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Research article

A risk-based approach to cumulative effects assessment for large marine ecosystems to support transboundary marine spatial planning: A case study of the yellow sea

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ABSTRACT

Cumulative effects assessment (CEA) should be conducted at ecologically meaningful scales such as large marine ecosystems to halt further ocean degradation caused by anthropogenic pressures and facilitate ecosystem-based management such as transboundary marine spatial planning (MSP). However, few studies exist at large marine ecosystems scale, especially in the West Pacific seas, where countries have different MSP processes yet transboundary cooperation is paramount. Thus, a step-wise CEA would be informative to help bordering countries set a common goal. Building on the risk-based CEA framework, we decomposed CEA into risk identification and spatially-explicit risk analysis and applied it to the Yellow Sea Large Marine Ecosystem (YSLME), aiming to understand the most influential cause-effect pathways and risk distribution pattern. The results showed that (1) seven human activities including port, mariculture, fishing, industry and urban development, shipping, energy, and coastal defence, and three pressures including physical loss of seabed, input of hazardous substances, nitrogen, and phosphorus enrichment were the leading causes of environmental problems in the YSLME; (2) benthic organisms, fishes, algae, tidal flats, seabirds, and marine mammals were the most vulnerable ecosystem components on which cumulative effects acted; (3) areas with relatively high risk mainly concentrated on nearshore zones, especially Shandong, Liaoning, and northern Jiangsu, while coastal bays of South Korea also witnessed high risk; (4) certain risks could be observed in the transboundary area, of which the causes were the pervasive fishing, shipping, and sinking of pollutants in this area due to the cyclonic circulation and fine-grained sediments. In future transboundary cooperation on MSP, risk criteria and evaluation of existing management measures should be incorporated to determine whether the identified risk has exceeded the acceptable level and identify the next step of cooperation. Our study presents an example of CEA at large marine ecosystems scale and provides a reference to other large marine ecosystems in the West Pacific and elsewhere.

1. Introduction

The increasing pressures exerted by expanding footprints of human activities have led to the ongoing decline of marine ecosystem health and biodiversity loss worldwide (United Nations, 2021; Halpern et al., 2019). This alarming situation prompted the proposal of ambitious actions such as the 2030 Agenda for Sustainable Development (United Nations, 2015), the Convention on Biological Diversity targets (Convention on Biological Diversity, 1993), and the United Nations' Ocean Decade Actions (United Nations, 2020) to facilitate the

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sustainable development of the ocean. One core strategy to mitigate the cumulative anthropogenic effects of these plans is the application of ecosystem-based marine management (Arkema et al., 2006; Long et al., 2015), of which a widely recognized tool is marine spatial planning (MSP). Cumulative effects assessment (CEA) is seen as one of the key enabling factors for effective marine spatial planning (Zuercher et al., 2022). Various MSP initiatives, such as the European Union's Marine Spatial Planning Directive (Friess and Grémaud-Colombier, 2021), have incorporated CEA to understand how and to what extent human drivers are affecting different ecosystem components. Meanwhile, the recognition of the cross-border nature of these cumulative effects as well as marine ecosystems has promoted transboundary cooperation on MSP in recent years, such as in the Baltic Sea and the Benguela Current Large Marine Ecosystem (Jay et al., 2016; Janβen et al., 2018; Finke et al., 2020).

A promising and broadly applied approach to CEA is environmental risk assessment, as they share the same nature of assessing the likelihood of the environment being impacted as a result of exposure to one or more pressures (Judd et al., 2015; Stelzenmüller et al., 2018; U.S.Environmental Protection Agency, 1992). Most risk assessment methods were developed and evolved based on the cumulative effects mapping established by Halpern et al. (2008) (e.g., Bevilacqua et al., 2018; Menegon et al., 2018; Stelzenmüller et al., 2010). This method usually includes three key steps: (1) quantifying and mapping the intensity of pressures, (2) mapping the occurrence of ecosystem components, and (3) developing impact weight to express the vulnerability of the ecosystem component to a pressure (Korpinen and Andersen, 2016). CEA has been conducted at local, regional, and global scales, targeting either one or multiple ecosystem components (Halpern et al., 2008; Bevilacqua et al., 2018; Kelly et al., 2014). Despite the advances made globally, few holistic studies exist at large marine ecosystems scale considering multiple pressures on multiple ecosystem components (but see Kirkman et al., 2019; Bergström et al., 2019), especially in the West Pacific area.

LMEs are large-scale delineated ecosystem units that are distinguished by unique natural characteristics of bathymetry, hydrography, productivity, and trophically dependent populations (Sherman et al., 2005). As highly ecologically-connected areas (Sherman et al., 2005), they will play a key role in promoting transboundary cooperation on ecosystem-based MSP due to the common concern about the transboundary environmental issues of bordering countries (Kirkman et al., 2019). CEA, therefore, should be undertaken at scales such as large marine ecosystems to better align management objectives. However, the diversity of methodologies, principles, and definitions poses challenges to CEA outcomes communication, and cooperation (Foley et al., 2017). Stelzenmüller et al. (2018) proposed a risk-based approach to provide standardized and comprehensive guidance for CEA. This framework ensures that the identification of key cause-effect pathways is in line with regional governance settings. This further guides the data and information gathering and gap-filling process for the risk assessment of cumulative effects to achieve a robust and standardized outcome to better inform cooperation and management.

The Yellow Sea is a transboundary semi-closed large marine ecosystem (Tang et al., 2016) that has been identified to be at risk of cumulative effects from a multitude of anthropogenic activities (Zhang et al., 2019). It is such an area where neighboring countries have different progress of MSP (e.g., MSP is under revision and development in China and South Korea, respectively) yet the cooperation on tackling transboundary problems is paramount because of the degradation of the ecosystem (United Nations Development Programme/Global Environment Facility, 2018). To date, no CEA has been conducted at the YSLME scale to identify the cause-effect pathways between drivers, pressures, and ecosystem components and understand the risk distribution of cumulative effects. However, the call for transboundary cooperation to facilitate more effective mitigation of environmental issues in the area (United Nations Development Programme/Global Environment Facility, 2018; United Nations Development Programme/Global Environment Facility, 2019) requires such knowledge to inform future policy direction.

Therefore, this study aims to identify and map the risk of cumulative effects of human pressures in the YSLME by applying the risk-based CEA framework. Specifically, we (1) identified the main anthropogenic activities, their associated pressures, and vulnerable ecosystem components through a systematic literature review, (2) analyzed the relationships between different components using a conceptual Driver-Pressure-State-Impact (DPSI) model and network analysis, and (3) mapped the most concerning cumulative pressures and vulnerable ecosystem components to identify areas at risk. This is the first comprehensive assessment of cumulative effects in the YSLME and our findings will provide implications for the transboundary cooperation on MSP in the region and a reference to other large marine ecosystems in West Pacific and elsewhere.

2. Material and methods

2.1. Study area

The YSLME extends between 119 and 127° E and 31–40°N. The northern boundary is a northeasterly line drawn from Penglai on the Shandong Peninsula to Lvshun and the southern boundary is a line drawn from the north bank of the Yangtze River estuary to Jeju Island, and then northwards to the Korean mainland (Fig. 1) (United Nations Development Programme/Global Environment Facility, 2020). The maritime jurisdiction of North Korea is excluded from our study due to data limitations (however the term "YSLME" is still used hereinafter to refer to the study area). The YSLME has abundant marine resources and high biodiversity along the coast supporting a dense coastal population. It provides more than two million tons of capture fisheries and over 14 million tons of mariculture production annually (Sun et al., 2022). Tourism thrives due to the beautiful scenic spots and bathing beaches the YSLME provides, attracting a growing number of tourists each year. Several metroplexes have grown around the YSLME. It is also an important maritime shipping route, with the world's top trade ports, such as Qingdao Port, distributed along the coast. It is expected that the shipping density will continue to increase with the robust economic growth of the bordering countries (Choi, 2022). Additionally, the ambitious goals of carbon neutrality announced by China and South Korea are boosting the renewable energy industry, for example, the expanding installation of offshore wind turbines.

2.2. Risk identification

The starting point of CEA is risk identification, which establishes the linkages between human activities, their corresponding pressures, and the effects on the respective ecosystem components, processes, and functions (Stelzenmüller et al., 2020). At first, we conducted a systematic literature review, to identify the main human activities and pressures as well as important ecosystem components and services in the YSLME. We used the DPSI framework to structure the relationships between human activities (*Drivers*), their associated pressures (*Pressures*), and key ecosystem components (*State*) and services (*Impact*) (Elliott et al., 2017). Further, we deployed a network analysis to unfold the interconnectedness between pressures and ecosystem components.

To obtain as much information on the cause-effect pathways of our study area, we used different keyword combinations to search the literature via the Web of Science (Table S1 in Supplementary Material). The search was not date-restricted and all document types were accepted. Particular attention was paid to the study area during the search process due to the area-specific nature of our research. When there were few studies on considered activities and associated effects regarding the study area, searching was no longer limited to the Yellow Sea but refined to China and South Korea instead (e.g., energy) or even

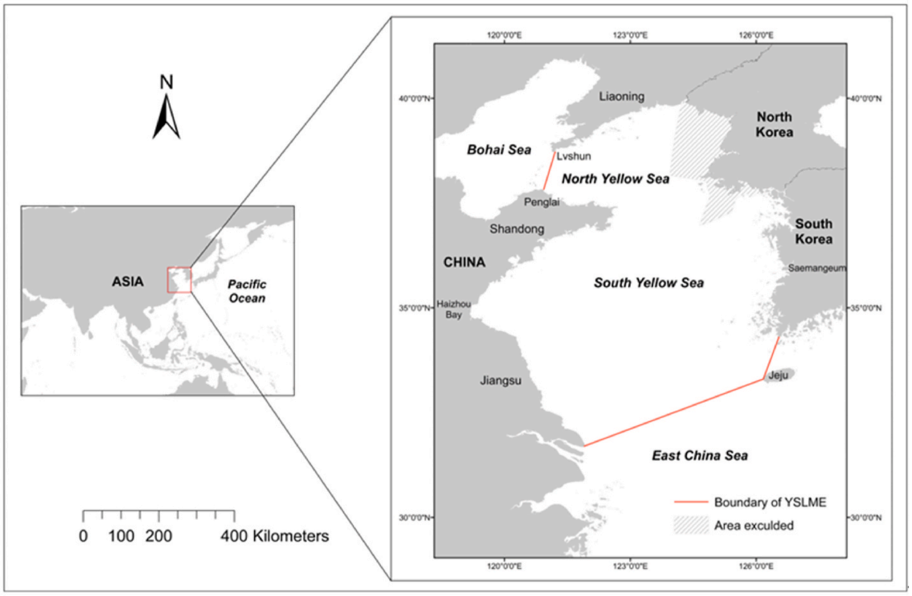

Fig. 1. Geographical location of the study area. Sea areas under North Korea's jurisdiction were excluded due to data scarcity. The southern spatial scope is UN-defined EEZ boundary.

no region limitation at all (e.g., cable and pipeline). Additional publications obtained from references and three papers in Chinese were also included using Google Scholar and China National Knowledge Infrastructure (CNKI), respectively. Besides, keyword research was conducted for reclamation because most human activities involve this activity.

The reviewing process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) working flow to extract information on named activities, their associated pressures, and impacted ecosystem components while ensuring transparency (Fig. S1 in Supplementary Material). The literature research resulted in a total of 1507 records (excluding duplicates). A first screening of the title and abstract was performed to exclude publications irrelevant to the considered category of activities and associated effects, leaving a total of 647 relevant publications. Further screening was conducted based on the full article contents. The criteria for exclusion in this step were whether the publications mentioned the effects of considered activities and whether the effects were on marine ecosystems. The second screening led to a reduction to 377 records. A total of 413 publications (including 36 publications from Google Scholar and CNKI) were included in the review of pressure-state relationships in the YSLME.

Following the general idea of a unifying DPSI framework proposed by Elliott et al. (2017) in this study *Drivers* are represented by human activities in the study area, *Pressures* reflect the mechanisms of natural and social system changes induced by human activities, *State* refers to the ecosystem state as a result of multiple pressures and is represented by different ecosystem components, and *Impact* is the resultant impacts on social welfare, represented by ecosystem services (Elliott et al., 2017).

A total of 12 human activities including mariculture, agriculture, fishing, shipping, port, industry and urban development, energy, tourism, mineral and mining, disposal and dumping, cable and pipeline, and coastal defence were incorporated based on the classifications defined by China's Marine Functional Zoning and South Korea's Marine Spatial Planning and Management Act (Table S2 in Supplementary Material). Climate change was also included, considering that it has started to attract attention due to its potential prominent effects on the study area (Ma et al., 2019). The categorization of pressures was adapted from the EU MSFD and classifications applied in previous studies (Borgwardt et al., 2019; HELCOM, 2018). In the end, 16 pressures grouped in five categories were determined, which are substances (e.g., N&P enrichment), biological (e.g., input of non-indigenous species), physical (e.g., physical loss of seabed), energy (e.g., input of sound) and chemical (e.g., acidification) pressure types. The typologies of *State* and *Impact* were gradually identified through a literature review, indicating key ecosystem components and services at risk.

We explored the vertex strength and detected clusters. Vertex strength indicates the overall weight of each node (namely the total links going through the node), in which the node represents each component of the DPSI model, and cluster detection provides an insight into what nodes are the most connected (Luke, 2015). Network analysis was performed in 'R' (R Core Team, 2013) with the "igraph" package (Csardi and Nepusz, 2006).

2.3. Spatially explicit risk analysis

We conducted a spatially explicit risk analysis to identify areas with high risk of cumulative effects. Based on the results of the DPSI and the network analysis, we selected the top seven activities (port construction, mariculture, fishing, industry and urban development, shipping, energy, and coastal defence), three pressures (physical loss of seabed, input of hazardous substances, and N&P enrichment), and six ecosystem components (benthic organisms, four fish species, algae including microalgae and Chl-a, tidal flats, seabirds, and marine mammals) as inputs to the spatially explicit risk analysis according to their vertex strength (see details in section 3.1). The ecosystem services (*Impact*) identified in the DPSI were not included. Data on human activities and pressures ($N = 10$), and ecosystem components ($E = 10$) included in the spatial analysis are primarily openly available datasets collected from publications, reports, governmental websites, and remote sensing data (for details see "Data sources and processing" and table S3 in Supplementary Material).

To make each layer comparable, we log $(x+1)$-transformed all layers and rescaled them between 0 and 1. For activities of port, industry and urban development, and coastal defence, a buffer zone representing their effect distances was applied to obtain the respective spatial footprints (Table S3 in Supplementary Material).

Ecologically significant areas (ESAs) were first identified by aggregating the ecosystem components and summarized as:

$$ESAs = \sum_{j=1}^{m} E_j \tag{1}$$

where E_j is the j ecosystem component. All included ecosystem components were treated as equally vulnerable in this study. Thus, the higher the value for a respective area, the more ecosystem components it has.

We constructed two different scenarios to quantify the risk of cumulative effects for the here-defined ESAs: (1) equal weight and (2) weight based on the number of links identified through the DPSI and the vertex strength, which reflected the relative importance of different pressures (Table S4 in Supplementary Material). The spatial distribution of cumulative pressures (CP) of the two scenarios was calculated as:

$$CP = \sum_{i=1}^{n} I_i w_i, \sum w_i = 1 \tag{2}$$

where I_i is the i pressure layer, and w_i is the weight of I_i.

Subsequently, the risk of cumulative effects (CE) was calculated following Halpern et al. (2008):

$$CE = CP * ESAs \tag{3}$$

3. Results

3.1. Disentangling cause-effect pathways

The systematic literature review process produced a nested DPSI model (Fig. 2A). Activities (*Drivers*) were linked to a variety of different pressures. Seven top activities with the largest vertex strength caused the most pressure: port (31), mariculture (24), fishing (23), industry and urban development (19), shipping (18), energy (18), and coastal defence (18) (Fig. 2B). The studies on the effects of disposal and dumping, and agriculture were mainly related to pollution. To date, there was less research on the environmental impacts of tourism (14), mineral and mining (11), and cable and pipeline (8). Additionally, climate change (7) emerged as a concerning topic as its significant effects on the YSLME started to be increasingly recognized. The focus of climate change was mainly on the rise in sea surface temperature, acidification, sea level rise, and their effects on fisheries, algae, and coastal security.

The three highest-ranking pressures were physical loss of seabed (44), input of hazardous substances (34), and nitrogen and phosphorus enrichment (N&P enrichment) (31) (Fig. 2B). The loss of seabed mainly refers to the loss of coastal tidal flats caused by reclamation for port construction, mariculture, industrialization and urbanization, and agriculture (Koh and de Jonge, 2014; Wang et al., 2014). Besides, the emerging installation of offshore wind turbines also contributes to seabed loss in the offshore area. Hazardous substances were mainly released, inter alia, through mariculture antibiotics, oil leaking from shipping, persistent organic pollutants (e.g. polycyclic aromatic hydrocarbons, PAHs), and heavy metals discharged from land-based activities. The excessive input of nutrients has long been a concern in the YSLME, as symptoms of eutrophication such as harmful algal blooms and hypoxia have only become more frequent and prominent (J. J. Wang et al., 2020). For example, the green tide blooms in the Yellow Sea have become a recurrent transboundary disaster since its first appearance in 2007, in which high nutrient concentration is believed to be an indispensable contributing factor (Wang et al., 2015; Zhang et al., 2020). In addition, marine litter, including microplastics, also started to receive attention in the academic community. However, relatively less attention was paid to the remaining pressures.

The most vulnerable ecosystem components emerging from the literature included both biotic and abiotic components. The most concerning top six were mainly marine organisms: benthic organisms (57), fishes (34), algae (27), seabirds (23), and marine mammals (20) (Fig. 2A and B). Only tidal flats (27) were among those top six ecosystem components, the other non-biotic components received a smaller proportion of attention. Seabed loss indicates a direct threat to the survival of benthic organisms. Besides, the widely distributed bottom trawling effort (Zhang et al., 2016) and long-distance transported contaminants through currents also pose threats to benthic communities. The composition of fish is shifting from demersal, high-value species to pelagic, lower-value species, and further to demersal, low-value species (Wu et al., 2019). Besides, the reproduction of fishes is also decreasing due to pollution, eutrophication, and climate change (Tang et al., 2016). Pollution and coastal construction also reduce ecologically significant algae such as *Silvetia siliquosa* (KORDI and KEI, 2006). Furthermore, a structural change in phytoplankton has been observed due to the change in N/P and N/Si ratio, leading to a regime shift from diatoms to dinoflagellates (Li et al., 2021; Moon et al., 2021). The loss of tidal flats is closely related to the survival of seabirds. It was reported that degraded and shrunk tidal flats had caused a drastic decline in the population of seabirds in the area (Duan et al., 2022; Studds et al., 2017). The same is true of marine mammals. Bycatch, habitat reduction, and human disturbance such as noise and collision are the main factors threatening marine mammals (Byun et al., 2013; Kim et al., 2012; Song, 2011; Yan et al., 2018). Especially, the spotted seal and narrow-ridged finless porpoise are under threat, with the latter listed as an endangered species by the IUCN Red List. In China and South Korea, the two species are now listed as protected mammals. However, marine mammals are largely understudied in terms of their biodiversity priority areas and response to threats (KORDI and KEI, 2006).

The multitude and high intensity of pressures in the study area have probably led to a great loss of ecosystem services such as biodiversity maintenance and food supply (Fig. 2A and B). For example, it was estimated that food supply was reduced by 21–23% and 22–27% in the South and North Yellow Sea from 2000 to 2010, respectively, and the loss of biodiversity maintenance contributed greatly to this reduction (Song et al., 2021).

The cluster detection presented nine subsets (Fig. 3). The first one is climate change and associated pressures such as sea level rise and acidification. The second cluster contains the remaining *Drivers* with a wide range of pressures they produce. These pressures are the ones that represent physical and chemical disturbances, for example, siltation and input of organic matters. The third cluster contains pressures that are directly linked to biotic ecosystem components such as extraction of species and entanglement. The larger fifth cluster is distributed with abiotic ecosystem components and potentially lost ecosystem services. The remaining clusters present ecosystem components and services that are also impacted but relatively less connected with other nodes.

3.2. Mapping ecosystem components at risk and risk of cumulative effects

3.2.1. Ecologically significant areas

Fig. 4 shows the ESAs that indicate the number of occurring ecosystem components. Many ESAs with high values are distributed along the coastal areas of the study site, especially the Liaoning (E = 10, Fig. 4A), Shandong (E = 9, Fig. 4B), and northern Jiangsu Provinces (southern Haizhou Bay) (E = 9, Fig. 4C and D). These areas are important spawning and feeding grounds for fishes and important habitats for algae, seabirds, and mollusks. The coastal zones of Liaoning Province and southern South Korea (E = 8, Fig. 4E) are also priority areas for marine mammals such as spotted seals. The middle coasts of Jiangsu Province (E = 3) and South Korea (E = 6) (Fig. 4C and E) are also critical habitats for many endangered seabirds due to the wide distribution of tidal flats. Besides, hotspots of ESAs were also found in the central area of the Yellow Sea (E = 4, Fig. 4F), which provide feeding and wintering grounds for fishes. Regions between coastal and central areas have relatively lower values for ESAs.

3.2.2. Risk of cumulative effects

Fig. 5A and B represent the spatial distribution of cumulative

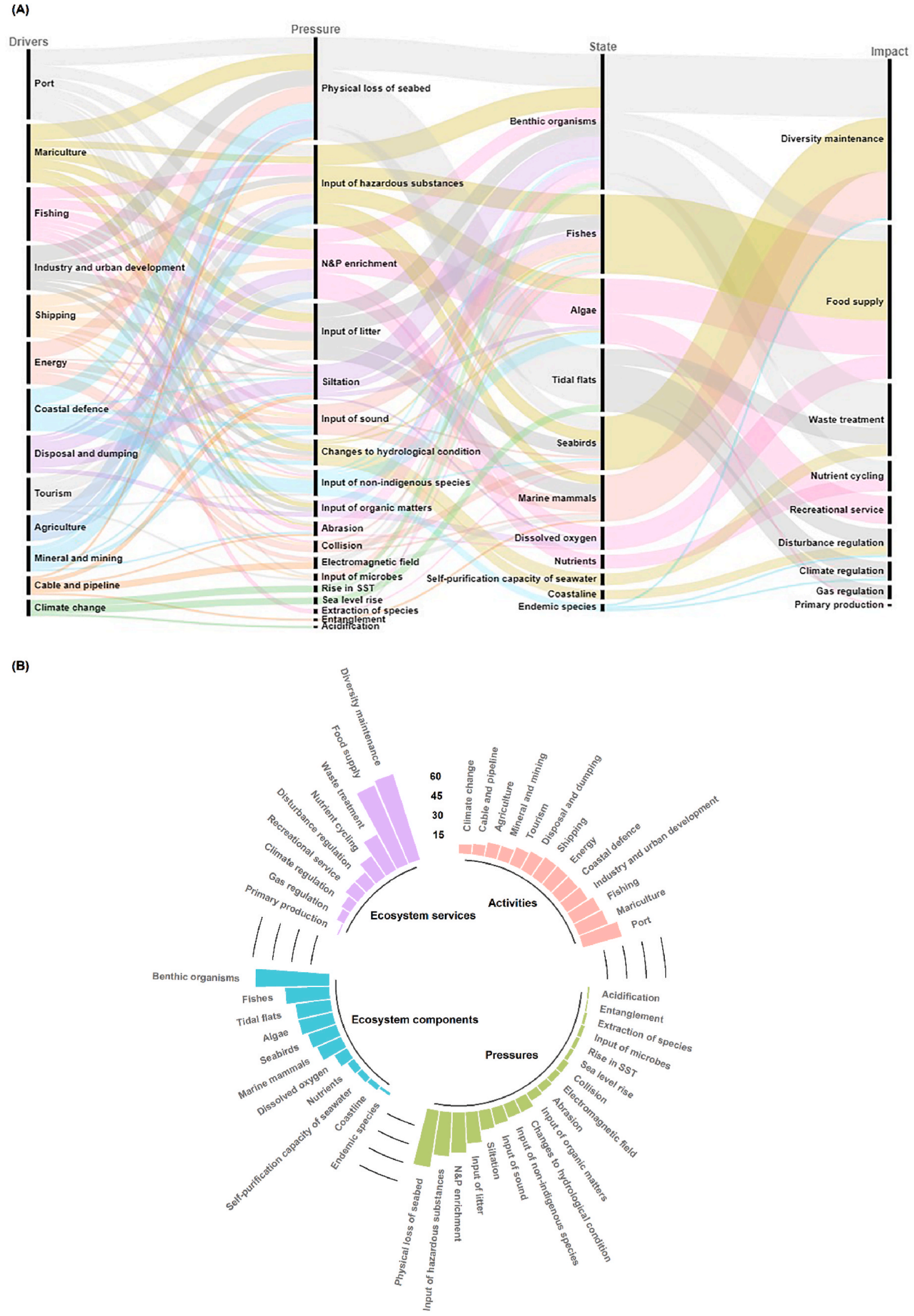

Fig. 2. (A) DPSI model illustrating the cause-effect pathways in the study area identified through a systematic literature review. (B) Barplot of vertex strength. The green bars represent activities (*Drivers*), the orange bars represent pressures (*Pressures*), the purple bars represent ecosystem components (*State*), and the pink bars represent ecosystem services (*Impact*). The height of the bars represents the vertex strength of different nodes in the DPSI.

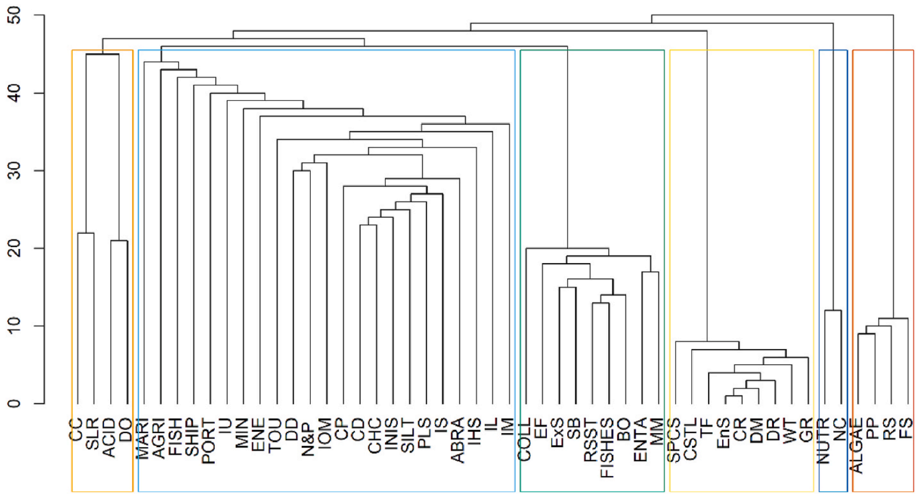

Fig. 3. DPSI network clusters. Nodes within each subset are more connected. See Table S5 in Supplementary Material for the full name of each node.

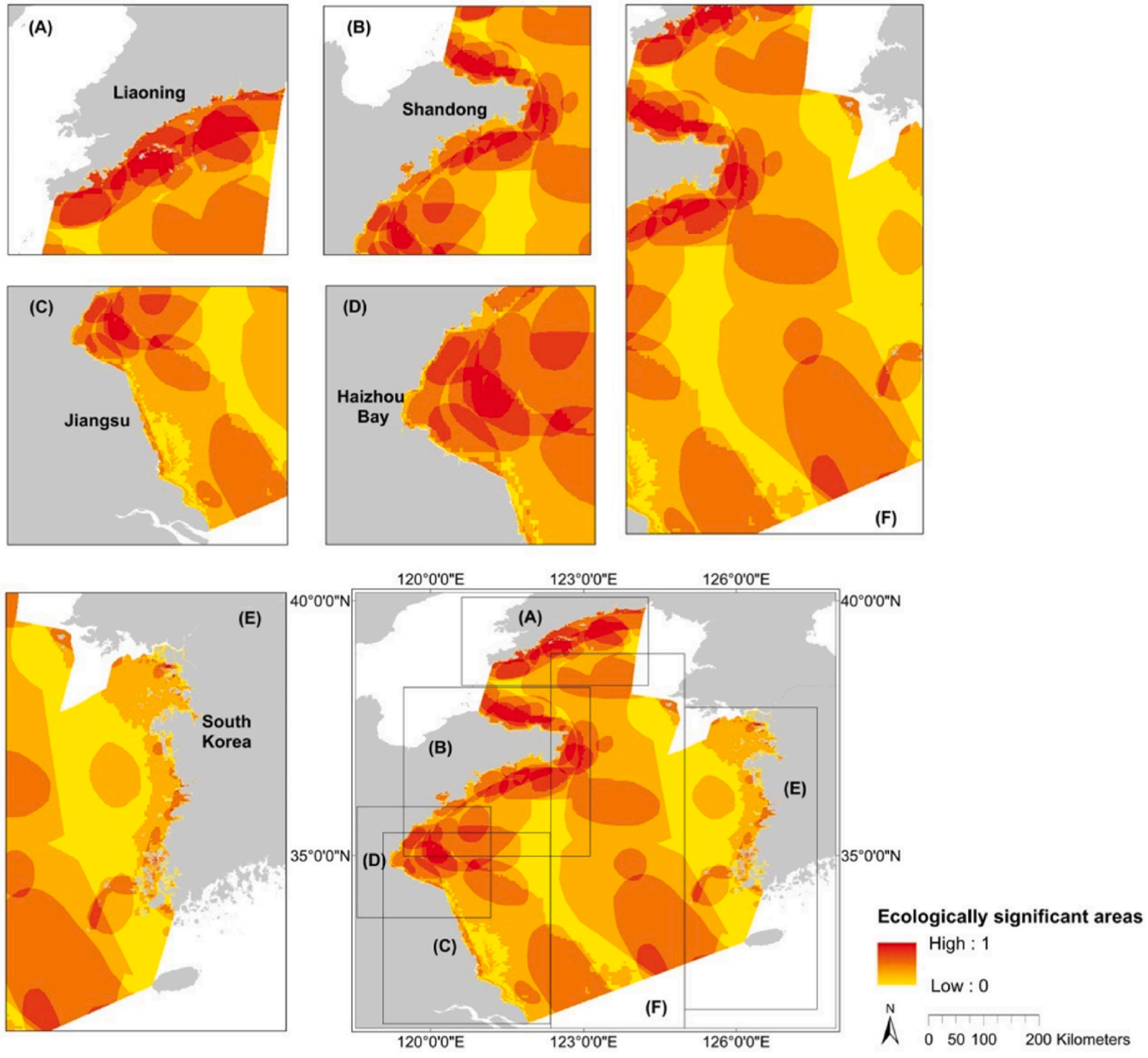

Fig. 4. Ecologically significant areas (ESAs) identified through the aggregation of ecosystem components. (A) Nearshore area of Liaoning Province, (B) nearshore area of Shandong Province, (C) nearshore area of Jiangsu Province, (D) Haizhou Bay shared by Shandong and Jiangsu Provinces, (E) nearshore area of South Korea and (F) offshore area.

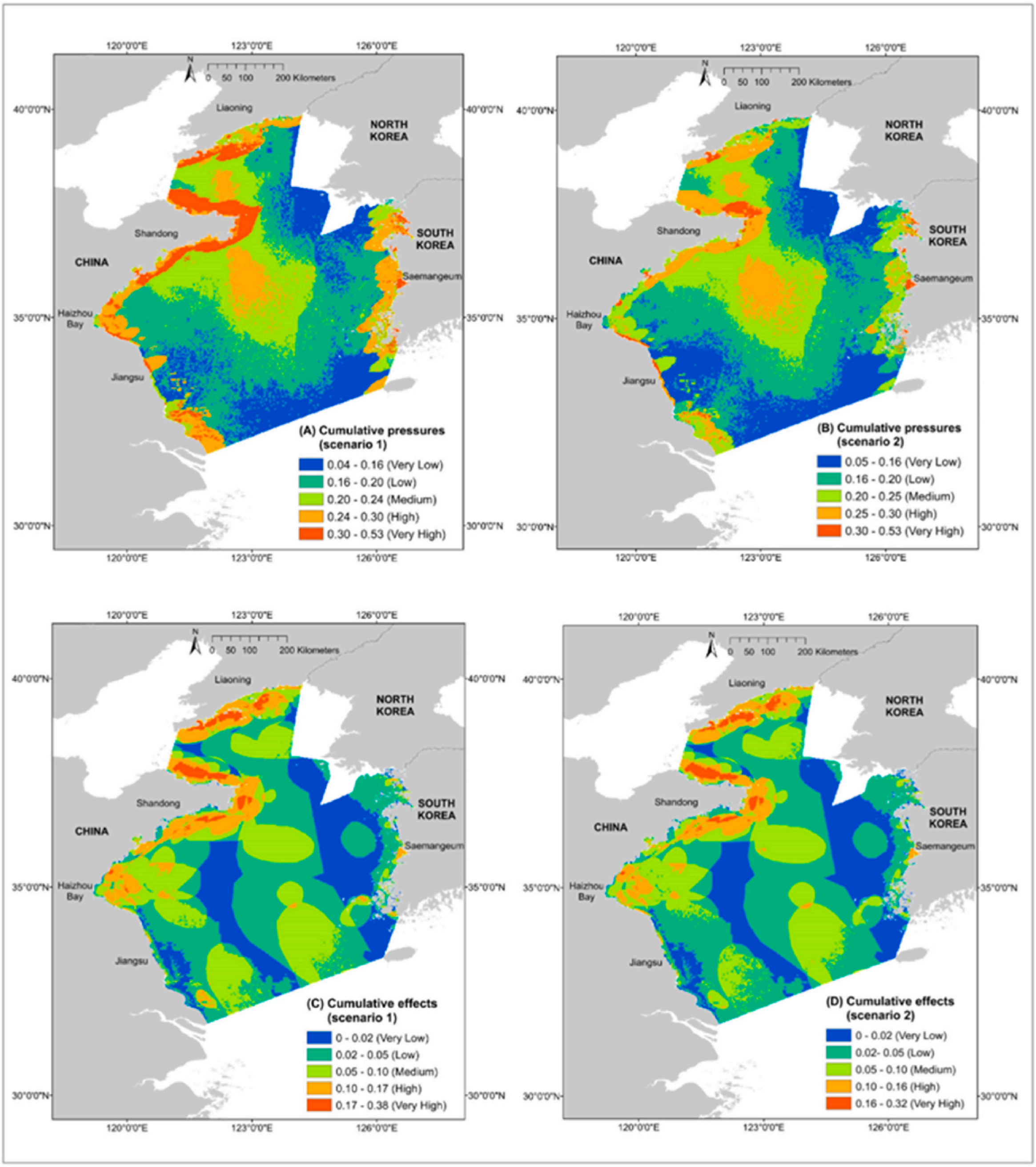

Fig. 5. Distribution of cumulative pressures (A and B) and risk of cumulative effects (C and D). Cumulative pressures were calculated based on the overlay of ten pressures. Cumulative effects were the product of cumulative pressures and ESAs. Scenario 1 reflects equal weight, and scenario 2 reflects weight based on the number of links.

pressures of the different weighting scenarios. No part of the study area was free from cumulative pressures. In general, in both scenarios, a larger proportion of the study area (scenario 1: 80%, scenario 2: 87%) scored very low-to medium-high (Fig. 6A). These areas were primarily distributed in the offshore part. However, almost all near-shore areas scored high to very high in both scenarios. A weighting of the pressures (scenario 2) shrunk the very high-pressure areas around the Shandong Peninsula, and along the coast of Liaoning Province (7%–2%). The areas under high pressure also reduced notably in nearshore areas of South Korea and Jiangsu Province in scenario 2 (13.7%–11.6%). But the pressure level in South Korea's coastal bays and coastal area of Jiangsu Province remained high. The central area of the YSLME scored high in both scenarios.

Fig. 5C and D shows the risk maps of cumulative effects. In both scenarios, areas with a high-risk score of cumulative effects are the result of a high intensity of cumulative pressures and ESAs values. The two scenarios showed a quite similar risk distribution pattern. Overall, the risk score mainly ranged from very low to medium in both scenarios (scenario 1: 89%, scenario 2: 90%). The risk of cumulative effects was relatively high near coastal zones. The areas scoring the highest were almost identical for the two scenarios, with scenario 1 having a larger proportion of high-scored areas (scenario 1: 20.1%, scenario 2: 19.6%, Fig. 6B). On China's side, regions with high risk are mostly concentrated on the near coasts of Liaoning and Shandong Provinces and Haizhou Bay. High-risk areas were also seen in the near-shore area of South Jiangsu Province. The risk of cumulative effects on South Korea's side

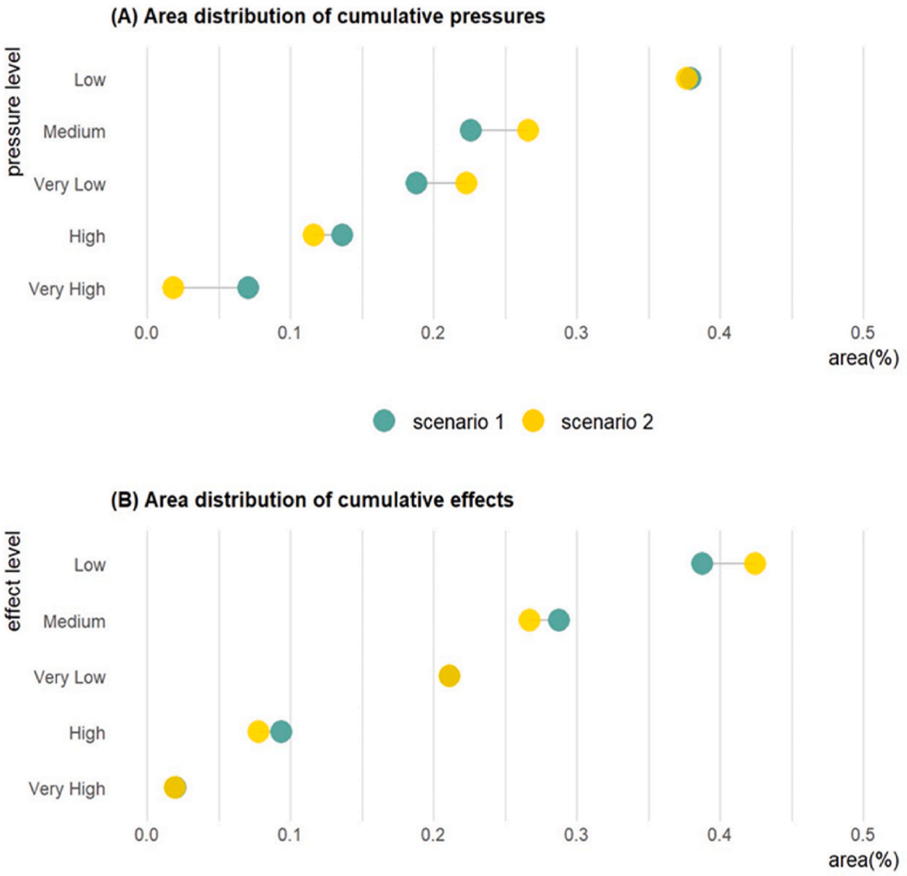

Fig. 6. Area distribution of cumulative pressures (A) and risk of cumulative effects (B). The y-axis is ordered by the area of scenario 1, indicating a decrease in area from top to bottom. Scenario 1 reflects equal weight, and scenario 2 reflects weight based on the number of links.

was lower than that of China. Like areas showing the highest levels of cumulative pressures, high-risk areas were primarily located around bays with the largest risk distributed in the Saemangeum area. Due to the relatively higher ecological importance and high cumulative pressures, the central area of YSLME also presented a certain amount of risk.

4. Discussion

4.1. Risk of cumulative effects

To our knowledge, this study is the first attempt to conduct a holistic cumulative effects assessment of the YSLME. We followed the risk-based CEA procedure proposed by Stelzenmüller et al. (2018), with a focus on risk identification and spatially-explicit risk analysis, aiming to understand the most influential cause-effect pathways and risk distribution pattern. This was further accomplished by combining literature review with DPSI model and network analysis, and spatial analysis tools such as ArcGIS.

The risk identification based on the literature review showed that physical loss of seabed, input of hazardous substances, and nitrogen and phosphorus enrichment (N&P enrichment) were the most frequently mentioned pressures. This result is consistent with the outputs of the Transboundary Diagnostic Analysis for the YSLME (United Nations Development Programme/Global Environment Facility, 2020; United Nations Development Programme/Global Environment Facility, 2007), which identified the pressing transboundary environmental problems facing the YSLME (see section 4.2). Globally, sea use change (e.g., coastal wetlands converted to agricultural land) and pollution (including contaminations and nutrients) are the dominant pressures resulting in marine biodiversity loss (Jaureguiberry et al., 2022). Similarly, economic incentives to develop maritime shipping, mariculture, coastal industries and cities in the last four decades caused a loss of approximately half of the natural tidal flats in the Yellow Sea region (Yim et al., 2018), along with various pollutants discharged from both land- and sea-based activities. The rest of the non-climate pressures ranked low mainly because of their lower number of effects on the ecosystem components or a lower number of associated drivers reported in the literature. Climate change is seen as an emerging menace to the YSLME and has recently been added as a regional priority (United Nations Development Programme/Global Environment Facility, 2020). Recent studies started to recognize the intertwined effects of climate change and overfishing, and the importance of conservation and restoration of tidal flats to mitigate the effects of climate change (MacKinnon et al., 2012; Moores et al., 2019). The low vertex strength and connectedness of climate change in our DPSI highlighted the need for more in-depth research on these potential interactive effects of climate change with other pressures and cascading effects on the YSLME in the future.

The literature review followed the PRISMA workflow to ensure a transparent and structured process, although the search may not have been exhaustive. For example, we did not include articles published in Chinese and Korean, except for several (n = 3) Chinese publications from CNKI. The additional literature was used as supplementary evidence when searched studies on the effects of certain activities were sparse or when there were only case studies from elsewhere instead of our study area. However, given the systematic process adapted for the review, the obtained literature was deemed adequate to provide the knowledge base for identifying the most concerning activities and their associated pressures in the YSLME. Further, the here presented findings are also consistent with previous studies (United Nations Development

Programme/Global Environment Facility, 2020).

In the DPSI model, we mainly distinguished between *State* and *Impact* to include both natural and societal components because we acknowledged that ecosystem-based management needs to consider the full array of environmental, economic, and societal impacts of human activities (Elliott et al., 2017). However, we did not include the ecosystem services identified in the mapping analysis as the main focus of our study was to assess the spatial pattern of cumulative effects of the YSLME. Nevertheless, including ecosystem services can highlight the negative feedback of unsustainable human activities on social welfare, and ecosystem services mapping is an emerging topic to spatially express the degradation of ecosystem services due to cumulative anthropogenic pressures. But quantifying and mapping marine ecosystem services remain challenging due to less available data and methods (Buonocore et al., 2021; Lavorel et al., 2017). Future comparison of the effects of cumulative pressures on ecosystem services would facilitate the trade-offs between conservation and socio-economic development.

Hotspots of ESAs were identified by aggregating the best available presence data of selected ecosystem components, which include four commercially important fishes (anchovy, chub mackerel, small yellow croaker, and Spanish mackerel), priority areas of algae, coastal mollusks, and marine mammals, and key biodiversity areas of seabirds, and tidal flats (see Fig. S3 in Supplementary Material). ESAs hotspots are found at nearshore Shandong, Liaoning, and northern Jiangsu Provinces. It is contrast with other nearshore areas of Jiangsu and South Korea. This variation can be mainly explained by the higher aggregation of spawning grounds for fishes in these areas due to the nutrient-rich waters brought by nearby rivers (Li et al., 2018). The ESAs values of Korea might be underestimated because we do not have access to data on species migrating in the Korean coastal area. Besides, there is no available detailed information on benthic organisms in both nearshore and offshore regions. Existing datasets of coastal mollusks concentrate on the Shandong, Liaoning, and South Korea's coasts. Data on marine mammals is available for nearshore areas of the Liaoning Province and southern South Korea, with no information about offshore areas. The relatively less available information for the regions between coastal and central areas probably resulted in lower values for ESAs. As demonstrated by the maps (Fig. 5C&D), the risk pattern is largely dominated by available ecological information. Therefore, the abovementioned gaps need to be addressed in future studies.

Our study provides the first assessment of the spatial differentiation of anthropogenic cumulative effects. In either scenario, the overall pattern of cumulative pressures and risk distribution are similar. Relatively high cumulative pressures and risk concentrate along the nearshore areas. This pattern is conformed with observations from other parts of the world (e.g., Menegon et al., 2018; Beauchesne et al., 2020; Andersen et al., 2020; Hammar et al., 2020), where diverse activities, such as coastal development (industries and cities), port construction, and mariculture usually aggregate in the immediate vicinity, resulting in the overlap of multiple pressures with high intensities. Meanwhile, South Korea and Jiangsu Province of China, by contrast, possess a comparatively lower risk than Shandong and Liaoning Provinces of China. This is because these two regions have higher fishing hours, shipping density, and port throughputs, whilst also owning higher ESAs values than South Korea and Jiangsu. As for the observed risks in the transboundary area of the YSLME, the main contributors can be ascribed to the more widely distributed fishing and shipping activities (Fig. S2 in Supplementary Material) across the YSLME, as well as the sinking of pollutants from land- and sea-based activities in this area due to the cyclonic circulation and fine-grained sediments (Wang et al., 2017). Since fishes are highly migratory species, overfishing could inevitably lead to the degradation of fishery resources throughout the Yellow Sea. The footprints of these pressures all expanded to the transboundary area and contributed to the risks in this area, thus becoming transboundary issues.

Different pressures tend to contribute disproportionally to the overall risk due to their way of operation (Halpern and Fujita, 2013). For example, port construction can directly cause loss of seabed, while shipping mainly produces pollution and noise, whereas seawater can absorb a certain amount of disturbance due to its self-purification capacity and marine life always show avoidance behavior (Kong and Ye, 2014; Erbe et al., 2019). The exposure to a pressure, combined with the intrinsic characteristics of sensitivity and adaptive capacity of an ecosystem component, would allow for a determination of the vulnerability of the ecosystem component to the pressure (Adger, 2006). However, a full characterization of ecosystem sensitivities and adaptive capacities concerning the relevant pressures is beyond the scope of this study. A common practice to acquire the vulnerability score is expert consultation, whereas calibration using ground-truthing data is also crucial because the result could be fairly different (Bevilacqua et al., 2018; Halpern and Fujita, 2013). Ideally, an important aspect of risk identification is the definition of risk criteria relevant to vulnerabilities, reflecting e.g., the threshold of the acceptable level of risk, indicating beyond which the ecosystem starts to decline and management action should be taken (Stelzenmüller et al., 2020). However, in our case, such information is not available. For example, the mechanisms of pollution effects on marine mammals are not clear (Jo et al., 2017). Therefore, it should be noted that the risk level identified here represents no absolute value and cannot be viewed as the criterion to judge whether some high risk has exceeded the acceptable level, but rather as a reference to identifying areas with potentially higher risk than other regions within the study area. Notwithstanding, our risk pattern can be considered as a footprint of likely cumulative effects (Fig. 5C) (Halpern et al., 2008).

We further designed scenario 2 for the spatially explicit risk analysis using vertex strength as a proxy of weight under the simple assumption that the more attention a pressure receives in studies, the greater contribution to cumulative effects it is likely to make. The overall pattern between the two scenarios is quite similar, with variations being observed at a local scale, for instance, a decreased risk in the nearshore region of southern Jiangsu and an increased risk in the central area. Such change can be of significance because it might be vital to determine whether further exploitation can continue in an ecologically important area (e.g., fishing ground) or should be designated as a protected area.

The data collected in this study represents the first compilation of publicly available data across the whole study area. Yet, data limitations are always a challenge in cumulative effects assessment (Andersen et al., 2020; Hammar et al., 2020). This might represent an underestimate of cumulative pressures and effects. Besides the ecological data gaps mentioned above, which resulted in the large percentage of 0-value risk area (Fig. S4 in Supplementary Material), constraints also exist in socio-economic aspects. For instance, the mariculture distribution was interpreted from satellite images. This method could result in a loss of actual locations because many facilities are also placed underwater. Thus, to prompt a more improved understanding of risk distribution, socio-economic information is another dimension that needs gap-filling.

Our attempt to conduct an integrated and comprehensive assessment with partially lacking data and knowledge might increase the uncertainty of the aggregated risk results. However, the combination of risk analysis using DPSI and spatially-explicit risk approach allowed us to follow a clear research hypothesis, i.e., building the risk of cumulative effects identification on the most concerning pressures identified through literature review to get an overview of cumulative risk distribution in the Yellow Sea.

4.2. Implications for transboundary MSP

Transboundary MSP is widely agreed as a process in which at least two states, sharing a boundary at the territorial sea or the exclusive economic zone, jointly manage a marine area (Hassan et al., 2015). However, transboundary MSP is still in comparative infancy worldwide mainly due to differentiated institutional arrangements and lacking communication between interested parties (Moodie and Sielker, 2022;

Wang et al., 2022). Fundamental to a successful transboundary MSP is a common goal or vision (e.g., environmental protection) that could provide valid links between existing MSP frameworks, thus building coherence (Friess and Grémaud-Colombier, 2021). The established collaboration and exchange lay the foundation of transboundary cooperation in MSP (Jay et al., 2016). China and South Korea have established cooperation in marine science and technology since 1994 (Zhang et al., 2019). Especially, since its first launch, the YSLME project funded by the United Nations Development Programme and Global Environment Facility has brought together China and South Korea to negotiate solutions to transboundary environmental issues. Transboundary anthropogenic problems identified by the phase I (2005–2010) project include pollution and contamination, ecosystem change such as increased frequency of harmful algal bloom, overfishing, and biodiversity loss (United Nations Development Programme/Global Environment Facility, 2007). In phase II (2014–2021), emerging issues including climate change, impacts of marine ranching, re-employment of displaced fishers, new pollutants, and marine protected areas expansion were added as new concerns (United Nations Development Programme/Global Environment Facility, 2020).

Our study took a step further and offered a footprint distribution of cumulative effects to highlight more impacted areas. Although the highest risk emerges near the coast as is often observed (Menegon et al., 2018; Beauchesne et al., 2020; Andersen et al., 2020; Hammar et al., 2020), the YSLME also experiences a relatively medium level of risk in the transboundary area. As discussed above, pollution is one of the key pressures explaining this risk level. It was reported that the threshold effects level of PAHs, i.e., the minimal concentration in benthic organisms at which a toxic reaction has started to be observed, is 768 ng/g (Khim et al., 2018). The values in the transboundary area are still below this threshold (maximum 414 ng/g). However, the concentration of PAHs is likely to be underestimated because the survey was conducted before 2017 (see Table S3 in Supplementary Material). Given the constant accumulation of PAHs in marine environments from various sources including shipping (P. Wang et al., 2020), the values are probably higher. In addition, we did not include other pollutants of concern such as mercury, which was estimated to have reached the threshold effects level in 2014 in this area (Luo et al., 2012; Yu et al., 2021). Fishing becomes a transboundary problem mainly due to the migration of fishes. Many commercially important fish species such as Chub mackerel have been reported to be overexploited (Y. -B. Wang et al., 2020). Their spawning, feeding, and wintering grounds across the YSLME also degraded due to multiple pressures (Li et al., 2018). Furthermore, in the future, human activities are expected to intensify in the central region. For example, deep-sea salmonid cage culture covering 50,000 m^3 of the central Yellow Sea Cold Water Mass has started in 2020, with an expected optimal annual yield of 1500t (Dong, 2019). The first environmental impact assessment indicated that the water, sediment physicochemical parameters, and microbial community structure changed during the culture period (Li et al., 2022).

These developments, therefore, must receive close attention, and monitoring programs must be put in place to prevent further increases in risk. So far, various actions have been taken according to the National Strategic Action Plans built upon the Strategic Action Programme developed by the project. Among those actions are the reduction of fishing efforts by 25–30%, rebuilding of over-exploited marine living resources, and contaminations discharge control (see Table S6 in Supplementary Material) (United Nations Development Programme/Global Environment Facility, 2020). However, the performance of these management efforts remains largely unclear. For example, despite the adoption of total allowable catch control, it is difficult to implement in practice due to the wide distribution and migration of fishes, thus leading to uncertain impacts on the recovery of fish biomass (Chen et al., 2018). Besides, current efforts are mostly confined to individual countries, with limited cross-border cooperation (United Nations Development Programme/Global Environment Facility, 2019). A key issue to tackle therefore is to concentrate efforts on evaluating the impacts of measures on the YSLME, because it is important to determine the remaining capacity of the ecosystem to absorb disturbances and threshold under residual cumulative pressures (Stelzenmüller et al., 2020). Looking forward, the identification of risk criteria and evaluation of existing management measures should be incorporated in the future transboundary MSP initiative to determine context-specific criteria to better understand risk levels and identify the next step for better cooperation.

Another enabling factor of transboundary MSP is data and information sharing (Jay et al., 2016). Despite the conceivable challenges, sufficient data constitutes the basis of elaborated CEA and broader evidence-based transboundary management (see section 4.1). In this regard, joint survey and monitoring plans could be initiated by the YSLME Interim Commission Council, the regional governance mechanism (Zhang et al., 2019), and it would be the organization responsible for data storage and distribution to ensure data availability and standardization as much as possible. In addition, the risk pattern identified is helpful in the construction of marine protected areas network under discussion in the YSLME now, which could serve as a starting point for transboundary cooperation on MSP (Gissi et al., 2018). It could be used to identify conservation priority areas that possess a concurrent high ESAs value and high risk, and elimination of this kind of conflict is crucial (Boyce et al., 2022).

5. Conclusion

This study presents the first comprehensive assessment of the risk of cumulative effects in the YSLME based on the best knowledge available. Risk identification via literature review demonstrated that seven human activities including port, mariculture, fishing, industry and urban development, shipping, energy, and coastal defence, and three pressures including physical loss of seabed, input of hazardous substances, nitrogen and phosphorus enrichment were the major factors causing environmental problems of the YSLME. Five biotic ecosystem components, including benthic organisms, fishes, algae, seabirds, and marine mammals, and one abiotic ecosystem component, namely tidal flats, emerged as the most affected endpoints of the natural system. The impacted ecosystem components further led to the loss of ecosystem services such as diversity maintenance and food supply, posing threats to social welfare. Relatively higher cumulative effects are mainly concentrated on nearshore areas, especially Shandong, Liaoning, and northern Jiangsu Provinces, and some coastal bays of South Korea such as Saemangeum. Meanwhile, quite a certain amount of risk could also be observed in the transboundary area of the YSLME, which could be ascribed to the more pervasive fishing, shipping, and sinking of contaminants in this area. Current measures mainly are confined to individual countries and their effectiveness remains largely unknown. To facilitate more effective ecosystem-based management, transboundary cooperation on MSP will be needed in the future. Necessary steps in transboundary MSP include (1) determination of context-specific risk criteria, which indicate the vulnerabilities of ecosystem components to different pressures, to further understand the threshold of the acceptable level of risk and determined the absolute value of current risk, (2) evaluation of existing management efforts to inform policy adjustment in cooperation, (3) gap-filling of ecological and socio-economic data.

Credit author statement

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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 sources were provided in the Supplementary Material.

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Appendix A. Supplementary data

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References

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change 16 (3), 268–281.

Andersen, J.H., Al-Hamdani, Z., Harvey, E.T., Kallenbach, E., Murray, C., Stock, A., 2020. Relative impacts of multiple human stressors in estuaries and coastal waters in the North Sea-Baltic Sea transition zone. Sci. Total Environ. 704, 135316.

Arkema, K.K., Abramson, S.C., Dewsbury, B.M., 2006. Marine ecosystem-based management: from characterization to implementation. Front. Ecol. Environ. 4 (10), 525–532.

Beauchesne, D., Daigle, R.M., Vissault, S., Gravel, D., Bastien, A., Bélanger, S., Bernatchez, P., Blais, M., Bourdages, H., Chion, C., Galbraith, P.S., Halpern, B.S., Lavoie, C., McKindsey, C.W., Mucci, A., Pineault, S., Starr, M., Ste-Marie, A.S., Archambault, P., 2020. Characterizing exposure to and sharing knowledge of drivers of environmental change in the St. Lawrence system in Canada. Front. Mar. Sci. 7, 383.

Bergström, L., Miloš, A., Haapaniemi, J., Rani Saha, C., Arndt, P., Schmidtbauer-Crona, J., 2019. Cumulative Impact Assessment for Maritime Spatial Planning in the Baltic Sea Region. Pan Baltic Scope, Latvia.

Bevilacqua, S., Guarnieri, G., Farella, G., Terlizzi, A., Fraschetti, S., 2018. A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. Sci. Rep. 8 (1), 1757.

Borgwardt, F., Robinson, L., Trauner, D., Teixeira, H., Nogueira, A.J., Lillebø, A.I., Piet, J., Kuemmerlen, M., O'Higgins, T., McDonald, H., Arevalo-Torres, J., Barbosa, A.L., Iglesias-Campos, A., Hein, T., Culhane, F., 2019. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. Sci. Total Environ. 652, 1396–1408.

Boyce, D.G., Tittensor, D.P., Garilao, C., Henson, S., Kaschner, K., Kesner-Reyes, K., Pigot, A., Reyes, R.B., Reygondeau, G., Schleit, K.E., Shackell, N.L., Sorongon-Yap, P., Worm, B., 2022. A climate risk index for marine life. Nat. Clim. Change 12 (9), 854–862.

Buonocore, E., Grande, U., Franzese, P.P., Russo, G.F., 2021. Trends and evolution in the concept of marine ecosystem services: an overview. Water 13 (15), 2060.

Byun, G.-H., Moon, H.-B., Choi, J.-H., Hwang, J., Kang, C.-K., 2013. Biomagnification of persistent chlorinated and brominated contaminants in food web components of the Yellow Sea. Mar. Pollut. Bull. 73 (1), 210–219.

Chen, N., Zhang, C.-L., Sun, M., Xu, B.-D., Xue, Y., Ren, Y.-P., Chen, Y., 2018. The impact of natural mortality variations on the performance of management procedures for Spanish mackerel (*Scomberomorus niphonius*) in the Yellow Sea, China. Acta Oceanol. Sin. 37 (8), 21–30.

Choi, J., 2022. Assessing the need for the designation of the Yellow Sea particularly sensitive sea area (PSSA). Mar. Pol. 137, 104971.

Convention on Biological Diversity, 1993. https://www.cbd.int/sp/targets/. (Accessed 27 November 2022).

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJournal, Complex Systems 1695 (5), 1–9.

Dong, S., 2019. Researching progresses and prospects in large salmonidae farming in Cold water mass of Yellow Sea. J. Ocean Univ. China 49 (3), 1–6 (in Chinese).

Duan, H., Yu, X., Xia, S., Liu, Y., 2022. Conserving unprotected important sites for shorebirds on China's coasts. Ecosphere 13 (2), e3950.

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. Mar. Pollut. Bull. 118 (1–2), 27–40.

Erbe, C., Marley, S.A., Schoeman, R.P., Smith, J.N., Trigg, L.E., Embling, C.B., 2019. The effects of ship noise on marine mammals—a review. Front. Mar. Sci. 606.

Finke, G., Gee, K., Gxaba, T., Sorgenfrei, R., Russo, V., Pinto, D., Nsiangango, S.E., Sousa, L.N., Braby, R., Alves, F.L., Heinrichs, B., Kreiner, A., Amunyela, M., Popose, G., Ramakulukusha, M., Naidoo, A., Mausolf, E., Nsingi, K.K., 2020. Marine spatial planning in the benguela current large marine ecosystem. Environ. Dev. 36, 100569.

Foley, M.M., Mease, L.A., Martone, R.G., Prahler, E.E., Morrison, T.H., Murray, C.C., Wojcik, D., 2017. The challenges and opportunities in cumulative effects assessment. Environ. Impact Assess. Rev. 62, 122–134.

Friess, B., Grémaud-Colombier, M., 2021. Policy outlook: recent evolutions of maritime spatial planning in the European Union. Mar. Pol. 132, 103428.

Gissi, E., McGowan, J., Venier, C., Carlo, D.D., Musco, F., Menegon, S., Mackelworth, P., Agardy, T., Possingham, H., 2018. Addressing transboundary conservation challenges through marine spatial prioritization. Conserv. Biol. 32 (5), 1107–1117.

Halpern, B.S., Fujita, R., 2013. Assumptions, challenges, and future directions in cumulative impact analysis. Ecosphere 4 (10), 1–11.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319 (5865), 948–952.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world's ocean. Sci. Rep. 9 (1), 1–8.

Hammar, L., Molander, S., Palsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., Hume, D., Kagesten, G., Mattsson, D., Tornqvist, O., Zillen, L., Mattsson, M., Bergstrom, U., Perry, D., Caldow, C., Andersen, J.H., 2020. Cumulative impact assessment for ecosystem-based marine spatial planning. Sci. Total Environ. 734, 139024.

Hassan, D., Kuokkanen, T., Soininen, N. (Eds.), 2015. Transboundary Marine Spatial Planning and International Law. Routledge, Abington.

HELCOM, 2018. Thematic Assessment of Cumulative Impacts on the Baltic Sea 2011-2016. Baltic Sea Environment Proceedings No. 159. http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/. (Accessed 11 September 2022).

Janßen, H., Varjopuro, R., Luttmann, A., Morf, A., Nieminen, H., 2018. Imbalances in interaction for transboundary marine spatial planning: insights from the Baltic Sea Region. Ocean Coast Manag. 161, 201–210.

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S., Guerra, C.A., Takahashi, U.J.Y., Settele, J., Diaz, S., Molnár, Z., Purvis, A., 2022. The direct drivers of recent global anthropogenic biodiversity loss. Sci. Adv. 8 (45), eabm9982.

Jay, S., Alves, F.L., O'Mahony, C., Gomez, M., Rooney, A., Almodovar, M., Gee, K., Suárez de Vivero, J.L., Goncalves, J.M.S., Fernandes, M.D.L., Tello, O., Twomey, S., Prado, I., Fonseca, C., Bentes, L., Henriques, G., Campos, A., 2016. Transboundary dimensions of marine spatial planning: fostering inter-jurisdictional relations and governance. Mar. Pol. 65, 85–96.

Jo, Y.-S., Won, C.-M., Fritts, S.R., Wallace, M.C., Baccus, J.T., 2017. Distribution and habitat models of the Eurasian otter, *Lutra lutra*, in South Korea. J. Mammal. 98 (4), 1105–1117.

Judd, A.D., Backhaus, T., Goodsir, F., 2015. An effective set of principles for practical implementation of marine cumulative effects assessment. Environ. Sci. Pol. 54, 254–262.

Kelly, C., Gray, L., Shucksmith, R.J., Tweddle, J.F., 2014. Investigating options on how to address cumulative impacts in marine spatial planning. Ocean Coast Manag. 102, 139–148.

Khim, J.S., Park, J., Song, S.J., Yoon, S.J., Noh, J., Hong, S., Kwon, M.O., Ryu, J.-S., Zhang, X.-W., Wang, T.-Y., Lu, Y.-L., Giesy, J.P., 2018. Chemical-, site-, and taxa-dependent benthic community health in coastal areas of the Bohai Sea and northern Yellow Sea: a sediment quality triad approach. Sci. Total Environ. 645, 743–752.

Kim, J.-Y., Mjelde, J.W., Kim, T.-K., Lee, C.-K., Ahn, K.-M., 2012. Comparing willingness-to-pay between residents and non-residents when correcting hypothetical bias: case of endangered spotted seal in South Korea. Ecol. Econ. 78, 123–131.

Kirkman, S.P., Holness, S., Harris, L.R., Sink, K.J., Lombard, A.T., Kainge, P., Majiedt, P., Nsiangango, S.E., Nsingi, K.K., Samaai, T., 2019. Using systematic conservation planning to support marine spatial planning and achieve marine protection targets in the transboundary Benguela ecosystem. Ocean Coast Manag. 168, 117–129.

Koh, C.H., de Jonge, V.N., 2014. Stopping the disastrous embankments of coastal wetlands by implementing effective management principles: yellow Sea and Korea compared to the European Wadden Sea. Ocean Coast Manag. 102, 604–621.

Kong, X., Ye, S., 2014. The impact of water temperature on water quality indexes in north of Liaodong Bay. Mar. Pollut. Bull. 80 (1–2), 245–249.

Korpinen, S., Andersen, J.H., 2016. A global review of cumulative pressure and impact assessments in marine environments. Front. Mar. Sci. 3, 153.

Lavorel, S., Bayer, A., Bondeau, A., Lautenbach, S., Ruiz-Frau, A., Schulp, N., Seppelt, R., Verburg, P., Teeffelen, A.V., Vannier, C., Arneth, A., Cramer, W., Marba, N., 2017.

Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. Ecol. Indicat. 74, 241–260.

Li, X.-W., Zhao, J.-M., Liu, H., Zhang, H., Hou, X.-Y., 2018. Status, Problems and optimized management of spawning, feeding, overwintering grounds and migration route of marine fishery resources in Bohai Sea and Yellow Sea. Trans. Oceanogr. Limnol. 5, 147–157 (in Chinese).

Li, X.-Y., Yu, R.-C., Geng, H.-X., Li, Y.-F., 2021. Increasing dominance of dinoflagellate red tides in the coastal waters of Yellow Sea, China. Mar. Pollut. Bull. 168, 112439.

Li, S., Li, L., Gao, Q., Dong, S., Shi, S., 2022. Deep-sea cage culture altered microbial community composition in the sediments of the Yellow Sea Cold Water Mass. Mar. Pollut. Bull. 183, 114081.

Long, R.D., Charles, A., Stephenson, R.L., 2015. Key principles of marine ecosystem-based management. Mar. Pol. 57, 53–60.

Luke, D.A., 2015. A User's Guide to Network Analysis in R. Springer, New York.

Luo, W., Wang, T.-Y., Jiao, W.-T., Hu, W.-Y., Naile, J.E., Khim, J.S., Giesy, J.P., Lu, Y.-L., 2012. Mercury in coastal watersheds along the Chinese northern bohai and yellow seas. J. Hazard Mater. 215, 199–207.

Ma, S.-Y., Liu, Y., Li, J.-C., Fu, C.-H., Ye, Z.-J., Sun, P., Yu, H.-Q., Cheng, J.-H., Tian, Y.-J., 2019. Climate-induced long-term variations in ecosystem structure and atmosphere-ocean-ecosystem processes in the Yellow Sea and East China Sea. Prog. Oceanogr. 175, 183–197.

MacKinnon, J., Verkuil, Y.I., Murray, N., 2012. IUCN situation analysis on East and Southeast Asian intertidal habitats, with particular reference to the Yellow Sea (including the Bohai Sea). In: Occasional Paper of the IUCN Species Survival Commission No. 47. IUCN, Gland, Switzerland and Cambridge, UK.

Menegon, S., Depellegrin, D., Farella, G., Gissi, E., Ghezzo, M., Sarretta, A., Venier, C., Barbanti, A., 2018. A modelling framework for MSP-oriented cumulative effects assessment. Ecol. Indicat. 91, 171–181.

Moodie, J.R., Sielker, F., 2022. Transboundary marine spatial planning in European Sea Basins: experimenting with collaborative planning and governance. Plann. Pract. Res. 37 (3), 317–332.

Moon, J.Y., Lee, K., Lim, W.A., Lee, E., Dai, M.H., Choi, Y.H., Han, I.S., Shin, K., Kim, J. M., Chae, J., 2021. Anthropogenic nitrogen is changing the East China and Yellow Seas from being N deficient to being P deficient. Limnol. Oceanogr. 66 (3), 914–924.

Moores, N., Young, L., Millington, S., Xia, S., Yu, L., Yu, X., Ri, K.-S., Kim, T.-S., Lim, J., Glenk, F., 2019. National actions and international frameworks for the conservation and wise use of tidal flats and other coastal wetlands in the Yellow Sea. In: An, S., Verhoeven, J. (Eds.), Wetlands: Ecosystem Services, Restoration and Wise Use. Ecological Studies. Springer, Cham, Switzerland, pp. 159–184.

R Core Team, 2013. R: A Language and Environment for Statistical Computing.

Sherman, K., Sissenwine, M., Christensen, V., Duda, A., Hempel, G., Ibe, C., Levin, S., Lluch-Belda, D., Matishov, G., McGlade, J., 2005. A global movement toward an ecosystem approach to management of marine resources. Mar. Ecol. Prog. Ser. 300, 275–279.

Song, K.-J., 2011. Status of J stock minke whales (*Balaenoptera acutorostrata*). Anim. Cell Syst. 15 (1), 79–84.

Song, J.-J., Zhang, Z.-P., Chen, L., Wang, D., Liu, H.-J., Wang, Q.-X., Wang, M.-Q., Yu, D.-D., 2021. Changes in ecosystem services values in the south and north Yellow Sea between 2000 and 2010. Ocean Coast Manag. 202, 105497.

Stelzenmüller, V., Lee, J., South, A., Rogers, S.I., 2010. Quantifying cumulative impacts of human pressures on the marine environment: a geospatial modelling framework. Mar. Ecol. Prog. Ser. 398, 19–32.

Stelzenmüller, V., Coll, M., Mazaris, A.D., Giakoumi, S., Katsanevakis, S., Portman, M.E., Degen, R., Mackelworth, P., Gimpel, A., Albano, P.G., 2018. A risk-based approach to cumulative effect assessments for marine management. Sci. Total Environ. 612, 1132–1140.

Stelzenmüller, V., Coll, M., Cormier, R., Mazaris, A.D., Pascual, M., Loiseau, C., Claudet, J., Katsanevakis, S., Gissi, E., Evagelopoulos, A., Rumes, B., Degraer, S., Ojaveer, H., Moller, T., Gimenez, J., Piroddi, C., Markantonatou, V., Dimitriadis, C., 2020. Operationalizing risk-based cumulative effect assessments in the marine environment. Sci. Total Environ. 724, 138118.

Studds, C.E., Kendall, B.E., Murray, N.J., Wilson, H.B., Rogers, D.I., Clemens, R.S., Gosbell, K., Hassell, C.J., Jessop, R., Melville, D.S., Milton, D.A., Minton, C.D.T., Possingham, H.P., Riegen, A.C., Straw, P., Woehler, E.J., Fuller, R.A., 2017. Rapid population decline in migratory shorebirds relying on Yellow Sea tidal mudflats as stopover sites. Nat. Commun. 8 (1), 1–7.

Sun, J., Guo, Y., Park, G.S., Hudson, A., 2022. Dynamics of ecosystems and anthropogenic drivers in the Yellow Sea Large marine ecosystem. Acta Oceanol. Sin. 41 (6), 1–3.

Tang, Q.-S., Ying, Y.-P., Wu, Q., 2016. The biomass yields and management challenges for the Yellow sea large marine ecosystem. Environ. Dev. 17, 175–181.

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations, New York, NY, USA, pp. 23–24.

United Nations, 2020. United Nations Decade of Ocean Science for Sustainable Development (2021-2030). https://www.oceandecade.org/. (Accessed 27 November 2022).

United Nations, 2021. The Second World Ocean Assessment. World Ocean Assessment II. United Nations. https://www.un.org/regularprocess/woa2launch. (Accessed 27 November 2022).

United Nations Development Programme/Global Environment Facility (UNDP/GEF), 2007. UNDP/GEF Project: Reducing Environmental Stress in the Yellow Sea Large Marine Ecosystem. Transboundary Diagnostic Analysis (Incheon, Republic of Korea).

United Nations Development Programme/Global Environment Facility (UNDP/GEF), 2018. Interim Review Report on the Progress of Implementation of the National Strategic Action Programme for YSLME 2009-2020 of the People's Republic of China (Beijing, China).

United Nations Development Programme/Global Environment Facility (UNDP/GEF), 2019. An Analytical Study on the Implementation of the National Strategic Action Plan (NSAP) for the Yellow Sea Large Marine Ecosystem (YSLME) of the Republic of Korea (Incheon, Republic of Korea).

United Nations Development Programme/Global Environment Facility (UNDP/GEF), 2020. Transboundary Diagnostic Analysis for the Yellow Sea Large Marine Ecosystem (2020). UNDP/GEF Yellow Sea Large Marine Ecosystem (YSLME) Phase II Project, p. 75. Incheon, Republic of Korea.

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

Wang, Z., Xiao, J., Fan, S., Li, Y., Liu, X., Liu, D., 2015. Who made the world's largest green tide in China?—an integrated study on the initiation and early development of the green tide in Yellow Sea. Limnol. Oceanogr. 60 (4), 1105–1117.

Wang, C.-L., Zou, X.-Q., Zhao, Y.-F., Li, Y.-L., Song, Q.-C., Wang, T., Yu, W.-W., 2017. Distribution pattern and mass budget of sedimentary polycyclic aromatic hydrocarbons in shelf areas of the Eastern China Marginal Seas. J. Geophys. Res. Oceans 122 (6), 4990–5004.

U.S. Environmental Protection Agency (USEPA), 1992. A Framework for Ecological Risk Assessment. Risk Assessment Forum, Washington, DC. EPA 630/R-92-001.

Wang, J.-J., Beusen, A.H.W., Liu, X.-C., Van Dingenen, R., Dentener, F., Yao, Q.-Z., Xu, B.-C., Ran, X.-B., Yu, Z.-G., Bouwman, A.F., 2020. Spatially explicit inventory of sources of nitrogen inputs to the Yellow Sea, east China sea, and SouthSouth China sea for the period 1970-2010. Earth's Future 8 (10), e2020EF001516.

Wang, P., Mi, W.-Y., Xie, Z.-Y., Tang, J.-H., Apel, C., Joerss, H., Ebinghaus, R., Zhang, Q.-H., 2020. Overall comparison and source identification of PAHs in the sediments of European baltic and North seas, Chinese bohai and yellow seas. Sci. Total Environ. 737, 139535.

Wang, Y.-B., Wang, Y.-C., Liu, S.-D., Liang, C., Zhang, H., Xian, W.-W., 2020. Stock assessment using LBB method for eight fish species from the Bohai and Yellow Seas. Front. Mar. Sci. 7, 164.

Wang, S., Liu, C., Hou, Y., Xue, X., 2022. Incentive policies for transboundary marine spatial planning: an evolutionary game theory-based analysis. J. Environ. Manag. 312, 114905.

Wu, Q., Ying, Y.-P., Tang, Q.-S., 2019. Changing states of the food resources in the Yellow Sea large marine ecosystem under multiple stressors. Deep Sea Res. 2 Top. Stud. Oceanogr. 163, 29–32.

WWF, Korea Ocean Research and Development Institute (KORDI), Korea Environment Institute (KEI), 2006. The Yellow Sea Ecoregion - A Global Biodiversity Treasure. https://www.wwf.or.jp/activities/lib/pdf/%5BENG%5DYellowSea_Ecoregion-A_global_treasure_a_global_responsibility(Fact%20sheet).pdf. (Accessed 25 June 2022).

Yan, H.-K., Wang, N., Wu, N., Lin, W.-N., 2018. Maritime construction site selection from the perspective of ecological protection: the relationship between the Dalian offshore airport and spotted seals (*Phoca largha*) in China based on the noise pollution. Ocean Coast Manag. 152, 145–153.

Yim, J., Kwon, B.O., Nam, J., Hwang, J.H., Choi, K., Khim, J.S., 2018. Analysis of forty years long changes in coastal land use and land cover of the Yellow Sea: the gains or losses in ecosystem services. Environ. Pollut. 241, 74–84.

Yu, C.-H., Xiao, W.-J., Xu, Y.-P., Sun, X.-J., Li, M.-Y., Lin, H.-M., Tong, Y.-D., Xie, H., Wang, X.-J., 2021. Spatial-temporal characteristics of mercury and methylmercury in marine sediment under the combined influences of river input and coastal currents. Chemosphere 274, 129728.

Zhang, S.-M., Jin, S.-F., Zhang, H., Fan, W., Tang, F.-H., Yang, S.-L., 2016. Distribution of bottom trawling effort in the Yellow Sea and east China sea. PLoS One 11 (11), e0166640.

Zhang, Z.-H., Qu, F.-Y., Wang, S.-Q., 2019. Sustainable development of the Yellow Sea Large marine ecosystem. Deep Sea Res. 2 Top. Stud. Oceanogr. 163, 102–107.

Zhang, H., Su, R., Shi, X., Zhang, C., Yin, H., Zhou, Y., Wang, G., 2020. Role of nutrients in the development of floating green tides in the Southern Yellow Sea, China, in 2017. Mar. Pollut. Bull. 156, 111197.

Zuercher, R., Ban, N.C., Flannery, W., Guerry, A.D., Halpern, B.S., Magris, R.A., Mahajan, S.L., Motzer, N., Spalding, A.K., Stelzenmüller, V., Kramer, J.G., 2022. Enabling conditions for effective marine spatial planning. Mar. Pol. 143, 105141.