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An integrated strategy maximises cobenefits of conservation and restoration for ecosystem services in coastal wetlands

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Abstract: Coastal wetlands are among the most valuable but threatened ecosystems globally. Here we address the need to move beyond isolated, site-based restoration by developing an integrated spatial strategy that co-optimizes conservation and restoration to maximize multiple ecosystem benefits. Using the Yellow River Delta as a case study, we combined systematic conservation planning with spatial optimization modeling to identify priority areas for both conservation and restoration under budget constraints. Restoration cost was assessed by added hydrological accessibility and we explored restoration feasibility by elevation-based habitat suitability for tidal vegetation. We find that an optimal integrated pattern, achievable under a 50% target level for mitigating ecosystem service losses, could enhance total ecosystem service value by 19% compared with the current baseline. We

further proposed tailored management strategies, focusing on enhancing habitat connectivity, managing regional carbon and aquaculture wastewater. Our integrated conservation-restoration framework highlights co-benefits that are missed by separate strategies for conservation and restoration and facilitates informed decision making.

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Introduction

Coastal wetlands are among the most valuable ecosystems globally, yet they have been encroached and suffered severe degradation due to population pressure, urban expansion, and land reclamation¹⁻⁴. To counteract these detrimental impacts, numerous restoration projects have been undertaken along coastlines globally to mitigate the loss and degradation of ecological structure and functions of coastal wetlands^{5,6}. Over the past 20 years, although the Chinese mainland has witnessed a significant expansion of salt marshes, attributed to reduced human activities and intensified conservation and restoration efforts^{7,8}, the restoration achievements have not sufficiently mitigated the loss and degradation of coastal wetlands, biodiversity, and ecosystem services (ESs) along the Chinese coastline over the past decades⁹. There remains an urgent need to protect existing natural coastal wetlands whilst restoring degraded ones to ensure the sustainable development of coastal regions.

Conservation and restoration have traditionally been viewed as separate strategies for maintaining or enhancing ecosystem functioning^{10,11}. Despite having shared goals, restoration is often considered less of a priority than conservation because of its higher economic costs and uncertainties in terms of ecological outcomes¹². Increasing evidence indicates that restoration and conservation are highly interdependent and need to be integrated and coordinated to achieve cobenefits across research, practice, and policy¹³⁻¹⁷. However, prevailing coastal restoration practices often operate in isolation, focusing on site-specific successes without considering the broader ecological context^{18,19}. This fragmented implementation of restoration projects limits the potential for forming ecological networks with existing conservation areas that could enhance overall ecosystem functioning and resilience^{12,20,21}. Further, existing conflicting management strategies between protected areas and adjacent regions have exacerbated anthropogenic disturbances, and undermined restoration potential of coastal wetlands^{4,22}. For example, while protected areas may enforce strict conservation measures, adjacent lands may be subject to development pressures that degrade habitat quality and connectivity²³.

In addition, prevailing regional-scale restoration planning is rarely spatial-explicitly optimized for

site selection; site-based restoration activity often achieves limited effectiveness and fails to adequately mitigate wetland loss or the degradation of ecosystem services caused by human activities^{18,19,24}. A global meta-analysis of 621 wetland sites indicated that biological function remains on average 23%–26% lower than that at reference sites, even a century after restoration efforts¹⁸. Similarly, a meta-analysis of 1,101 wetland restoration projects in China revealed that current restoration practices generally focus on site-based success and lack in addressing coordination among individual restoration projects to collectively maximize regional ecological benefits at a larger (landscape) scale^{24–27}. These findings suggest that wetland restoration may benefit from moving beyond isolated, site-based interventions toward a regionally coordinated and spatially integrated approach^{28,29}. However, optimizing site selection under budget constraints remains a major challenge, as a successful restoration requires strategically allocating and delivering ESs across the landscape^{30–33}. In addition, there is a need to develop a methodological framework to maximize ES cobenefits by synergizing conservation and restoration priorities of coastal wetlands to ensure their resilience and sustainability.

Given budgetary and socioeconomic constraints, it is impractical to restore all damaged wetlands, making spatial prioritization essential for cost-effective resource allocation and long-term sustainability^{34,35}. Current restoration frameworks often emphasize feasibility factors, such as damage assessments, restorable potential, and water resource accessibility, while neglecting comprehensive spatial prioritization strategies^{36–38}. This oversight can lead to inefficient resource allocation, as projects may fail to target the most ecologically or strategically valuable areas. In addition, recent spatial planning approaches, such as integrated conservation–restoration planning and ecological corridor analyses have been used to identify strategic areas for conservation and restoration, they still however do not fully account for cost-effective spatial allocation^{39–41}.

Although integrated modeling frameworks have been increasingly used in quantifying multiple ESs, three critical gaps remain in their application to coastal wetland management. First, most studies treat conservation and restoration as isolated strategies, failing to synergize their interdependencies and quantify their combined cobenefits^{15,16}. Second, few models integrate coastal-specific feasibility

constraints (e.g., tidal elevation, hydrological accessibility) with ES optimization, leading to impractical spatial solutions for saltwater-freshwater transitional ecosystems^{24,42}. Third, existing frameworks are often diagnostic (assessing ES under fixed scenarios) rather than decision-oriented, lacking explicit optimization of target levels to balance ES cobenefits and costs^{12,32}. To address these gaps, we extend the systematic conservation planning framework to coastal wetlands, developing a unified optimization model that synergizes conservation and restoration under explicit feasibility and cost constraints, and identifies the target level cost-effectively maximizing ES cobenefits.

As a globally used conservation planning framework, the systematic conservation planning has increasingly been extended to prioritize wetland conservation and restoration patterns based on the principle of ecological complementarity, adequacy, representativeness, and efficiency, and in addressing hydrological connectivity of ecological futures (e.g., species, habitat/ecosystem types, ESs)^{28,43–45}. This integrated strategy can achieve co-benefits that exceed those obtained from conservation or restoration alone and performs more cost-effectively than single-action approaches^{5,13,15,46}. However, most of them focus on evaluating ecological or functional outcomes rather than developing spatially explicit, cost-constrained frameworks for joint optimization. Therefore, research that systematically integrates conservation–restoration priorities with feasibility and cost considerations remains limited. Our study builds upon that foundation by proposing an integrated decision-making framework that co-optimizes conservation and restoration patterns to maximize cobenefits of multiple ES in coastal wetlands.

In this study, we extended the systematic conservation planning-based integrated conservation and restoration framework in coastal wetlands, demonstrated by the case study in the Yellow River Delta (YRD). We identified the best solution for an integrated conservation and restoration pattern and proposed tailored management strategies to support the ecological benefits (i.e., habitat quality, carbon storage, and water purification). Our research aimed not only broadly validating the integrated conservation and restoration framework but also providing empirical support for its implementation, thus offering perspectives for integrated conservation and restoration practices. Currently, numerous conservation and restoration projects have been implemented in the coastal wetlands of the YRD, but

it is still unclear whether local-scale conservation and restoration projects can be integrated to effectively magnify and enhance multiple ESs at the regional scale^{47,48}. In this research, we specifically aimed to (1) refine a methodological framework to maximize multiple ESs cost-effectively by integrating conservation and restoration patterns for coastal wetlands, (2) explore potential synergistic cobenefits between conservation and restoration patterns, and (3) develop management strategies tailored with integrated conservation and restoration patterns to consolidate ES co-benefits.

Results

key damaged zones and potential restoration pattern

The area of coastal wetlands associated with their key ESs damaged by all types of land reclamation (i.e., key damaged zones, KDZs) was estimated at 1.9×10^5 hm² during 1976–2015, accounting for 15% of the total area of the YRD, and aquacultural fields, salt pans and cultivated land contributed for 56.6%, 24% and 14% of the total KDZs, respectively (Fig. 1a). Based on the elevational threshold intervals for vegetation survival determined by Gaussian simulation, the suitable habitats of tidal vegetation were extracted from DEM, and the potential restorable sites of estuarine wetlands preferred by salt, freshwater vegetation and mixed habitats in the YRD were identified from the KDZs (Fig. 1b), of which mixed habitats showed the least area, supporting mixed growth of both salt and freshwater vegetation. By integrating current wetlands and potential restoration, we can identify the integrated distribution pattern of the potential restoration wetland and current wetland (Fig. 1c).

The total regional habitat quality, carbon storage and water purification after restoration of the potential restoration pattern of coastal wetlands were 3.25×10^5 , 2.87×10^7 t and 2.23×10^5 t, respectively. They were enhanced by 57%, 38% and 14.58%, respectively, compared with the current. The three ESs of the coastal wetland were 1.50, 1.27 and 2.59 times higher than those in the current, contributing 77.8%, 57.46% and 52.19% to the total regional services, respectively (Fig.2).

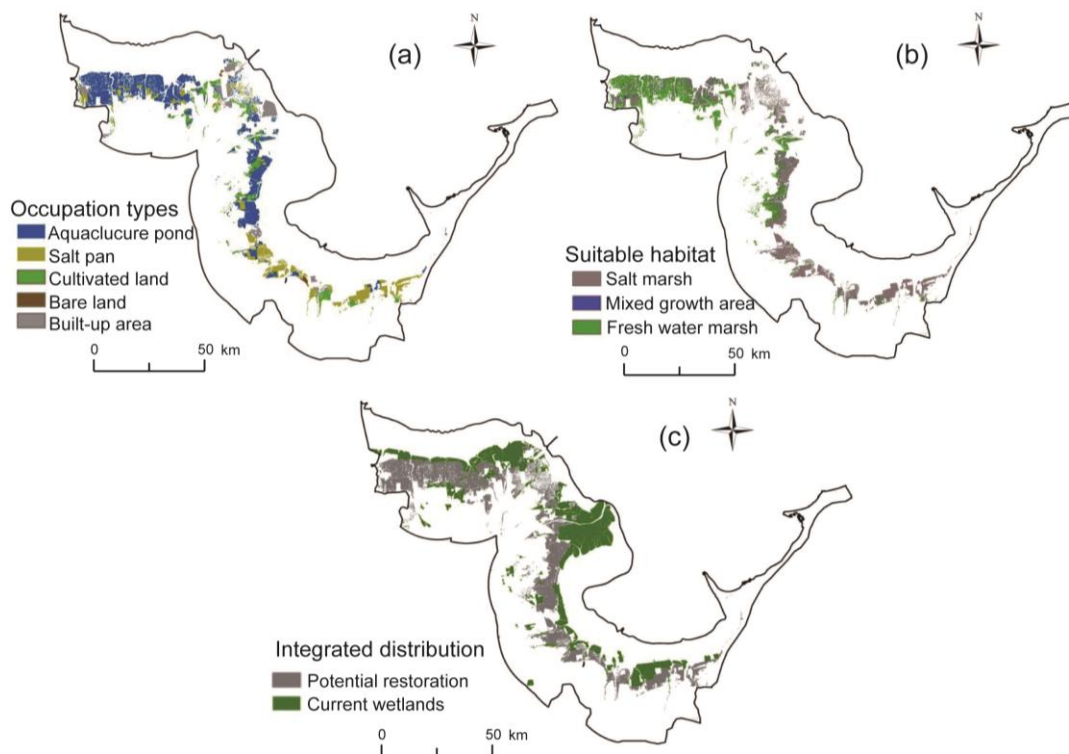


Fig. 1 Land reclamation types and potential restoration patterns based on key damaged zones of coastal wetlands in the Yellow River Delta. **a** Land reclamation types in key damaged zones, **b** suitable habitat in key damaged zones, **c** the integrated distribution pattern of potential restoration wetland and current wetland.

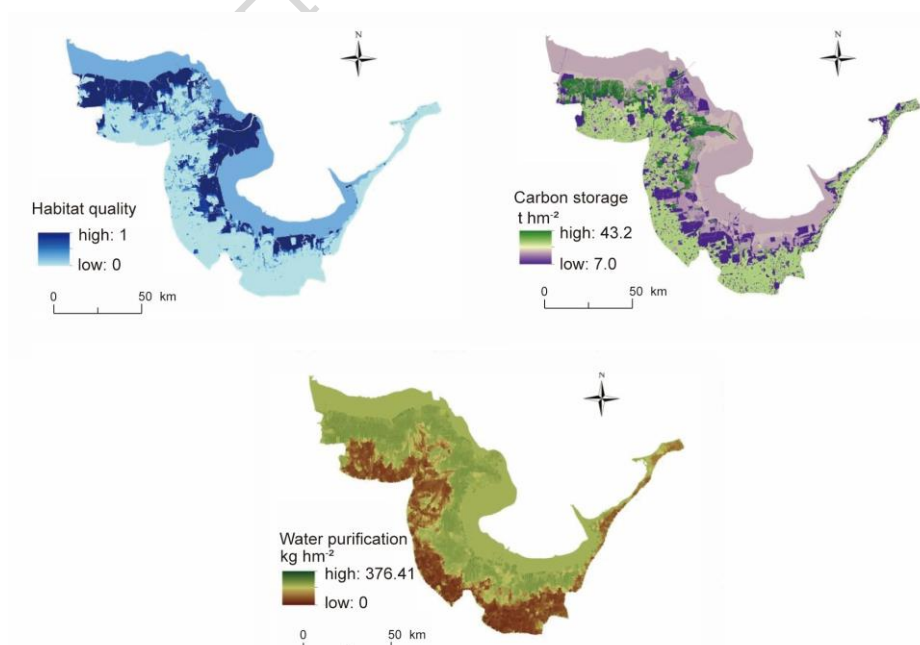


Fig. 2 Key ecosystem services spatial distribution under potential conservation and restoration patterns of the Yellow River Delta. The key ecosystem services are habitat quality (0~1), carbon storage (t hm^{-2}), and water

purification (kg hm^{-2}), respectively. This pattern represents the distribution of key functions in the Yellow River Delta, assuming that all potential restoration areas are fully restored to suitable habitats.

Optimal integrated pattern

The optimized integrated pattern showed quickly increased areas for both conservation and restoration, following with rising target levels, of which prioritized conservation areas would be dominant by far when target level $< 80\%$. Driven by a raised target level, those unprotected tidal wetlands along the coastline would increasingly be allocated for conservation priority, particularly focusing on the Binzhou (northern YRD coastline) and Laizhou (southern YRD coastline). Those natural coastal wetlands prioritized for conservation with the target levels $< 30\%$ were concentrated within the YRD National Nature Reserve (Fig. 3), indicating the high priority for natural coastal wetlands in the nature reserve to be allocated for conservation due to their greater ESs and lower conservation costs. When target levels exceed 20% , those intact tidal wetlands around Laizhou Bay would be captured and allocated for conservation priority, while there are still remnant natural wetlands unselected for conservation solutions within the nature reserve, indicating their greater irreplaceability in enhancing regional ESs and the need to be incorporated into the existing protected area as the key conservation gap in the YRD.

The aquacultural fields around the nature reserve would be selected first as restoration sites under lower target levels ($< 30\%$), and those aquacultural & salt fields distant from the nature reserve throughout tidal area of the YRD would increasingly be captured and allocated for restoration priority driven by added target level. The sharply increased area allocated for restoration with added target levels demonstrated that the more restorable sites are needed to meet the demands of enhancing regional ES even incurring higher costs (Fig. 3). Under the highest target level (90%), the demands of area allocated for restoration would exceed that for conservation (Fig. 3).

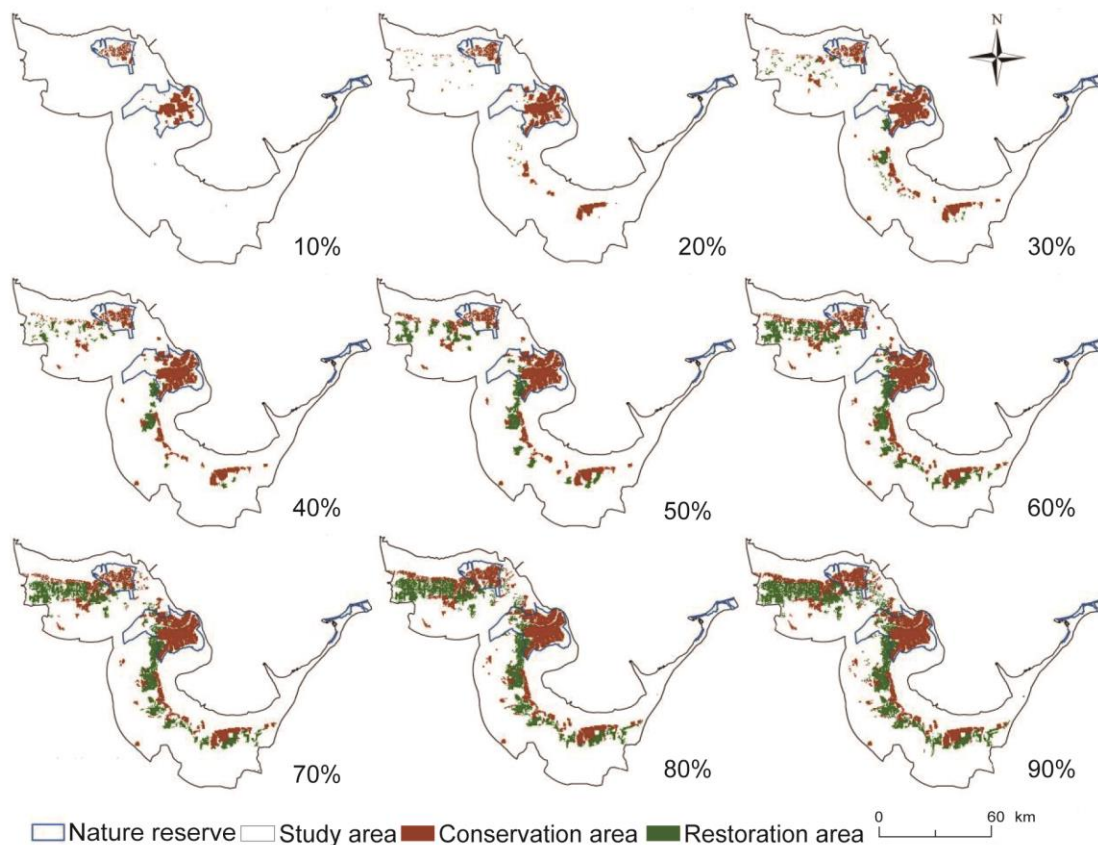


Fig. 3 Systematic spatial optimization to integrate conservation and restoration patterns for each target ratio (10%–90%) in the Yellow River Delta. For each target ratio, the figure presents the spatially optimized solution for an integrated conservation and restoration pattern, identified under minimum cost constraints via Boundary Length Modifier sensitivity analysis.

Comparing across all optimal integrated patterns under the different target levels, the cost-effective analysis revealed that the optimal pattern under the 50% target level for synergizing conservation and restoration of the coastal wetlands in the YRD could deliver the highest total ES values (RMB 4.53×10^9), exceeding 19.15% over that of existing situation (Fig.4a). Beginning with the 50% target level, the expansion rate of prioritized area for conservation area decelerated substantially, whereas restoration area demonstrated a continuous and pronounced increasing trend. By the 90% target level, the restoration area had exceeded the conservation area (Fig.4b).

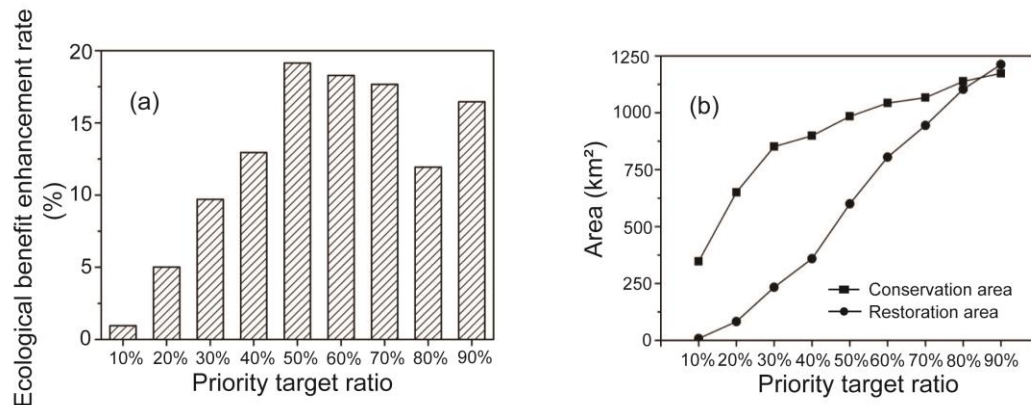


Fig. 4 Ecological benefit enhancement rate and conservation and restoration area under different target level ratios (10%–90%). **a** An ecological benefit enhancement rate is calculated by comparing the total ecosystem service value before (current baseline) and after (post-optimization) implementing the conservation-restoration pattern. **b** Area of spatially optimized solution for the integrated conservation and restoration pattern.

Management strategies for key ecosystem services

Habitat modelling revealed that all high-quality habitat patches would be almost characterized with greater ecological connectivity, in comparison with the lower quality habitats associated with poor connectivity, indicating that biological connectivity may play a key role in determining habitat quality. In the integrated optimal pattern (best solution), those well-connected intact habitats (i.e., core habitats) mainly centralize within the YRD nature reserve and along the southern shoreline of Laizhou Bay, functioning as the core habitats (feeding & breeding) particularly for those endangered waterbirds (e.g., *Grus japonensis* and some migratory shorebirds) sensitive to habitat fragmentation and disturbance in the YRD (Fig. 5). In addition, the high-quality habitat with relatively lower connectivity mostly distributes along the northern and southern coastline of the YRD, where the wetland habitat could be restored from aquaculture ponds outside the YRD nature reserve and preferred by those waterbirds less sensitive to the habitat fragmentation and disturbance (e.g., Seagull and Anatidae). Furthermore, those lower quality habitats with less biological connectedness exhibit as several isolated small patches between the core habitats, which may serve as stepping stone habitats for those migratory species.

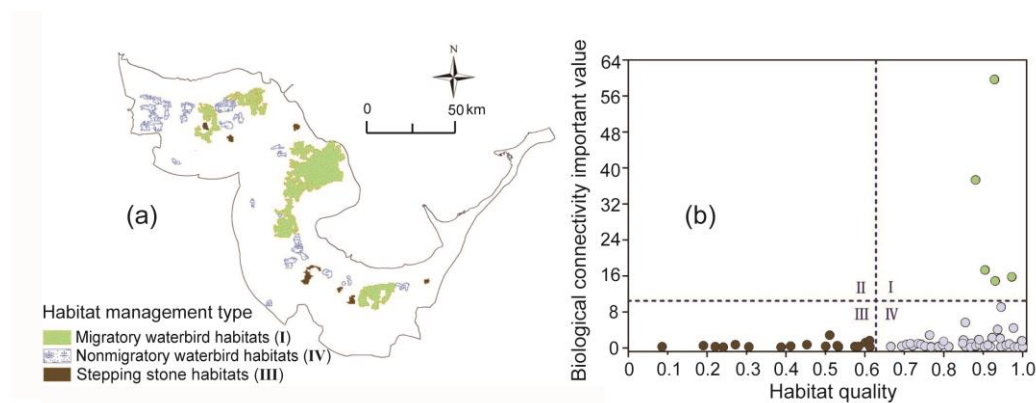


Fig. 5 The integrated biodiversity zoning management scheme and habitat quality and biological connectivity importance value zones of each wetland patch. **a** The distribution of combinations for habitat quality and connectivity importance was examined to support biodiversity-oriented management zoning in the optimal pattern under the 50% target level. **b** Zonal distribution of habitat quality and biological connectivity importance (dPC) for wetland patches. Dots represent wetland patches. Natural Breaks: dPC – 9.291; Habitat Quality – 0.6314

The carbon stock would be enhanced by 5.52×10^6 t after coastal wetland restoration within optimal integrated pattern, and the carbon budget was estimated at 5.54×10^6 t, indicating the considerably promoted capacity of carbon sequestration by the optimal integrated pattern which could transform land use of carbon source (e.g., aquacultural & salt fields, cultivated land) into carbon sink (e.g., salt marsh).

In the optimal integrated pattern, the intact natural wetlands combining with prioritized restoration area is nearly five times that of the existing aquaculture ponds, which enable complete purification of potential nitrogen and phosphorus pollutants from the aquacultural discharges. The largest purifiable patch of aquacultural pond is estimated at 1410 hm², located in Zhanhua County. Most of prioritized restorable sites are identified around the historically restored wetland patches.

Discussion

This study advances the integrated conservation-restoration framework in coastal environments. The integration of conservation and restoration efforts in the YRD represents an approach to maximizing the cobenefits of ESs in coastal wetlands. By employing a systematic conservation planning framework and leveraging the Marxan model, our study provides a strategic approach to address the complex challenges facing coastal wetlands. Specifically, it identifies priority areas for

conservation and restoration cost effectively while highlighting the needs for habitat and carbon management. These enhancements broaden the framework's applicability and provide implementable guidance for managing coastal wetlands, supporting informed decision-making under budget constraints and environmental pressures.

In the optimal integration framework, conservation and restoration compete for constrained budgets, showing both trade-offs and synergies. At lower target levels, the priority is given to conservation due to its lower costs. It is only when the selected units for conservation alone fail to meet the increased target level that the priority pattern begins to select sites for restoration. As target levels increase, restoration becomes increasingly important, even with much greater costs. During the retrieval optimization processes, the conservation and restoration patterns achieve integration by trading off and synergizing the multiple ESs against the costs (Fig. 3). This shift underscores the necessity for integrated solutions that can effectively allocate resources to maximize ecological benefits. Our results indicate that the optimal pattern for synergizing conservation and restoration in the YRD can deliver the highest total ES values under a 50% target level, exceeding the current situation by 19.15% (Fig. 4). These findings indicate that combining conservation with targeted restoration delivers superior ecological benefits by leveraging their complementarity. Conservation safeguards existing high-quality, well-connected habitats (e.g., YRD National Nature Reserve). Restoration, in turn, enhances degraded areas (e.g., aquacultural fields near Laizhou Bay) and expands ecological connectivity. Thus, the integrated configuration outperforms the hypothetical limitations of single-strategy approaches by jointly preserving existing ecosystem functions and generating new ecological gains.

The findings of this study provide actionable insights for the management and planning of coastal wetlands in the YRD. For instance, a total of 416 km² of natural wetlands identified as conservation gaps within integrated optimal pattern under best target level (50%) should be incorporated into existing conservation systems (e.g., YRD nature reserve and national park), primarily along the Laizhou Bay coastline (Fig. 6). Simultaneously, a total area of 600 km² should be allocated for restoration priority, with aquacultural ponds being the dominant potential restoration sites, followed

with cultivated land (Fig. 6). Salt marsh would be dominant restoration targets, accounting for 86.79% of the area in the optimal integrated pattern, followed by freshwater marsh (10.2%) and mixed growth wetlands (3.01%).

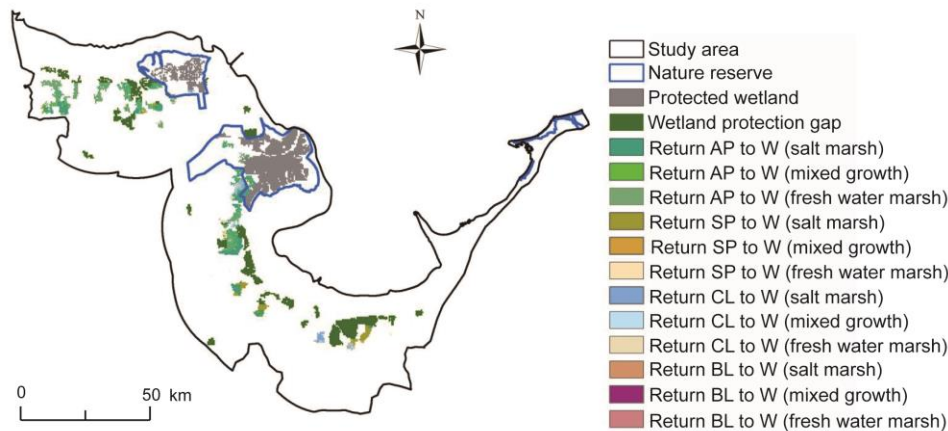


Fig. 6 Prioritized conservation and restoration areas associated with implementary measures based on the integrated optimal pattern under best target level (50%). AP: aquaculture pond; W: wetlands; SP: salt pans; CL: cultivated lands; BL: bare lands.

The management strategy should focus on enhancing habitat quality and connectivity, which are critical for preserving coastal biodiversity^{49,50}. The high-quality habitat patches identified in this study are characterized by greater ecological connectivity, indicating that biological connectivity plays a key role in determining habitat quality. This finding corroborates previous research on endangered waterbirds, which prefer suitable habitats with high connectivity⁵¹. Therefore, management efforts should prioritize the restoration of well-connected habitats to support migratory species and enhance overall biodiversity. Carbon management strategies should be developed to leverage the enhanced carbon sequestration capacity of restored wetlands. The estimated carbon budget can be used to define the upper limit of carbon emissions, thereby maintaining regional carbon balance and aligning with global efforts to mitigate climate change and promote low-carbon economies. Under the optimal integrated pattern (with 50% target level), the coastal wetland could effectively purify the aquacultural pollutant estimated at current scale due to greatly enhanced capacity of purification from prioritized restorable wetlands mostly adjacent to aquacultural ponds. With an ecological economic view, an integrated fishery-wetland hybrid scheme can be advocated and tailored to the integrated optimal

pattern, which can pursue fishery production profits whilst leverage the wetlands' water purification for pollutants from surrounding aquacultural fields.

The identified conservation-restoration priorities should be embedded into YRD National Park masterplan as “ecological control lines”, guiding the delineation of non-negotiable wetland cores and adaptive reuse zones for compatible development. While the integrated framework provides a robust scientific basis for conservation and restoration, its implementation requires addressing socio-institutional complexities. In China, wetland restoration often involves reclaiming aquaculture ponds managed by private entities, necessitating compensation mechanisms and stakeholder negotiations⁵². Fragmented governance across water, land, and environmental departments may also hinder integrated planning. Therefore, coordinated efforts among different stakeholders and policy integration are essential for the successful implementation of the proposed conservation and restoration strategies⁶.

Our integrated optimal pattern demonstrates a balanced approach that could strategically maximize ecological benefits whilst keep management costs reasonable. Although our study underscores the importance of considering multiple ESs simultaneously when designing conservation and restoration strategies, we shall address that our study design prioritized synergistic ES cobenefits rather than testing trade-offs among individual ESs, due to the YRD wetland management goal of maximizing multiple ecological functions. The “trade-offs” here refer to cost-benefit analysis across target levels, indicating that higher target levels shall require more cost but may yield decreasing the total ES values gains.

Our integrated conservation-restoration model demonstrates potential global advantages as a Nature-based Solution. Unlike traditional approaches reliant on large-scale engineering interventions (e.g., sediment diversions or barrier reconstruction), our framework optimizes the site selection of conservation and restoration actions to minimize unnecessary engineering input and associated costs while enhancing ecological outcomes such as carbon storage, habitat quality and biodiversity connectivity. By unifying conservation and restoration via ecosystem service-driven spatial trade-offs, our research offers a scalable template for identifying optimal spatial patterns for conservation and

restoration in coastal regions, where the degradation of coastal wetland threatens their key multiple ESs. Further, the research outcome directly supports Sustainable Development Goals (SDG) 14 by improving marine ecosystem health and SDG 13 by enhancing blue carbon sinks to mitigate climate change, and also advance SDG 15 by protecting critical habitats for migratory birds and endangered species^{53,54}.

Future research should build upon this work by more explicitly examining how ES distributions, ecological connectivity, and restoration feasibility interact to shape the spatial optimization outcomes. In particular, clarifying the mechanisms by which individual ES layers influence planning-unit selection probabilities would strengthen the theoretical foundation of integrated modelling. A key limitation of this study is that the transferability of the integrated framework has not yet been tested in other coastal wetland systems. Future research should evaluate its performance across different geomorphic, ecological, and management contexts to assess its generalizability and robustness. Additionally, more robust data sources and advanced modeling techniques could improve the accuracy and reliability of cost estimates and spatial prioritization. Comparative analyses with other global coastal wetland systems could provide broader insights into the applicability of the proposed framework. Finally, incorporating dynamic factors such as long-term climate change and socioeconomic activities could enhance the resilience of conservation and restoration strategies over time.

Conclusion

This study presents a comprehensive and efficient approach to integrating conservation and restoration in the YRD. By identifying priority areas and developing management strategies based on ecological and economic considerations, this research provides a valuable framework for enhancing the sustainability and resilience of coastal wetlands. Specifically, restoration areas may have higher priority even with higher costs under the premise of equal importance, underscoring the necessity for integrated solutions that can effectively allocate resources to maximize ecological benefits. The prioritized sites for coastal wetland conservation and restoration should be embedded into the YRD National Park master plan as “ecological control lines”, guiding the delineation of non-negotiable wetland cores and adaptive reuse zones for compatible development. The integrated framework

provides a robust scientific basis for conservation and restoration planning, capable of promoting the restoration of damaged wetlands and the integration of existing protection systems to improve overall ecological management. The framework constructs and optimizes multiple ecosystem service conservation and restoration patterns of coastal wetlands, identifying high-priority cross-boundary sites for protected coastal wetland and minimizing costs. Our study prioritized maximizing multiple ecosystem service co-benefits to align with the YRD wetland management goal of integrating conservation and restoration pattern. Our approach aligns with global efforts to mitigate climate change and promote low-carbon economies by enhancing blue carbon sequestration and supporting sustainable economic development. Although its transferability still requires further testing, the integrated framework based on systematic conservation planning would potentially be replicable elsewhere for coastal wetland conservation and restoration planning to mitigate ESs loss and degradation by land reclamation.

Methods

Study area

Located on the southern bank of Bohai Bay and the western bank of Laizhou Bay in China, the YRD is one of the three major estuary deltas in China with a land area of 12,300 km² (Fig. 7). The YRD is the youngest and widest coastal wetland ecosystem in the world's warm temperate zone, functioning as a key breeding and stopover site for a large number of migratory waterbirds along the East Asia-Australia migration route⁵⁵. The coastal wetlands of the YRD were designated as internationally important wetlands (i.e., Ramsar sites) in 2013 and joined the International Delta Alliance in 2015, and listed as a candidate of national park since 2024. Besides its globally significant biodiversity, the coastal wetlands of the YRD also provide enormous multiple ESs, such as blue carbon storage, habitat provisions and water purification^{42,55}. Since 1976, when the Yellow River was artificially diverted for oil field exploitation, the YRD has experienced extensive land reclamation, resulting in a substantial loss and degradation of the natural wetland ecosystem⁸. This has exacerbated the conflict between resource use and conservation of these globally significant coastal wetlands, underscoring the urgent need for a spatially explicit conservation and restoration strategy in the YRD.

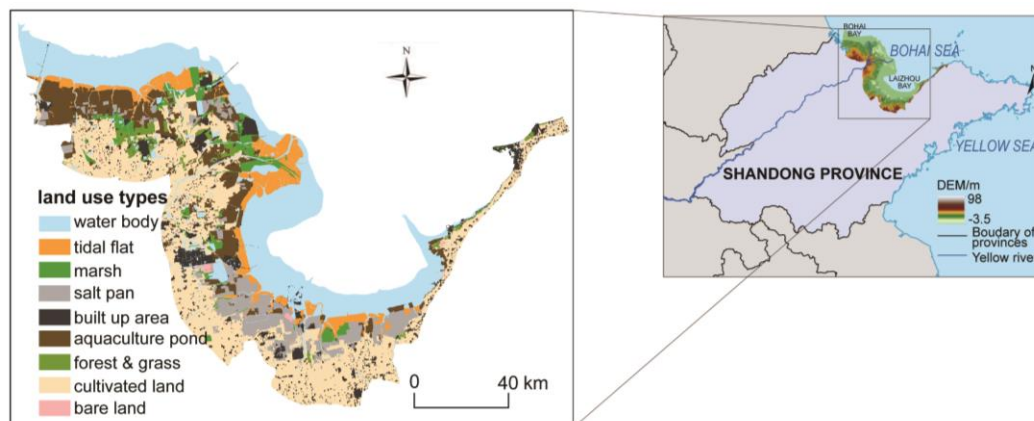


Fig. 7 Geographic location and land use map of the Yellow River Delta.

Methodological framework and data source

As a mainstream spatial planning framework for achieving conservation goals under limited funds^{56,57}, the systematic conservation planning and its decision support modelling tool-Marxan⁵⁸ were used to explore spatial solutions (i.e., optimal integrated conservation and restoration sites) for coastal wetland management at different target levels (i.e., mitigated proportions for the loss and degradation of ESs of coastal wetlands), considering their potential to provide key multiple ESs (i.e., habitat quality, carbon storage, water purification). The Marxan can use a simulated annealing algorithm to identify multiple alternative sets of planning units that meet a set of quantitative conservation targets at a minimum cost⁵⁹.

We proposed a methodological framework for identifying the optimal target levels that could effectively mitigate losses and enhance detrimental ESs in a cost-efficient manner by integrated conservation-restoration patterns (Fig. 8), which consists following steps: 1) Identifying KDZs based on their damages in ecosystem structure and function, and assessing their restoration potential and feasibility; 2) Exploring spatial systematic optimization by using Marxan from potential conservation and restoration patterns, and identifying optimal integrated conservation and restoration pattern (i.e., best solution) based on cost-effective analysis across different target level (10%-90%); 3) Proposing and developing management strategies in addressing key ESs tailored with the optimal pattern for the best target level.

The land-use/land cover dataset (1976–2015) in the YRD (with a spatial resolution of 30 m, an overall classification accuracy above 82% (Kappa = 0.80)) produced by the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences was used to identify KDZs, suitable habitats for *Suaeda salsa* and *Phragmites australis*, and support ES simulations⁶⁰. The DEM data were obtained from the Geospatial Data Cloud (<https://www.gscloud.cn/>). Based on the 90 m resolution SRTM (Shuttle Radar Topography Mission) data referenced to the EGM96 geoid, they were processed using a grid DEM–contour line–triangulated irregular network transformation for downscaling. This procedure enhanced vertical precision from 1 m to 0.5 m for application in vegetation habitat suitability simulations.

We provide the full parameters and descriptions for the ES simulations (including carbon density, threat information, habitat sensitivity, and retention efficiency) in the supplementary materials (Supplementary Table 1–5), based on established methodologies from previous studies⁴¹. In addition, the total value of ESs (i.e., the monetized ES value) was employed to estimate the ecological gains provided by optimal integrated patterns under different target levels, and quantified in terms of their key supporting, regulating, provisioning, and cultural functions^{61,62} (Supplementary Table 6).

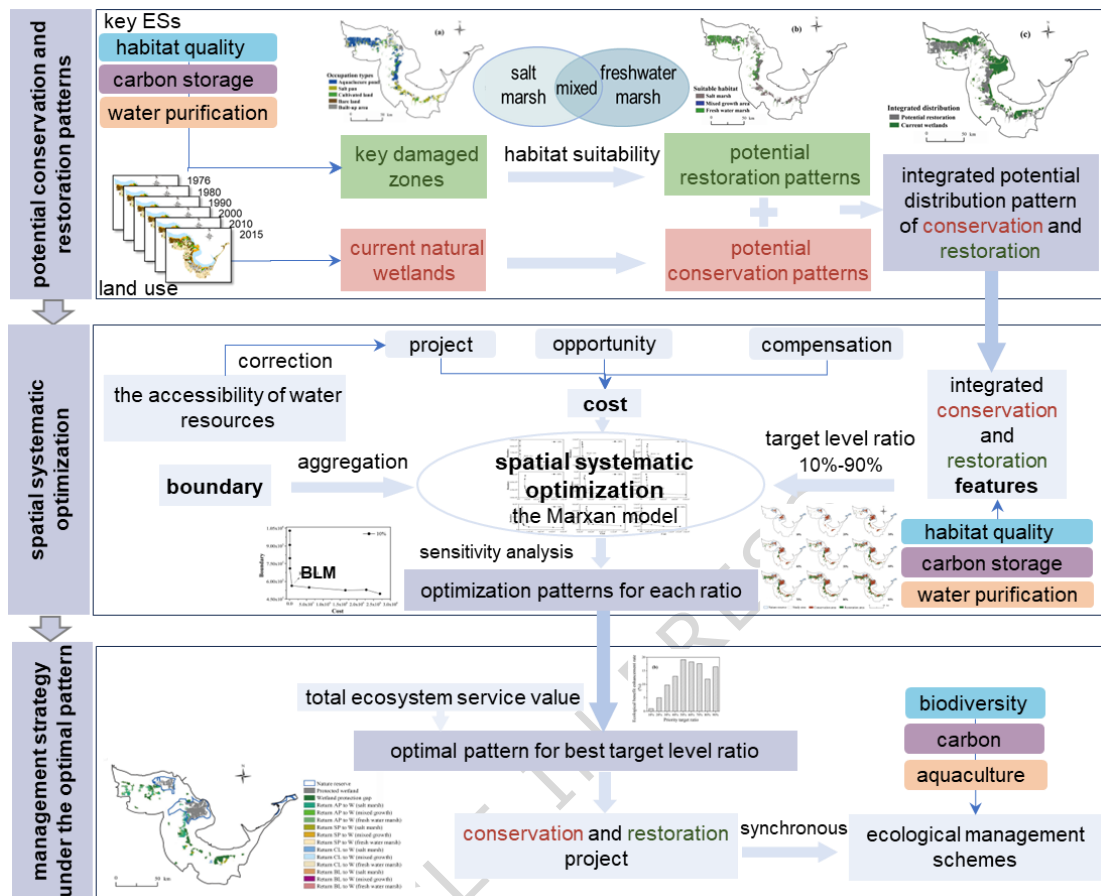


Fig. 8 The methodological framework and roadmap to integrate conservation and restoration for coastal wetlands in the Yellow River Delta. ESs means ecosystem services. BLM means Boundary Length Modifier.

Identifying potential conservation and restoration patterns

The KDZs, representing "shortcomings" in the structure and function of the current coastal wetland ecosystem, indicate areas that "should be restored." It is also necessary to further identify suitable areas for restoration, i.e., the potential restoration pattern⁶³. The KDZs were used to identify potential restoration sites, which were then assessed and screened based on restoration potential and feasibility (e.g., hydrological accessibility).

(1) KDZs of the ecosystem

The natural wetlands extracted from current land use types was recognized as potential protected area, while the identification of potential areas is the key to determine the pattern of potential conservation and restoration. In our study, the KDZs were delineated as the sites that suffer damages

to both ecosystem structure (i.e., land use) and ecological function (i.e., key ESs). Thus, KDZs were identified based on the intersection of (i) ecosystem structure degradation (defined as the area experiencing loss in area of natural wetlands due to conversion to human-dominated land uses); and (ii) ecosystem function degradation (defined as the area experiencing loss in provisions of the ESs).

Three key ESs of coastal wetlands in the YRD, i.e., carbon storage, habitat quality, and water purification were addresses and included as the targets for optimizing integrated conservation and restoration pattern by using InVEST model. The input datasets consisted primarily of land-use/land-cover categories and those biophysical parameters for habitat suitability, carbon densities and nutrient export, and were sourced from previous studies^{41,42} (Supplementary Table 1–5).

(2) Potential restoration pattern

The *Suaeda salsa* and *Phragmites australis* were selected as the targeted vegetation for restoration of coastal wetlands in our research, as they are both dominant tidal vegetation and can be used as indicator species for the tidal habitats (salt and freshwater marsh)⁶⁴. Previous research has revealed that tidal elevation determines those key habitat factors such as hydrological and salinity conditions and substantially affect growth and distribution pattern of tidal vegetation⁶⁵⁻⁶⁷. Therefore, we used tidal elevation as the key habitat parameter to spatial-explicitly model potential habitats of *Suaeda salsa* and *Phragmites australis* based on Gaussian model. The elevation value for each vegetation type was extracted from the land-use and DEM data (interpolated with vertical accuracy 0.5 m), the vegetation habitat suitability was assessed by counting the vegetation distribution frequency in different elevation segments. The modelling results revealed a highly significant ($P < 0.001$) Gaussian relationship between the distribution frequencies and elevation for both salt marsh (*Suaeda salsa*) and freshwater marsh (*Phragmites australis*) vegetation, and the potential suitable habitats after restoration could be delineated based on their modelling elevation gradients for salt (-0.59–1.18m), freshwater (1.45–3.02m) and mixed growth marsh (1.18–1.45m, mixed growth of salt and freshwater vegetation) (Fig. 9). This result is fairly consistent with the elevation range suitable for wetland vegetation in the YRD reported by previous research⁶⁸. Finally, the potential restorable sites were refined by extracting the potential suitable habitats from the KDZs.

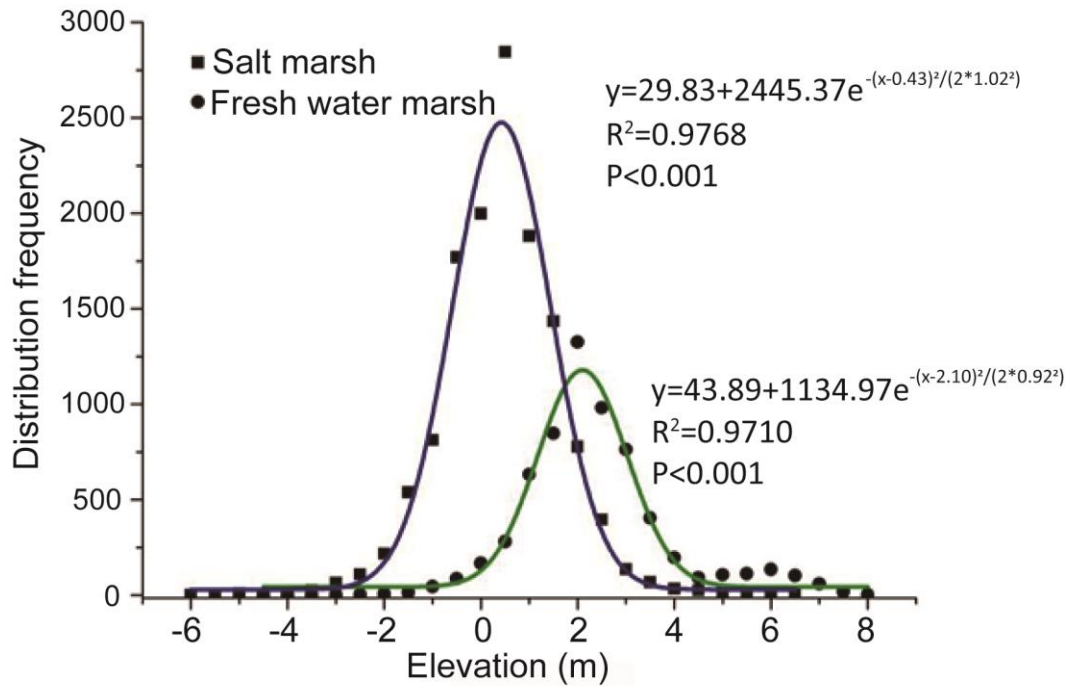


Fig. 9 Gaussian fit of the frequency of salt marsh vegetation and freshwater marsh vegetation distributions with elevation. Dots represent number of sampling points under each elevation from which elevation values for salt marsh and fresh water marsh were extracted using land-use and DEM data.

Prioritizing cost-effective areas for integrating conservation and restoration

The spatial optimization software-Marxan was utilized to determine a cost-effective selection of conservation and restoration sites. This approach addresses the "minimum set problem" by achieving user-defined objectives at the lowest possible cost using a simulated annealing algorithm. The spatial optimization was implemented using single-zone Marxan. To facilitate the modelling, the planning units were created with 500m × 500m squared size, and the conservation-restoration objects were the three key ESs under the potential conservation and restoration patterns identified earlier. Additionally, for each planning unit in both objectives, we calculated the management cost of conservation and restoration interventions. Our optimization goal for the conservation and restoration of coastal wetlands in the YRD can be expressed as:

$$objective = \sum_{PUS} Cost + SPF \times \sum_{PUS-SPS} ESSPenalty + BLM \times \sum_{PUS} Boundary \quad (1)$$

where objective refers to Marxan's minimum-set formulation, which minimizes total management cost

while meeting predefined ecosystem service representation targets. $\sum_{PUS} Cost$ is the sum of the conservation or restoration costs of all the planning units (*PUs*). Conservation and restoration costs were treated as distinct and spatially variable inputs. Conservation costs only include opportunity costs, while restoration costs related to land reclamation, hydrological engineering and revegetation, varying with hydrological accessibility. These spatially explicit cost layers (Supplementary Figure 1) were input into Marxan to ensure cost-minimization in optimization. *SPF* is the species penalty factor for conservation features or species (*SPs*) in Marxan, ESs were used as surrogates for *SPs* (conservation and restoration features) in our research, and a uniform *SPF* of 1 was applied to the three key ESs. $\sum_{PUS-SPS} ESSPenalty$ is the sum of ES functions of all the *PUs* and types of *SPs*. *Boundary* length indicates the degree of aggregation in the landscape pattern, and BLM (Boundary Length Modifier) is used to adjust this aggregation. A critical design of the model is BLM, which balances spatial aggregation (to enhance habitat connectivity) and cost efficiency. Sensitivity analysis of BLM (values: 0.000001–10,000) identified inflection points where the trade-off between aggregation and cost was optimized (Supplementary Figure 2), ensuring the selected pattern supports both ES maximization and ecological connectivity for each target level (10–90%).

For the proportional conservation or restoration optimization target scenario (i.e., target level), we initially set a 10% baseline target level for each key ES in the YRD, incrementally increasing it by 10% up to 90% for individual services. For example, assuming that the total values for habitat quality, carbon storage, and water purification in the potential integrated conservation and restoration pattern are 100, 200 t, and 300 t respectively, and the conservation and restoration target is set at 20%, this means that the ecological functions in optimization pattern will certainly exceed 20, 40 t, and 60 t respectively. For each level, Marxan ran 100 repetitions (1,000,000 iterations each) to generate alternative spatial patterns. The Marxan-based integrating conservation and restoration aimed to identify the minimum-cost configuration of planning units that simultaneously meet predefined target levels for maintaining the three key ecosystem services, aligning with Marxan's minimum-set optimization objective.

These different target level settings do not assume trade-offs between ESs; instead, they serve as a sensitivity gradient to test how varying ES improvement demands influence cost-benefit outcomes.

The optimization pattern was identified under minimum cost constraints (through BLM sensitivity analysis between cost and boundary) at each target level, and the best target level was determined under which the optimal pattern could achieve the highest total value of ESs with the lowest costs. To evaluate the ecological benefits under different integrated conservation restoration patterns, we examined how the total value of ESs changed across a gradient of ES target levels (10–90%). The ecological benefit enhancement rate was determined by comparing the monetary total value of ESs before (2015) and after (post-optimization) implementing conservation-restoration patterns. By comparing these frameworks with existing protected areas, we can identify conservation gaps and prioritize sites for restoration, ensuring targeted and efficient conservation and restoration efforts.

Conservation and restoration costs

The costs of coastal wetland conservation and restoration in the YRD incorporated the opportunity costs, compensation costs and engineering costs, which was calculated as:

$$Cost = \sum_{pu} Cost_c + \sum_{pu} Cost_o + \sum_{pu} Cost_p \quad (2)$$

where $Cost$ refers to the total costs of conservation and restoration for coastal wetlands in the YRD; $Cost_c$ is the compensation payment for returning cultivated land or aquacultural fields to natural tidal wetlands, which were set equally at 178,900 RMB hm^{-2} for aquacultural fields and 15,000 RMB hm^{-2} for cultivated land according to the field survey, market price, related policy and governmental reports; $Cost_o$ is the opportunity costs both for conservation and restoration equal to the potential economic income that the government gives up in the paid leasing of natural wetlands for aquaculture, and was estimated at 6,000 RMB hm^{-2} based on the reports from Department of Ocean and Fisheries of Shandong Province; $Cost_p$ is the cost of project engineering for restoration and was set at 1000 RMB hm^{-2} , referred by the average cost of stand protection in nature reserves in China⁶⁹.

In addition, hydrological accessibility needs to be considered in the $Cost_p$, which determine the feasibility and socioeconomic costs of restoration project⁷⁰. The inclusion of water intake points in the cost adjustment function reflects their dual role in coastal wetland restoration: Ecologically, they are the primary water source for maintaining wetland vegetation and functions (avoiding

desiccation/salinity imbalance); Economically, greater distance from intake points increases engineering complexity (e.g., building pumping stations, long channels) and costs⁷¹⁻⁷³. Therefore, the SHRD model was used to calculate the hydrological accessibility⁷⁴ based on the assumption that each grid acquires water resource from the nearest water intake point, and thereby assessing the regional water resources accessibility. The calculation formula is as follows:

$$P_i = \text{Exp}(-|C_1|S_i - |C_2|H_i + |C_3|R_i - |C_4|D_i) \quad (3)$$

where P_i is hydrological accessibility of wetland restoration planning unit i with a value between (0–1), greater value indicates better water resource accessibility and vice versa; S_i is the slope of restoration site i , H_i is the elevation deviation between restoration site i and its nearest water intake points (m), R_i is the subcatchment area of restoration planning unit i (hm^2), and D_i is the minimum Euclidean distance between restoration planning unit i and their nearest water intake points (m); C_1 – C_4 denote regional fitting coefficients, which integrated into the hydrological accessibility equation to create assessment model for potential restoration sites. Using the geometrical interval method, the four factors were each divided into 11 levels, corresponding to hydrological accessibility ranging from 0 to 1 (with an interval of 0.1). After normalization by range scaling, the dimensionless grade values of the factors were used to determine C_1 – C_4 with the grade of water resource accessibility as the dependent variable and the grade values of different factors as the independent variables (Supplementary Figure 3). Finally, accessibility of water resources to the potential restoration area was used as a correction factor for the $Cost_p$:

$$Cost_p = \frac{Cost_{ct} \times \bar{P}}{P_i} \quad (4)$$

where $Cost_p$ is the rectified engineering costs considering hydrological accessibility; \bar{P} is the average value of hydrological accessibility for the entire study area (i.e., the YRD), P_i is the value of hydrological accessibility for planning unit i , a higher score indicates that the area's topographic, hydrological, and spatial conditions are more favorable for water conveyance, and thus, the required engineering difficulty and cost are lower. $Cost_{ct}$ is the direct engineering cost before rectification. The total cost for each planning unit was calculated by adding its cost of conservation and restoration

(Supplementary Figure 2).

Management of key ecosystem services

Habitat fragmentation reduces the migration success of organisms and increases mortality, and genetic diversity is significantly reduced⁷⁵, and understanding the biological connectivity between wetland habitat patches is critical to ensuring that species and ecosystem functions are effectively conserved⁷⁶. From the perspective of carbon management, coastal wetland restoration projects involve the transformation of carbon sinks and sources; thus, how the system-optimized coastal wetland pattern contributes to the regional carbon balance and whether other adjustments need to be made to maintain regional low-carbon development need to be clarified.

The biodiversity connectivity importance values of the patches in the coastal wetlands of the YRD under the best solution for system optimization were calculated using the Conefor Sensinode 2.6 model⁷⁷. Waterbirds are considered important species in characterizing biological connectivity among coastal wetland patches⁷⁸; thus, in line with habitat quality, patch connectivity was assessed using waterbirds as the representative taxa. The dispersal range of birds is at the kilometer level, ranging from 1000–3000⁷⁹, and more than 92% of waterbirds in the YRD are migratory with strong flight ability⁸⁰. Accordingly, 3000 m was adopted as the maximum dispersal threshold for constructing the connectivity graph. Euclidean distances among patch centroids were converted into connection probabilities using an exponential decay function, and the resulting node and link files were imported into Conefor to compute the delta Probability of Connectivity (dPC), which quantifies each patch's contribution to maintaining overall landscape connectivity. The derived dPC values were then assigned to individual planning units as their biodiversity connectivity importance. Based on both habitat quality and connectivity importance, each patch was independently classified into high or low levels using the natural break method, and the distribution of the four resulting combinations was examined to support biodiversity-oriented management zoning.

The carbon budget was assessed under the optimal integrated pattern using carbon emission coefficient method, which could provide evidenced-based management thresholds for controlling

carbon emissions to maintain regional carbon balance. The carbon sequestration and emission were calculated as:

$$IC = \Delta A - \Delta E = (\sum S_{ai} - \sum S_{bj}) - (\sum T_{ai} \times \lambda_{ai} - \sum T_{bj} \times \lambda_{bj}) \quad (5)$$

where ΔA is the net change in the carbon sink under optimal integrated pattern; ΔE is the net change in carbon emissions under optimal integrated pattern; S_{ai} and S_{bj} represent the carbon storage of patches under land use type i (after integrated optimization) and land use j (before integrated optimization), respectively; T and λ represent the area of land use type and carbon emission coefficient. The carbon emission coefficients for different land use types were referred by the previous relevant research⁸¹.

This study focused on the removal of aquaculture pollutants (nitrogen and phosphorus) by restored coastal wetland habitat patches for water purification. We applied the "aquaculture and wetlands" integrated management scheme to estimate the maximum aquaculture area that can be supported by the purification capacity of coastal wetlands (Eq. 6).

$$S_m = \frac{P_w}{Q_m \times E_m + A} \quad (6)$$

where S_m is the largest farming area that can be used for the "aquacultural & wetlands" eco-economic composite mode; P_w is the purification amount of nitrogen and phosphorus pollutants in natural wetlands; Q_m is the yield per unit area of aquaculture production; E_m is blowdown coefficient (g kg^{-1}), and refers to the amount of pollutants directly discharged into water bodies in the amount of pollutants generated by aquaculture production per kilogram of aquatic products under normal aquaculture production conditions; A is atmospheric nitrogen and phosphorus deposition.

Table 1 The average aquaculture yield and pollutant discharge coefficient of each county in the Yellow River Delta

Parameters	Counties in the Yellow River Delta						
	Zhanhua	Lijin	Kenli	Guangrao	Shouguang	Changyi	Laizhou
Q_m (t hm^{-2})	1.25	0.48	0.70	0.67	4.51	15.57	42.34
E_m (g kg^{-1})	1.31	0.29	0.08	0.24	0.24	1.31	1.03

Notes: Q_m is the yield per unit area of aquaculture production; E_m is blowdown coefficient (g kg^{-1});

Data source “China Pollution Source Census: Manual of production and discharge coefficient of aquaculture pollution sources”

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Author Contributions

XW.L., BS.C., and TT.M. conceived the study. LH.Z. and X.L. drafted the initial manuscript and conducted formal analysis. TT.M. and LH.Z. developed the methodology and prepared all figures. TT.M. curated the data. XW.L., LH.Z., and WH.G. supervised the project and acquired funding. XW.L., LH.Z., X.L., and DW.W. critically reviewed the manuscript and provided commentary or revisions.

Data availability

The dataset supporting this study is publicly available on Zenodo (<https://doi.org/10.5281/zenodo.18634553>), including key ecosystem services raster layers (carbon storage, habitat quality, and water purification) under potential conservation and restoration patterns and the complete Marxan v2.43 input files and parameter settings.

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Competing interests

The authors declare that they have no competing interests.

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Figure captions

Fig. 1 Land reclamation types and potential restoration patterns based on key damaged zones of coastal wetlands in the Yellow River Delta. **a** Land reclamation types in key damaged zones, **b** suitable habitat in key damaged zones, **c** the integrated distribution pattern of potential restoration wetland and current wetland.

Fig. 2 Key ecosystem services spatial distribution under potential conservation and restoration patterns of the Yellow River Delta. The key ecosystem services are habitat quality (0~1), carbon storage ($t\text{ hm}^{-2}$), and water purification ($kg\text{ hm}^{-2}$), respectively. This pattern represents the distribution of key functions in the Yellow River Delta, assuming that all potential restoration areas are fully restored to suitable habitats.

Fig. 3 Systematic spatial optimization to integrate conservation and restoration patterns for each target ratio (10%–90%) in the Yellow River Delta. For each target ratio, the figure presents the spatially optimized solution for an integrated conservation and restoration pattern, identified under minimum cost constraints via Boundary Length Modifier sensitivity analysis.

Fig. 4 Ecological benefit enhancement rate and conservation and restoration area under different target level ratios (10%–90%). **a** An ecological benefit enhancement rate is calculated by comparing the total ecosystem service value before (current baseline) and after (post-optimization) implementing the conservation-restoration pattern. **b** Area of spatially optimized solution for the integrated conservation and restoration pattern.

Fig. 5 The integrated biodiversity zoning management scheme and habitat quality and biological connectivity importance value zones of each wetland patch. **a** The distribution of combinations for habitat quality and connectivity importance was examined to support biodiversity-oriented management zoning in the optimal pattern under the 50% target level. **b** Zonal distribution of habitat quality and biological connectivity importance (dPC) for wetland patches. Dots represent wetland patches. Natural Breaks: dPC – 9.291; Habitat Quality – 0.6314

Fig. 6 Prioritized conservation and restoration areas associated with complementary measures based on the integrated optimal pattern under best target level (50%). AP: aquaculture pond; W: wetlands; SP: salt pans; CL: cultivated lands; BL: bare lands.

Fig. 7 Geographic location and land use map of the Yellow River Delta.

Fig. 8 The methodological framework and roadmap to integrate conservation and restoration for coastal wetlands in the Yellow River Delta. ESs means ecosystem services. BLM means Boundary Length Modifier.

Fig. 9 Gaussian fit of the frequency of salt marsh vegetation and freshwater marsh vegetation distributions with elevation. Dots represent number of sampling points under each elevation from which elevation values for salt marsh and fresh water marsh were extracted using land-use and DEM data.

Tables

Table 1 The average aquaculture yield and pollutant discharge coefficient of each county in the Yellow River Delta

Parameters	Counties in the Yellow River Delta						
	Zhanhua	Lijin	Kenli	Guangrao	Shouguang	Changyi	Laizhou
Q_m (t hm ⁻²)	1.25	0.48	0.70	0.67	4.51	15.57	42.34
E_m (g kg ⁻¹)	1.31	0.29	0.08	0.24	0.24	1.31	1.03

Notes: Q_m is the yield per unit area of aquaculture production; E_m is blowdown coefficient (g kg⁻¹); Data source "China Pollution Source Census: Manual of production and discharge coefficient of aquaculture pollution sources"

Editorial summary:

Integrated optimisation of conservation and restoration in the coastal wetlands of the Yellow River Delta can mitigate up to half of historical losses of key ecosystem services and enhance ecosystem service value by almost 20%, according to analyses using spatial optimisation modelling.

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