Handbook of Ecosystem Restoration for Coastal Hazard Mitigation: Oyster Reefs

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Organizations and Personnel

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INTRODUCTION

Natural disasters are among the most pressing global challenges facing humanity today. To effectively address their severe impacts, approaches such as Nature-based Solutions (NbS) and Ecosystem-based Disaster Risk Reduction (Eco-DRR) have gained significant global attention. These strategies aim to leverage ecosystem services for disaster mitigation through the protection, restoration, and sustainable management of ecosystems, ultimately ensuring sustainable and resilient socio-economic development. These approaches are highly aligned with China's vision of ecological civilization and its modern principles of disaster prevention and mitigation.

In coastal areas, ecosystems such as salt marshes, oyster reefs, sandy shores, and seagrass beds serve as natural buffers, protecting against tides and waves while reinforcing embankments and safeguarding shorelines. These ecosystems act as "guardians of the sea," playing a crucial role in mitigating the risks of marine disasters. Through the ecological protection and restoration of coastal zones, the disaster mitigation functions of these ecosystems can be fully realized, enhancing the ability of coastal areas to withstand typhoons, storm surges, and other marine hazards. To guide practical work in this field, the Ministry of Natural Resources has launched a series of handbooks on coastal ecosystem restoration. These handbooks aim to integrate ecological benefits with marine hazard mitigation, focusing on the restoration of coastal salt marshes, oyster reefs, sandy shores, and seagrass beds. They offer detailed guidance on ecological baseline surveys, problem diagnosis, restoration objectives, intervention measures, and the entire chain of technical steps, including monitoring, evaluation, and adaptive management. Emphasizing science popularisation, practicality, and operability, the handbooks are concise and well-illustrated, providing valuable technical support for the scientific implementation of ecological disaster mitigation and restoration in coastal areas.

This series of handbooks has been developed with support from the Ministry of Finance and the International Union for Conservation of Nature (IUCN), to whom we express our sincere gratitude. We also extend our appreciation to the practitioners and experts dedicated to coastal zone ecological disaster mitigation and restoration.

Due to the limited time and resources available for the preparation of these handbooks, there may be unavoidable shortcomings. We welcome your feedback and suggestions for improvement.

CONTENTS

1.Scope of Application

This handbook delineates the principles, technical processes, baseline surveys, degradation diagnostics, restoration goals, restoration plan design, restoration measures, follow-up monitoring, effect evaluation, and adaptive management for the ecological restoration of oyster reefs.

This handbook is applicable to the ecological restoration of degraded oyster reefs in coastal and estuarine areas. The restoration targets include oyster reefs that are currently degrading and areas where oyster reefs historically existed but are now nearly extinct.

2.Terms and Definitions

The following terms and definitions apply to this handbook.

(1) Oyster Reef

An aggregate formed by living oysters and dead oyster shells.

(2) Oyster Reef Ecosystem

An interactive whole formed by organisms inhabiting the oyster reef and their environment.

(3) Control Area

An area selected with similar natural conditions to the restoration area but at an appropriate distance, used to analyze and evaluate the effectiveness of ecological restoration.

(4) Reference System

A reference system constituted by specific values of key indicators reflecting ecosystem characteristics, capable of indicating the quality of the ecosystem at a certain stage.

(5) Adaptive Management of Ecological Restoration

An ecological management approah that evaluates the achievement of restoration goals and the effectiveness of technical measures based on monitoring results of the restored ecosystem, continuously testing and adjusting restoration management decisions to promote positive ecosystem development.

3.Restoration Principles

The ecological restoration of oyster reefs should adhere to the following principles:

Problem-oriented, site-specific approach. Identify ecological issues scientifically and accurately, analyze the causes of ecosystem degradation, and justify the necessity of ecological restoration thoroughly. Base restoration on ecological baselines and natural endowments, considering factors such as technology, time, funding, and ecological impacts to develop site-specific categorized measures.

Natural recovery as primary, artificial restoration as supplementary. Follow the inherent mechanisms and succession laws of natural ecosystems to maintain ecosystem diversity and connectivity. Emphasize the protection of natural oyster reefs, prioritizing the restoration of degraded oyster reefs. Take full advantage of the natural recovery capacity of oyster reef ecosystems to minimize human interference; apply artificially assisted measures only when natural recovery is unattainable to promote self-regulation of the oyster reef ecosystem.

Holistic planning and steady progress. Ensure that restoration projects comply with regional development, territorial spatial planning, and marine, island, and land-use regulations to prevent damage to other important wetlands and impacts on navigational channels and other purposes resulting from the ecological restoration of oyster reefs. Consider the spatial and systematic nature, as well as the temporal continuity, of ecological restoration activities. Implement restoration in steps and phases, and conduct comprehensive supervision, ecological environment monitoring, and adaptive management throughout the process.

Reasonable and economical with risks manageable. Adopt economically viable restoration methods, technologies, and materials while ensuring restoration effectiveness. Fully consider the interaction between ecological restoration activities and adjacent areas, focusing on the livelihoods and benefits of nearby communities, and avoid using measures that may have unpredictable adverse effects on the restoration area or surrounding areas.

4.Overall Technical Process

The ecological restoration of oyster reefs comprises several key stages, including baseline surveys, degradation diagnosis, setting restoration goals, determining restoration methods, preparing restoration plans, implementing restoration projects, monitoring, evaluating effectiveness, and adaptive management. The project implementation process is outlined as follows:

(1) Based on baseline surveys, understand the current ecological status of degraded oyster reefs and their surrounding areas, assess the degree of degradation of the oyster reef ecosystem, analyze the manifestations and causes of regional ecological issues, and identify the core factors contributing to ecosystem damage in the area;

(2) Conduct necessity and feasibility analysis of the restoration project based on the baseline survey and the analysis of oyster reef degradation causes;

(3) Establish a reference system, and develop medium- and long-term goals for ecological restoration focusing on enhancing the dominant functions of the oyster reef ecosystem, eliminating stress factors, and optimizing the regional ecological landscape. Determine the ecological restoration methods;

(4) Prepare plans based on the conclusions of ecological degradation analysis and restoration goals, specifying detailed restoration content and technical measures, and clarifying short-term specific goals of the restoration project;

(5) Carry out project approval, bidding, and other procedures in accordance with relevant administrative requirements. Implement restoration project construction based on the plan and design documents. Conduct synchronous ecological environment monitoring during construction;

(6) Continuously conduct post-restoration monitoring and evaluate restoration effectiveness in phases. Identify problems and risks in the ecological restoration process against the restoration goals, adjust and correct timely, and implement ecosystem-based adaptive management of ecological restoration.

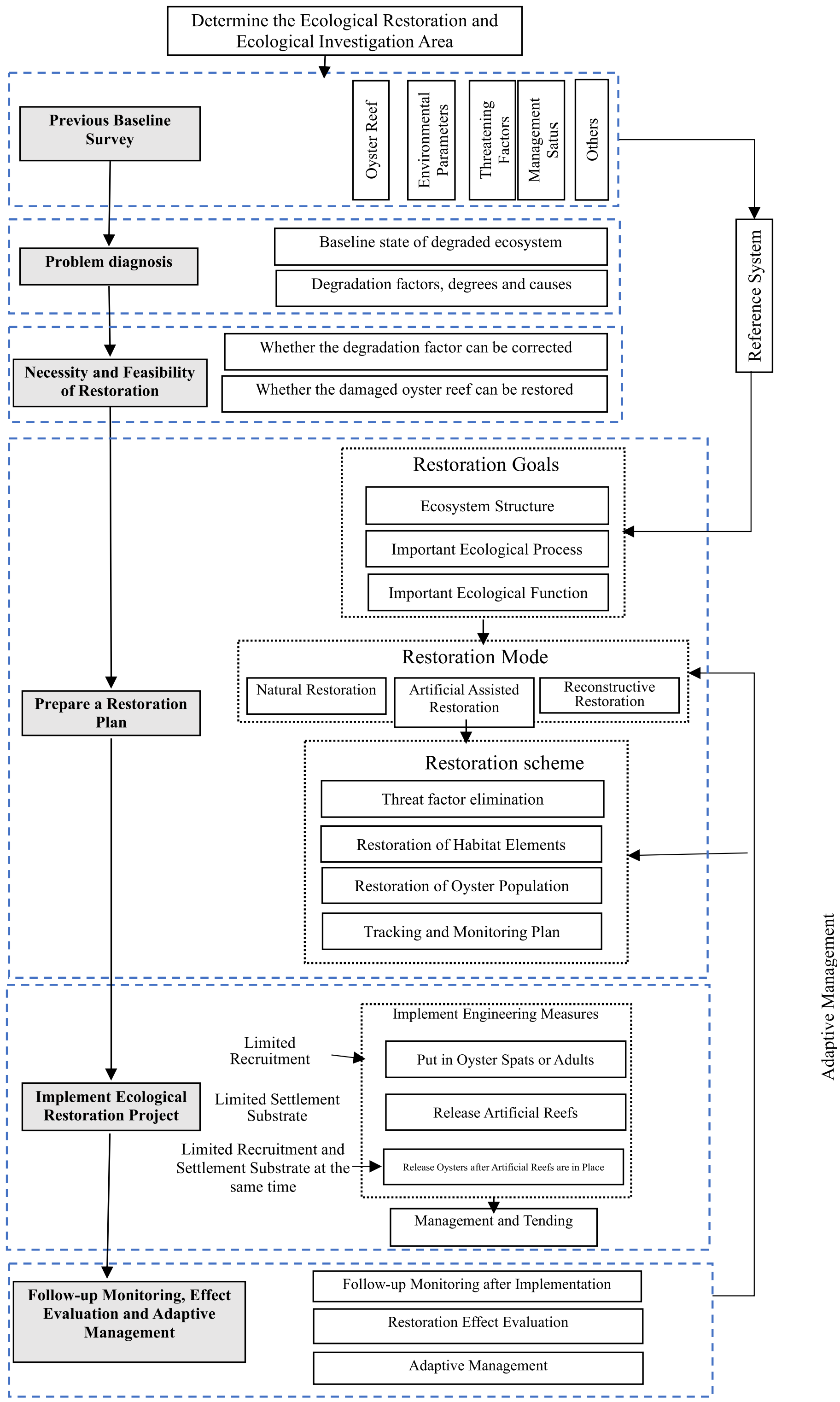


Fig.1 Flow chart of Coastal Oyster Reef Ecosystem Restoration for the Co-benefits of Ecological Significance and Marine Hazard Mitigation

5.Baseline Survey

5.1 Survey Objectives

The objective of the ecological baseline survey is to assess the current status of the oyster reef ecosystem and evaluate the historical distribution of oyster reefs in the area. This serves as the foundation for analyzing the extent of oyster reef degradation, establishing restoration goals, selecting restoration methods, and devising ecological restoration plans. Additionally, it provides comparative data to evaluate the effectiveness of oyster reef restoration efforts.

5.2 Survey Content and Methods

5.2.1 Survey Area

For projects with a clearly defined oyster reef restoration area, the baseline survey should encompass the proposed restoration area and the surrounding regions that could impact or be impacted by the project.

For areas with historical oyster reefs or oyster distributions, or where there is a need for oyster reef ecological functions but no specific restoration area defined, the survey area should include estuaries, bays, and other regions where oysters are distributed. If necessary, it may also encompass adjacent estuaries and bays. If there are reference systems or control areas available, the survey area should cover these regions as well.

How to set the reference system?

A) The reference system can be the oyster reef ecosystem before degradation. Collect historical data of the survey area, including representative ecosystem data such as routine monitoring, special survey and literature, which can reflect the changes of the ecosystem;

B) If the ecosystem information of the oyster reef before degradation is unavailable or insufficient to meet the needs of degradation diagnosis and restoration goal setting, the natural oyster reef with similar habitat conditions in the surrounding area can be selected as the reference system;

C) If the above conditions are not met, an ideal ecosystem model can be constructed through literature and historical data.

How to select the control area?

The distance between the control area and the restoration area should be determined according to the size of the restoration area, avoiding the impact of the ecological restoration project, generally 5 to 10 times the length or diameter of the restoration area from the edge of the restoration area.

5.2.2 Survey Content

Oyster reefs, as structural coastal habitats, play a crucial role in resisting wave, current, and tidal erosion on adjacent salt marshes or coastal protection structures. Research indicates that oyster reefs located within ±0.6m of the mean lower low water (MLLW) level in bays and estuaries with short-term wind waves (effective wave height less than 0.9m) can significantly attenuate wave action [1]. Baseline surveys for coastal ecosystem restoration of oyster reef for the co-benefits of ecological significance and marine hazard mitigation projects should focus on four key aspects of oyster reefs, environmental factors, threat factors, and management status. Key survey indicators include:

Oyster Reefs: 1) Current status and historical distribution: oyster reef footprint, reef area, reef heigh; 2) Oysters: species, density, shell height, recruitment and settlement peak periods;

Environmental Factors: 1) Water quality: temperature, salinity, dissolved oxygen, pH, suspended solids, chlorophyll-a; 2) Substrate environment: substrate type, sedimentation rate, depth of silt/ soft soil (for silty substrates); 3) Hydrodynamic environment: water level/tidal level, wave height, flow velocity, flow direction; 4) Topography: water depth, slope, location, and elevation of eroded shorelines or dikes; and 5) Wind Conditions;

Threat factors: 1) Shoreline erosion or damage; 2) Factors leading to oyster reef degradation, such as predators, water pollution, diseases, coastal development, drifting garbage in the sea, etc.;

Management status: 1) Spatial planning related to the restoration area; 2) Marine usage status in the project area and surrounding sea areas; 3) Progress and effects of ongoing ecological protection and restoration projects.

The baseline survey should be conducted through data collection, field surveys, and social surveys. Surveys of the project area, reference system, and control area should be carried out simultaneously. The baseline survey and routine monitoring should ideally be conducted in the spring. The survey timing for oyster settlement peak periods and recruitment should be scheduled according to the local oyster species' breeding periods.

5.2.3 Survey Methods

(1) Oyster Reef Survey

① Current Status and Historical Distribution

The survey elements reflecting the overall condition of the oyster reef area should include, but are not limited to, the area of oyster reef patches, the total area of the reef, and the height of the reef.

【Area Survey】

Area serves as the most informative metric reflecting the status of oyster reefs. Both the oyster reef footprint and the oyster reef area can portray the distribution area of oyster reefs. For oyster reefs situated in the intertidal zone, aerial photography using unmanned aerial vehicles (UAVs) or surveys conducted with global positioning systems (GPS) can be employed to delineate the boundaries of oyster reef patches; for those in the subtidal zone, sonar in conjunction with submersible sampling can be utilized for the same purpose. Subsequent to field surveys, a geographic information system (GIS) platform is employed for spatial analysis of survey images to outline the distribution range of oyster reefs. The total area occupied by oyster reefs, representing the area of oyster reef patches, is then quantified. The outer perimeter of oyster reef patches is delineated, and the area enclosed by this perimeter, representing the oyster reef area, is calculated.

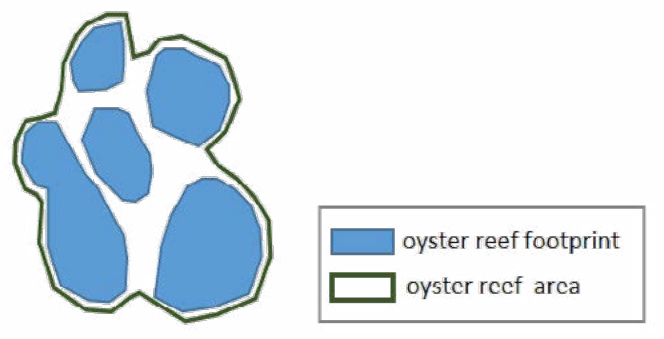


Fig.2 Schematic of oyster reef footprint and oyster reef area

(Source:Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

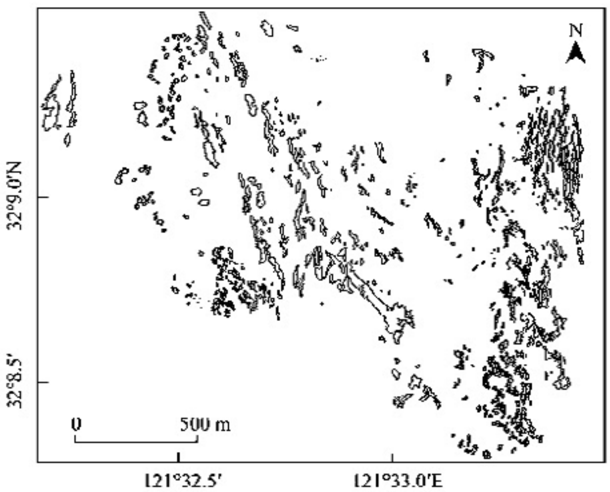


Fig.3 Distribution map of oyster reef patches in the intertidal zone of Liya Mountain, Haimen, Jiangsu Province, as interpreted by UAVs aerial photography. (Source: Quan Weimin, East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences)

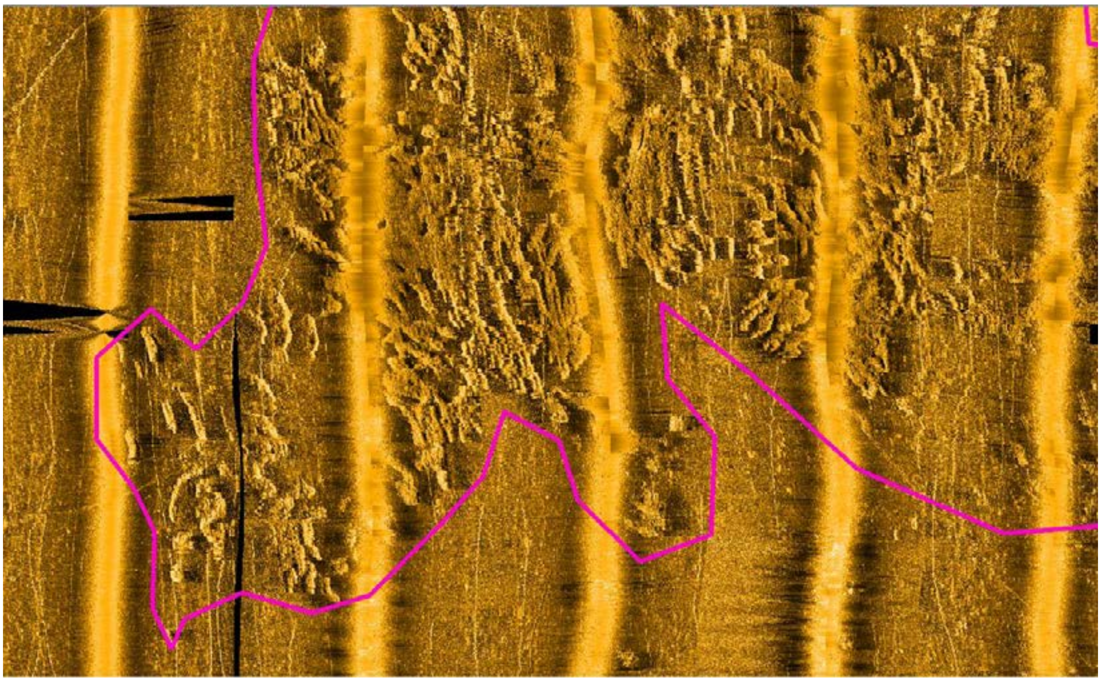


Fig.4 Distribution of oyster reefs in Dashentang surveyed using single-beam bathymetry and side-scan sonar measurements

(Source: Zhang Yi, North China Sea Ecological Center, Ministry of Natural Resources)

【Reef Height Survey】

The height of oyster reef refers to the elevation of the reef relative to the substrate to which the oysters are settled, which can reflect the annual growth of the oyster reef. Measurements of reef height should be conducted along the direction of the reef ridge or the central axis of the long axis of the oyster reef, and drilling measurements may be necessary.

Traditional measurement methods, such as using rulers to measure after artificial drilling, can be employed for intertidal reefs. In areas where conducting manual surveys is challenging, real-time dynamic measurement, UAV digital photography, or airborne LiDAR scanning methods can be utilized for measurements.

For subtidal reefs, traditional measurement methods involve using rulers after underwater drilling. In areas where manual survey is challenging, depth sounding rods can be used. Alternatively, single-beam and multi-beam depth sounding can be combined with shallow seismic profiling measurements, supplemented by drilling for verification.

When using traditional methods for measurement, if the length of the reef ridge or the long axis of the reef area exceeds 200 meters, the interval between measurement points should be 20 to 50 meters. If the length of the reef ridge or the long axis of the reef area is less than or equal to 200 meters, the interval between measurement points should be 5 to 10 meters.

② Oyster Survey

Oysters are the main component species of oyster reefs, and their growth status is closely related to the overall condition of the oyster reef. The survey parameters for oysters should include, but are not limited to, species, density, shell height, recruitment and peak period for settlement. Field survey methods are primarily used to obtain this information.

Principles of establishing sections for oyster reef survey

a) When establishing survey sections, it is essential to ensure comprehensive spatial coverage of the entire survey area. This approach enables a holistic representation of the ecological status of oyster reefs within the surveyed area.

b) Choose representative locations for section layout, encompassing distribution areas with active, deceased, and restored oyster reefs, to accurately portray the diverse ecological states of oyster reefs within the study area;

c) Align the orientation of the sections perpendicular to the coastline or in accordance with the gradient change of environmental parameters (e.g., water depth, salinity, etc.);

d) The quantity of sections is established according to the extent of oyster reef distribution or the length of oyster reef distribution along the coastal zone.

Oyster Reef Survey Station Layout Method

a）Arrange stations based on the distribution characteristics and accessibility of oyster reefs. In principle, no fewer than 3 stations should be established for each section;

b）Ensure that site selection is representative. For oyster reef patches not covered by a section, set up separate stations;

c）After determining the stations, record the geographical coordinates of each station for long-term monitoring.

【Species Survey】

During on-site surveys, a minimum of 3 quadrats measuring 25 cm × 25 cm should be sampled at each site. Live oysters should be collected and transported to the laboratory for species identification, based on criteria such as distribution area, external morphology, internal structure, and molecular methods.

Fig.5 Sampling of intertidal oyster reefs

(Source: Zhang Yi, North China Sea Ecological Center, Ministry of Natural Resources)

Fig.6 Subtidal oyster reef sampling

(Source: Wang Wei, Institute of Oceanology, Chinese Academy of Sciences)

近江牡蛎 *Crassostrea ariakensis* | 熊本牡蛎 *Crassostrea sikamea* | 葡萄牙牡蛎 *Crassostrea angulata*

Fig.7 Three types of oysters in Jiantiao Harbor, Sanmen County.

(Source: Quan Weimin, East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences)

【Density and Recruitment Survey】

Oyster density refers to the quantity of live oysters per unit area and can be determined using samples collected during species surveys. Oyster recruitment, on the other hand, refers to the quantity of oyster spat per unit area. Recruitment surveys should be conducted 3 to 5 months after the peak period of oyster spat settlement. Hanging plates can also be used for recruitment surveys, with plates deployed before the peak settlement period and recovered 3 to 5 months later.

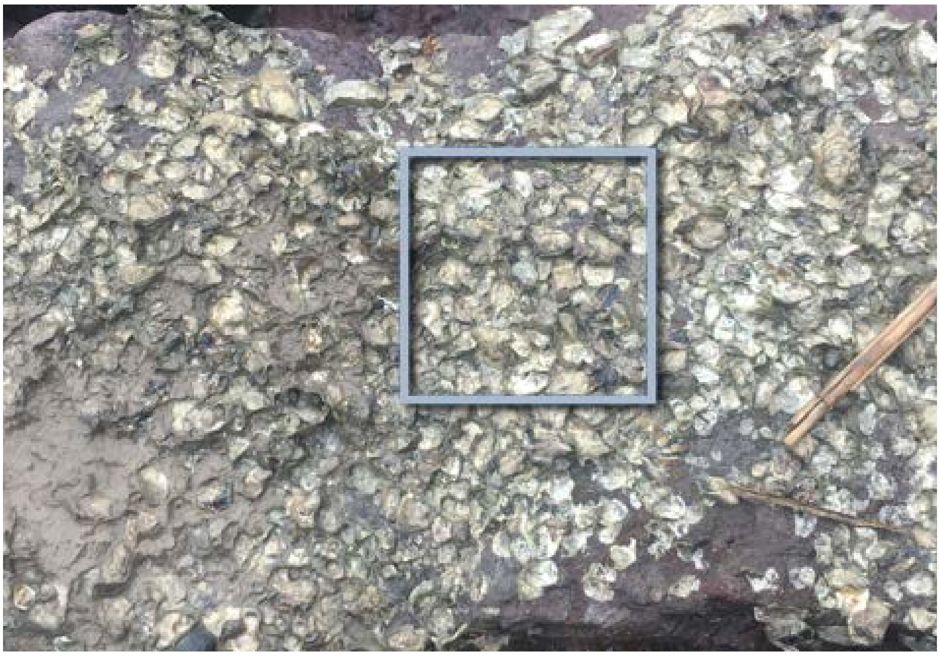


Fig.8 Survey of oyster density using quantitative frames

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.9 Oyster larvae

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

【Shell Height Survey】

A substantial amount of shell height data from oysters reflects the size distribution of individuals in the oyster population, which can indicate the survival or mortality of the population during a specific stage of oyster growth. Using the oyster samples collected, measure the shell height of each live oyster separately with a vernier caliper. Group the oysters based on every 5mm difference in shell height, record the quantity of oysters in each group, and create a histogram with shell height as the x-axis and the average oyster density per group as the y-axis.

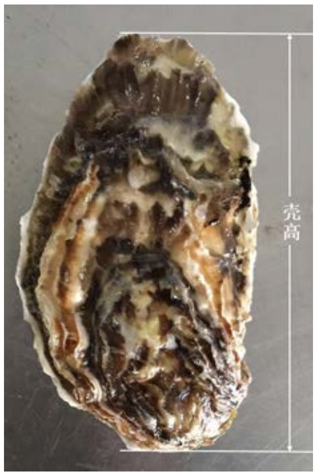


Fig.10 Schematic diagram of oyster shell height measurement

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

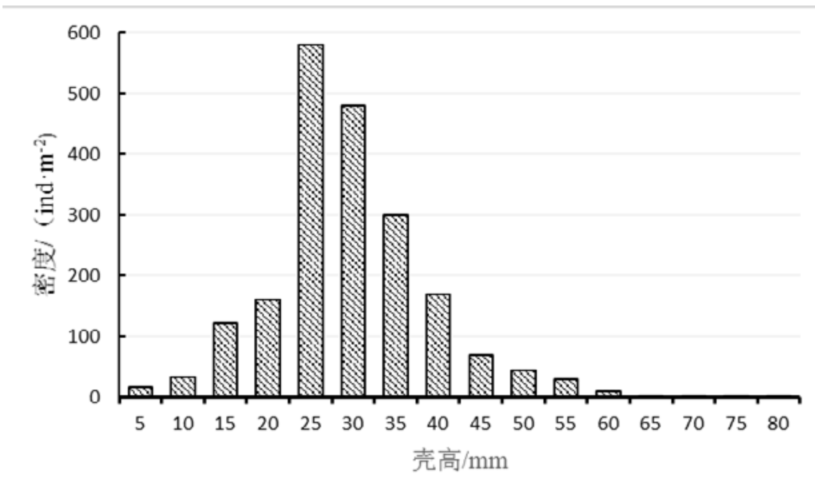


Fig.11 Example of oyster shell heights-- frequency distribution map

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

【Peak Settlement Period Survey】

Two methods can be employed for peak settlement period surveys.

One method involves oyster larvae trawling during the oyster breeding season. Typically, 5 to 6 days after oyster spawning, oyster larvae are collected in the intended restoration area. A zooplankton net made of No. 25 sieve silk is used to trawl in the middle and lower layers of the water every 1 to 2 days to sample oyster larvae at different developmental stages. The peak settlement period is considered when the larvae reach a shell height of 300μm or more, and the percentage of larvae counted by naked eye exceeds 30%. Alternatively, the peak settlement period can be determined when late-stage larvae at top of the shell reach a density of at least 25 to 60 individuals/m^3.

The second method involves using hanging plates made of stone chips, shells, or rough epoxy-phenolic glass cloth laminate. Beginning from the start of the oyster breeding season, a set of plates is hung every 7 days, with the time and number of each plate recorded. The plates are regularly checked for the settlement of oyster spat. The hanging time of the plate with the highest oyster spat density is considered the peak settlement period.

Fig.12 Hanging of test plates

(Source: Xu Fei, Institute of Oceanology, Chinese Academy of Sciences)

Fig.13 Shell test plate

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

(2) Environmental Factors

Environmental factor surveys can indicate whether the habitat conditions are suitable for oyster growth and population establishment. These surveys encompass water quality, substrate environment, hydrodynamic environment, topography, wind conditions, etc.

① Water Quality

Water quality survey factors should include, but are not limited to, water temperature, salinity, dissolved oxygen, pH, suspended solids, and chlorophyll a. Historical data should be collected to obtain average and extreme values.

Different oyster species are adapted to different temperature ranges. For example, the optimal temperature for the growth of the Crassostrea giga, distributed in the north of China, is 5℃ to 30℃ , with the optimal breeding temperature being 20℃ to 26℃. In contrast, the optimal temperature for the growth of the Crassostrea hongkongensis in southern China is 6℃ to 32℃ , with the optimal breeding temperature ranging from 24 to 31℃ . Although oysters can maintain aerobic metabolism for several days at low oxygen levels, extreme heat can inhibit their aerobic metabolic rate, and low water temperatures can significantly slow down the growth rate of oyster individuals.

Different oyster species are adapted to different salinity ranges. For example, the Ostrea denselamellosa thrives in high-salinity sea areas of 25 to 34, while oysters such as Crassostrea ariakensi and Crassostrea hongkongensis prefer low-salinity sea areas. While some oyster species can tolerate high or low salinity environments for a short period, long-term exposure can affect their disease resistance and survival rate.

Dissolved oxygen levels are typically a growth-limiting factor for subtidal oysters. In areas with excessive water depth, hypoxia and anoxia may occur, leading to oyster mortality.

Oysters are typical calcified organisms. If seawater pH is too low, the oyster calcification rate will decrease, potentially causing abnormal development or death of oyster larvae.

Oysters are filter-feeding bivalves that feed by filtering suspended particles in the water. Excessive sediment content in the water can lead to suffocation and death of oysters.

Chlorophyll a is an important pigment in phytoplankton, and its content can reflect the biomass of algae in water. Oysters feed on microalgae and organic debris. If the biomass of algae in the water is too low, it may lead to insufficient feeding for oysters; If the biomass of algae in the water is too high, it may lead to eutrophication of the water.

② Substrate Environment

Survey elements for the substrate environment should include substrate type, sedimentation rate, and depth of mud/soft soil foundation. Substrate type and depth of mud/soft soil foundation are determined through on-site surveys, while sedimentation rate is primarily based on collected data.

Substrate types are classified into hard-phase substrate (rocks, biological reefs, concrete, etc.) and soft-phase substrate (mudflats, sandy mudflats, sandy beaches, etc.). The substrate type can help determine whether the surveyed area lacks substrate for settlement, whether it is suitable for constructing artificial reefs, and the types of artificial reefs suitable for use as settlement substrate.

Sedimentation rate is measured in years, calculating the annual thickness of marine sediments accumulated per unit area. If on-site measurement is required, field surveys should be evenly distributed, measuring the sediment thickness of the substrate within one year. Based on the sedimentation rate, a preliminary judgment can be made on the suitability of constructing oyster reefs and the design weight of artificial reefs. It is generally not recommended to carry out oyster reef restoration projects in areas with high sedimentation rates.

The depth of mud/soft soil foundation is surveyed using drilling methods.

③ Hydrodynamic Environment

Survey elements for the hydrodynamic environment should include but not limited to water level, wave height, flow rate, and flow direction, utilizing a combination of field surveys and data collection. Feasibility assessments and plan designs for oyster reef disaster mitigation projects require an understanding of the water level and wave height in the restoration area.

Water level affects the duration of oyster exposure to the surface and is a key factor influencing the growth of intertidal oyster reefs in estuarine areas. Water level survey data can provide a reference for the placement and design height of artificial reefs. Oysters should not be exposed for more than 4 hours.

Wave height significantly affects the stability of artificial reefs. A storm surge can cause the entire oyster reef to tilt or collapse.

Flow rate and direction have a significant impact on oyster larvae during the settlement period. Oyster larvae have weak swimming abilities and mainly drift with the seawater. When they reach a certain stage of development, they choose a hard settlement substrate for settlement and metamorphosis. If the flow rate is too high at this stage, oyster larvae will struggle to settle.

④ Topography

Topography surveys include, but are not limited to, water depth, slope, and the position and elevation of eroded shorelines or dykes, providing a reference for the design phase of oyster reef ecological restoration.

⑤ Wind Conditions

Wind condition surveys focus on data collection, supplemented by field surveys.

(3) Threat Factors

The threat factor survey serves two main purposes: firstly, analyzing the causes of shoreline erosion or damage, and secondly, conducting a preliminary analysis of oyster reef degradation to determine the suitability of oyster reef ecological restoration.

① Threat Factors of Shoreline Erosion or Damage

Sea level rise contributes to coastal erosion and retreat, albeit with a relatively minor impact.

Wave action significantly contributes to coastal erosion.

Tidal currents transport suspended matter to other locations, leading to coastal erosion.

Storm surges cause water level rises, which, when combined with strong winds and waves, can exacerbate coastal erosion.

Organism metabolism and reproduction can cause damage to coastal rocks, resulting in coastal erosion.

Anthropogenic factors include unreasonable coastal engineering, sand mining activities, and upstream water conservancy projects in rivers flowing into the sea.

② Threat Factors of Oyster Reef Degradation

Threat factors include natural and anthropogenic factors.

Natural factor surveys primarily encompass predators, competitors, oyster diseases, and Invasive oyster species.

Predators of oysters include fish such as black porgy, stingrays, mullets, and barracuda; carnivorous snails such as red whelks, Thais, and Natica; echinoderms such as petrels and starfish; crustaceans such as Scylla paramamosain and Scylla serrata; and birds such as oystercatchers.

Oyster competitors include barnacles, Mytilus galloprovincialis, Musculus senhousei, sea squirt, obelia, bryozoan, and other organisms.

Various oyster diseases, some leading to mass mortality, are caused by burrowing organisms such as Polydora ciliata, burrowing clams, and Clionidae, which bore through oyster shells, inhabit them, and cause bacterial diseases. They can also concentrate in burrowing at the top of the shell, causing oysters to fall off the reef. Common oyster diseases include Bonamiasis, Marteilia Refringens, Perkinsus marinus, herpesvirus, and trematodes.

Invasive oyster species refer to foreign oyster species threatening the stability of oyster reef ecosystems, usually introduced due to nearby oyster aquaculture.

Anthropogenic factors surveys include fishing, filter-feeding bivalve aquaculture, marine engineering, and pollution discharge. Fishing and marine engineering are the main reasons for the sharp decline in China's natural oyster resources. Driven by economic interests, the methods of oyster fishing have transitioned from traditional diving practices to large-scale bottom trawling, resulting in severe damage to coastal oyster reefs. Additionally, marine engineering activities have encroached upon the natural habitats of coastal oysters, leading to siltation of coastal mudflats and subsequent habitat changes, causing degradation of the natural oyster reef ecosystems.

Fig.14 Oyster shells after harvesting

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

(4) Current Situation of Protection, Management, and Utilization

Methods for surveying the regional protection, management, and utilization status include data collection, field surveys, sampling surveys, interviews, and questionnaire surveys, etc. The survey content using data collection should cover information at the municipal and county levels.

The survey content includes, but is not limited to, the following:

Relevant planning for the proposed restoration area and surrounding areas, including land spatial planning, regional development planning, ecological protection red lines, etc.

Tenure status of the proposed restoration area, administrative authorities, potential social impacts (risks), and stakeholders of oyster reef ecological restoration.

The current status of protection and management of the proposed restoration area, including the scope and management of the protection area, the status of implemented restoration projects, etc.

For projects with a large restoration area, it is advisable to understand the availability of reef materials, adult oysters, and juvenile oyster in the region or surrounding areas. Such as the source and supply volume of rocks, shells, the species, quantity, specifications, prices of adult oysters, the supply capacity of juvenile oyster in the nursery, or the ability to attach juveniles, etc.

6.Problem Diagnosis

6.1 Disaster Problem Diagnosis

Based on the situation of coastal erosion or damage, analyze the causes of disaster problems and whether the implementation of oyster reef ecological restoration projects can change the status of coastal erosion.

6.2 Oyster Reef Ecological Problem Diagnosis

Based on the ecological baseline survey, analyze the status of degraded oyster reefs and reference sites, including the health status of oyster reefs, the status of biological communities and habitat conditions. When conditions permit, analyze the status of important ecological processes and functions of oyster reefs.

Using the reference or set target values as the baseline values, assign average values to the changes in oyster reef footprint, changes in reef height, changes in oyster density at each station, and average values of oyster recruitment changes at each station, to assess the health status of oyster reefs. Conduct single-factor assessment or qualitative assessment of factors other than oysters to assess whether oyster reefs are degraded and the degree of degradation, and identify degradation factors. Specific assessment methods refer to HY/T 0460.7-2024.

Compare the similarities and differences of biological factors, hydrological factors, water chemistry factors, and threat factors in the same reef area during the baseline survey and the follow-up survey, and analyze the reasons for the degradation of oyster reefs and whether the degraded elements need to be restored through restoration measures. Clearly define the restoration objectives for degraded oyster reefs, and identify the factors that need to be restored (which can be a habitat factor, a biological factor, or an ecological process, etc.) in accordance with the objectives.

Common oyster reef degradation scenarios:

a) Direct encroachment of oyster habitat by marine engineering;

b) Loss of oyster habitat due to shoreline siltation;

c) Changes in hydrological conditions affecting oyster spat settlement, leading to a lack of spat recruitment in oyster reefs, resulting in their gradual aging and disappearance;

d) Overharvesting leading to a significant reduction in the number of oyster populations, making it difficult for them to form reefs;

e) Bottom trawling damaging subtidal oyster reefs, causing fragmentation of oyster patches;

f) High sediment content in water and environmental changes such as hypoxia leading to oyster mortality;

g) Climate change causing changes in seawater temperature, salinity, and pH, affecting oyster growth and development, leading to the degradation of oyster reef ecosystems;

h) Parasites, diseases, bacteria, and viruses causing low oyster reproductive capacity and even death.

6.3 Repair suitability assessment

According to the results of the problem diagnosis, carry out the assessment of the suitability of oyster reef ecological disaster mitigation and restoration, the assessment and analysis mainly include -

Mechanism analysis of oyster reef damage: including ecological damage to oyster reefs, siltation of shore and beach, neighboring human activities, impacts of marine engineering, water quality pollution, etc;

Policy and planning suitability analysis: the site selection for oyster reef restoration should be in line with, but not limited to, the policy and planning requirements such as policies and regulations, marine functional zoning, sea area use planning, territorial spatial planning, urban construction planning, and so on.

Suitability analysis of hydrological environment: Adopt on-site investigation and numerical simulation to analyze the potential impacts of temperature, salinity, waves, tides, currents and other hydrological and hydrodynamic conditions on the growth of oyster reefs in the restoration area and its surrounding waters, so as to study and judge the suitability of restoration.

Topography and geomorphology suitability analysis: analyze whether the restoration area has, or through artificial measures to form, a topography and geomorphology environment suitable for the growth of oyster reefs;

Suitability analysis of water quality and substrate environment: analyze whether the water quality and sediment in the restoration area can meet the restoration requirements, and analyze the impact of restoration on the evolution of oyster reef ecosystem in the following period.

7.Restoration Goals

Corresponding restoration objectives are set according to the main purpose of the project (e.g., to reduce coastal zone erosion, to enhance the water quality of the Bay Area, etc.) and the expectations of the main stakeholders (e.g., economic employment opportunities, aesthetics of the landscape, conformity with local culture, etc.). The ecological restoration objectives are the basis for setting and selecting the ecological restoration contents and technical measures, as well as the criteria for evaluating the success of ecological restoration.

For oyster reef restoration projects aiming at ecological disaster mitigation, two aspects need to be considered when setting the objectives: on the one hand, the ecological attributes of oyster reefs should be considered to establish sustainable populations, and on the other hand, it is necessary to consider that oyster reefs constructed from the viewpoint of disaster mitigation and prevention should be able to play an optimal role in slowing down the flow, eliminating the waves, and promoting the siltation.

7.1 Short-term Goals

Short-term assessment monitoring indicators reflect the level expected to be achieved by the specific object/ecosystem element being restored during the duration of the restoration project or in the initial period after restoration. The period of realization of the short-term indicators of the restoration project is 2~5 years. Specific indicators can be set in relation to the specific content of the project implementation, considering the following:

Proliferation of oyster populations: oyster reef patch area, reef area, reef height, oyster density, oyster replenishment, proportion of adult oysters, etc;

Disaster prevention and mitigation capabilities: degree of wave attenuation;

Water quality improvement: suspended sediment concentration, inorganic nitrogen, etc;

Biodiversity enhancement: benthic organisms, microorganisms, eggs, larvae, etc;

Elimination of threatening factors: harvest control, pollutant discharges, number/area of entrenched substrates, pests and diseases, control of predator and competitor populations, amount and degree of impact of drifting garbage in the sea, etc.

7.2 Medium and Long-term Goals

When setting the medium- and long-term assessment and monitoring indicators, the biological and natural environment factors can be set at 10 years, and the restoration of ecological processes and ecological functions at 20 years. The setting of medium- and long-term assessment and monitoring indicators can refer to the following:

Disaster prevention and mitigation capacity: degree of wave attenuation, coastal elevation, shoreline erosion rate, sedimentation rate, etc;

Recovery of biological communities: benthic organisms, microorganisms, fish eggs, juvenile fish, etc;

Restoration of important ecological processes: primary production, ecosystem stability, oyster regeneration, biological and chemical exchanges with the surrounding water environment, etc.

8.Restoration Methods

Three types of oyster reef ecological restoration include natural restoration, artificially assisted restoration, and reconstructive restoration.

Natural restoration. The oyster ecosystem is degraded due to overfishing, pollution, predators and competitors, etc. In the above cases, if the oyster reefs are relatively mildly degraded, the oyster ecosystem can be restored by strengthening fishing management, controlling land-based pollution, and controlling the oyster ecosystem. In the above case, if the degree of oyster reef degradation is relatively mild, the disturbances causing oyster reef degradation can be eliminated through management measures such as strengthening harvest management, controlling land-based sources of pollution, and increasing the harvesting of oyster predators and competitors (see 9.1 for specific measures to eliminate threatening factors). With the removal of external pressures or disturbances, oyster reefs can restore themselves through natural regeneration and do not require the implementation of artificial restoration measures.

Artificially assisted restoration. An environment that is hydrologically and ecologically suitable for oyster growth and has sufficient oyster replenishment, but lacks the substrate for oyster fixation growth is called a substrate-limited environment; an environment that is hydrologically and ecologically suitable for oyster growth and has a large distribution of substrate suitable for oyster fixation growth, but has low oyster replenishment, is called a replenishment-limited environment. In hydrologically and ecologically suitable areas, oyster populations have declined significantly, generally due to either supplementation limitation or fixation base limitation. In the case of limited replenishment, oyster populations can be enhanced through artificially assisted measures to replenish existing reef structures with adult oysters or juvenile mussels; in the case of limited anchorage, natural restoration of oyster reef ecosystems can be facilitated through the replenishment of hard-phase substrate materials that provide oysters with substrates for anchorage metamorphosis (see 9.2 for specific measures).

Reconstructive Restoration. When both supplementation and fixation substrates are limited, oyster reefs are usually severely degraded and require restorative restoration, i.e., not only eliminating the disturbing factors that cause degradation, but also reestablishing oyster populations that can reproduce and grow sustainably, where feasible. Reconstructive restoration should be approached with extreme caution when ecological restoration of oyster reefs is undertaken. Reconstructive restoration is not recommended for areas within and adjacent to the proposed restoration area where oysters have not been distributed historically or in the current time period. If there were oysters in the proposed restoration area and nearby waters historically and there is no oyster distribution in the current period, the necessity and feasibility of restoration should be rigorously demonstrated before reconstructive restoration is carried out. Reconstructive restoration requires the placement of hard-phase substrate material followed by artificial replenishment of adult oysters or juvenile mussels.

Table 1 Restoration Method Selection

Causes of Degradation	Degree of Degradation	Natural Regeneration Ability	Limiting Conditions	Restoration Methods	Restoration Measures
Overfishing, pollution, excessive predators and competitors	Low	Intact	Hydrological and ecological conditions suitable, with sufficient oyster recruitment	Natural recovery	Eliminate threat factors
Lack of settlement substrates	Moderate high	Weak	Suitable hydrological and ecological conditions for oyster growth, with sufficient oyster recruitment	Artificially assisted restoration	Eliminate threat factors and construct artificial reef structures

Causes of Degradation	Degree of Degradation	Natural Regeneration Ability	Limiting Conditions	Restoration Methods	Restoration Measures
Insufficient oyster recruitment	Moderate high	Weak	Suitable hydrological and ecological conditions for oyster growth, with a large distribution of suitable oyster settlement substrates	Artificially assisted restoration	Recruit oysters
Existence of serious threat factors or changes in habitat conditions	Severe	Weak or completely lost	Historical presence of oyster growth	Reconstructive restoration	Eliminate threat factors, then construct artificial reef structures, and finally recruit oysters

9.Restoration Measures

9.1 Mitigating Threat Factors

Threats to oyster reefs encompass both human-induced and natural factors. Human activities such as overharvesting and water pollution contribute to these threats, while natural factors include non-biological disasters, biological enemies, and oyster diseases.

(1) Addressing Human-Induced Threats

To mitigate threats from overharvesting, corresponding restrictive protection measures should be adopted, including the restriction of harvesting areas, adherence to harvesting specifications, and the imposition of harvesting quotas. Additionally, management of clam diggers, bottom trawlers, and other activities should be strengthened to minimize human interference. This approach allows for the natural recovery of oyster reef ecosystems and promotes self-regulation within these ecosystems.

For threats to oyster reefs caused by water pollution, the basic situation of the pollution source should be analyzed. In general sea areas, stringent control over the total amount of pollutants entering the sea is essential. In ecologically protected sea areas, the discharge of pollutants should be prohibited.

Restored oyster reefs in Longgang City

Some of the oysters were harvested

Fig.15 Longgang City sets a sign banning on oyster harvesting

(Source: Sun Li, Second Institute Of Oceanography, Ministry of Natural Resources)

(2) Addressing Natural Threat Factors

① Measures for Non-biological Threat Factors

Salinity: Oysters exhibit a certain tolerance range for salinity. Exceeding this range can lead to an imbalance in osmotic pressure, particularly for oysters near estuaries like *Crassostrea ariakensis*. When constructing reef structures or releasing oysters, operations should be conducted in areas where salinity levels are suitable for oyster growth.

Temperature: Oysters display resilience to temperature variations. However, oysters in the intertidal zone, such as *Crassostrea sikamea* in southern regions, often die due to exposure to intense sunlight in summer, especially newly settled spat. Oysters in northern intertidal zones are more likely to die due to low winter temperatures. It is challenging to eliminate the impact of temperature. Therefore, when designing oyster reef ecological restoration projects, local temperatures and the tidal level of the restoration area should be fully considered to prevent prolonged exposure of oyster reefs above the water surface.

Wind and Waves: Typhoon-induced huge waves can inflict severe damage on oyster reefs. On one hand, huge waves may dislodge oysters near the intertidal zone along with their settlement substrates; on the other hand, the waves stir up seabed silt, causing suffocation and death of oysters. Oyster reefs located in the intertidal zone are more affected by typhoons. There are few operational preventive measures that can be taken before a typhoon strikes. After the typhoon, oyster reefs should be immediately salvaged and cleaned up, the debris should be removed, and the reefs should be straightened to prevent oysters from being buried by floating mud.

② Elimination Measures for Biological Threat Factors

Biological threat factors mainly rely on artificial harvesting or eradication.

Economic Fish: Marine Economic Species: Carnivorous fish such as pufferfish, rays, black porgy, Ditrema temmincki Bleeker, along with carnivorous gastropods including Rapana bezoar, Thais, Natica, and crustaceans such as Scylla serrata, are among the organisms that pose a threat to oysters. These species are economically valuable but can be controlled through artificial harvesting methods such as purse seine or trapping.

Attached Organisms: Attached organisms such as barnacles and saddle-oyster that occupy the same ecological niche as oysters will compete with oysters for settlement substate and food, affecting the settlement and growth of oysters. Since the breeding season of barnacles generally precedes that of oysters, it is necessary to carefully seize the timing of placing settlement substates and collecting spats to avoid the peak reproductive period of other competitive attached organisms. The reproductive times of different species of barnacles in different sea areas are different. For example, the peak reproductive period of the Balanus reticulates in the Nanji

Islands, Zhejiang Province, is July and August; the Balanus uliginosus is about one month earlier than the Balanus reticulates, with the settlements period in Lv Siyang from June to October and from April to October in Quanzhou Bay; the settlements period of the main distribution area of the Balanus trigonus along the coast of Zhejiang is from June to October, with the peak period in August [2]. In addition, there are generally more oyster settlements at depths of 15~65 cm below the average low tide level, and fewer barnacles' settlements. Therefore, attention should be paid to the tidal level when placing settlements substrates and collecting spats.

(3) Oyster Diseases

There are various diseases that affect oysters, including viral, bacterial, fungal, protozoal diseases such as Marthella and Perkinsosis, as well as diseases caused by helminths and parasitic crustaceans. Currently, there is no effective treatment for ecologically restored oyster reefs.

Some diseases may cease attacking oysters when environmental conditions change. For instance, herpesvirus diseases are more common in high-temperature sea areas. When the sea water temperature drops to 12℃ to 18℃ , the infected oysters may stop being infected and die. The mortality rate of oysters infected with monosporosis is 90% to 95% in high-salinity areas and 50% to 70% in low-salinity areas. Oysters infected with Perkinsosis generally do not die when the salinity is below 15 or the water temperature is below 20℃ [3]. Some diseases do not cause significant oyster mortality, and oysters can survive with the disease.

Preventive measures for oyster diseases

a) Thoroughly clean the settlement substrate before oyster settlement and growth, completely removing the shells of diseased old oysters;

b) When oysters reach a suitable size, harvest them regularly in appropriate quantities;

c) Avoid using infected oysters as parent oysters.

9.2 Construction of Artificial Reefs

Before employing artificially assisted methods for oyster reef ecological restoration, it is essential to eliminate the threat factors contributing to the degradation of oyster reefs. In environments where settlement substrates are limited, the construction of artificial oyster reefs is necessary to provide hard structures for oyster spat settlement.

9.2.1 Construct artificial reefs

9.2.1.1 Siting of restoration areas

The location of oyster reef ecological restoration projects directly affects the effectiveness of restoration. On a large scale, restoration areas should be selected in estuaries and bays with a short wave period (wave height less than 0.9m), and it is not suitable to select areas in open sea or areas where large waves occur frequently.

When selecting sites for restoration areas, it is necessary to consider the distribution of oysters, water temperature, salinity, dissolved oxygen, pH, hydrodynamics, topography, sedimentation rate, substrate type, oyster bait and other influencing factors. Among them, the dissolved oxygen should be greater than 5mg/L for more than 16h in 24h in a row, and not less than 3mg/L for the rest of the time; the pH value ranges from 7.8 to 8.5; the hydrodynamic should be in the environment where the tidal currents are fluent, there are no whirlpools and collision currents, and the average flow velocity during the peak period of oyster fixation is not greater than 60cm/s; the terrain should be gentle, and the slope is less than 5 °; the deposition rate should be less than the height growth rate of oyster reefs; and the sedimentation rate should be less than the growth rate of oyster reef height. The sedimentation rate should be less than the height growth rate of oyster reefs, and a balanced or slightly scouring environment is preferred, with an adequate supply of phytoplankton.

The substrate should be hard and with little silt accumulation, avoiding soft mud bottom with deep silt and fine sand bottom with high flow velocity. The strength of the substrate should be able to support human walking; mud substrate with the thickness of soft mud not exceeding 0.3m can also be selected; some studies have shown that there is no significant difference between pebble substrate and mud substrate on the abundance of live oysters[4];

After completing the site selection, the extent of the restoration area should be further determined. Different oyster species have different water depth requirements for suitable growth. According to oyster species, the intertidal oyster reef restoration area should be selected between the mean sea level and the mean minimum tide level, and the subtidal oyster reef restoration area should be selected in the area from the mean sea level to the following 10m water depth. When determining the scope of restoration, the number of patches should be increased as much as possible to prevent siltation of the reefs while increasing the seawater circulation channels.

9.2.1.2 Restoration Program Design

Restoration programs need to be designed with both ecological and disaster prevention and mitigation objectives in mind, meeting basic oyster growth conditions such as tidal levels and holding substrate, as well as designing reef inundation levels, reef heights, and reef widths based on mitigation needs. Factors to be considered in the design of oyster reef restoration programs in terms of ecological and project objectives, respectively, are shown in the table below.

Table 2 Key Design Criteria for Oyster Reef Restoration Plans Aimed at Coastal Ecosystem Restoration for the Co-Benefits of Ecological Significance And Marine Hazard Mitigation[5]

Design Factors	Ecological perspective (Formation of self-sustaining oyster reefs)	Engineering perspective (Wave attenuation, sediment accumulation)	Ecological and Engineering Interaction Perspective
Restored reef Presence (Reef location)	Larval supply-availability and timing Habitat suitability (e.g. salinity, hydrology) Trajectory of colonization	Decrease in cross-shore sediment transport Wave attenuation	Influence of oyster metrics (e.g. density, size) on waves and sediment transport Influence of wave energy on oyster persistence (e.g. recruitment, survival, mortality) Sediment accretion and oyster settlement, survival

Design Factors	Ecological perspective (Formation of self-sustaining oyster reefs)	Engineering perspective (Wave attenuation, sediment accumulation)	Ecological and Engineering Interaction Perspective
Reef material	Spat settlement Refuge from predation	Structural stability and integrity	Wave-induced turbulence on spat settlement How this changes with different reef complexity or rugosity
Reef length	Patch size and shape—impacts on reef recruitment (e.g. edge effects)	Enhancement of shore-parallel currents	Influence of oyster metrics (e.g. density, size) on currents
Reef width	Spatial configuration of patches—impacts on reef recruitment and survival (e.g. edge effects on settlement, food)	Relationship between width of the reef and incident wavelength for wave	Reef edge effects (e.g. velocity magnitude) on oyster metrics and persistence (e.g. recruitment, survival, mortality)
Reef height	Optimum tidal range and depth for oyster settlement, growth and survival	Wave breaking Wave set-up	Change in wave breaking and set-up with oyster colonization over time

(1) Ecological disaster reduction layout design

The layout of oyster reefs for the purpose of wave attenuation and mitigation is usually laid out in a linear or curvilinear manner along the isobath of the natural environmental water depth. In order to protect the coast length, wave numerical simulation should be carried out for the storm surge (about one in 2~10 years) in the location of the restoration area, to analyze the degree of wave attenuation, to predict the impact of different lengths of oyster reefs on the coast, and to determine the length of oyster reefs that need to be laid out. If conditions permit, the direction of oyster reef layout should be based on the results of numerical or physical model simulation to maximize the role of oyster reefs in blocking water flow and consuming wave energy.

(2) Oyster reef restoration project location design

Oyster reefs play an important role in dissipating waves and weakening currents and preventing shoreline erosion. The principle of oyster reef ecological mitigation is that when the reef is submerged or partially submerged underwater, the wave propagation process from the deep sea to the near-shore oyster reefs is affected by the drastic change of water depth and the friction of the bottom bed, and shallowing, fragmentation, and attenuation along the reefs occurs; the sediment in the coastal zone will be reduced by the weakening of the wave energy to reduce the scouring and transit, and alleviate the loss of sediment; slowing down of the water current also promotes the sedimentation of suspended particulate in the water in the reefs to the shore side, thus slowing down the shoreline recession and beach erosion. The slowing down of water flow can also promote the sedimentation of suspended particles in the water body from the reef to the shore side, thus slowing down the shoreline retreat and beach erosion. The tidal zone setting of oyster reef restoration sites aiming at ecological disaster mitigation needs to take into account both engineering purposes (i.e., dissipating wave energy and stabilizing sediments) and ecological purposes (i.e., suitable for the growth of oyster populations), so that the oyster reefs can maximize the long-term performance of the shoreline protection function, and at the same time, have multiple benefits such as the enhancement of biodiversity. Most of the oyster reefs in China (except Kumamoto oyster) grow near the average low tide level, therefore, oyster reef restoration projects for the purpose of ecological disaster mitigation should be set up in the intertidal zone from low tide to mid-tide. For ecological disaster mitigation restoration projects targeting subtidal reef-building oyster species, the feasibility of subtidal oyster reef restoration for wave mitigation can be assessed through mathematical or physical modeling, taking into account local conditions such as water depth, wave height, and topography.

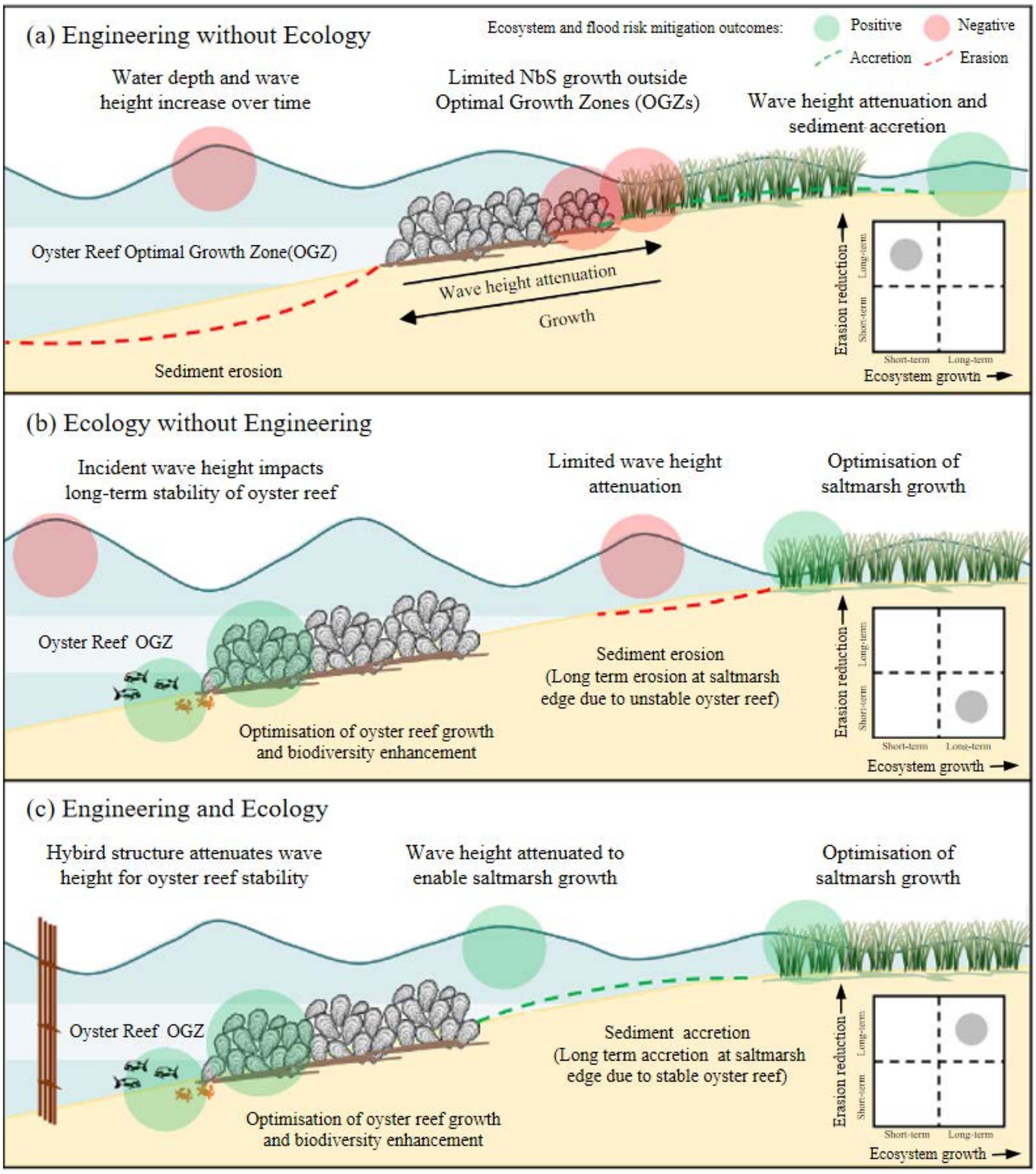


Fig.16 Cross-section of an estuarine shoreline with implemented oyster reef and saltmarsh[6]

(Source：Dunlop et al. 2023)

For the restoration project aiming at the function of fish proliferation, it is preferable to build the reef in the subtidal zone, so as to construct a complex three-dimensional structure and provide habitat space for marine organisms.

For restoration projects aiming at improving water quality, it is preferable to build the reefs in the subtidal zone, and evenly spread them over a large area to maximize the oyster filtering time.

(3) Reef material selection

Reefs constructed with loose oyster shells are prone to lose structural integrity and stability in environments with fast currents and high wave energy, thus affecting oyster seed replenishment, oyster population growth, and reef structure growth. For restoration aimed at ecological mitigation functions, heavy materials such as rocks and concrete blocks should be used for reefs, and the degree of reef subsidence should be considered in conjunction with site substrate conditions.

(4) Reef sizing

Reef sizing with the goal of ecological mitigation requires designing the length, height and width of the reef from ecological and engineering perspectives based on local hydrodynamic, topographic and substrate characteristics such as wave height, water depth, bottom slope, substrate settlement, etc. under the premise of suitable for long-term growth of oyster populations. Usually, the depth between the top of the reef and the water level (i.e., the depth of reef submergence) is negatively correlated with the wave reduction effect[7, 8], and the width of the top of the reef is positively correlated with the wave reduction effect[9]. It has been shown that designing the top of oyster reefs 0.3-0.5m below mean sea level reduces wave height by 30-50% on average when the water depth is 0.5-1.0m, 0-20% when the water depth is 1.0-1.5m, and <10% when the water depth is greater than 1.5m[10]. For silty substrate environments, the design of reef height should also consider the settlement of the reef. In addition, with the growth and development of oyster reefs, the size of the reef body, oyster density, surface roughness and other morphological changes, and the degree of interaction with hydrodynamics and sediment transportation will also change, and need to strengthen the later monitoring and mitigation effect research.

(5) Designed to maximize ecological disaster mitigation functions

In order to maximize the ecological disaster mitigation function of oyster reefs, in actual ecological disaster mitigation and restoration projects, they are usually used together with the restoration of other typical ecosystems in the coastal zone, such as mangroves, salt-marsh plants, seagrass bed and so on, to jointly build a comprehensive ecological disaster mitigation system in the coastal zone. For example, the wave dissipation function of oyster reefs is utilized to support the early growth and development of mangrove forests, and the combination of seagrass beds and oyster reefs is utilized to protect against wave attacks in both nearshore and offshore environments.

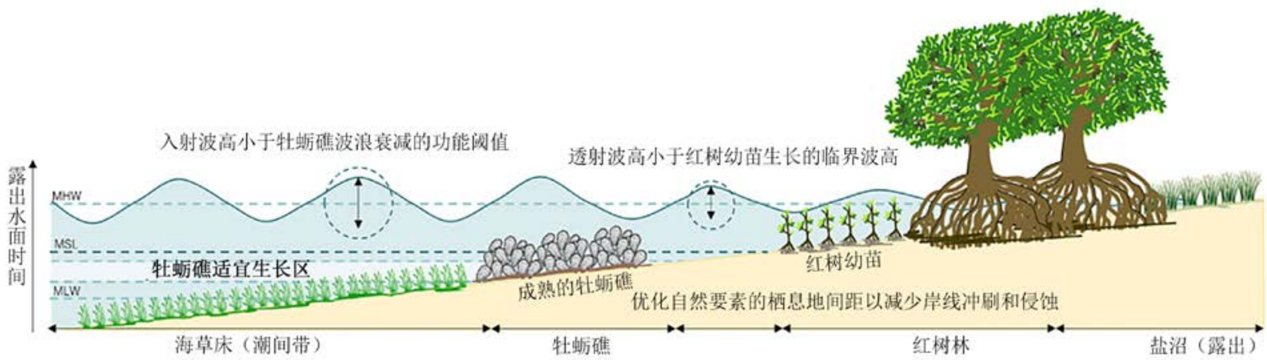


Fig.17 Utilization of oyster reefs for wave attenuation to support early mangrove growth and development[6] (Source:Dunlop et al. 2023)

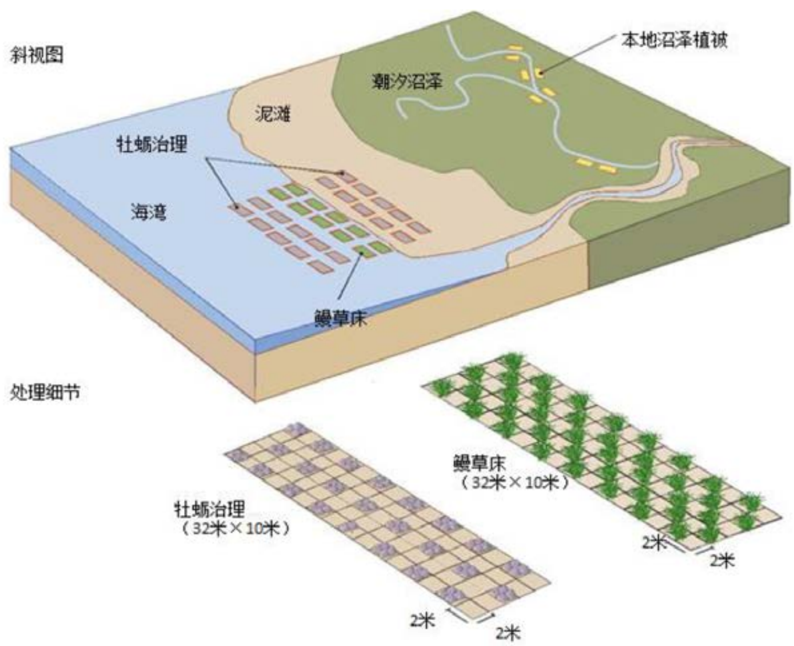


Fig.18 Model of Coastal Protection Effects of Oyster Reefs (Nearshore + Offshore) in Combination with Eelgrass Beds[11]

(Source: Brad Evans/Environmental Science Association, as cited in “Natural Shoreline Infrastructure: Technical Guidance for the California Coast”)

The composite coastal zone ecological disaster mitigation system not only has a superimposed effect on the disaster mitigation function, but the seagrass (seaweed) field or salt marsh wetland adjacent to oyster reefs can also provide sufficient food debris for oysters. Studies have found that oyster reefs near seagrass (seaweed) fields have higher shellfish fixation rates and more significant restoration effects than oyster reefs isolated on mudflats. Seagrass (seaweed) fields also provide a safe corridor for organisms such as crabs to move between oyster reefs and salt marshes, providing ecosystem stability for oyster reefs.

9.2.1.3 Preparation before Implementation of Restoration Project

(1) Preparation of the Implementation Plan for Coastal Ecosystem Restoration for the Co-benefits of Ecological Significance and Marine Hazard Mitigation

a) The implementation plan should adhere to relevant planning frameworks such as regional spatial planning, coastal zone protection and utilization planning, comprehensive watershed planning, and professional planning for tide (flood) prevention. It should also comply with requirements for ecological red line protection and coastal line control;

b) The implementation plan should thoroughly consider factors such as connectivity, integrity, and ecological buffering of marine and terrestrial ecosystems. It should propose spatial layout methods for coastal oyster reef ecosystem restoration projects aimed at marine hazard mitigation based on spatial divisions and different types of coastlines, combined with suitability assessment results, tailored to local conditions;

c) The design of the implementation plan should prioritize maximizing ecological and disaster mitigation benefits while avoiding spatial resource consumption and the creation of new ecological and environmental problems caused by engineering construction;

d) The design of the implementation plan should outline in details the technical requirements, construction methods, scope, and scale of specific measures;

e) The implementation plan should undergo comprehensive analysis and demonstration from economic, social, and environmental perspectives. It should serve as the main content of engineering construction, with the level of detail meeting the requirements of the feasibility study report for engineering;

(2) Environmental Impact Assessment (EIA) of Restoration Projects

According to the requirements of the "Classification and Management List of EIA for Construction Projects (2021 Edition)," environmental impact assessments should be carried out for marine ecological restoration projects as required.

Table 3 Requirements for the Classification and Management of EIA for Marine Ecological Restoration Projects

Marine Ecological Restoration Project Categories	EIA Category
Dredging and mudflat reclamation projects with a volume of 100,000 m3 or more; Dam removal and temporary cofferdam construction projects in environmentally sensitive areas that alter hydrodynamics	EIA Report
Dredging and mudflat reclamation projects with a volume of less than 100,000 m3; Other marine ecological restoration projects in environmentally sensitive areas	EIA Report Form
Demolition of nearshore structures such as removal of aquaculture enclosures, fenses, and breakwaters in non-environmentally sensitive areas; Planting of mangroves, seagrass beds, and seepweed; Restoration of transplanted coral reefs, oyster reefs, etc.	EIA Registration Form

Note: According to the "Classification and Management List of EIA for Construction Projects (2021 Edition)" of the Ministry of Ecology and Environment, environmentally sensitive areas include: (1) natural reserves and special marine protected areas; (2) ecological protection red line control areas excluding (1) marine parks, habitats for key protected wildlife, breeding sites for key protected wild plants, closed and semi-closed sea areas.

(3) Justification of Marine Use Projects

Following the ecological restoration of oyster reefs, it is essential to enhance post-restoration management. To define the management entity clearly, it is advisable to establish marine usage rights in accordance with relevant regulations. The construction of artificial reefs impacts the local hydrodynamic environment, offering significant disaster mitigation functions. When conducting marine use assessments, hydrodynamic environmental numerical simulations should be performed, emphasizing ecological and disaster mitigation functions.

(4) Verification of Restoration Pilot Projects

Once site selection is finalized, small-scale experimental restoration should commence to verify the feasibility of the oyster reef ecological restoration project in the chosen area. The area for small-scale experimental restoration projects typically does not exceed 5000 m^2.

9.2.1.4 Recruitment of Oyster Settlement Substrates

(1) Types and Preparation of Settlement substrates

The settlement substrate for oysters can include natural rock reefs, reef blocks, discarded stones, or cement bars from oyster farms, seawall compression layers, hydraulic structures, oyster shells, scallop shells, cement components, etc. The specific material selection needs to consider the seabed sediment and sea conditions of the site. It should prioritize environmental protection, convenient sourcing, economic durability, as well as roughness and a large settlement area of the substrate. Rubber products, while not dissolving in seawater, are prone to aging and pollution. Therefore, it is not recommended to use rubber-containing materials in ecosystem restoration projects.

Before deploying the artificial reef, the reef materials should undergo treatment to eliminate other species and pathogens. Treatment methods include heat treatment, chlorine treatment, freshwater soaking, weathering exposure, etc. For large quantities of shells, weathering and exposure for at least 6 months is necessary. During this period, shell materials should be spread out flat and turned periodically to ensure most shells receive adequate exposure.

Fig.19 Oyster reef constructed in the intertidal zone for shoreline protection[12]

(Source:Chowdhury et al., 2021)

a-c: Reef structures constructed directly with oyster shells or oyster shell packs (Photo credit: Loren D. Coen, Judy Haner, Judy Haner); d-f: Reef structures constructed by placing oyster shells in gabion or metal cages (Photo credit: Brenda Walles, Mark Dumesnil, Mark Dumesnil); g-l: Reef structures constructed with concrete components (Photo credit: Megan La Peyre, Peter Kingsley-Smith, Megan La Peyre, Megan La Peyre, Megan La Peyre, M. Shah Nawaz Chowdhury).

The principles for selecting settlement substrate materials are as follows:

a) Choose materials that are as pollution-free, environmentally friendly, sturdy, durable, easily obtainable, and low-cost as possible;

b) Select and use settlement substrates based on their applicable scope and advantages and disadvantages; for oyster reef restoration projects aimed at ecological disaster mitigation, which are typically located in areas with fast-flowing water and high wave energy, it is recommended to use durable and heavy settlement substrates, such as stones, concrete components, or metal cages filled with oyster shells, to construct reef structures. Reef structures built with lightweight settlement substrates, such as loose oyster shells and small stones, have poor stability in such environments;

c) Conduct experiments on different settlement substrate materials and choose materials preferred by local oyster species for settlement.

(2) Preparation of Restoration Sites

In the context of oyster reef ecological restoration in the intertidal zone, site preparation is crucial before deploying settlement substrates to enhance oyster settlement rates. During ebb tides, it is essential to clear the intertidal zone of any debris and enemy organisms. If necessary, tidal channels should be cleared vertically along the coast, extending from the mid-tide zone to the low-tide zone. This clearing ensures smooth tidal flow, facilitates material transportation and management operations, and promotes reef stability. Site preparation activities should not extend into the subtidal zone, and restoration areas should preferably be chosen in regions with flat seabed topography.

(3) Placement of Artificial Reefs

Artificial oyster reefs should be positioned in the intertidal zone (with an average low tide level below 1m) to the subtidal zone (with a water depth of less than 10m at average low tide), or in areas where existing oyster reefs have been damaged. The optimal reef construction site, reef structure, and layout plan should be determined based on the specific restoration goals.

To enhance oyster settlement efficiency, the placement of artificial reefs should occur before the peak oyster settlement period or within one month before oyster transplantation.

For placement in intertidal or shallow water areas, reefs can be directly deployed from a platform during high tide or lowered into the sea from a crane, with manual sorting conducted on-site during low tide. For placement in deep-water areas, large reef components should be lifted from the sea surface to the seabed using a crane before releasing to improve placement accuracy and reef stability. For rock reefs, stone blocks can be transported by a stone dumper to the designated area for placement.

9.2.2 Oyster Recruitment

In environments with limited oyster populations, oyster recruitment is necessary.

Native oyster species should be selected whenever possible, and the choice between adult oysters or spat depends on the restoration requirements. Generally, large-scale restoration benefit from using oyster spat. Adult oysters can be sourced from locally farmed native species, while larvae can be cultivated in nurseries or harvested from natural marine areas. The transplantation of shellfish is the main pathway for the spread of invasive species and disease transmission, and shellfish transplantation between water bodies with different ecological environments should be avoided.

Fig.20 Schematic diagram of oyster settlement substrate

(Source: Quan Weimin, East China Sea Fisheries Research Institute,

Chinese Academy of Fishery Sciences)

9.2.2.1 Recruitment of Adult Oysters

Adult oysters can be sourced from raft-farmed oysters or artificially mudflat-raised native oyster species.

Transport immediately after catch. Generally, dry transportation is used, with temperatures kept below 15° C, protected from wind and sun during transportation, and transportation time within 10 hours, with a survival rate of over 95%. If the temperature exceeds 15° C, cover with grass curtains, etc., and carry seawater with the vehicle, regularly moistening the grass curtains with seawater during transportation to maintain a certain humidity for the oysters.

Individual oysters should be secured using mesh bags, mesh cages, or similar methods to prevent their dispersal by waves. Oysters cultivated on hanging ropes can have the ropes affixed directly to the reefs slated for restoration. Oysters fixed onto stone bars can be stacked directly or vertically erected in the restoration area. The specific placement method depends on the seabed type, and if the seabed is relatively firm, oysters can also be spread directly in the restoration area.

9.2.2.2 Recruitment of Oyster Spat

(1) Nursery Cultivation

Select parent oysters with uniform size, robust physique, undamaged shells, and free from disease. Typically, shells (oyster, scallop, clam, etc.) and small stone pieces serve as settlement substrates. Deployment of settlement substrates should precede oyster larvae metamorphosis. These substrates can be strung together and hung in pools or spread flat on the pool bottom. Spat density should be no less than 1 piece/cm^2. Under favorable conditions, spat can be moved to nearby sea areas for temporary rearing after settling for 5 to 7 days. When Crassostrea gigas, Crassostrea angulata, etc. reach an average shell length of 2 to 3 cm, and Crassostrea sikamea reach 1 to 2 cm, the settlement substrates are removed and transported to the restoration site. If the scale of restoration is too large to move juvenile shellfish to sea areas for temporary rearing, they can be reared directly in nursery ponds to the above size before transportation to the restoration site with the settlement substrate and larvae.

Fig.21 Preparation of substrate before spat settlement

(Photo Credit: Li Li and Wang Wei, Institute of Oceanology, Chinese Academy of Sciences)

Fig.22 Spat settlement in nursery pond

(Source: Li Ao, Institute of Oceanology, Chinese Academy of Sciences)

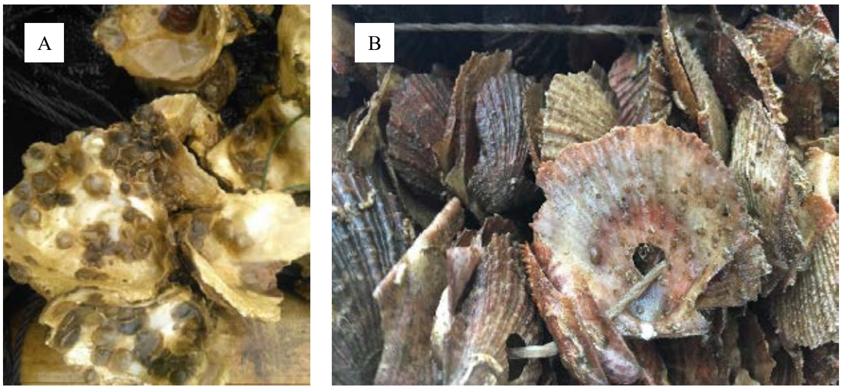


Fig.23 Settlement substrate with spats

(Source: A. Li Ao, Institute of Oceanology, Chinese Academy of Sciences; B. Wang Wei, Institute of Oceanology, Chinese Academy of Sciences)

(2) Semi-Artificial Collection of Spat in Natural Marine Areas

The selection of spat collection sites should prioritize areas with a distribution of oyster larvae and relatively calm wind and waves, typically in flat areas.

Different spat collection methods should be employed based on the substrate material. For soft mud bottoms, inserting stakes is suitable, while for harder sandy mud bottoms, throwing stones is preferable. Raft-style collection of spats does not require specific substrate conditions.

Settlement substrates are generally placed near the mid-low tide zone of the intertidal area, at a shallow water depth of approximately 0.4m. It is recommended that the substrate is exposed to air for no more than 4 hours during each high tide period.

The placement of settlement substrates should be timed within 7 days before the annual peak oyster breeding period. Different oyster species have varying peak breeding periods, and the ideal water temperature for spat collection also differs. The main oyster species used in reef construction in China have peak breeding period indicators detailed in the table below.

Table 4 Partial indicators of the peak breeding period for the main oyster species used in reef construction in China

Oyster species	Breeding period	Breeding Temperature and Salinity	
		Temp.	Salinity
Crassostrea hongkongensis	April to July September to November	24℃ ~31℃	3~20
Crassostrea angulata	April~October	22℃ ~30℃	20~30
Crassostrea gigas	May-August	20℃ ~26℃	20~30
Crassostrea sikamea	June-August	20℃ ~28℃	18~35
Crassostrea ariakensis	May-August	24℃ ~31℃	15~25

The effectiveness of spat collection should be assessed 4 days after the deployment of settlement substrates. Typically, the oyster density should exceed 1 piece/cm^2. If there is a predominance of barnacles with few oysters, the settlement substrates should be cleaned, and a repeat spat collection should be conducted.

Fig.24 Stone-based spat collection

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.25 Raft-based spat collection

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.26 Cement-made component spat collection

(Source: Sun Li, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.27 Scallop shell cage spat collection

(Source: Xu Fei, Institute of Oceanology, Chinese Academy of Sciences)

(3) Transportation

Spat and settlement substrates are transported together, typically using dry transportation methods. The settlement substrates are packed in boxes or loaded directly onto vehicles, and grass curtains are used to cover them. Spare seawater is carried on the vehicle, and the grass curtains are regularly moistened with seawater during transportation to keep the oysters moist. Transportation should be completed within 8 hours when the temperature is below 25 ℃ , and within 10 hours when the temperature is 7 ℃ ; under these conditions, the survival rate of oyster spat can still exceed 90%[13].

(4) Placement

For restoration areas located in the intertidal zone, spat and settlement substrates should be deposited together in the restoration area reefs during low tide, avoiding intense sunlight at noon. If necessary, use string bags, hemp ropes, or similar materials for fixation.

The general management period for restoration areas is 2 years or more.

Within 1 month after the completion of the oyster reef restoration project, measure the area of the oyster reef area and GPS positioning, draw a digital map of the oyster reef distribution, and set obvious signs around the reef.

Perform at least one routine maintenance check annually. Additionally, in the aftermath of severe events such as typhoons, storm surges, red tides, green tides, or instances of marine pollution, conduct an additional emergency maintenance assessment. Inspect the integrity and stability of artificial oyster reefs, and take remedial and restoration measures for overturned, damaged, and displaced artificial reefs. Check for siltation of mud and accumulation of debris on the surface and around the oyster reef, and carry out cleaning and maintenance work according to the degree of siltation.

Implement irregular measures such as capturing and driving away to remove predators, competitors, and invasive species of oysters.

Implement regular patrols and inspections to prevent harvesting and vandalism.

9.3 Aftercare measures

After the oyster reef restoration is completed, the general care period is more than 2 years.

Within 1 month after the completion of oyster reef restoration works, the area of oyster reef area shall be measured and GPS localization shall be carried out, digital maps of oyster reef distribution shall be drawn, and obvious markings shall be set up around the reefs. If conditions permit, a seine net can be arranged on the outside of the restoration area to prevent artificial oyster harvesting.

Carry out routine maintenance at least once a year, and add one emergency maintenance after strong typhoons, storm surges, red tides, green tides, marine pollution and other marine disaster events. Check the integrity and stability of artificial oyster reefs, and take remedial and repair measures for the artificial reefs that are overturned, damaged or displaced. Check the surface of oyster reefs and the surrounding silt and debris accumulation, depending on the degree of siltation to carry out appropriate cleaning and maintenance work.

Take measures to remove oyster predators, competitors and invasive organisms from time to time by catching and driving away.

Regularly patrol and inspect to prevent artificial harvesting and destruction. The restoration of subtidal oyster reefs in Xiangyun Bay, Hebei Province, can be referred to the experience of Tangshan Ocean Ranch Industry Co., Ltd. where the restoration body reached a cooperation agreement with a sea fishing company to jointly manage and protect the restored oyster reef habitats, and the sea fishing company can rely on the sea to organize and implement sea fishing activities; and the restoration pilot experience of the intertidal oyster reefs implemented by the Nature Conservancy and the East China Sea Fishery Research Institute of the Chinese Academy of Aquatic Sciences in Sanmen County, Zhejiang Province. In the pilot experience of oyster reef restoration, the restoration body reaches a cooperation agreement with the local community or nearby farmers and fishermen, and the local community or coastal people are responsible for caring for the restored oyster reefs, and consider that after the oyster reef community has been evaluated and stabilized, oysters can be appropriately harvested after the oyster reproduction period[14].

10. Follow-up Monitoring, Effect Assessment and Adaptive Management

To evaluate the ecological restoration effect, control areas and reference systems should be set up.

The control area is a selected area with a natural environment similar or close to the ecological restoration area and maintaining an appropriate distance. The distance between the control area and the restoration area should be determined according to the size of the restoration area, avoiding the impact of the ecological restoration project, generally 5 to 10 times the length or diameter of the restoration area from the edge of the restoration area.

Reference system refers to a specific ecological system that can serve as the target or benchmark for ecological restoration. It is advisable to select existing or historically well-developed oyster reef ecosystems in the sea area near or at a similar latitude to the restoration area as the reference system.

10.1 Ecological Restoration Monitoring

10.1.1 Monitoring Scope

The monitoring scope should cover the entire restoration area, control area, reference system, and should be expanded to the area that may be affected by the project implementation.

10.1.2 Monitoring Indicators and Monitoring Methods

The ecological restoration monitoring indicators for oyster reefs include four aspects: water environment, oyster reefs, biological communities, and other indicators. According to the requirements of oyster reef ecological restoration effect assessment, it is advisable to refer to but not limited to Table 5. Water environment samples should be collected on-site according to the requirements of Chapter 4 of GB 17378.3, but only one water layer 2m away from the bottom.

For oyster reef ecosystem restoration aimed at marine hazard mitigation, in addition to monitoring the growth and distribution of oyster reefs themselves, it is also important to focus on monitoring environmental indicators related to disaster mitigation effectiveness, including hydrodynamic environments such as water level/tide level, flow rate, flow direction, wave height attenuation rate; and topographic features such as water depth, slope, and shoreline erosion rate.

Table 5: Monitoring Indicators and Monitoring Methods for Oyster Reef Ecological Restoration

Type of indicator	Monitoring indicators	Monitoring Methods	Scope of application		
			Routine monitoring	Assessment of the achievement of project objectives	Ecosystem restoration effectiveness assessment
Water environment	Water temperature	Use the temperature-salinity-depth gauge method or the inverted temperature method as determined by GB/T12763.2 to measure only the temperature of the bottom seawater	★		
	Salinity	Use the temperature-salinity-depth gauge method or the salinometer method as determined by GB 17378.4 to measure only the salinity of the bottom seawater	★		
	Dissolved oxygen	Use the iodometric method as determined by GB 17378.4 or use a dissolved oxygen meter	★		
	pH value	Use the pH meter method as determined by GB 17378.4.	★		
	Chlorophyll-a	Use the fluorescence spectrophotometry method or the spectrophotometry method as determined by GB 17378.7.		★	★

Type of indicator	Monitoring indicators	Monitoring Methods	Scope of application		
			Routine monitoring	Assessment of the achievement of project objectives	Ecosystem restoration effectiveness assessment
Water environment	Active phosphate	Use the Phospho-molybdenum blue method as determined by GB 17378.4		★	★
	Nitrate	Use the cadmium column reduction method and the zinc-cadmium reduction method as determined by GB 17378.4		★	★
	Nitrite	Use the naphthyl ethylenediamine dihydrochloride spectrophotometry method as determined by GB 17378.4		★	★
	Ammonium salt	Use the indophenol blue spectrophotometry method or the hypo bromate oxidimetry method as determined by GB 17378.4		★	★
	Turbidity	Use the turbidimeter method as determined by GB 17378.4		★	★
	Suspension	Use the weight method as determined by GB 17378.4		★	★
Oyster reef	Oyster reef patch size	Refer to section 5.3.2 of this document	★	★	★
	Reef area	Refer to section 5.3.2 of this document	★	★	★
	Reef height	Refer to section 5.3.2 of this document	★		★
	Oyster density	Refer to section 5.3.2 of this document	★	★	★
	Oyster recruitment	Refer to section 5.3.2 of this document	★	★	★

Type of indicator	Monitoring indicators	Monitoring Methods	Scope of application		
			Routine monitoring	Assessment of the achievement of project objectives	Ecosystem restoration effectiveness assessment
Oyster reef	Plumpness of oysters	Randomly select no less than 10 adult oysters at each station. After prying open the shells, dry the soft tissue until constant weight is achieved and measure the dry meat weight. Remove parasites and impurities from the oyster shells, dry until constant weight is achieved, and measure the dry shell weight. Calculate the oyster plumpness according to formula (1). $C = \frac{F}{B} \times 100\%$ .... (1) In the formula: C --Oyster plumpness; F -Dry meat weight of oysters in grams (g); B -Oyster dry shell weight in grams (g).	★		★
	Shell height	Refer to section 4.2.3 of this document	★		★
Other biomes	Composition, number, and density of macrobenthos	Per GB/T 12763.6		★	★
	Oyster predators and competitors	Per GB/T 12763.6	★		
Other indicators	Sediment and debris coverage	Use visual inspection to determine the coverage of sediment and debris, and estimate the percentage of sediment and debris coverage area to the area of the oyster reef patch.	★		

Type of indicator	Monitoring indicators	Monitoring Methods	Scope of application		
			Routine monitoring	Assessment of the achievement of project objectives	Ecosystem restoration effectiveness assessment
Other indicators	Artificial reef retention rate	Visually assess the current state of the artificial reef and estimate whether the artificial reef can meet the conditions for oyster growth and reef building, considering it to be in an effective state. Calculate the percentage of artificial reef in the survey area that are in an effective state to the total number of artificial reefs deployed.	★	★	
Note: "★" indicates applicable.					

10.1.3 Monitoring Stations

The layout of monitoring stations should follow the following principles:

a) Not less than 3 monitoring stations should be set up in the restoration area, control area, reference system, and areas that may be affected by the restoration project;

b) The station setup should be representative, and the number of stations should meet the requirements of the assessment of the ecological restoration effect of oyster reefs;

c) For oyster reef patches that cannot be covered by sections, separate stations should be set up.

10.1.4 Monitoring Duration and Frequency

(1) Monitoring Duration

Ecological restoration monitoring should cover the different stages of the ecological system before, during, and after the implementation of ecological restoration. If ecological monitoring does not involve a control area, ecological monitoring should start before the implementation of ecological restoration measures, and at least one ecological monitoring should be conducted in the restoration area; if a control area is used to represent the pre-restoration status of the ecological restoration area, synchronous monitoring of the restoration area and the control area can be conducted after restoration.

If environmental monitoring of surrounding areas is conducted during the implementation of the restoration project, it should be carried out in accordance with the requirements of the "Technical Regulations for Environmental Impact Tracking and Monitoring of Construction Projects in the Marine Environment."

After the implementation of the oyster reef ecological restoration project, the time span of the follow-up monitoring is consistent with the time for achieving the restoration objectives, providing monitoring data for evaluating the achievement of the restoration objectives. The monitoring time for biological communities and habitat conditions can be set at 10 years, and it is appropriate to monitor ecological functions for 20 years. If the conditions for conducting long-term follow-up monitoring are not met, the monitoring period can be set at 5 years to meet the needs of short-term objective evaluation.

Monitoring of the reference system and the control area should be conducted for at least 1 year; when conditions permit, the monitoring period can be the same as that of the follow-up monitoring in the restoration area.

(2) Monitoring Frequency

For ecological restoration projects mainly focusing on recruiting oysters, within 1 year after the completion of the project, oyster survival rate should be monitored every 3 months. For ecological restoration projects mainly focusing on placing settlement substrates, within the same year after the completion of the project, oyster density should be monitored every month within 3 months after the peak of oyster reproduction.

In the early stage of oyster reef ecological restoration (within 2-5 years), ecological monitoring should be conducted annually, with at least one monitoring per year. The monitoring intensity of threat factors should be set according to the type of threat factors.

The monitoring time and frequency of mid- and long-term monitoring of oyster reef ecological restoration should be determined according to demand.

If the ecological restoration project sets phased objectives, the monitoring frequency should also be set based on the time for achieving the phased objectives.

Fig.28 Monitoring of the Settlement Effect of Artificial Reef Structures

(Source: Cheng Jie, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.29 Monitoring of the Settlement Effect of Artificial Reef Structures

(Source: Cheng Jie, Second Institute of Oceanography, Ministry of Natural Resources)

Fig.30 Biomass Assessment of Newly Formed Natural Oyster Reef Areas

(Source: Wang Wei, Institute of Oceanology, Chinese Academy of Sciences)

10.2 Ecological Restoration Effect Assessment

10.2.1 Assessment Content

Based on the phased objectives, medium- and long-term goals of ecological restoration, and the progress of ecological restoration monitoring, conduct phased and final assessments of the ecological system restoration effect. Select the content of ecological restoration effect assessment according to the actual project circumstances. The assessment may include, but is not limited to:

Restoration of oyster reef area;

Restoration of biological communities;

Restoration of habitat conditions;

Wave attenuation and disaster mitigation;

Elimination of threat factors;

Restoration of important ecological functions.

The assessment of oyster reef ecological restoration effect should be based on the predetermined indicators set before the implementation of the ecological restoration project. The assessment indicators should correspond to the monitoring parameters, and the calculation methods should be clearly defined.

Within 5 years after completing the ecological restoration project, focus on evaluating the recovery of oyster populations, the restoration of biological communities, the degree of coastal disaster prevention and mitigation, the effectiveness of threat elimination, etc. For oyster reef ecosystem restoration aimed at marine hazard mitigation, the effect assessment should focus on selecting indicators such as wave height attenuation rate and coastal erosion rate.

Five years after the completion of the ecological restoration project, it is recommended to intensify the evaluation of crucial ecological processes and functions, such as ecosystem maturity, biodiversity maintenance, and the self-replenishment capacity of oyster reefs.

10.2.2 Assessment Methods

Each assessment indicator utilizes the average value from all monitoring stations as the assessment result for the restoration area. The assessment of ecological restoration effects can be conducted based on the results of ecological restoration monitoring, focusing on two aspects: improvement and enhancement assessment of ecological system indicators, and the achievement of ecological restoration goals. The assessment methods can be referenced from T/CAOE 21.6-2020.

(1) Target Value Determination

The determination of the target value should follow the following principles:

When evaluating the achievement of project objectives, the anticipated effect indicator values set before, during, or after the project implementation should be utilized as target values.

When evaluating the restoration effect of the ecosystem, the monitoring values of the reference ecosystem baseline should be employed as the target values;

In cases where the reference system is a historically well-developed oyster reef ecosystem, historical data should serve as the basis, with expert evaluation guiding its use as the target value

If target values cannot be obtained from the reference system for assessment indicators, the maximum value of the indicator or data from relevant literature can be used as the target value

(2) Improvement and Enhancement Assessment of Ecological System Indicators

Ecological restoration projects can assess the improvement and enhancement of ecological system indicators by comparing the current status values of assessment indicators with the pre-restoration status values or the current status values of the reference ecosystem. This assessment method allows for the analysis of changes and trends in each indicator, reflecting the improvement of the ecological system and the enhancement of its functions.

(3) Degree of Achievement of Ecological Restoration Goals

For assessment indicators with clearly defined restoration target values, the achievement of ecological restoration goals is determined by comparing the current status values of relevant indicators with the target values. If no target values for assessment indicators are set during the restoration target setting stage, the current status values of assessment indicators can be compared with the status values of the reference system. When these indicators reach or approach the status of the reference system, it can be considered that the ecosystem has been restored.

When assessing the degree of achievement of ecological restoration objectives, indicators that have not shown significant restoration may undergo further analysis through expert consultation or surveys and experiments to determine whether they are still in a degraded state or are adversely affecting ecosystem restoration.

Based on the objectives, indicator selection, and achievement assessment methods of ecological disaster mitigation and restoration projects, formulate corresponding monitoring plans for evaluation and analysis.

10.3 Adaptive Management

Based on the results of ecological system indicators improvement and enhancement assessment, the achievement of ecological restoration objectives, and routine monitoring indicators, the effectiveness of oyster reef ecological restoration measures can be comprehensively analyzed, and adaptive management can be carried out with reference to the 0 for adaptive management.

Table 6 Explanation of Assessment Results and Adaptive Management Measures

Purpose of the assessment	assessment level	Grading explanation	Adaptive management measures
Assessment of the degree of achievement of ecological restoration goals	I	Ecological restoration measures are effective and the oyster reef ecological restoration project has reached its expected goals.	Continue to implement oyster reef ecological restoration projects according to the implementation plan.
	II	Ecological restoration measures are effective, and the oyster reef ecological restoration project has basically realized its expected goals	The reasons that may affect the realization of the project objectives are analyzed in the light of the results of the assessment of the regular monitoring indicators and the achievement of the indicators. If the impact is not due to force majeure factors, ecological restoration measures that may have an impact will be fine-tuned and implemented after expert verification.

Purpose of the assessment	assessment level	Grading explanation	Adaptive management measures
Assessment of the degree of achievement of ecological restoration goals	III	Ecological restoration measures have had some positive effects, but the oyster reef ecological restoration project has not achieved its intended goals	Combined with the results of the assessment of the regular monitoring indicators and the achievement of the indicators, the reasons affecting the achievement of the project objectives shall be analyzed. If the impact is not due to force majeure factors, the ecological restoration measures causing the impact shall be appropriately adjusted and, after expert verification, reported to the competent project department for agreement before implementation.
	IV	Ecological restoration measures are largely ineffective, and the oyster reef ecological restoration project has not achieved its intended goals, and may not even be able to achieve them	Combine the results of the assessment of the regular monitoring indicators and the achievement of the indicators, analyze the reasons affecting the achievement of the project objectives, and demonstrate the feasibility of continuing the implementation of the ecological restoration project. If feasible, adjust the ecological restoration program and, after expert verification, submit it to the competent project department for approval before implementation.

Purpose of the assessment	assessment level	Grading explanation	Adaptive management measures
Ecosystem Indicator Improvement and Enhancement Assessment	I	Oyster reef ecosystems are better restored and moving towards stabilized ecosystems	Analyze the stability of the oyster reef ecosystem and whether the ecosystem has the ability to restore itself. Decide whether it is necessary to continue the ecological restoration measures after expert verification.
	II	Oyster reef ecosystems are better restored, but not at reference system levels	Retain and continue to implement existing ecological restoration measures.
Ecosystem Indicator Improvement and Enhancement Assessment	III	Oyster reef ecosystems are not well restored and fall short of reference levels	Make appropriate adjustments to the ecological restoration measures and implement them after modification by expert verification.
	IV	Ecological restoration measures have not worked and oyster reef ecosystems have remained largely unimproved or even deteriorated	Adjust the ecological restoration plan and implement it after the modification by expert verification.

According to different types of restoration methods and restoration stages, various improvement measures can be adopted. Based on the assessment of ecological restoration effects, the effectiveness of restoration techniques will be evaluated. For those with unsatisfactory results or unachieved objectives, an analysis will be conducted to determine the reasons for the failure. Restoration measures and techniques will be adjusted accordingly, and new ones may be introduced if necessary.

Different improvement measures that can be taken for various restoration methods:

a) Naturally Restored Oyster Reefs

For ecological restoration projects using natural restoration methods, if the oyster population in the restoration area does not reach the desired target, a small number of adult oysters or spat of the same species can be recruited.

b) Artificially Assisted and Reconstructive Restorations

For restoration projects that recruit adult oysters, regular monitoring of oyster mortality and spat settlement should be conducted within one year after project implementation. If the mortality rate of adult oysters exceeds 50%, it is advisable to recruit additional adult oysters. If the number of larvae settlements is low after the peak oyster breeding period, consider changing the source of adult oysters and introducing them before the next year's peak oyster breeding period.

For restoration projects that recruit spat, the mortality rate of spat should be monitored once a month within three months after project implementation. If the mortality rate of spat exceeds 75%, it is advisable to recruit additional spat. When recruiting spat again, consider changing the source of spat, such as changing the parent oyster source in the nursery, or changing the location of spat collection.

For restoration projects that deploy settlement substrates, monitor the settlement of spat after the peak oyster breeding period. If the settlement effect of spat is poor, consider changing the settlement substrate.

11.Oyster Reef Restoration Cases

11.1 Case1—Oyster Reef Ecosystem Restoration Project aimed at Marine Hazard Mitigation in Alabama, USA

Oyster reefs are increasingly recognized as natural infrastructure and are being utilized in coastal protection and ecological shoreline construction projects. For instance, the oyster reef ecosystem restoration project for marine hazard mitigation in Alabama, USA, aimed to safeguard the coastline and mitigate shoreline erosion (refer to Appendix 2 for details). The San Francisco Bay Ecological Shoreline Pilot Project also restored oyster reefs and seagrass beds in the intertidal to near—subtidal zones, resulting in increased biodiversity and a 30% reduction in wave energy [15]. Another study conducted oyster reef restoration experiments on eroded intertidal mudflats on Kutubdia Island, Southeastern Coast of Bangladesh. Monitoring revealed a 54% reduction in erosion on the landward side of the oyster reef in the experimental area compared to the control area, effectively enhancing mudflat stability and promoting salt marsh expansion[16].

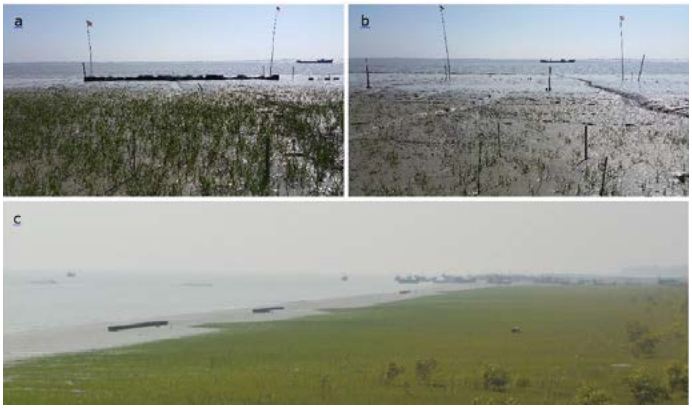


Fig.31 Differences in salt marsh plant growth between oyster reefs taken in December 2017 on Kutubdia Island, southeast coast of Bangladesh (a) and control areas (b), as well as seaward expansion of salt marshes taken in February 2019 (Source: Chowdhury et al., 2019)

11.1.1 Environmental Situation

Alabama, USA, situated in the northern Gulf of Mexico, was historically home to subtidal oyster reefs towering over 3 meters along its coastlines. These reefs acted as natural barriers, shielding the salt marsh wetlands from wave erosion and creating a conducive environment for the growth of seagrass beds, consequently maintaining clean water conditions [17]. However, the region underwent significant degradation due to consecutive droughts and the presence of oyster predators (such as the Urosalpinx cinerea), leading to physical destruction and sediment accumulation. Studies suggest that the oyster reefs in the Gulf of Mexico have dwindled by at least 50% compared to historical records[18], with the 2010 Deepwater Horizon oil spill exacerbating the situation. This environmental catastrophe resulted in the direct loss or reproductive failure of approximately 4 to 8.3 billion adult oysters[19], necessitating a $160 million restoration fund for the local oyster natural resources. The decline of oyster reefs has also contributed to the deterioration of salt marshes, seagrass beds, and tidal flats due to coastal erosion. In some areas of Alabama, the shoreline retreats at a rate of up to 1.86 meters per year[20], which, combined with the state's 600-mile coastline, translating to a projected loss of 18,000 acres of land valued at $1.8 billion over fifty years[21].

11.1.2 Restoration Goals

In response to these challenges, the Restore Coastal Alabama Partnership, comprising the Nature Conservancy (TNC), the Alabama Coastal Foundation, Mobile Baykeeper, and the Ocean Foundation, initiated the" 100-1000: Restore Coastal Alabama Partnership" project. The goal is to stabilize the coastline by restoring 100 miles of oyster reefs, thus facilitating the recovery of 1000 acres of salt marshes and seagrass beds. This endeavor not only aims to provide habitats for marine life but also seeks to create sustainable development opportunities for local fishing communities [22].

11.1.3 Implementation of Restoration

(1) Restoration Planning and Methods

After extensive deliberations and utilizing the "Coast Resilience" tool, the project conducted simulations and analyses based on the local bay's disaster risk, ecological conditions favorable for oyster reef habitat restoration, and socio-economic factors. This process identified optimal locations for the Oyster Reef Ecosystem Restoration Project aimed at Marine Hazard Mitigation (i.e., constructing breakwaters composed of oyster reefs) to achieve maximum wave energy reduction and optimize protection of coastal properties.

(2) Reef Construction

Since 2011, the project team has designed and deployed oyster reef "breakwaters" at various sites. This includes 3295 Reef Balls™ (as shown in Figure 2-1A), 14,000 Oyster Castles, 190,000 oyster shell bags (as shown in Figure 2-1B), and 489 ReefblkSM oyster cage arrays (as shown in Figure 2-1C), totaling 3600 meters in length. The construction phase involved significant engagement from the local community, with over 1500 local volunteers contributing to the project's execution.

(A) (B) (C)

Fig.32: Oyster Reef Breakwater Construction in Alabama using (A) Reef Balls™, (B) Oyster Shell Bags, and (C) Oyster Cage Arrays (ReefblkSM), photo credit: (A) and (B) Erika Nortemann/TNC; (C) Beth Maynor Young.

(3) Monitoring of Restoration Effects

Subsequent continuous monitoring has demonstrated that the Oyster Reef Ecosystem Restoration Project aimed at Marine Hazard Mitigation in Alabama has effectively mitigated coastal erosion. For instance, the approximately 840-meter-long oyster reef breakwater constructed at Alabama Port has facilitated the inland expansion of seagrass beds and salt marsh wetlands landward, thereby reducing wave erosion along the coastline. The breakwater–like oyster reef deployed at Swift Tract has effectively reduced the rate of coastal erosion. After four years of growth, the erosion rate decreased from a historical average (1957–1981) of 0.35 m yr−1to 0.02 m yr−1[21]. Apart from the disaster prevention and mitigation benefits, the project has generated job opportunities for the local community during implementation, stimulating sales in industries such as cement manufacturing. Furthermore, unlike traditional hard structures like seawalls for coastal protection, restored oyster reefs also serve as habitats for economically valuable fish, shrimp, crabs, and other organisms, thereby promoting local commercial fishing and related industries such as recreational fishing. Currently, the method of restoring oyster reef ecosystems for marine hazard mitigation is being applied in other areas along the Gulf of Mexico coast, safeguarding local shorelines and infrastructure[22].

Fig.33 Oyster Reef Ecosystem Restoration for Marine Hazard Mitigation along the Coast of Louisiana, USA, using a similar breakwater design as in Alabama, photo credit: Erika Nortemann/TNC.

11.2 Case2—Xiangyun Bay Oyster and Seaweed Reef Ecosystem Restoration Project

11.2.1 Implementation of Restoration

Xiangyun Bay is located in the Bohai Sea vertical warm current zone and the Luan River confluence, for the muddy sandy seabed, water depth of 6 to 15 meters, good water exchange conditions, historically used to be the mouth of the Luan River fishery, fishing disappeared in the 80s of the last century. Historically, the northwestern coast of Bohai Bay, the development of ancient oyster reefs[23], known as the "oyster reef plains", is the world's three famous oyster reef groups. The ancient oyster reefs of Dawuzhuang, Hai District, Tangshan City, are as thick as 6 meters, with 25 species and genera of diatoms distributed. According to a preliminary survey conducted in 2019, there are still about 14.5 km^2 of natural oyster reefs in the Tangshan anadromous estuary and coastal areas, where oysters and macroalgae coexist.

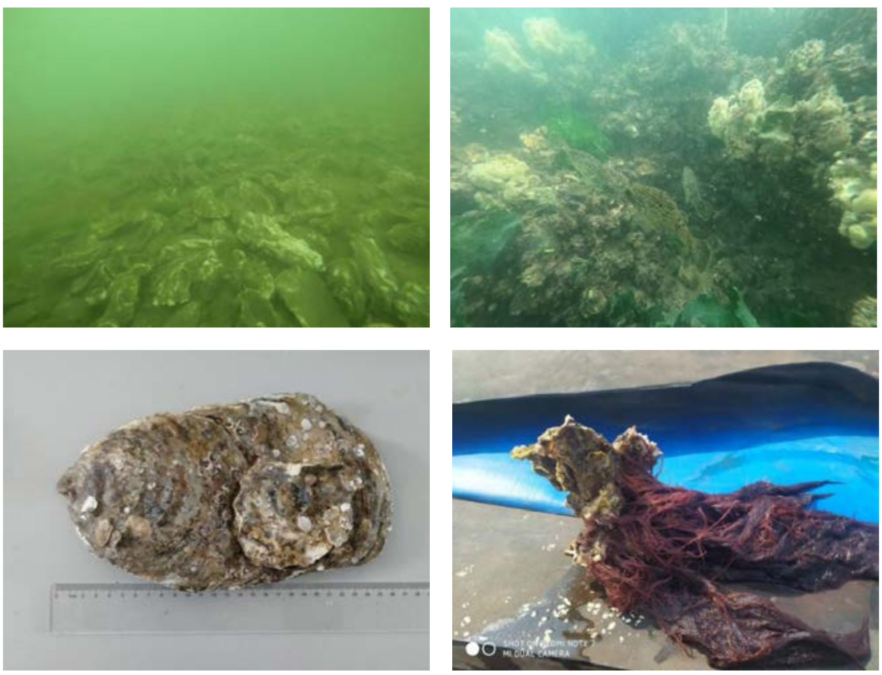


Fig.34 Status map of natural oyster reefs in Xiangyun Bay（Source：Zhang Yunling,Hebei Provincial Technology Innovation Center for Coastal Ecology Rehabilitation）

11.2.2 Restoration goals

Since 2009, Tangshan Ocean Ranch Co., Ltd. has been trying to build a marine ranch by putting artificial reefs to construct seaweed farms and utilizing the natural marine ecosystem, and since 2016, in order to create a healthy composite ecosystem centered on live oyster reefs and large-scale seaweed farms, and characterized by naturalness, connectivity, mutualism, and recycling, it has implemented ecological restoration work targeting the three ecosystems: oyster reefs, seaweed farms, and seagrass beds. The ecological restoration of oyster reefs, seaweed farms and seagrass beds has been implemented.

11.2.3 Rehabilitation implementation

(1) Restoration Program

The oyster species in Xiangyun Bay are mainly long oysters. As there is sufficient oyster and seaweed replenishment in Xiangyun Bay, the restoration technique is based on putting in attachment bases, supplemented by artificial replenishment of wild oyster seedlings. In addition, the biomass of seaweeds was increased by throwing macroalgae spores and macroalgae transplantation.

(2) Reef construction

The types of attachment bases experimentally placed include floating raft net reefs, scrapped fishing boats, stones, steel caissons, steel plate frames, cement components and various combined reefs. The best results for oyster and seaweed attachment were obtained from rock pile reefs, steel framed rock combination reefs, and cement component reefs.

The reefs are laid out in a "point-line-surface" arrangement. Reefs cover about 10% of the total reef area. The point reef layout is to use the steel frame rock attached reef and 16 holes of small and medium-sized caisson reef, attached diatoms, seaweed retention, gathering debris food. Line reef layout is to use granite rocks to build a strip-type oyster and seaweed reef, change the original habitat lack of oyster and seaweed attached to the base condition, and reduce turbulence and waves. Point reefs and line reefs are spaced apart to form a complete surface reef placement layout.

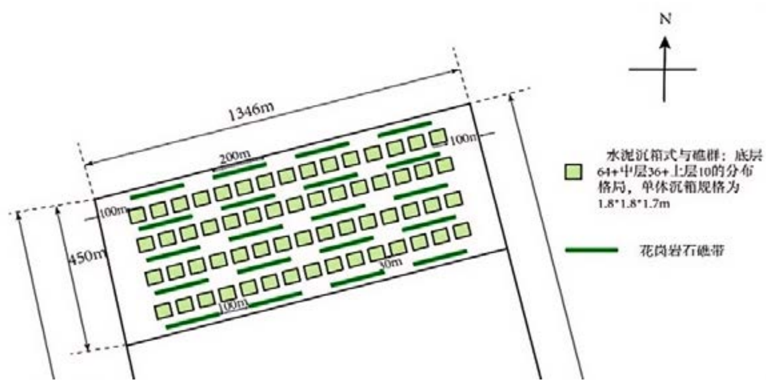


Fig.35 Schematic diagram of the "point-line-plane" layout of a oyster and seaweed reef (Source：Zhang Yunling,Hebei Provincial Technology Innovation Center for Coastal Ecology Rehabilitation)

(3) Restoration effect monitoring

Until 2018, Tangshan Sea Ranch restored a total of 3213.5 acres of oyster and seaweed reefs, experimented with 4 major categories and more than 20 types of reefs, and put in 770,000 empty square meters of artificial reefs. Three years after the end of the oyster and seaweed reef restoration project, the monitored shellfish therein were mainly oysters, and the seaweed included Sargassum, Ulva forskohlii, and Undaria pinnatifida, etc. The average density of oysters was 187, which was the highest in the world. The average oyster density reached 187 oysters/m^2, the biomass of macroalgae was about 145g/m^2 wet weight, and the seaweed coverage reached more than 15%. The scale of the oyster and seaweed reef ecosystem was assessed to be much larger than that of the early ecosystem, with a 5-fold increase in total system energy circulation, a 4-fold increase in total primary productivity, a 4.3-fold increase in total productivity, and a 42.3-fold increase in total biomass. The average path length of the food chain in the reef ecosystem increased by 20%, and the diversity of energy flow paths increased by 47%. The energy transfer efficiency between trophic levels I-II was 87%, an increase of 1.9 times compared with the pre-restoration period, which was much higher than the energy transfer efficiency value of 10% in general natural ecosystems, and the energy transfer efficiency between trophic levels II–III was 10%, an increase of 4.9 times, which was up to the energy transfer efficiency value of general natural ecosystems.

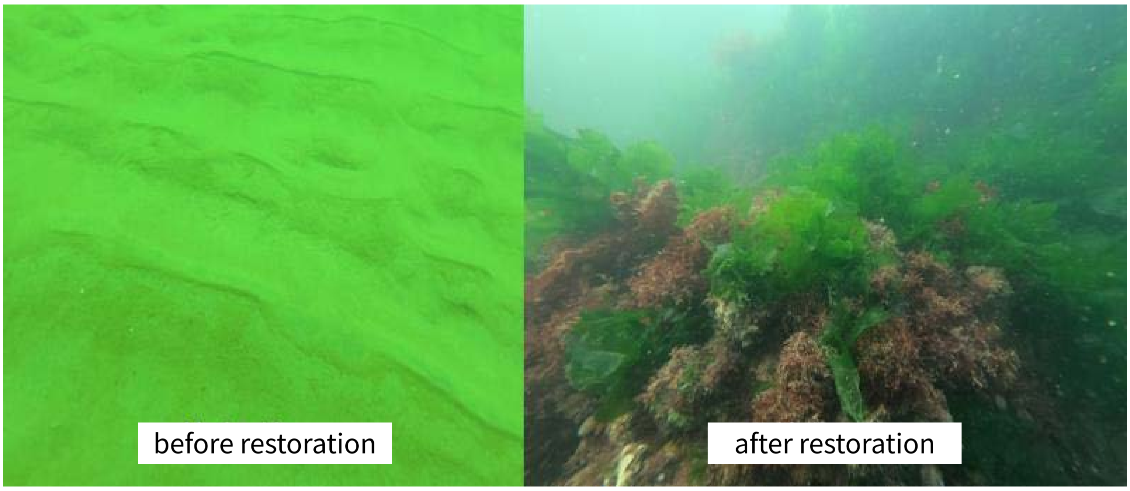


Fig.36 Comparison of oyster and seaweed reefs in Xiangyun Bay before and after restoration
(Photo credit: Hebei Offshore Ecological Restoration Technology Innovation Centre, Zhang Yunling)

11.3 Case3—Restoration of oyster reefs for offshore oysters in Laizhou Bay, Shouguang City, Weifang, China

11.3.1 Environmental situation

The project is located in Laohekou area of Shouguang City, Weifang City, more than 20 years ago, the local oyster species are mainly near-river oysters, which are distributed in the riverbed and near the mouth of the estuary where the water flows freely below the low-tide line of the estuarine low-salt waters, and are exposed at the time of high tide and low tide. Since the substrate of this sea area is mostly mud and sand, there is no fixed base, oysters are fixed in individual shells, and over time, they form clumps, which are similar to reefs, and local fishermen call them "oyster mountains". There are oysters distributed in the nearby branch ditches, Xiaoqing River, Old River, Weifang River, JiaoLai River, etc., with a distribution area of about $80hm^2$ and a total amount of resources of about 0.95×10^4t; among them, oysters are most densely distributed in the vicinity of the Old Estuary area.

In recent years, due to the development of industry and agriculture in the coastal zone and the expansion of urban land, the coastal shallow water area has been developed into aquatic land, salt land, construction land, etc., and the area of mudflat wetland has been reduced; and the rapid development of the economy in the coastal area has led to the increase of the total amount of pollutants entering the sea in the area, the turbidity of the water body and the serious eutrophication, and the massive reduction of the number of oysters in the near river, which has led to the degradation of the local ecosystems of oyster reefs and the decrease of biodiversity, and only part of the protected areas have been reduced. As a result, the local oyster reef ecosystem has been degraded and the biodiversity has been reduced, and there is only a small amount of distribution in some protected areas.

11.3.2 Restoration goals

In response to the increasingly severe situation of marine ecological protection, the Weifang Municipal People's Government, Weifang Municipal Bureau of Marine

Development and Fisheries, and Shouguang Municipal Marine Fisheries Development Center have organized the declaration and implementation of the Weifang Marine Ecological Protection and Restoration Project for 2021, with the aim of restoring the degraded near-river oyster reef clusters at the site, strengthening the disaster prevention and mitigation capacity of the area, increasing biodiversity, and improving the function of ecosystem services.

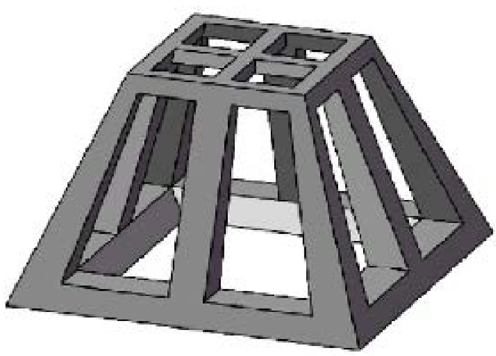
11.3.3 Project implementation

(1) Project Design

Based on the environmental survey of the project area, Shandong Qinghai Ecological Environment Research Institute Co., Ltd. designed to put basalt artificial reefs and oyster seedling attachment bases according to the substrate and existing oyster reefs, in order to increase the amount of oyster attachment carriers and seedling replenishment, and to improve the restoration effect.

(2) Project Implementation

The project has been implemented since May 2022, using two types of basalt artificial reefs (Figure 37) and tying inshore oyster restoration units on the surface of the reefs, with each unit consisting of 30 pieces of inshore oyster attachment substrate on a 3-meter-long basalt rope string (Figure 38). A total of 19,200 reefs were deployed, with 10 million pieces of near-river oyster larvae attached, a reef deployment area of 33 ha, and an oyster reef restoration area of 107 ha.



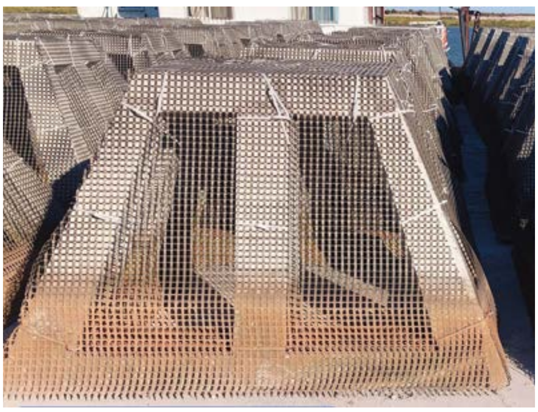


Fig.37 basalt artificial reef

(Source：Ma Xiufen, Shandong Qinghai ECOLOGY AND ENVIRONMENT research Institute co., ltd.)

Fig.38 Oyster Oyster Seedling Attachment

(Source：Ma Xiufen, Shandong Qinghai ECOLOGY AND ENVIRONMENT research Institute co., ltd.)

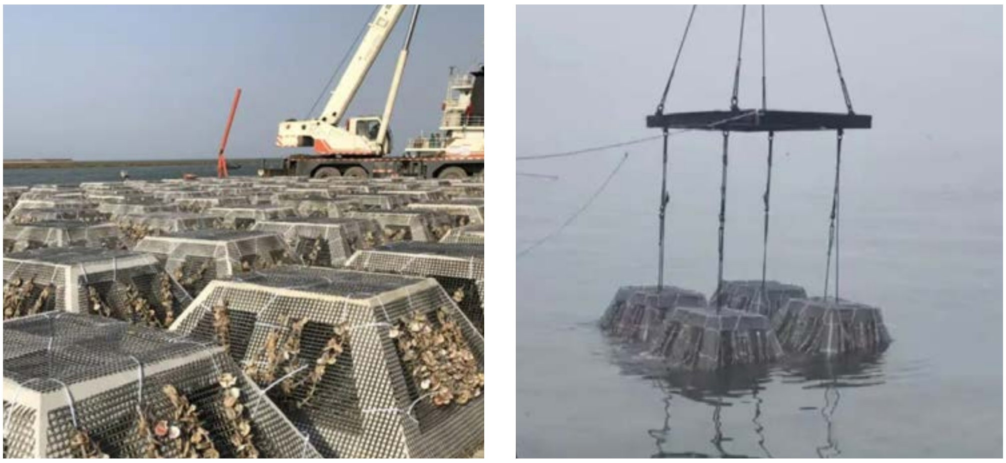


Fig. 39 Restoration implementation site

(Source：Ma Xiufen, Shandong Qinghai ECOLOGY AND ENVIRONMENT research Institute co., ltd.)

(4) Tracking and monitoring of restoration effect

One year after the implementation of the project, the restoration effect has been preliminarily shown, according to the monitoring results, the density of oysters in the near river in the project area is 338 oysters/m^2, the oyster replenishment is 56 oysters/m^2, and the average survival rate is 79.00%.

Fig. 40 Aerial view of restored Konoha oyster reef area

(Source：Lan Siqun, Shandong Qinghai ECOLOGY AND ENVIRONMENT research Institute co., ltd.)

After the restoration of the near-river oyster reefs, the three-dimensional structure of the oyster reefs provides a good habitat and foraging place for other aquatic organisms, and the biodiversity in the project area has been significantly improved, with schools of perch and golden seahorses appearing one after another, which promotes the benign cycle of the ecosystem.

Fig. 41 Marine life inside an oyster reef in Omi River

(Source：Lan Siqun, Shandong Qinghai ECOLOGY AND ENVIRONMENT research Institute co., ltd.)

11.4 Case4—Oyster Reef Restoration in the Yangtze River Estuary[23]

The restoration of oyster reefs in the Yangtze River Estuary commenced in 2004 to mitigate the damage and depletion of estuarine biological resources and fish habitats caused by the construction of the deep-water channel regulation project. The scientific team from the East China Sea Fisheries Research Institute of the Chinese Academy of Fishery Sciences proposed an innovative approach by utilizing the concrete modules of the deep-water channel regulation project's waterworks (North and South guide banks and dike) in the Yangtze River Estuary as substrates for oyster settlement. By propagating 50 tons of artificially cultivated near-river oyster parents, China's first artificial oyster reef ecosystem was established, covering an area of 26 hm^2.

Continuous monitoring from 2005 to 2010 revealed the establishment of a self-sustaining population of near-river oysters in the Yangtze River Estuary. Oyster density ranged from 400 to 800 individuals/m^2, biomass (fresh meat weight) ranged from 2000 to 3000 g/m^2, with a total of 59 billion oysters and a total weight of 1.06 million tons.

Fig.42 Restored oyster reef in the Yangtze River Estuary
(Source: Quan Weimin, East China Sea Fisheries Research Institute of the Chinese Academy of Fishery Sciences)

Appendix: Common Oyster Species and Distribution of Oyster Reefs along China's Coastline

Currently, there are more than 30 known species of oysters distributed along China's coast[24-30]. The main species of oysters in the genus *Crassostrea* are mainly *Crassostrea gigas*, *Crassostrea angulata*, *Crassostrea hongkongensis*, *Crassostrea sikamea*, *Crassostrea ariakensis*, *Crassostrea nippona*, and *Crassostrea iredalei*. These are mostly important farmed oyster species in China and are also common oyster reef species [31、32]. The main distribution is shown in Figure 43 and Table 7. Species of the genus Saccostrea, such as *Saccostrea echinata* and *Saccostrea mordax*, are common oyster species in the southern coastal areas of China and are distributed from Fujian to the south, but there have been no reports of these oysters in the coastal areas north of the Yangtze River[33-35]. *Ostrea denselamellosa* of the genus *Ostrea* generally inhabits shallow seas with relatively high and stable salinity below the tidal zone to a depth of 30 meters. It is distributed in both the South and North China Seas, but there are few investigations and assessments specifically targeting Ostrea denselamellosa, so the specific di

Fig. 43 Distribution of oyster species of the Crassostrea genus along the coast of China, Source: Institute of Oceanology, Chinese Academy of Sciences, copied by Luo Yongmei in 2022 (Review No. GS Jing(2022)0140). Cited in Oyster Reef Habitat Conservation and Restoration in China/The Nature Conservancy (TNC).

Table 7 Main distribution areas of several common oyster species in China

No.	Oyster species	Species Characteristics	Main Distribution Areas:
1	*Crassostrea ariakensis*	Low-salinity, wide-temperature, widely-distributed species	From the mouth of the Yalu River to the coast of Hainan, in estuaries, bays, and shallow sea areas from the low tide line to a depth of 10 meters with low salinity
2	*Crassostrea gigas*	Wide-temperature species	From Liaoning to Jiangsu coast, in intertidal zones to shallow sea areas up to 10 meters deep.
3	*Ostrea denselamellosa*	Wide-temperature, widely-distributed species	Distributed along the coast north of Guangdong, mainly growing in shallow sea areas with higher and stable salinity from the subtidal zone to a depth of 30 meters.
4	*Crassostrea sikamea*	Subtropical species	Coastal bays and intertidal zones south of Nantong, Jiangsu
5	*Crassostrea angulata*	Subtropical species	Coastal areas south of Zhejiang, from intertidal zones to shallow sea areas up to 10 meters deep, with the core distribution areas being Guangdong and Fujian
6	*Crassostrea hongkongensis*	Subtropical species	Coastal areas of Guangdong, Guangxi, and Hainan, from intertidal zones to shallow sea areas up to 10 meters deep
7	*Saccostrea. echinata*	Subtropical species	Intertidal zones in coastal areas south of Zhejiang

China has not yet carried out a comprehensive survey on the distribution of oyster reefs, but it is known that there are oyster reefs in Bohai Bay, the Yellow River Delta, Jiangsu Xiaomiaohong, Shenhu Bay and other sea areas.

1.Caofeidian-Laoting Oyster Reefs

The Caofeidian-Laoting Oyster Reef in Tangshan City, Hebei Province is situated in a semienclosed bay between Caofeidian Industrial Zone and Jingtang Port. According to the survey results in 2019 [36], the oyster reef in the Caofeidian-Laoting area is currently the largest known natural oyster reef in China, with a total area of approximately 15 km^2, mainly distributed on both sides of the Laolonggou tidal channel, upstream river channel and upstream river mouth, and the Laoyujian area on the west side of ShijiuTuo and Yaotuo (Figure 44). The main reef-building species is Crassostrea gigas, with an average density ranging from 104 to 3912 individuals/m^2. All three oyster reef areas contain a certain number of adult oysters and spat, and the oyster shell height also shows a unimodal normal distribution, indicating that the oyster population is currently in a sustainable growth state.

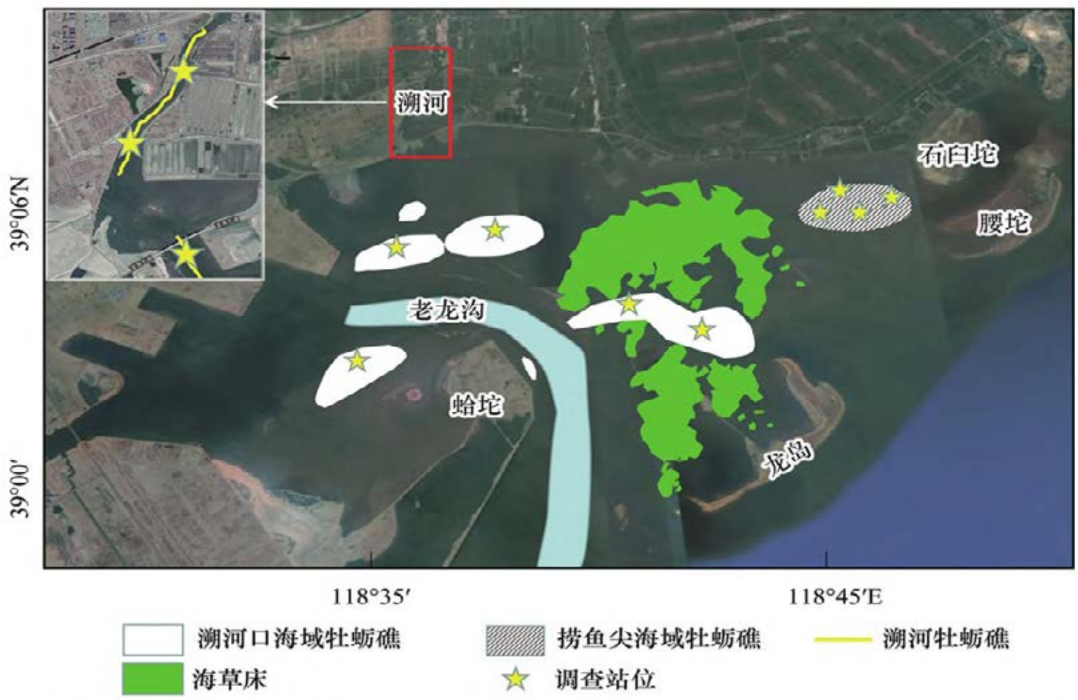


Fig. 44 Distribution range of oyster reefs in Caofeidian-Laoting sea area

(Source: Quan Weimin et al., 2022)

2. Dashentang Oyster Reef

Tianjin Dashentang Oyster Reef is located in the waters south of Dashentang on the northwest coast of Bohai Bay, including the large and small Shagang and their marginal waters, which are subtidal reefs with water depths ranging from approximately 0.5 to 4.5 meters. The oyster reef area reached 35 km^2 in the 1970s.

In 2007, the Tianjin Geological Survey Center's Coastal and Quaternary Geology Department conducted a survey of the active oyster reefs in the lower intertidal zone of Dashentang. The survey results showed that there were only three scattered reef areas remaining in Dashentang, namely the northwest (reef area of approximately 0.9 km^2), south (reef area of approximately 0.9 km^2), and northeast (reef area of approximately 1.4 km^2) parts, with a total area reduced by over 90% compared to the 1970s. In 2011, the results of a subsequent survey showed that the original northwest reef had disappeared, the south reef area had decreased to approximately 0.5 km^2, and the largest northeast oyster reef, with a relatively stable shape and distribution, remained[37].

To protect the oyster reef ecosystem in this area and its surrounding marine environment, the former State Oceanic Administration approved the establishment of the Tianjin Dashentang Oyster Reef National Marine Special Protection Area on December 21, 2012, with a total area of approximately 34 km^2.

Since 2012, in order to protect and restore the oyster reef ecosystem of Dashentang, the Tianjin Municipal Oceanic Bureau of has successively deployed approximately 170,000 bags of artificial oyster reefs. The survey results in 2019 showed that a new contiguous oyster reef appeared north of the largest northeast oyster reef in Dashentang, with an area of over 2 km^2[38].

In 2020, the former North China Sea Ecological Center of the Ministry of Natural Resources conducted a survey of the Tianjin Dashentang Oyster Reef National Marine Special Protection Area and surrounding waters, showing that the No. 2 reef group in the southern part of the Tianjin Dashentang oyster reef had disappeared, while the No. 1 reef group in the northeast continued to grow northward, exceeding the northern boundary of the protected area. The No. 1 reef group consists of three large reefs, three small reefs, and several scattered reefs, with a length from north to south of about 1.9 km, a width from east to west of about 2.5 km, and a net area of about 2.076 km^2 (Figure 45).

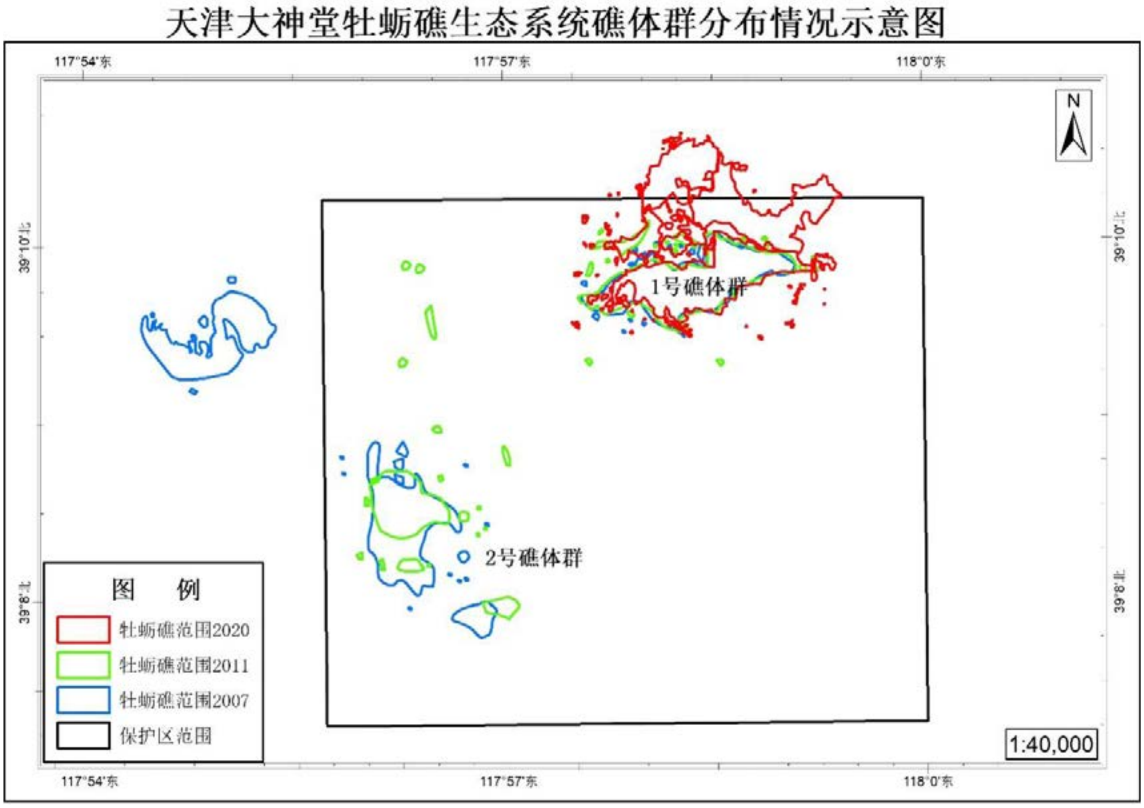


Fig.45 Schematic of the Distribution of
Tianjin Dashentang Oyster Reef in 2007, 2011, and 2020
(Source: Zhang Yi, North China Sea Ecological Center,
Ministry of Natural Resources).

3. Yellow River Delta Oyster Reef

The oyster population in the Yellow River Delta is mainly composed of Crassostrea gigas and Crassostrea ariakensis. Crassostrea ariakensis is mainly distributed in the main estuary area of the Shandong Yellow River Delta National Nature Reserve.

In 2017, the Institute of Oceanology, Chinese Academy of Sciences, discovered a wild population of Crassostrea ariakensis in the estuarine areas of Taoer River and Majia River. The scattered distribution of this oyster reef patch in the subtidal zone covers an area of approximately 1.5 km^2[39]. In 2018, Liu Lulei discovered a more concentrated subtidal oyster reef in the Dongying Kenli area, with a total area of 0.24 km^2. This reef is mainly composed of adult Crassostrea ariakensis, accounting for 95.8% of the main reef area, and no oyster spat were found[40]. In 2020, the Shandong Yellow River Delta National Nature Reserve Management Committee discovered a 4 hm^2 oyster reef in the southern part of the Dawenliu.

In 2021, the North China Sea Bureau of the Ministry of Natural Resources, together with the Institute of Oceanology, Chinese Academy of Sciences, and the Shandong Yellow River Delta National Nature Reserve Management Committee, conducted a survey of oyster resources in the protected areas, including the Yellow River Estuary Station and Dawenliu Station, and found a large number of wild Crassostrea gigas populations in the wave breakwaters of the oil extraction area[41].

4. Jiangsu Haimen Liya Mountain Oyster Reef

In the 1960s, the total area of the Haimen Lijia Mountain oyster reef was 3.55 km^2, with multiple oyster species and clear stratification[42]. The bottom layer is mainly formed by Crassostrea ariakensis, with shell heights exceeding 30cm; the upper layer is Crassostrea sikamea, the main reef-building species in this reef[43、44]. At the beginning of the 21st century, the average relative height of the reef was 1 to 1.5 meters[42]. In 2013, Quan Weimin used UAV aerial photography to measure the total area of reef patches in Xiaomiaohong, which had decreased to 0.2 km^2[44-46].

5. Shenhu Bay Oyster Reef

The Shenhu Bay oyster reef is located in the Shenhu Bay Submarine Ancient Forest Relics National Nature Reserve in Fujian. The ancient oyster reefs here are mainly distributed in the middle and lower tidal zones, with a length of about 500 meters, a maximum width of about 200 meters, and a height of about 20 to 40 cm, formed by the cement of oyster shells of different sizes. According to the on-site investigation by the East China Sea Fisheries Research Institute of the Chinese Academy of Fishery Sciences in 2020, there are still hundreds of square meters of live oyster reefs in the reserve, with the main reef-building oyster species being Crassostrea angulata.

6. Pearl River Estuary Oyster Reef

The natural oyster reefs in the Pearl River Estuary are mainly distributed near Zhuhai and Jiangmen Taishan.

The intertidal oyster reefs in Zhuhai are mainly located near the waters close to Macao, and the intertidal oyster reefs near the Fisherman's Statue on Lover's Road in Zhuhai are relatively large. There are Saccostrea oyster reefs near Haiquan Bay. The characteristic of oyster reefs in this area is their wide distribution, but the individual reef area is not large. The main reef-building species in the intertidal reefs are Crassostrea hongkongensis and Crassostrea ariakensis, while Crassostrea gigas and Saccostrea mordax coexist in the subtidal reefs.

The natural oyster reefs in Taishan, Jiangmen are mainly located in the traditional harvesting area near Chixi Town, and the oyster species are mainly Crassostrea hongkongensis, Crassostrea sikamea, and Saccostrea species.

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