.

Li, X., Zhang, C., 2021. Effect of natural and artificial afforestation reclamation on soil properties and vegetation in coastal saline silt soils. Catena 198, 105066.

Li, Y., Feng, Y., Guo, X., Peng, F., 2017. Changes in coastal city ecosystem service values based on land use—A case study of Yingkou, China. Land Use Policy 65, 287-293.

Liao, C., Qiu, J., Chen, B., Chen, D., Fu, B., Georgescu, M., He, C., Jenerette, G.D., Li, X., Li, X., Li, X., Qiuying, B., Shi, P., Wu, J., 2020. Advancing landscape sustainability science: theoretical foundation and synergies with innovations in methodology, design, and application. Landscape Ecol 35, 1-9.

Lin, W., Xu, D., Guo, P., Wang, D., Li, L., Gao, J., 2019. Exploring variations of ecosystem service value in Hangzhou Bay Wetland, Eastern China. Ecosyst Serv 37, 100944.

Liu, L., Liu, Z., Gong, J., Wang, L., Hu, Y., 2019. Quantifying the amount, heterogeneity, and pattern of farmland: Implications for China's requisition-compensation balance of farmland policy. Land Use Policy 81, 256-266.

Liu, L., Zhou, D., Chang, X., Lin, Z., 2020a. A new grading system for evaluating China's cultivated land quality. Land Degrad Dev, 1-20.

Liu, X., Zhao, C., Song, W., 2017. Review of the evolution of cultivated land protection policies in the period following China's reform and liberalization. Land Use Policy 67, 660-669.

Liu, Y., Hou, X., Li, X., Song, B., Wang, C., 2020b. Assessing and predicting changes in ecosystem service values based on land use/cover change in the Bohai Rim coastal zone. Ecol Indic 111, 106004.

Liu, Y., Li, J., 2020. The patterns and driving mechanisms of reclaimed land use in China's coastal areas in recent 30 years (in Chinese). SCIENTIA SINICA Terrae 50, 761-774.

Lu, Q., Bai, J., Zhang, G., Wu, J., 2020. Effects of coastal reclamation history on heavy metals in different types of wetland soils in the Pearl River Delta: Levels, sources and ecological risks. J Clean Prod 272, 122668.

Meng, W., Hu, B., He, M., Liu, B., Mo, X., Li, H., Wang, Z., Zhang, Y., 2017. Temporal-spatial variations and driving factors analysis of coastal reclamation in China. Estuar. Coast. Shelf Sci. 191, 39-49.

Miao, D., Xue, Z., 2021. The current developments and impact of land reclamation control in China. Mar. Policy 134, 104782.

Murray, N.J., Phinn, S.R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M.B., Clinton, N., Thau, D., Fuller, R.A., 2019. The global distribution and trajectory of tidal flats. Nature 565, 222-225.

Murray, N.J., Worthington, T.A., Bunting, P., Duce, S., Hagger, V., Lovelock, C.E., Lucas, R., Saunders, M.I., Sheaves, M., Spalding, M., Waltham, N.J., Lyons, M.B., 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. Science 376, 744-749.

Qiao, Y., Feng, J., Cui, S., Zhu, L., 2017. Long-term changes in nutrients, chlorophyll a and their relationships in a semi-enclosed eutrophic ecosystem, Bohai Bay, China. Mar Pollut Bull 117, 222-228.

Qiu, L., Zhang, M., Zhou, B., Cui, Y., Yu, Z., Liu, T., Wu, S., 2021. Economic and ecological trade-offs of coastal reclamation in the Hangzhou Bay, China. Ecol Indic 125, 107477.

Qiu, L., Zhu, J., Pan, Y., Hu, W., Amable, G.S., 2017. Multi-criteria land use suitability analysis for livestock development planning in Hangzhou metropolitan area, China. J Clean Prod 161, 1011-1019.

Ran, P., Hu, S., Frazier, A.E., Qu, S., Yu, D., Tong, L., 2022. Exploring changes in landscape ecological risk in the Yangtze River Economic Belt from a spatiotemporal perspective. Ecol Indic 137, 108744.

Rani, M., Rehman, S., Sajjad, H., Chaudhary, B.S., Sharma, J., Bhardwaj, S., Kumar, P., 2018. Assessing coastal landscape vulnerability using geospatial techniques along Vizianagaram–Srikakulam coast of Andhra Pradesh, India. Nat Hazards 94, 711-725.

Sengupta, D., Chen, R., Meadows, M.E., 2018. Building beyond land: An overview of coastal land reclamation in 16 global megacities. Appl. Geogr. 90, 229-238.

Slamet, N.S., Dargusch, P., Aziz, A.A., Wadley, D., 2020. Mangrove vulnerability and potential carbon stock loss from land reclamation in Jakarta Bay, Indonesia. Ocean Coast Manage 195, 105283.

Sousa, C.A.M., Cunha, M.E., Ribeiro, L., 2020. Tracking 130 years of coastal wetland reclamation in Ria Formosa, Portugal: Opportunities for conservation and aquaculture. Land Use Policy 94, 104544.

Su, S., Yang, C., Hu, Y., Luo, F., Wang, Y., 2014. Progressive landscape fragmentation in relation to cash crop cultivation. Appl. Geogr. 53, 20-31.

Sun, T., Lin, W., Chen, G., Guo, P., Zeng, Y., 2016. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. Sci Total Environ 566-567, 627-640.

Sun, X., Li, Y., Zhu, X., Cao, K., Feng, L., 2017. Integrative assessment and management implications on ecosystem services loss of coastal wetlands due to reclamation. J Clean Prod 163, S101-S112.

Sun, Z., Sun, W., Tong, C., Zeng, C., Yu, X., Mou, X., 2015. China's coastal wetlands: Conservation history, implementation efforts, existing issues and strategies for future improvement. Environ Int 79, 25-41.

Tian, B., Wu, W., Yang, Z., Zhou, Y., 2016. Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010. Estuar. Coast. Shelf Sci. 170, 83-90.

Tian, P., Li, J., Cao, L., Pu, R., Gong, H., Liu, Y., Zhang, H., Chen, H., 2021. Impacts of reclamation derived land use changes on ecosystem services in a typical gulf of eastern China: A case study of Hangzhou bay. Ecol Indic 132, 108259.

Wang, H., She, D., Sun, X., Tang, S., Zheng, Y., 2021a. Analysis of unsaturated shear strength and slope stability considering soil desalinization in a reclamation area in China. Catena 196, 104949.

Wang, J., Liu, Z., Yu, H., Li, F., 2017. Mapping spartina alterniflora biomass using LiDAR and hyperspectral data. Remote Sens-Basel 9, 589.

Wang, W., Liu, H., Li, Y., Su, J., 2014. Development and management of land reclamation in China. Ocean Coast Manage 102, 415-425.

Wang, X., Chen, W., Zhang, L., Jin, D., Lu, C., 2010. Estimating the ecosystem service losses from proposed land reclamation projects: A case study in Xiamen. Ecol Econ 69, 2549-2556.

Wang, X., Xiao, X., Xu, X., Zou, Z., Chen, B., Qin, Y., Zhang, X., Dong, J., Liu, D., Pan, L., Li, B., 2021b. Rebound in China's coastal wetlands following conservation and restoration. Nature Sustainability 4, 1076-1083.

Wang, X., Yan, F., Su, F., 2021c. Changes in coastline and coastal reclamation in the three most developed areas of China, 1980–2018. Ocean Coast Manage 204, 105542.

Wu, W., Yang, Z., Tian, B., Huang, Y., Zhou, Y., Zhang, T., 2018. Impacts of coastal reclamation on wetlands: Loss, resilience, and sustainable management. Estuar. Coast. Shelf Sci. 210, 153-161.

Wu, W., Zhi, C., Gao, Y., Chen, C., Chen, Z., Su, H., Lu, W., Tian, B., 2022. Increasing fragmentation and squeezing of coastal wetlands: Status, drivers, and sustainable protection from the perspective of remote sensing. Sci Total Environ 811, 152339.

Xie, X., Pu, L., Zhu, M., Wu, T., Xu, Y., Wang, X., 2020. Effect of long-term reclamation on soil quality in agricultural reclaimed coastal saline soil, Eastern China. J Soil Sediment 20, 3909-3920.

Xie, X., Pu, L., Zhu, M., Xu, Y., Wang, X., 2019. Linkage between soil salinization indicators and physicochemical properties in a long-term intensive agricultural coastal reclamation area, Eastern China. J Soil Sediment 19, 3699-3707.

Xu, Y., Pu, L., Zhang, R., Zhu, M., Zhang, M., Bu, X., Xie, X., Wang, Y., 2021. Effects of Agricultural Reclamation on Soil Physicochemical Properties in the Mid-Eastern Coastal Area of China. Land 10, 142.

Yang, W., Jeelani, N., Cai, A., Cheng, X., An, S., 2021. Coastal reclamation alters soil microbial communities following different land use patterns in the Eastern coastal zone of China. Sci Rep-Uk 11, 7265.

Yang, W., Jin, Y., Sun, T., Yang, Z., Cai, Y., Yi, Y., 2017. Trade-offs among ecosystem services in coastal wetlands under the effects of reclamation activities. Ecol Indic 92, 354-366.

Yang, W., Sun, T., Yang, Z., 2016. Effect of activities associated with coastal reclamation on the macrobenthos community in coastal wetlands of the Yellow River Delta, China: A literature review and systematic assessment. Ocean Coast Manage 129, 1-9.

Yu, S., Cui, B., Xie, C., Ma, X., Man, Y., Yan, J., Fu, J., 2021. A quantitative approach for offsetting the coastal reclamation impacts on multiple ecosystem services in the Yellow River Delta. Ecosyst Serv 52, 101382.

Zhang, M., Jin, B., Bi, Q., Li, K., Sun, C., Lin, X., Zhu, Y., 2022. Variations of earthworm gut bacterial community composition and metabolic functions in coastal upland soil along a 700-year reclamation chronosequence. Sci Total Environ 804, 149994.

Zhang, R., Pu, L., Li, J., Zhang, J., Xu, Y., 2015. Landscape ecological security response to land use change in the tidal flat reclamation zone, China. Environ Monit Assess 188, 1.

Zhang, W., Chang, W.J., Zhu, Z.C., Hui, Z., 2020a. Landscape ecological risk assessment of Chinese coastal cities based on land use change. Appl. Geogr. 117, 102174.

Zhang, Y., Chen, R., Wang, Y., 2020b. Tendency of land reclamation in coastal areas of Shanghai from 1998 to 2015. Land Use Policy 91, 104370.

Zhao, Q., Bai, J., Lu, Q., Gao, Z., Jia, J., Cui, B., Liu, X., 2016. Polychlorinated biphenyls (PCBs) in sediments/soils of different wetlands along 100-year coastal reclamation chronosequence in the Pearl River Estuary, China. Environ Pollut 213, 860-869.

Zhou, Y., Li, X., Liu, Y., 2021. Cultivated land protection and rational use in China. Land Use Policy 106, 105454.

Zhou, Y., Ning, L., Bai, X., 2018. Spatial and temporal changes of human disturbances and their effects on landscape patterns in the Jiangsu coastal zone, China. Ecol Indic 93, 111-122.