Marine Pollution Bulletin 225 (2026) 119201

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Combining the cumulative impact and marine use conflict-synergy assessment for identifying priority potential conservation areas for estuarine spatial planning

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ARTICLE INFO

Keywords:
Cumulative environmental effects
Marine spatial conflict
Synergistic interactions
Estuarine spatial planning
Priority protected areas
Yangtze River Estuary

ABSTRACT

Estuarine ecosystems worldwide are increasingly threatened by pollution and intensifying human activities, yet integrated approaches that reconcile conservation with sustainable resource use remain underdeveloped. This study addresses this gap by developing a novel framework to identify priority conservation areas in heavily polluted, multi-use estuaries. Focusing on the Yangtze River Estuary, one of the world's most impacted marine systems, we integrated a Marine Use Conflict-Synergy Assessment (MCSA) with a Cumulative Impact Assessment (CIA) targeting aquatic species. Here, *conflict* was defined as the spatial-functional incompatibility among human uses, while *synergy* reflected the efficiency gains from coordinated multi-use. Our results showed that pollution, shipping, and offshore infrastructure constituted the dominant pressures in the region. Approximately 87.94 % of areas with extremely high cumulative impacts overlapped with zones of high marine-use synergy, particularly in major shipping channels. Areas of pronounced use conflict were concentrated near the river mouth and within offshore wind-farm clusters. Based on a two-dimensional gradient of cumulative impact and conflict-synergy levels, five distinct conservation target types were delineated, which informed the design of an optimized marine spatial planning scheme for priority conservation. The proposed framework advances existing methodologies by operationally coupling cumulative impact and use-interaction assessments, providing a transferable approach for spatial planning adjustment in polluted, multi-stress estuaries worldwide. It thus contributes to both marine pollution science and evidence-based coastal management practice.

1. Introduction

Coastal and estuarine ecosystems face unprecedented pressures from rapid marine infrastructure expansion and associated pollution. Recent studies indicate that the rate of marine development now exceeds that of terrestrial urbanization rates in many regions. Estuarine zones are particularly vulnerable due to concentrated pollution from ports, seawalls, and land reclamation projects (Bugnot et al., 2020). This development creates an "infrastructure lock-in" effect that not only alters hydrodynamic regimes but also establishes persistent pollution pathways, leading to cumulative impacts on water quality and sediment toxicity (Seto et al., 2016). The resulting chemical contamination and habitat fragmentation pose significant threats to marine biodiversity, with restoration becoming increasingly challenging due to the legacy effects of pollution (Trindade-Santos et al., 2022). While international targets like the UN Sustainable Development Goal (SDG) 14 – "Life Below Water" (Vierros, 2021) and CBD 30 × 30 initiative aim to address these challenges, current protection efforts remain insufficient (CBD, 2022) – only 8.36 % of marine areas were protected by 2025 (UNEP-WCMC and IUCN, 2025). Effective conservation planning in these

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https://doi.org/10.1016/j.marpolbul.2025.119201
Received 14 August 2025; Received in revised form 26 December 2025; Accepted 29 December 2025
Available online 17 January 2026

polluted, multi-use seascapes requires innovative approaches that simultaneously address habitat protection and pollution mitigation. This need is especially critical in heavily modified estuarine systems where anthropogenic pressures are most intense.

Formulating Marine Spatial Planning (MSP) and identifying priority conservation areas are effective approaches for marine conservation, which necessitate a systematic assessment of anthropogenic impacts on marine ecosystems. Halpern et al. (2008) introduced the Cumulative Impact Assessment (CIA) model to evaluate global human impacts, laying a theoretical groundwork for decision-support tools in MPAs spatial planning (Hammar et al., 2020). The CIA's spatially explicit integration of multi-source stressors enables quantification of cumulative pressure on ecosystem components (Halpern et al., 2008). The methodology first maps the intensity of individual stressors and the distribution of target ecosystem components. A vulnerability weight is then applied to translate stressor intensity into projected impacts on habitats, ultimately generating a standardized metric for stressor effects (Halpern and Fujita, 2013). The CIA approach has been widely applied to map the negative effects of human activities in marine ecosystems at global scales (Halpern et al., 2025), regional scales (Jonsson et al., 2020; Loiseau et al., 2021), and for individual species (Lu et al., 2023), thereby supporting MSP and informing marine policies (Simeoni et al., 2023).

Meanwhile, diverse marine uses not only threaten marine ecosystems but also intensify competition for maritime space. The co-location and sustainable coordination among different marine activities have thus emerged as a critical issue (EC, 2014), underscoring the importance of understanding use-use interactions. To identify and assess these interactions, the Marine Use Conflict-Synergy Assessment (MCSA) was developed. This framework detects negative (conflict) or positive (synergy) interactions that arise between overlapping pairwise or multi-actor marine uses and ranks them by intensity and acceptability to inform maritime spatial planning. Within this approach, conflict refers to spatial-functional incompatibility among human uses, while synergy represents the efficiency gains achieved through coordinated multi-use. For instance, intensive shipping lanes intersecting with coastal recreational areas typically create conflict by diminishing amenity values and raising safety concerns (SwAM, 2015). In contrast, when spatially coordinated with artificial reefs, offshore wind farms may exhibit synergy by providing benthic structural habitats that reduce trawling and support fish species, potentially enhancing local population recovery (Dunkley and Solandt, 2022). Building on this theoretical foundation, Bonnevie et al. (2019) further classified interaction outcomes into specific types of conflicts (competition, antagonism, amensalism) and synergies (commensalism, mutualism), thereby refining the typology of marine use interactions. Tools like Symphony (Hammar et al., 2020) and SEANERGY (Bonnevie et al., 2020) consider multiple marine human uses to aid planning and decision-making. There is a growing consensus in academia for assessing the significance and intensity of symbiotic and conflicting relationships between marine multi-use activities and biodiversity protection in MPAs spatial planning (Bonnevie et al., 2020). The integration of CIA and MCSA provides us with a new perspective and methodology for marine zoning. Previous research has proposed certain concepts that multi-use are permitted only in areas with low cumulative impacts, thus optimizing marine space (Bonnevie et al., 2021). However, studies that systematically integrate CIA and SEANERGY methodologies remain limited, particularly in guiding marine spatial planning in intensively utilized coastal and estuarine regions.

Since 1980, China has set up 352 MPAs covering 93,300 km^2 (SCIO, 2024), yet the total protected area still falls well short of the COP15 30 % target. To enhance biodiversity conservation, China is developing a national park-centered protected area system, aiming to create the world's largest national park network comprising 49 parks by 2035 (Peng et al., 2020; Xu et al., 2023). However, only five small-scale marine national parks has been proposed, protecting merely 22 % of listed marine species (Xu et al., 2023). To address this research gap, our study develops a framework for prioritizing conservation in estuarine spatial planning by integrating conflict-synergy analysis of marine multi-use activities with CIA. We chose the Yangtze River Estuary (YRE), the world's third-largest estuary, as our case study. Recognized as a globally ecologically sensitive zone, the YRE was officially designated a World Natural Heritage Site in 2024. It hosts diverse rare and endangered aquatic species, such as the Chinese sturgeon (*Acipenser sinensis*), and serves as a crucial stopover for migratory birds and diadromous fish along the East Asian-Australian Flyway. However, being located in the economically vibrant and densely urbanized Yangtze River Delta, the estuary faces severe social-ecological conflicts due to intense human activities. Although basic Marine Protected Areas (MPAs) (e.g. Chongming Dongtan National Nature Reserve) have been established (SMG, 2023), the aquatic biodiversity and habitats continues to face pressures from multiple human activities in the YRE (Zhang et al., 2023). Thus, identifying priority conservation areas and establishing a more integrated MPAs system for the YRE is urgently needed.

Therefore, the specific aims of this study are to: (1) assess the cumulative impacts of anthropogenic pressures on target species and evaluate the degree of conflict and synergy among multiple marine uses; (2) develop a methodological framework that integrates MCSA with CIA for identifying potential priority conservation areas; and (3) and identify priority potential areas for MPAs in the YRE. Our results not only provide important insights for conservation prioritization in MSP but also inform estuarine environmental policies and other management practices globally.

2. Materials and methods

2.1. Method framework

Building on prior work on CIA and MCSA, this study proposes an integrated framework designed to address high-intensity human uses and conservation conflicts in estuaries by combining the CIA model (Halpern et al., 2015; Halpern et al., 2008) and MCSA method (Bonnevie et al., 2020). The framework improves cumulative pressure identification and uniquely analyzes conflict-synergy relationships among marine uses, supporting balanced estuarine management (Fig. 1). We applied this developed framework to the YRE to inform spatial planning. The detailed application is described in Sections 2.2–2.5.

2.2. Research area and target species selection

The study focuses on the YRE (120.90°–122.64° E, 30.86°–31.95° N; Fig. 2), a three-branched system extending from Xuliujing to the East China Sea. Characterized by water temperatures of 17.0–17.4 °C and high productivity, the YRE serves as a vital spawning, nursery, feeding, and migratory corridor for diverse aquatic species (Zhai et al., 2023). However, decades of intensive human activities (e.g., coastal reclamation, shipping, fishing, and pollution) have degraded critical habitats, including tidal flats and wetlands, while water quality deterioration (e.g., heavy metals) further threatens biodiversity (Zhang et al., 2023).

Three aquatic species Chinese sturgeon (*A. sinensis*), Chinese Mitten Crab (*Eriocheir sinensis*), and Osbeck's Grenadier Anchovy (*Coilia mystus*), were selected as target species in consideration of their conservation status, ecological and/or economic value, and habitat representativeness in YRE, which serves as a migration corridor and provides crucial habitats for overwintering, spawning, and feeding (Table S1) (Gao et al., 2017; Peng et al., 2024). Specifically, the YRE is a vital feeding and nursery ground for juvenile *A. sinensis*, and serves as a migration corridor for the adults (Zhao et al., 2018). It acts as a spawning, overwintering, and migration site for *E. sinensis* (Zhang et al., 2023) and plays a crucial role as a feeding and migration corridor for *C. mystus*.

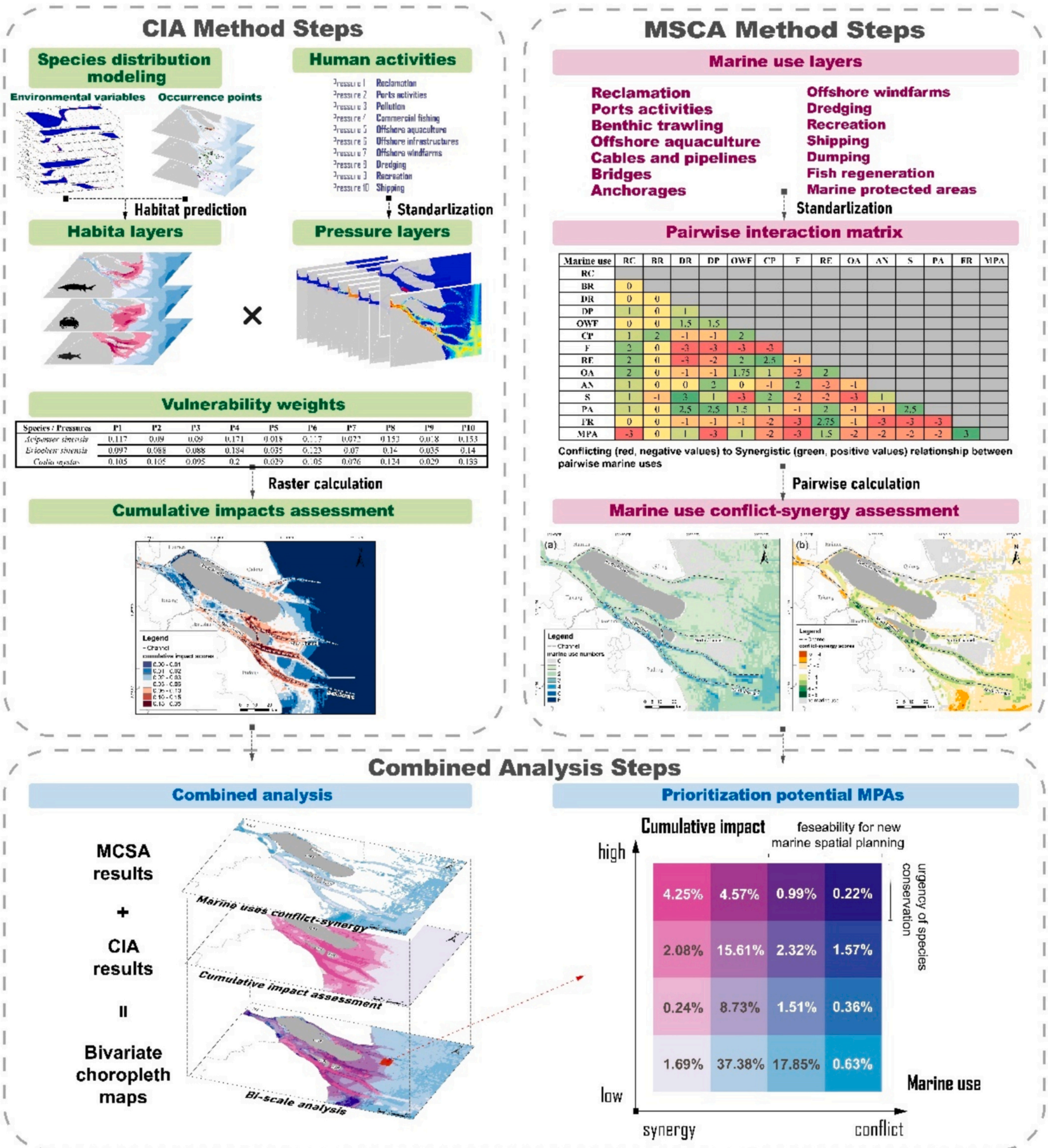

Fig. 1. The CIA-MCSA integrated framework for prioritizing protected areas in estuarine spatial planning.

2.3. Cumulative Impact Assessment

2.3.1. Pressure layers

To assess the cumulative impacts of human activities on typical species habitats in the YRE, relevant pressures were chosen through literature review of CIA focused on global estuaries (Clark et al., 2016) and the YRE (Wu et al., 2016a). Ten activities directly or indirectly impacting target species habitats were considered, including reclamation, port activities, pollution, commercial fishing, offshore aquaculture, offshore infrastructures, offshore wind farms, dredging, recreation, and shipping (Table 1). Details regarding the preprocessing of these activity variables are provided in Table S2.

2.3.2. Species distributions modeling

In this study, the occurrence data of juvenile *A. sinensis*, egg-carrying *E. sinensis*, and spawning *C. mystus* were sourced from historical records within the study areas. These records were compiled from trawl survey data reported in relevant articles (Wang et al., 2018), books (Zhuang

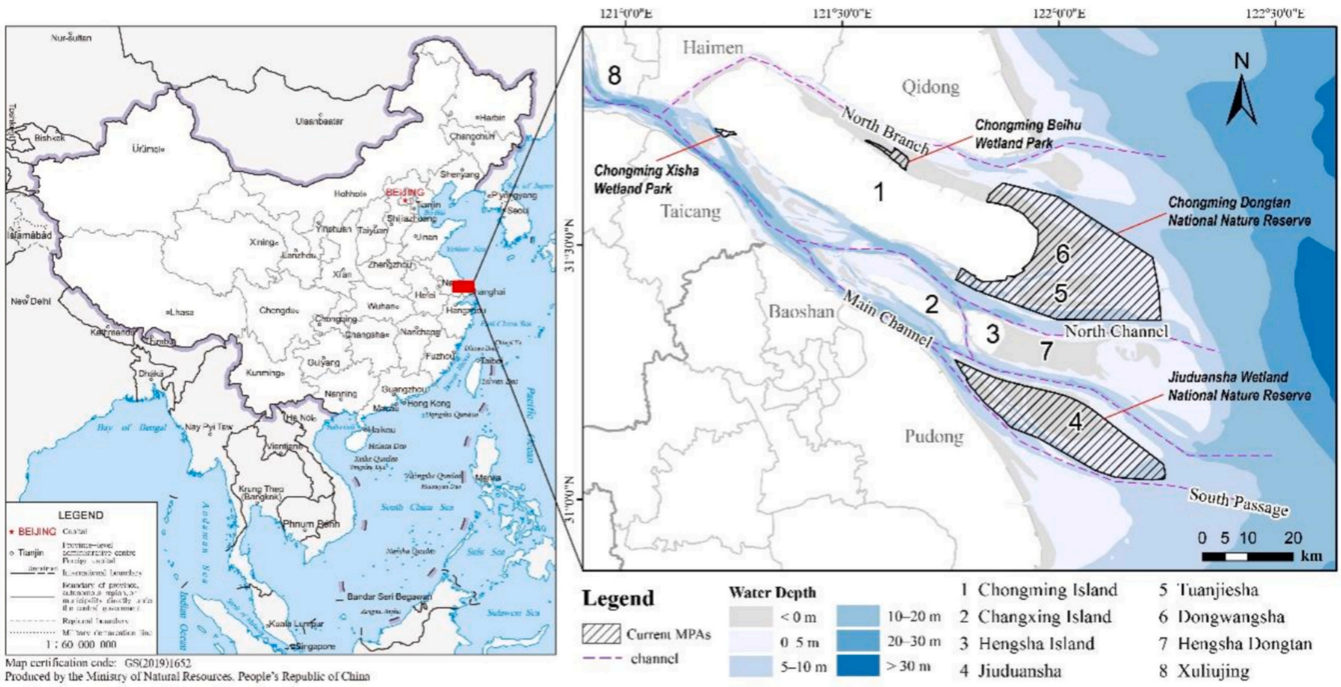

Fig. 2. Location of the study area in China (left) and its study areas (right). This Chinese map (left) is supervised and certified by the Ministry of Natural Resources of the People's Republic of China, with certification code: GS (2019)1652.
Retrieved from http://bzdt.ch.mnr.gov.cn/index.html.

Table 1
Correspondence between human activities (pressure layers) and marine use layers.

Pressure layer	Marine use layer	Spatial resolution	Time range	Source
Reclamation	Reclamation	Vector graphic	2020	Shanghai Marine Spatial Planning (2011−2020). Retrieved from https://www.gov.cn/zhengce/content/2012-11/06/content_2505.htm
Port activities	Port activities	Vector graphic	2020	
Pollution	–	Vector graphic	2020	Lin, J., Wang, P., Wang, J. et al. (2024) An extensive spatiotemporal water quality dataset covering four decades (1980–2022) in China. Earth Syst. Sci. Data, 16, 1137–1149.
Commercial fishing	Benthic trawling	0.01°	2015–2020	Copyright [2021], Global Fishing Watch, Inc. Accessed on 2023-11-12. https://globalfishingwatch.org/data-download/datasets/public-fishing-effort.
Offshore aquaculture	Offshore aquaculture	16 m	2020	Fu, Y, Deng, J., Wang, H., et al. (2020). A new satellite-derived dataset for marine aquaculture in the China's coastal region.
		10 m	2020	Sun, Z., Luo, J., Ma J., et al. (2023). A dataset of 10-m annual coastal aquaculture ponds in China and Vietnam from 2015 to 2020. V3. Science Data Bank.
Offshore infrastructures	Cables and pipelines Bridges Anchorages	Vector graphic	2020	Shanghai Marine Spatial Planning (2011–2020). Retrieved from https://www.gov.cn/zhengce/content/2012-11/06/content_2505.htm.
Offshore windfarms	Offshore windfarms	Vector graphic	2020	Wei, Z., Wang, F., Hou, Y., et al. (2023). Experimental Dataset for Extracting Spatial Distribution of Offshore Wind Power Generation Facilities from Sentinel 1 Radar Images [J/DB/OL]. Digital Journal of Global Change Data Repository.
Dredging	Dredging	Vector graphic	2020	Notification on maintenance of Main Channel and South Passage Channel at the Yangtze River Estuary. Retrieved from https://www.cjkhd.com/hdgl/hdwh/hdtg/202305/t20230506_315203.shtml.
Recreation	Recreation	Vector graphic	2020	Shanghai Marine Spatial Planning (2011–2020). Retrieved from https://www.gov.cn/zhengce/content/2012-11/06/content_2505.htm.
Shipping	Shipping	Vector graphic	2020	Global Maritime Traffic Density Service (GTMDS) retrieved from GlobalMaritimeTraffic.org, a service of MapLarge 2021. https://www.globalmaritimetraffic.org
–	Dumping	Vector graphic	2020	Provided by the managing authorities.
–	Fish regeneration	Vector graphic	2020	He, H. (2022). Ecological effect evaluation of Shanghai Yangtze River Estuary National Marine Ranching Demonstration area. (Master). Shanghai Ocean University, Shanghai.
–	Marine protected areas	Vector graphic	2024	Shanghai Protected Areas Conservation and Development Plan (2024–2035). Retrieved from https://lhsr.sh.gov.cn/zcqfzgh/20240318/77184a7d-3573-422e-b28e-c08d8ed420f1.html

et al., 2017; Zhuang et al., 2009), the Global Biodiversity Information Facility and the Ocean Biodiversity Information System. After Duplicate removed, 119 occurrence records were collected for *juvenile A. sinensis*, 189 for *E. sinensi*, and 90 for *C. mystus* were obtained.

The selection of variables related to physical environmental, oceanographic, and anthropogenic disturbance factors was based on their potential influence on habitat distribution (Table S1). All raster data were resampled to a uniform resolution of 30 m. Variables with a

Pearson's correlation coefficient exceeding 0.8 were excluded from further analysis (Table S3) (Shi et al., 2023). After comparing the performance of different models, ten major variables were ultimately selected (Table S4).

The Maxent software version 3.4.4 (Phillips et al., 2017) was employed for the modeling process. The final simulation results were generated by averaging the outcomes of 10 replicate model runs. Models with an area under the receiver operating characteristic curve (AUC) value greater than 0.75 were considered reliable. Among the reliable models, the one with the highest true skill statistic (TSS) value was selected for further analysis.

2.3.3. Cumulative impact calculation

A species-specific vulnerability matrix was developed through expert elicitation (Tables S5–S6). The expert panel consisted of 11 specialists from academia and management agencies, including aquatic biodiversity researchers and practitioners with extensive experience in YRE monitoring and regulation. Vulnerability weights for each pressure were quantified based on six criteria: (a) pressure frequency, (b) impact type (direct/indirect), (c) species resistance, (d) individual recovery time, (e) reproductive impact, and (f) population-level effects (Table S5; Supplementary Material B). For each species, pressure scores were summed and normalized (0–1 scale) to derive final vulnerability weights (Maxwell et al., 2013).

Cumulative impact was calculated based on the following formula (Halpern et al., 2009), and species distribution probability (habitat suitability) layers were used instead of ecosystem components layers for assessment. The species weighting scheme was developed through a comprehensive tri-criteria evaluation process, wherein 11 domain experts independently evaluated each species based on: (1) conservation urgency, (2) ecological role, and (3) socioeconomic value (Supplementary Material B). Expert-derived scores were subsequently aggregated through arithmetic averaging to generate the final weighting values:

$$I = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i \times \mu_{i,j} \times w_j \quad (1)$$

where I is the weighted average cumulative impact of selected species, P_i is the normalized value of pressure layer i, E_j is the predicted distribution probability of species j, $\mu_{i,j}$ is the weight score for P_i to E_j, and w_j is the weight of species j according to its value of conservation.

2.4. Identification of marine use conflicts

The marine multi-use conflict-synergy levels were established based on existing literature (Bonnevie et al., 2020, 2021; Hansen, 2019). For the study area, pressure layers were transformed into marine human use intensity layers (Table 1). Pairwise comparisons of multiple human uses were conducted to quantify cumulative positive and negative interactions, with MCSA scores assigned along a continuous scale from −3 (high conflict) to +3 (high synergy) (Table S7). Based on the foundational research of Bonnevie et al. (2020), we adapted the scoring matrix to align with the specific conditions of the YRE (Table 2). The total conflict-synergy scores were ultimately calculated using the following formula:

$$S = \sum_{u_1}^{n-1} \sum_{u_2=u_1+1}^{n} U_{u_{1,x,y}} \times U_{u_{2,x,y}} \times S_{u_1,u_2} \quad (2)$$

where U_1 and U_2 represent raster layers of different marine use intensities, where each layer contains standardized continuous values ranging from 0 (no presence) to 1 (maximum intensity). S is the total MCSA score, calculated as the sum of all pairwise marine use interaction scores. The double summation covers all unique, non-repeating, and unordered use-use combinations. Each pairwise score is computed by multiplying (1) the raster cell value of the first use ($U_{1,x,y}$), (2) the raster cell value of the second use ($U_{2,x,y}$), and (3) the conflict-synergy score ($S_{u1,u2}$) assigned to that specific use pair. The output is a spatial conflict-synergy score map, which quantifies cumulative interactions among marine uses in either current or proposed planning scenarios.

2.5. Marine protected areas prioritization and spatial planning zoning

Marine priority protected areas were delineated using Cumulative Impact Assessment (CIA) and MCSA, reflecting species habitat conservation needs under cumulative human pressures and protection opportunity costs, respectively. Higher CIA scores indicated greater conservation urgency, while higher MCSA scores denoted higher coordination effects and spatial reallocation cost. In this scoring system, positive values represent synergy, while negative values represent

Table 2
Quantified synergy-conflict matrix for pairwise marine uses.

Marine use	RC	BR	DR	DP	OWF	CP	F	RE	OA	AN	S	PA	FR	MPA
RC														
BR	0													
DR	0	0												
DP	1	0	1											
OWF	0	0	1.5	1.5										
CP	1	2	–1	–1	2									
F	2	0	–3	–3	–3	–3								
RE	2	0	–3	–2	2	2.5	–1							
OA	2	0	–1	–1	1.75	1	–2	2						
AN	1	0	0	2	0	–1	2	–2	–1					
S	1	–1	3	1	–3	2	–2	–2	–3	1				
PA	1	0	2.5	2.5	1.5	1	–1	2	–1	–1	2.5			
FR	0	0	–1	–1	–1	–2	–3	2.75	–1	–3	–3	–3		
MPA	–3	0	1	–3	1	–2	–3	1.5	–2	–2	–2	–2	3	

Positive values indicate synergy, with larger values representing stronger synergistic effects; negative values indicate conflict, with smaller values representing more intense conflict; zero values indicate a lack of recognized marine uses interactions supported by literature. A gradient color scale is used to represent varying degrees from synergy (green) to conflict (red).
Abbreviation: RC — reclamation, BR — bridges, DR — dredging, DP — dumping, OWF — offshore windfarms, CP — cables and pipelines, F — fishing, RE — recreation, OA — offshore aquaculture, AN — anchorages, S — shipping, PA — port activities, FR — fish regeneration, MPA — marine protected area.

conflict. To prevent misunderstanding, we will refer to the intensity of conflict in the following context, rather than describing the score itself as high or low. On one hand, the adjustment of low-conflict areas entails a relatively high opportunity cost. Co-located marine uses with consistent or complementary functions, will generate synergistic effects, thereby hindering spatial planning adjustment (Seto et al., 2016). On the other hand, relocating spatially conflicting marine uses is anticipated to enhance overall efficiency. Therefore, high-conflict areas are unlikely to meet the needs of future marine planning and should be prioritized for functional zoning adjustments. Furthermore, planning adjustments for areas with high cumulative impacts should primarily target ecological conservation.

Both CIA and MCSA layers were rasterized at a spatial resolution of 100 × 100 m. We used the 25th and 50th percentiles of CIA and MCSA values to classify grid cells into four levels (low, medium, high, extremely high). Percentile-based thresholds are widely used in spatial prioritization studies because they are robust to skewed distributions and allow relative ranking when absolute ecological thresholds are unknown. We also tested alternative cut-offs (e.g., 20th/40th percentiles) and found that the broad spatial patterns of priority areas remained consistent (results not shown), indicating that our conclusions are not overly sensitive to the exact percentile values. Binary mapping visualized spatial distributions, identifying priority zones. Areas with extreme cumulative impacts (top 25 % CIA) and high conflicts (top 50 % MCSA) were designated Target 1. Regions with CIA scores between 25 % and 50 % and MCSA in the top 50 % were assigned to Targets 2–3, while those with CIA in the top 50 % and MCSA between 50 % and 75 % were classified as Targets 4–5, posing greater challenges for MSP adjustment. Conservation urgency declined sequentially from Target 1 to 5. More specifically, areas with both high cumulative impact (high CIA scores) and high conflict present significant ecological risks and strong incompatibility among uses, indicating that the current spatial configuration is neither ecologically sustainable nor socio-economically efficient. Such areas are therefore prioritized for spatial re-zoning and ecological protection (Target 1), as functional reallocation may mitigate cumulative pressures and enhance overall use efficiency. In contrast, zones characterized by high CIA scores but low conflict (i.e., high synergy) typically involve coordinated and economically efficient human activities—such as shipping, dredging, and port operations in deep-water channels—yet still incur substantial ecological costs. These areas are often subject to “infrastructure lock-in,” where existing investments and high opportunity costs make short-term zoning adjustments politically and economically difficult. Consequently, they are assigned a lower priority for spatial reconfiguration, despite their continued ecological significance.

Based on the identified 5 targets, we further propose a brief MSP zoning scheme. Since we also considered local spatial utilization, socio-economic factors, and the ecological environment within the YRE, spatial discrepancies can be found when compared directly with the 5 targets. The zoning scheme includes: Ecological Conservation Zone, Ecological Control Zone, Marine Use Coordination Zone, Coastal Landscape Corridor, and Marine Use Development Zone, aiming to achieve a balance among habitat conservation, marine resource utilization, and blue civilization development (Table S8). The Ecological Protection Zone is designated in areas corresponding mainly to part of Target 1 and part of Target 2, where both CIA scores and conflict levels are high. The primary aim is strict ecological protection and habitat restoration for key species, with restrictions on most extractive uses. The Ecological Control Zone overlaps with intermediate CIA and conflict levels (part of Target 1, Targets 2–3), where cumulative impacts are substantial but uses are not fully “locked in”. Here, the goal is adaptive management, such as seasonal regulation of shipping intensity during critical life stages of protected species. The Coastal Landscape Corridors are proposed in areas with strong potential for integrating conservation and cultural ecosystem services, often overlapping with lower CIA scores but strategic conservation value (overlapping with Targets 3–4). These corridors are designed to maintain connectivity, support recreation and education, and link more strictly protected zones. The Marine Use Coordination Zones are located in areas with significant conflicts but lower ecological sensitivity or where multiple uses need to be optimized (mainly corresponding to partly Target 1, and Targets 2–3). The aim is to reduce conflicts and improve multi-use compatibility through spatial or temporal adjustments, pollution control, and improved coordination among sectors.

3. Results

3.1. Cumulative Impact Assessment

The results of CIA revealed that target aquatic species habitats in the YRE were significantly affected by cumulative anthropogenic pressures (Fig. 3). Areas exhibiting extremely high cumulative impact scores (>0.06) covered approximately 107.13 km^2, accounting for 10.03 % of the total water area, and were primarily distributed in the North Passage, North Channel, and South Channel waters (Fig. 3a). Regions with low cumulative impact scores (<0.01) were predominantly located outside the main estuary. Pollution (43.45 %) and shipping activities (23.56 %) were identified as the dominant anthropogenic stressors affecting key aquatic species in the YRE (Fig. 3b).

3.2. Marine use conflict-synergy assessment

Marine use frequency analysis (Fig. 4a) showed intensive multi-use overlap in the Main channel, North Channel, and South Passage, characterized by clustered infrastructure (navigation, fishing, aquaculture). The southern sector exhibited particularly high intensity due to overlapping fishing and shipping activities, while the North Branch had significantly lower utilization. Current MPAs (especially in Chongmingdongtan and Jiuduansha) demonstrated significantly fewer marine uses, validating their role in mitigating anthropogenic pressure.

MCSA results revealed marked spatial heterogeneity in marine multi-use synergies and conflicts (Fig. 4b). A synergistic corridor emerged from the estuary's inland reach through the Main channel and southern passage, extending to the adjacent sea, driven by coordinated navigation infrastructure (e.g., waterway construction, dredging, and shipping). Conflict hotspots clustered in hydrodynamic transition zones, branch flanks, and offshore wind farm areas along the southern coastal margin, with additional shipping-commercial conflicts in offshore waters.

3.3. Identification of potential priority conservation areas under multiple targets

3.3.1. Overlap analysis of CIA and MCSA

Overlap analysis (Fig. 5) identified that 0.22 % of the study area exhibited both high cumulative anthropogenic pressures and intense use conflicts, primarily in proximal estuarine waters and southern coastal zones. A key development area with elevated impacts and conflicts served as critical habitat for *E. sinensis*, where offshore wind farms showed low multi-use compatibility. Notably, 87.94 % of extreme cumulative impact zones (8.82 % of the area) were identified as marine use synergy hotspots (Fig. 4b), concentrated in central channel waters. Here, shipping and port infrastructure demonstrated high operational compatibility but imposed significant ecological stress on keystone species.

3.3.2. Identification of potential priority conservation areas

The analysis identified five priority conservation target types (Fig. 6a). Target 1 (highest priority) focuses on critical habitats in proximal estuarine waters, coastal zones, and northern channel entrances requiring urgent protection. Target 2 (high priority) expands coverage to include estuarine and eastern coastal waters, addressing additional ecological vulnerabilities. Target 3 (moderate priority)

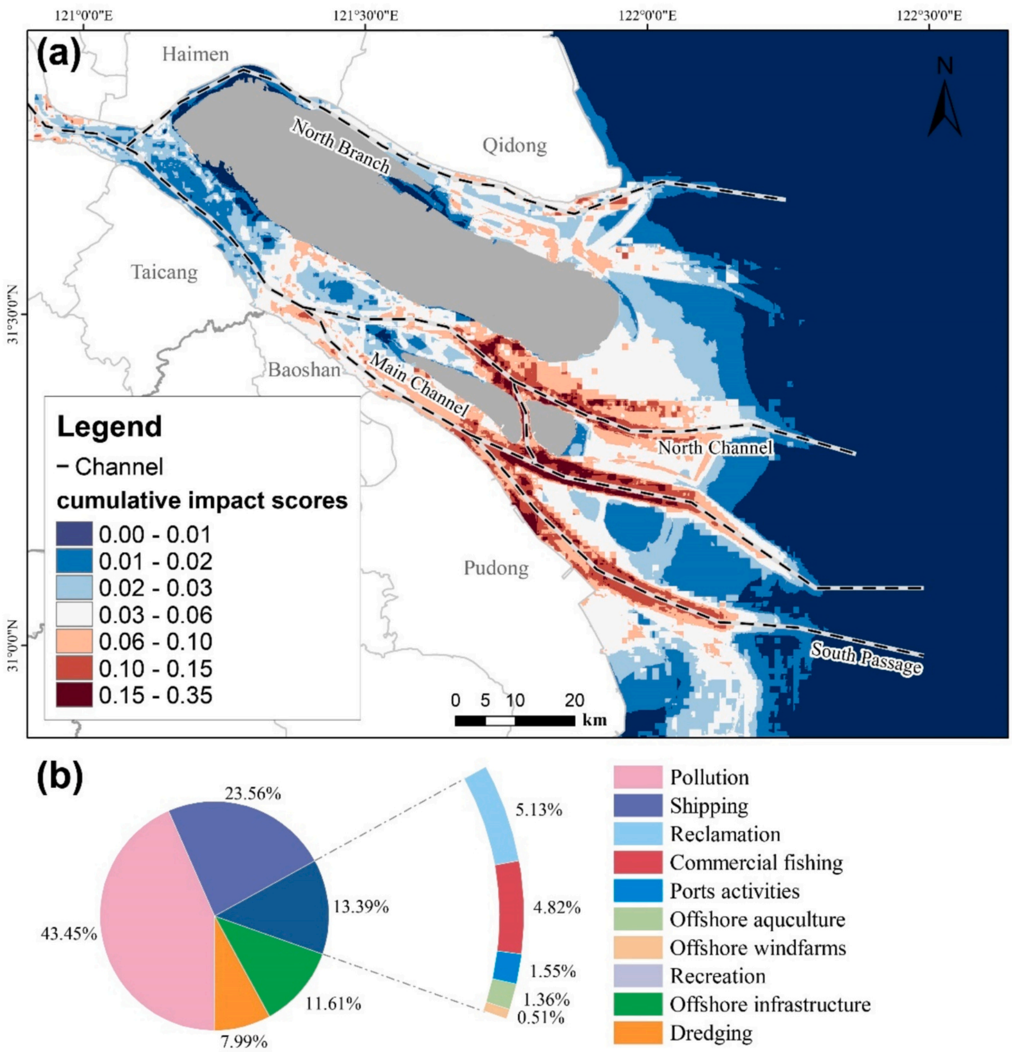

Fig. 3. Results of Cumulative Impact Assessment. (a) Spatial distribution of cumulative impacts on target aquatic species; (b) the proportion of cumulative impact scores attributed to each human activity pressure layer.

proposes phased conservation expansion to northern branches, prioritizing habitat preservation. Target 4 (4.57 % of total area) enhances migratory connectivity through central channel regions, while Target 5 (15.61 % coverage) offers extensive protection but faces implementation challenges due to high anthropogenic pressures, necessitating long-term adaptive management.

Fig. 6b shows habitat coverage for target species. At Target 3 level, newly designated areas increase coverage of moderately suitable habitat (0.6 < distribution probability < 0.9) by 5–10 %, while providing limited protection for highly suitable habitats (>0.9). Combined with existing protected areas, these zones provide adequate refuge for *A. sinensis* and *E. sinensis*, though coverage remains limited for *C. mystus* habitats.

Based on the comprehensive analysis, we propose implementing an optimized MSP framework in the YRE (Fig. 6c, Table S8). This framework comprises four spatially explicit management zones designed to balance ecological conservation with sustainable development: (1) An Ecological Conservation Zone (477.72 km^2) in the North Branch and waters south of Changxing Island for habitat restoration; (2) An Ecological Control Zone (211.58 km^2) covering areas south of the Chongming Dongtan Reserve and upper main waterway wetlands, to be managed with adaptive strategies such as seasonal shipping restrictions to protect key species (e.g., *A. sinensis*); (3) Marine Utilization Coordination Zones in the Xuliujing, North Channel, and eastern Nanhui areas, where enhanced pollution control is required; and (4) Coastal Landscape Corridors along the coastlines. Collectively, these zones form a tiered, spatially explicit governance framework for the YRE.

4. Discussion

4.1. Concentration of high CIA in shipping channels and primary stressors

Our findings indicate that areas with high cumulative impacts in the YRE are primarily located in the Main Channel, driven by shipping (Weng et al., 2020), pollution (Zhuang and Zhou, 2021), and dredging (Wu et al., 2016a). This aligns with Gao et al. (2024), who identified major shipping channels near ports as pollution hotspots. The YRE, one of the world's busiest shipping lanes, faces significant pressure from frequent large container vessel transit and intensive port operations, degrading water quality via pollutants (e.g., fuel emissions, ballast water, sewage). Continuous dredging to maintain navigational depth (12.5 m) further exacerbates environmental disturbances (Wu et al., 2016a). The Main Channel also serves as a critical migration route for protected species like *A. sinensis*, compounding cumulative stress from conservation needs and anthropogenic pressures.

Pollution is the dominant human pressure in the YRE, followed by shipping-related activities, consistent with global estuarine degradation trends (Clark et al., 2016). Unlike other Chinese coastal regions, the

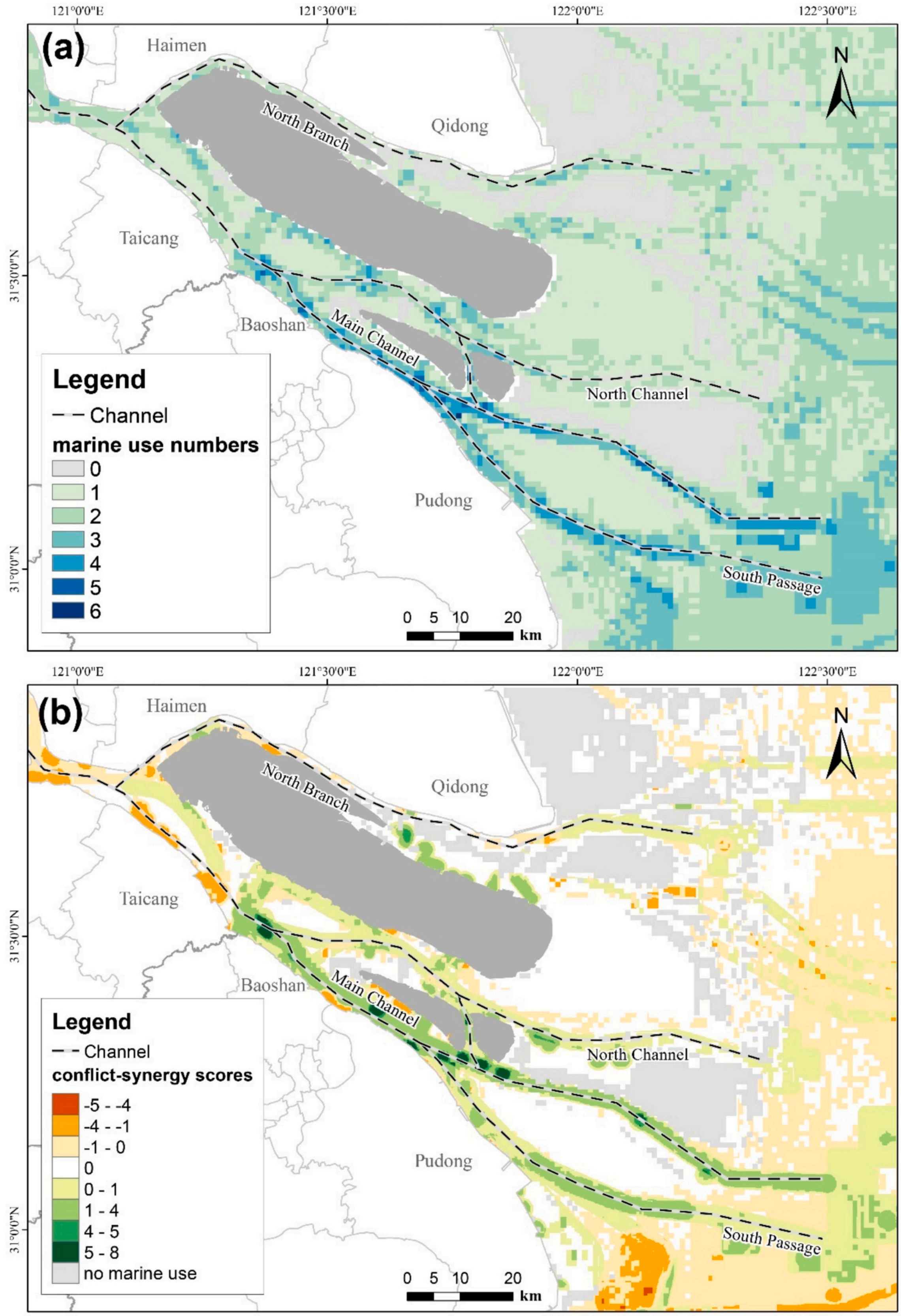

Fig. 4. Results of marine use conflict-synergy assessment. (a) Counts of marine uses; (b) total conflict-synergy scores of marine uses.

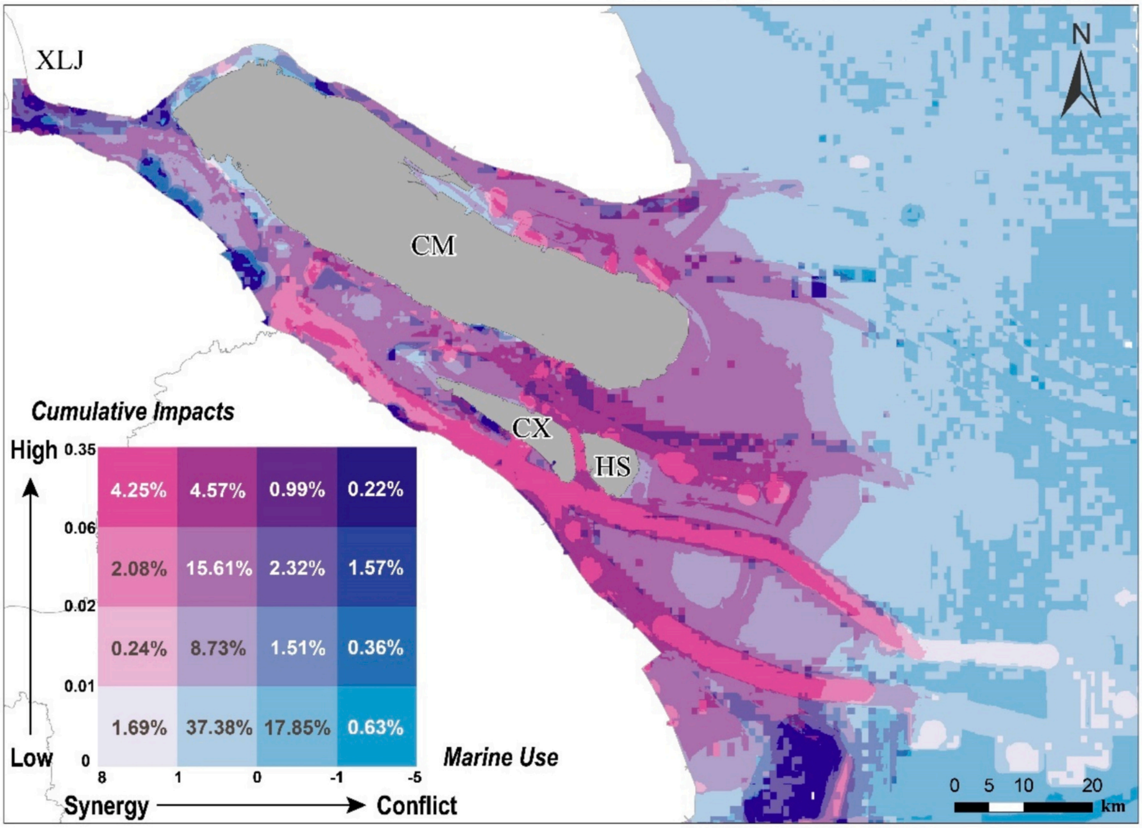

Fig. 5. Integrated assessment of cumulative impacts and marine use conflict-synergy in the YRE. The color informs combined classification of CIA and MCSA scores, the values within different color blocks in the legend represent the proportion of area respectively.

YRE's ecosystem health continues to decline, necessitating urgent conservation measures (Xu et al., 2023). Land-based discharges, rather than hydrocarbon exploitation, likely drive water quality deterioration and eutrophication. Similar problems are found in other estuarial zones with dense population and developed industry, for example, Jiaozhou Bay, China (Wu et al., 2016b) and Spencer Gulf, Australia (Jones et al., 2018). Shipping, offshore infrastructure (e.g., anchorages), and dredging account for 44.71 % of cumulative impacts. Given Shanghai's status as a major port city, managing conflicts between shipping development and marine conservation remains critical. However, spatial heterogeneity in human activities, ecosystems, and species habitats offers opportunities to mitigate cumulative impacts through strategic MSP (Micheli et al., 2013).

4.2. Spatial conflict and synergy distribution in multi-use marine areas

Our findings underscore the complex interplay between intensive human activities and ecological vulnerability in the YRE, mirroring patterns observed in major estuaries globally (Barbier et al., 2011). Jung et al. (2024) analysis of 2396 global estuaries supports this, revealing that around 44 % have been directly modified by synergistic marine uses (i.e., concurrent anthropogenic pressures). Similarly, our study shows that multiple human activities dominate most YRE regions, confirming that estuarine ecosystems are increasingly shaped by cumulative, interacting stressors. Notably, 87.94 % of areas in the YRE with extremely high cumulative impacts coincide with zones of synergistic marine utilization. This reinforces the "infrastructure lock-in" effect (Seto et al., 2016), where entrenched activities (e.g., shipping, dredging, infrastructure development) generate synergistic effects, creating path dependencies that hinder spatial reconfiguration. The deep-water shipping channel exemplifies this: it serves as both a hub of high-intensity human use and a primary source of cumulative impacts on habitats critical to species like *A. sinensis* and *C. mystus*. While coordinated infrastructure (e.g., dredging, port operations) has enhanced economic efficiency, it has simultaneously degraded key habitats. This lock-in effect imposes prohibitive costs—or even irreversibility—for future ecosystem restoration or adjustments in the YRE.

Despite the vertical and dynamic characteristics of estuaries, which facilitate ecological connectivity and material exchange (Laurino et al., 2021), incompatible uses of marine space often lead to functional conflicts among multiple human activities (Coccoli et al., 2018). This study identifies key conflict hotspots in the YRE concentrated in the river mouth of Xuliujing region and offshore wind farm clusters. The Xuliujing area, located at the confluence of the Yangtze River's freshwater discharge and the East China Sea's tidal regime, serves as a critical zone for maintaining estuarine ecological balance. This region simultaneously supports the logistical operations of megaports, resulting in extremely high vessel traffic densities. However, it also functions as a migratory corridor and habitat for endangered species, creating pronounced tensions between ecological conservation and activities such as shipping and land reclamation (Zhuang et al., 2009).

Offshore wind farm developments exacerbate these conflicts by occupying large maritime areas, thereby overlapping with traditional fishing grounds and shipping lanes. Cable-laying operations for wind farms disturb seabed sediments, disrupting benthic communities and degrading habitats critical to migratory fish species such as the *C. mystus*. These findings are consistent with the systematic review by Galparsoro et al. (2022), which documented significant adverse effects of offshore wind farms on marine mammal populations and ecosystem structure.

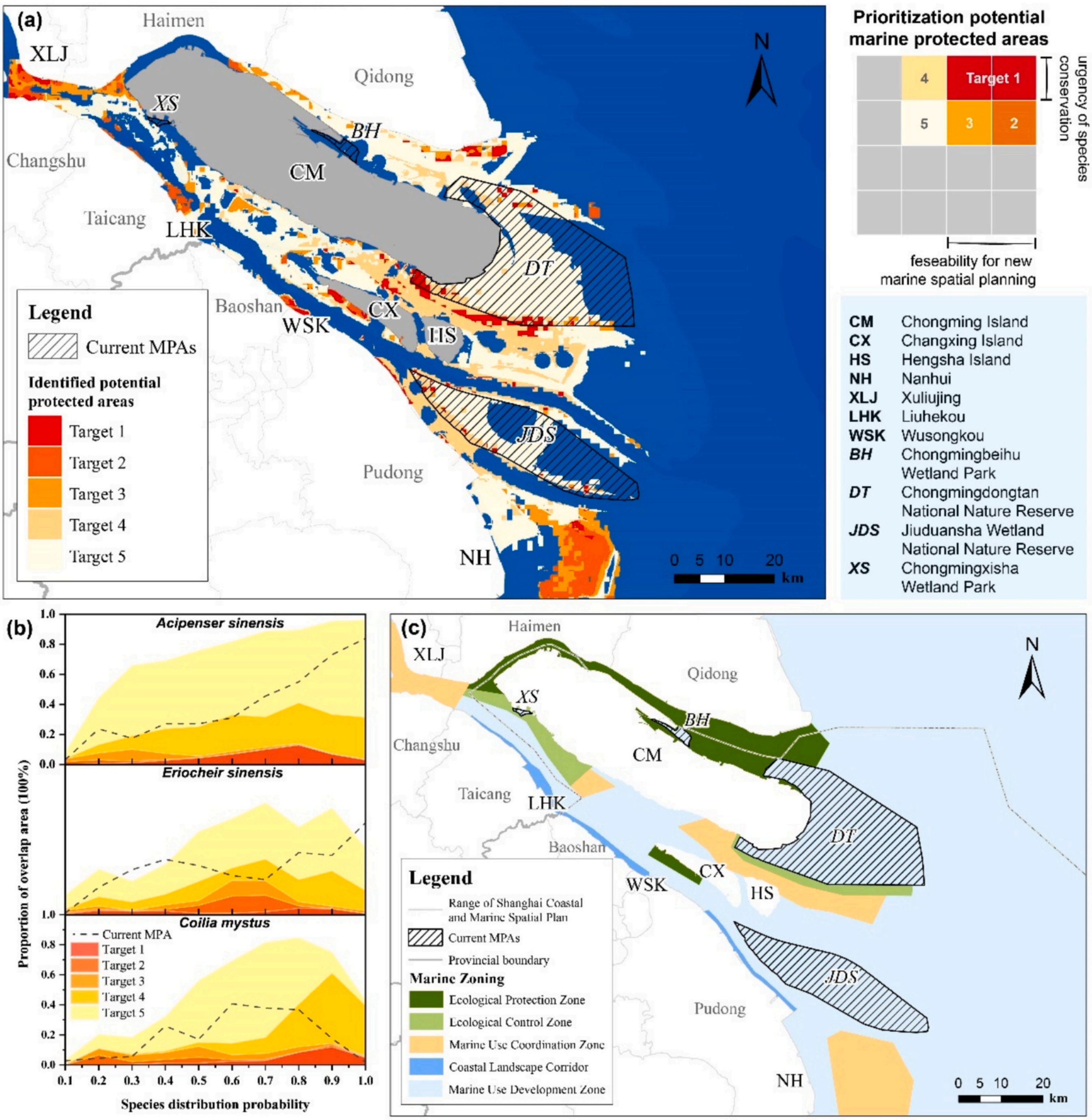

Fig. 6. (a) The potential priority conservation areas under multiple targets; (b) proportion of target species habitats by current and potential conservation areas; (c) proposal an optimized marine zoning scheme in the YRE.

4.3. Identification priority potential conservation areas for MSP and implications

Our study advances estuarine spatial planning by integrating CIA with marine use conflict-synergy analysis, offering a robust framework for prioritizing protected areas and optimizing MSP in the YRE. Building on prior research that has focused on systematic conservation planning for sensitive marine habitats (Yavarmoghadam et al., 2025), sector-specific conflicts (Coccoli et al., 2018), single-dimensional assessments (Almpanidou et al., 2021), and overlap analysis between species distribution and human activities (Sahri et al., 2021), our approach systematically evaluates multi-use interactions and provides spatially explicit guidance for policymakers to balance ecological conservation with marine resource development. More specifically, our framework makes three key methodological contributions. First, we operationally combine CIA and MCSA along a two-dimensional gradient reflecting ecological urgency (CIA) and the opportunity cost/feasibility of spatial re-zoning (MCSA), delineating five explicit conservation target types (Targets 1–5). Second, for the intensively used Yangtze River Estuary, we translate these targets into a concrete multi-zone marine spatial planning scheme—including Ecological Conservation, Ecological Regulation, Marine Use Coordination, and Coastal Landscape Corridor zones—thus directly linking priority classes to management actions. Third, by developing a stepwise implementation roadmap, we highlight how "infrastructure lock-in" varies across high-impact areas due to synergistic economic uses, and show that short-term conservation gains are more achievable where high cumulative impact coincides with high conflict among uses. Beyond informing potential optimization of marine functional zoning (Yang et al., 2022), our study emphasizes the importance of ecological conservation throughout the zoning process. Thus, this integrated framework not only provides a robust tool for prioritizing protected areas and optimizing marine spatial planning in the YRE, but also offers a transferable approach for systematic spatial planning in other heavily exploited coastal regions.

Our study underscores the necessity for integrated and adaptive management in the Yangtze River Estuary. We propose the establishment of an "Ecological Conservation Zone," implementing a strict negative list management approach. This would involve, for example, a comprehensive ban on land reclamation, dredging, bottom trawling, and seabed mining; stringent restrictions on vessel entry for non-scientific purposes; the setup of permanent ecological monitoring stations; and the formulation of long-term plans for fishing-to-wetland conversion and seagrass bed restoration to achieve habitat protection and ecological recovery. The "Ecological Control Zone" should adopt adaptive management strategies, such as implementing seasonal controls on shipping intensity in migratory corridors during critical life-history stages of protected aquatic species (e.g., *Acipenser sinensis*) and delineating dynamic temporary no-navigation areas. Coastal segments that integrate ecological conservation with landscape and cultural ecosystem services are identified as "Coastal Landscape Corridors." Their management should stipulate setback distances from the shoreline, height and style controls for new coastal constructions; plan continuous public waterfront pathways; restrict the siting of large-scale industrial facilities; and design nature-based ecological revetments to safeguard public shoreline access and landscape continuity. For the "Marine Use Development Zone" (or "Coordination Zone"), we emphasize that its management core is "optimizing and regulating existing uses" rather than "no regulation." Specifically, while strengthening pollution control and monitoring, it should promote spatial and temporal sharing of marine activities (e.g., coordinating the spatiotemporal layout of shipping, aquaculture, and recreation). Furthermore, measures such as establishing vessel traffic density standards, optimizing shipping lane layouts, and mandating the use of environmentally friendly technologies can be implemented to systematically reduce cumulative ecological impacts while promoting development.

This study provides a tiered priority framework for conservation actions in the YRE, offering an approach to balancing ecological needs with blue socio-economic demands. In the future, we propose integrating the Ecological Conservation Zone and Ecological Control Zone into a unified Yangtze River Estuary National Park to achieve holistic conservation, aligning with China's broader estuary conservation strategies (e.g., national park planning for the Yellow River and Pearl River estuaries) that emphasize systematic protected area networks. This approach supports ecosystem authenticity and integrity, consistent with China's Yangtze River conservation efforts and the decade-long fishing moratorium in the basin. Over the past five years, adaptive human management has proven effective in curbing overexploitation while enhancing ecological resilience, offering a replicable model for balancing biodiversity conservation with socio-economic demands in globally significant estuarine systems.

4.4. Limitations and future research directions

The CIA method is built upon several simplifying assumptions (Halpern and Fujita, 2013), which enhance its generalizability. In reality, human activities can have synergistic or antagonistic effects on ecosystem components, similar to marine uses interactions. Incorporating non-additive stressor interactions into the common additive model may mitigate potential misrepresentations of cumulative impact density (Stockbridge et al., 2025). Moreover, future research should focus on investigating non-linear response of ecosystems to stressor (Murray et al., 2025), because estuaries are complex, dynamic, and vertically structured ecosystems. The limitations of this study include its focus on the Yangtze system and the challenges of modeling pollution dispersion and ecological responses in dynamic estuaries. The linear response assumption may oversimplify complex, non-linear relationships between pollution stressors and ecosystem impacts (Hunsicker et al., 2016). Future research should incorporate temporal pollution variability and species-specific sensitivity thresholds to better predict ecosystem responses to cumulative pollution pressures, ultimately refining management strategies for pollution-impacted coastal systems.

Our MCSA framework offers a more realistic representation of marine use conflicts and synergies by considering multiple marine uses interactions, compared with previous assessment methods that relied on simple spatial overlays (Menegon et al., 2018). However, limited by data availability, we did not consider the temporal co-occurrence of different marine uses. For instance, during fishing seasons, conflicts between fishing and shipping may intensify, while it is opposite at other times. Such dynamic variations cannot be captured by annually averaged marine use layers in our study. Researchers should be aware of data gaps and the resulting unreliability in conflict-synergy assessments (Bonnevie et al., 2021). Therefore, we recommend that future studies incorporate the temporal dynamics and uncertainties of marine uses, and couple them with seasonal changes of key conservation targets (e.g., life history cycle of endangered species). This will provide a scientific basis for developing more precise adaptive management strategies. Furthermore, it is strongly advised to localize the conflict–synergy pairwise parameters, given that the differences in classification standards, intensity, and modes of marine use across countries are quite significant (Yang et al., 2022). Substantial knowledge gaps in understanding marine use interactions still exist, requiring integration insights from government managers, the public, and academia across sectors.

5. Conclusions

This study developed an integrated assessment framework combining MCSA with CIA to identify priority conservation areas in heavily polluted, multi-use estuaries. Our results quantify the "infrastructure lock-in" effect on estuarine ecosystems, revealing that 87.94 % of severely polluted areas coincide with marine use synergy zones, particularly in navigation channels where pollution emerges as the dominant stressor. The analysis pinpoints pollution hotspots in shipping lanes and documents intense use conflicts near the Xuliujing river mouth and offshore wind farm developments, areas particularly vulnerable to cumulative pollution impacts.

Methodologically, this study advances existing approaches by operationally integrating ecological urgency (CIA) and spatial re-zoning feasibility (MCSA) along a two-dimensional gradient. This integration enables the delineation of explicit conservation target types, which are subsequently translated into a concrete, multi-zone marine spatial planning scheme tailored to local conditions. This integrated framework provides a transferable tool for estuarine systems globally, enabling simultaneous evaluation of ecological pressure and human use interactions. By incorporating conflict-synergy dynamics into conservation prioritization, the framework supports the design of adaptive marine spatial plans that reflect real-world implementation constraints. The proposed zoning scheme—including Ecological Protection Zones, Ecological Control Zones, a Coastal Landscape Corridor, and Marine Use Coordination Zones—demonstrates how such an approach can structure conservation efforts along a gradient from immediate protection to long-term coordination. This work contributes to achieving SDG 14 and CBD targets by offering a scalable model for estuarine conservation planning in contexts of high pollution and competing marine uses, emphasizing the value of integrated assessment for balancing ecological integrity and sustainable development.

This study has limitations, including assumptions of linear ecological responses and the use of static annual data, which oversimplify dynamic estuarine systems and temporal interactions. Future research should incorporate non-linear stressor effects, species-specific sensitivity thresholds, and temporal variability in both human uses and key species life cycles to enable more adaptive and precise management strategies.

CRediT authorship contribution statement

Ziyu Zhu: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Cong Zeng:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Wenhui Yang:** Software, Methodology, Investigation, Formal analysis. **Wenbo Cai:** Writing – review & editing, Investigation, Funding acquisition. **Wanting Peng:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Chengzhao Wu:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant numbers 52208066; 72104232]; Shanghai Sailing Program [grant number 21YF1419600]; Fundamental Research Funds for the Central Universities; Soft Science Research Project by Shanghai Science and Technology Commission [grant number 24692116500], and National Social Science Foundation of China [grant number 20FGLB014]. I would like to extend my sincere gratitude to Prof. Ping Zhuang from the East China Sea Fisheries Research Institute of the Chinese Academy of Fishery Sciences for providing valuable information and guidance; We are grateful for Deputy Director Shufeng Ye and East China Sea Development Research Institute of the Ministry of Natural resources. We gratefully acknowledge Shanghai Chongming Dongtan Nature Reserve Management Center support and assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.119201.

Data availability

Data will be made available on request.

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