Handbook of Ecosystem Restoration for Coastal Hazard Mitigation: Coastal Salt Marshes

Ministry of Natural Resources

November 2024

Organizations and Personnel

Directed by

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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 is designed for application in the restoration of coastal salt marsh ecosystems in China, focusing on achieving co-benefits in ecological significance and marine hazard mitigation. It applies to the restoration of coastal salt marshes within a specific range, as well as areas that were historically coastal salt marshes but have been converted to mudflats or aquaculture ponds.

This handbook outlines the technical requirements and methods corresponding to the principles, technical processes, restoration goals and methods, and restoration measures for coastal salt marsh ecological restoration.

2.Terms and Definitions

The following terms and definitions apply to this technical handbook.

(1) Salt Marshes

Wetlands containing high levels of salt and supporting the growth of higher plants.

Note: Coastal salt marshes are distributed in estuaries or coastal shallow waters, formed by seawater immersion or tidal alternation.

(2) Salt Marsh Vegetation

Plant communities growing in salt marshes.

Note: The main dominant plants in coastal salt marshes in China include reeds (*Phragmites australis*), smooth cordgrass (*Spartina alterniflora*), Scirpus mariqueter, Suaeda salsa, and Cyperus malaccensis var brevifolius. Among them, Spartina alterniflora is listed as one of the the first batch of invasive species in China.

(3) Coastal Salt Marsh Ecosystem

An ecosystem primarily consists of salt marsh vegetation, along with other plants, animals, microorganisms, soil, and water bodies. These components are interdependent, mutually restrictive, and interact with the environment.

(4) Coastal Salt Marsh Ecological Restoration

The process involves restoring the biological communities, ecosystem functions, and services of coastal salt marsh ecosystems to their native state. This is achieved by introducing propagules of coastal salt marsh plants into degraded areas or by improving the habitat conditions of existing coastal salt marshes.

3.Restoration Principles

The coastal salt marshes ecosystem restoration for the marine hazard mitigation should adhere to the following principles:

(1) Tailored with categorized measures specific to each site. Given the extensive distribution of coastal salt marshes in China and the diverse natural conditions across regions, as well as the various causes of ecosystem degradation, restoration efforts should be tailored to geographical location, climate characteristics, and plant types, among other factors. Consideration should be given to functional needs, technical conditions, economic foundation, and other factors to develop suitable layouts, implementation strategies, and technical routes for ecological restoration. This approach promotes targeted and effective ecological restoration projects, with site-specific categorized measures being developed.

(2) Natural recovery as primary, artificial restoration as supplementary. Follow the inherent mechanisms and succession laws of coastal salt marshes and other natural ecosystems, adhering to ecological principles to maintain ecosystem diversity and connectivity. Emphasize the self-restoration ability of ecosystems, while minimizing unnecessary interference from human activities. In cases where natural ecosystem restoration is unattainable, appropriate artificially assisted measures should be taken. These measures should be based on existing natural conditions, and phased steps should be taken according to the succession pattern of the ecosystem itself to promote ecosystem restoration.

(3) Systematic and holistic restoration for synergistic ecology and disaster mitigation. Considering the interactions between the land and sea of coastal salt marshes in an integrated manner, and starting from the integrity of the ecosystem, the goal is to enhance the ecosystem service functions and resilience of the coastal zone. The systematic nature of ecological restoration activities in terms of spatial and temporal continuity should be fully considered, achieving harmonious multifaceted evolution of hydrology, soil, vegetation, and biological diversity, and promoting the

synergistic effects of coastal zone ecology and disaster mitigation.

(4) Maximum benefits with risks manageable. Restoration activities should undergo systematic and comprehensive analysis and demonstration to fully consider the complexity of ecosystems and the mutability of certain environmental elements. This consideration helps avoid negative impacts on the restoration and surrounding areas, minimizing risks. Efforts should be made to achieve maximum benefits with minimal risks and investments, considering ecological and disaster mitigation benefits, as well as social and economic benefits. This approach aims to maximize ecological, disaster mitigation, social, and economic benefits while minimizing risks and investments.

4.Overall Technical Process

The overall technical process for mitigating marine hazards through coastal salt marsh ecosystem restoration involves several pivotal stages. These include conducting ecological baseline surveys, diagnosing ecological issues, establishing restoration goals and methods, formulating restoration plans, implementing engineering projects, conducting follow-up monitoring, evaluating effectiveness, assessing impacts, and employing adaptive management strategies. Refer to Figure 1 for a detailed overview.

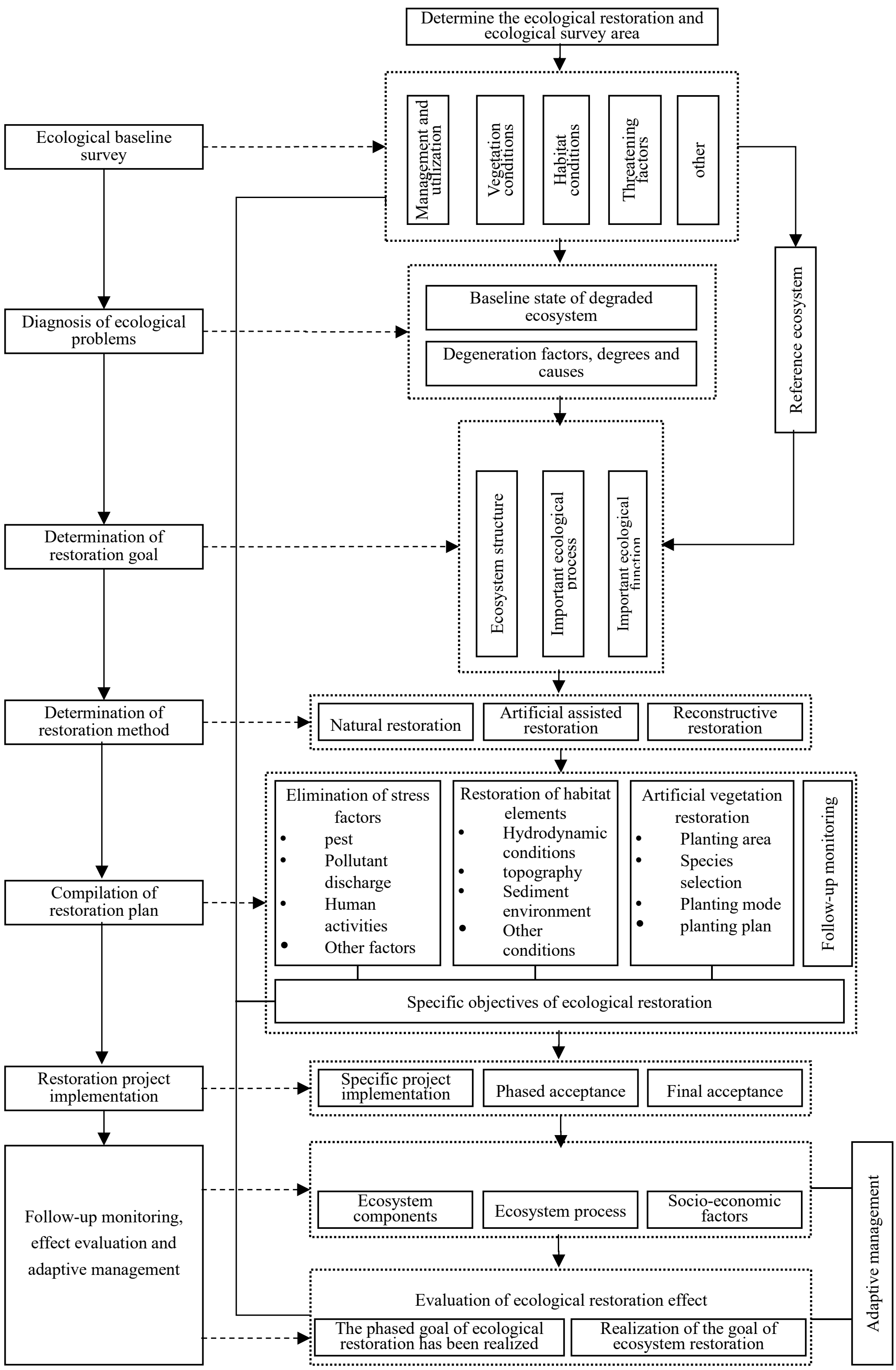


Figure 1 Flow Chart of Coastal Salt Marsh Ecosystem Restoration for the Co-benefits of Ecological Significance and Marine Hazard Mitigation

5.Baseline Survey

5.1 Survey Objectives

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

5.2 Survey Content

A thorough survey of the area slated for restoration is essential to grasp the ecosystem’s baseline status pre-restoration. Key components of the coastal salt marshes baseline survey include area status, salt marsh vegetation, habitat conditions, threat factors, disaster mitigation capacity, carbon sequestration and storage, and other crucial ecological functions (refer to Table 1 for specifics). Additionally, historical reference data on baseline surveys of coastal salt marsh ecosystems should be collected and organized.

Table 1 Content and Indicators of Ecological Baseline Survey of Coastal Salt Marshes

Category	Survey Element	Indicator	Survey Method
Status of the Area	Geographic Attributes	Specific location and geographic coordinates	Data collection and remote sensing survey
	Environmental Overview	Natural conditions, ecological characteristics, environmental status	On-site Survey
	Policies and Regulations	Laws and regulations, planning	Data collection
	Status of Protection, Restoration, and Utilization	Status of ownership/tenure and use of restoration areas, territorial spatial planning, status of protection of other important habitats, etc.	Data collection
Salt Marsh Vegetation	Salt Marsh	Area, distribution, width of vegetation belt	Remote sensing survey and on-site verification
	Plant Community	Species, density, coverage, average height, aboveground biomass, net primary productivity	On-site Survey
	Natural Regeneration of Vegetation	Phenology, propagule production, number of seedlings, etc.	On-site Survey
Environmental Factors	Substrate Environment	Particle size, total soluble salt content, pH value, organic carbon, redox potential, total nitrogen, total phosphorus, sulfide	On-site Survey
	Water Quality Environment	Turbidity, dissolved oxygen, pH value, organic carbon, ammonium, nitrate, nitrite, active phosphate	On-site Survey
	Hydrological Environment	Temperature, salinity, tidal currents, waves	
	Topography and Geomorphology	Water depth, elevation, geomorphological units (coastal zone types)	On-site Survey
Biological Community	Macrobenthos	Species, density, biomass	On-site Survey
	Birds	Species, quantity	On-site Survey

Category	Survey Element	Indicator	Survey Method
Threat Factors	Natural Factors	Natural disasters, sea level changes, coastal erosion, invasion of alien species, etc.	Data collection, on-site survey, social survey, etc.
	Human Factors	Aquaculture activities, grazing activities, fishing activities, coastal zone engineering, pollutiant discharge status, utilization of surrounding resources, tourism development activities, invasion of alien species, etc.	Data collection, on-site survey, social survey, etc.
Important Ecological Functions	Disaster Prevention and Mitigation Functions	Functions such as wave attenuation and shore protection for disaster prevention and mitigation and coastal protection	Data collection and on-site Survey
	Carbon Sequestration and Sink Enhancement Functions	Carbon stocks: biomass carbon density, dead organic matter carbon density, sediment carbon density	Data collection, on-site survey, social survey, etc.
		Carbon sink: carbon burial rate, growth rate and root-to-shoot ratio (woody plants), carbon flux, Greenhouse gas emission factors such as CH_4, etc.	Data collection, on-site survey, social survey, etc.

5.3 Survey Methods

The ecological baseline survey primarily relies on data collection, remote sensing analysis, and field surveys. Specific survey methods for various components such as area status, salt marsh vegetation, habitat conditions, biological communities, threat factors, and important ecological processes and functions are outlined below.

5.3.1 Status of the Area

Through data collection and field surveys, the survey should aim to understand the land spatial planning, ecological red line area protection planning, and other related planning in the area earmarked for the restoration project and its environs. Additionally, assess the current status of ecosystem-related protection and management, tenure status of the area, land use status, marine use rights certificates, analyze potential social impacts of coastal salt marsh ecological restoration, identify stakeholders, and grasp the overall situation of the proposed restoration area.

5.3.2 Salt Marsh Vegetation

Surveying salt marsh vegetation is pivotal in the ecological baseline survey. Indicators such as salt marsh area and distribution are obtained through remote sensing surveys and on-site verification. The width of salt marsh vegetation belts is calculated based on the average length of salt marsh habitats in the vertical shoreline direction. The average coverage of sample plots is calculated as the average coverage of each quadrat. Above-ground biomass is measured by harvesting the above-ground parts of plants within the quadrat.

Plant community characteristics are surveyed on-site. Representative survey sections in salt marsh areas should be selected reasonably, and survey stations should be established. When setting up survey sections, follow principles of comprehensiveness, typicality, and representativeness. Specifically, the number of section stations should comprehensively consider factors such as distribution area, location, and plant species. The layout of sections should spatially cover the entire survey area, including all representative plant community types, and ensure that typical and special plant communities in the survey area receive focused and detailed surveys. This ensures a balanced layout of survey sections that can reflect the overall situation of salt marsh vegetation in the survey area and provide a basis for community review and long-term monitoring for continuous management. To fully reflect the intertidal zone of vegetation distribution, at least three survey stations should be set up for each section in principle, and when typical and special biological communities are not covered by the section, separate survey stations should be established.

In parallel, plant community characteristics are assessed through plot surveys. Typically, each station establishes a sample plot, often measuring 10m×10m, with five quadrats positioned (typically at the four corners and center of the sample plot, as shown in Figure 2). The size of each quadrat should be determined based on the plant species and distribution characteristics, with a standard area of 1m×1m. In cases of high plant density and uniform distribution, the quadrat area may be reduced to 0.5m×0.5m. Conversely, in scenarios with diverse plant species and uneven distribution, all quadrats should be surveyed. For instances where plant species are singular and distribution is uniform, a minimum of three quadrats should be surveyed.

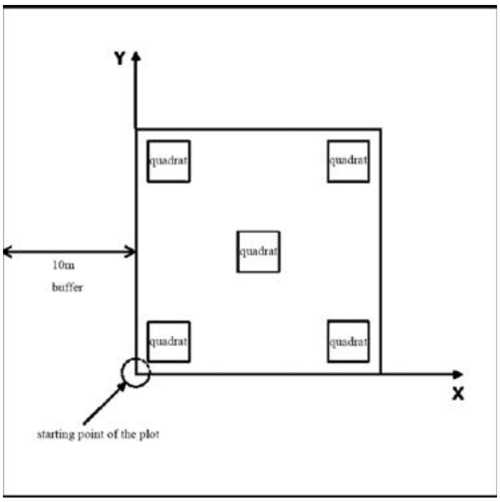


Figure 2 Design Drawings of Sample Plots and Quadrats

5.3.3 Eviromental Elements

The survey of environmental elements encompasses the substrate environment, water quality environment, hydrological conditions, as well as topographic and geomorphological features (see Table 1). If data for these environmental parameters are unavailable from existing sources or are insufficient to assess the habitat suitability of coastal salt marshes, on-site surveys should be conducted to obtain the necessary information.

The substrate environment survey should be conducted concurrently with the plant community sample plot survey. Samples should be collected within the plots designated for plant community surveys, with one sample collected at each station. The substrate environment survey primarily includes indicators such as granularity, total water-soluble salt content, pH value, organic carbon, redox potential, total nitrogen, total phosphorus, sulfides, etc. Sampling should aim to avoid low-lying waterlogged areas whenever feasible. During sampling, surface litter should be cleared first, followed by the random collection of a soil/sediment sample from 0cm to 15cm using a sampling shovel. Relevant parameters can then be determined through physical or chemical methods in the laboratory.

The water quality survey primarily focuses on key indicators such as turbidity, dissolved oxygen, pH, organic carbon, ammonium salts, nitrates, nitrites, and active phosphates. This assessment survey can be conducted concurrently with the plant community plot survey, with the methodology for each indicator following relevant technical standards.

The hydrological environment survey emphasizes parameters such as temperature, salinity, tidal currents, and waves. Like the water quality survey, it can be carried out in parallel with the plant community plot survey, with each factor's method determined according to the applicable technical standards.

Topographic and geomorphological surveys assess indicators including water depth, elevation, and geomorphological units. These surveys should cover representative areas on the section and can be conducted alongside the plant community plot survey. Attention should be given to measuring the elevation at the center of the plant community plot during the survey.

5.3.4 Biological Communities

The survey of macrobenthic communities can be conducted concurrently with the plant community sample plot survey. This survey should include recording the species, quantity, and biomass of macrobenthos in each quadrat. Bird surveys should document species and quantity, with survey timing based on local phenological characteristics.

5.3.5 Threat Factors

The survey of natural threat factors should gather information on natural elements that jeopardize the distribution and development of coastal salt marshes in the surveyed area. Common natural threat factors in China’s coastal zones mainly include typhoons, storm surges, floods, sea-level rise, coastal erosion, and other marine disasters. This survey should note if the survey area has experienced marine disasters and record details such as frequency, intensity, and associated losses.

Anthropogenic factors should focus on activities such as coastal engineering, mariculture, fishing, seawater pollution, utilization of surrounding resources, tourism development, and the invasion of alien species. Information can be gathered through various means including data collection, on-site surveys, and social surveys.

5.3.6 Disaster Prevention and Mitigation Function

Research and field observations have highlighted the significant role of coastal salt marshes in preventing and mitigating ocean dynamic disasters by attenuating waves and currents. The effectiveness of coastal salt marshes in reducing marine disasters is often measured by their wave attenuation capacity (which refers to the reduction in wave height after passing through a certain width of coastal salt marsh).

Assessing the disaster mitigation capacity of coastal salt marshes typically relies on field survey data. The field survey method for assessing this capacity usually involves cross-sectional observations. These cross-sections should ideally be parallel to the direction of incoming waves (typically perpendicular to the coastline direction) and selected to represent the characteristics of the entire salt marsh region. In areas with significant variations in salt marsh characteristics, multiple cross-sections should be chosen. Each cross-section should have typical stations, with at least two stations per cross-section—one at the seaward edge (seaward point) and one at the landward edge (landward point) of the salt marsh distribution area. These stations should observe wave height and water level at both seaward and landward points. When selecting observation periods, such as during typhoons and storm surges, the entire duration of the disaster impact should be considered as much as possible (refer to HY/T 0382-2023).

6.Problem Diagnosis and Suitability Assessment for Restoration

6.1 Problem Diagnosis

Based on the results of ecological baseline surveys, conduct a comprehensive analysis of coastal salt marsh vegetation, habitat conditions, biological communities, and other aspects to diagnose the main ecological problems in the area to be restored. The diagnosis of coastal salt marsh ecosystem restoration for marine hazard mitigation primarily involves ecological degradation diagnosis and assessment of disaster prevention and mitigation capabilities.

(1) Diagnosis of Ecological Degradation

Diagnosing ecological degradation in coastal salt marshes involves assessing factors, extent, and causes of vegetation and biological community degradation. For degraded areas, comparing them with historical reference ecosystems helps identify degradation factors. Analyzing the degree of degradation, assessing main controlling factors, evaluating causes, and exploring possibilities of self-recovery or the need for artificial restoration are crucial. Additionally, judging the repairability of degraded areas and comprehensively analyzing essential elements for restoration (habitat, biological factors, ecological processes, etc.) are key. It’s vital to assess habitat conditions for plant growth and determine if they can be restored. If the conditions are not suitable, it should be further clarified whether they can be restored to suitable conditions. Common signs of degradation include vegetation decline, shoreline erosion, soil salinization, alien species invasion, and water pollution.

(2) Diagnosis of Degradation of Disaster Prevention and Mitigation Capacity

The degradation of disaster prevention and mitigation capacity in coastal salt marshes is typically linked to ecological degradation. It is primarily characterized by the degradation of salt marsh vegetation, including reductions in area, density, and cover of plants, as well as the narrowing of vegetation belts. The factors and causes of degradation of disaster prevention and mitigation capacity in coastal salt marshes are essentially the same as those for ecological degradation, such as vegetation decline. The degree of degradation of disaster prevention and mitigation capacity in coastal salt marshes can be quantitatively assessed through field surveys, numerical simulations, physical model experiments, etc. By analyzing changes in the width, density, and height of salt marsh vegetation and the types of plants, a diagnostic assessment of the degradation of disaster prevention and mitigation capacity compared to historical reference ecosystems can be obtained.

The following are common manifestations of coastal salt marsh degradation:

- Decline, death, or loss of coastal salt marsh vegetation
- Increased salinization of soil within the region
- Coastal erosion leading to continuous retreat of the salt marsh
- Outbreaks of invasive species such as Spartina alterniflora, resulting in loss of native vegetation and bird habitats
- Proliferation of small crabs leading to crab damage, causing degradation of salt marsh vegetation
- Foul odor and discoloration of water bodies within the coastal salt marsh
- Algal blooms in coastal salt marsh wetlands
- Accumulation of large amounts of marine debris in coastal salt marsh wetlands
- Blockage of tidal channels
- Excessive levels of heavy metals in soil

6.2 Suitability Assessment for Restoration

Based on the findings of the problem diagnosis, a comprehensive assessment of the suitability of ecological disaster mitigation and the restoration of coastal salt marshes was conducted, focusing on the following key areas:

Analysis of coastal salt marsh damaged texture: This includes an analysis of vegetation and biological community damage, human activities in adjacent areas, shoreline erosion, the invasion of alien species, and water quality pollution.

Analysis of policy and planning suitability: Restoration site selection must adhere to, but is not limited to, various policies and planning frameworks, including marine functional zoning, sea area usage planning, territorial spatial planning, and urban construction planning.

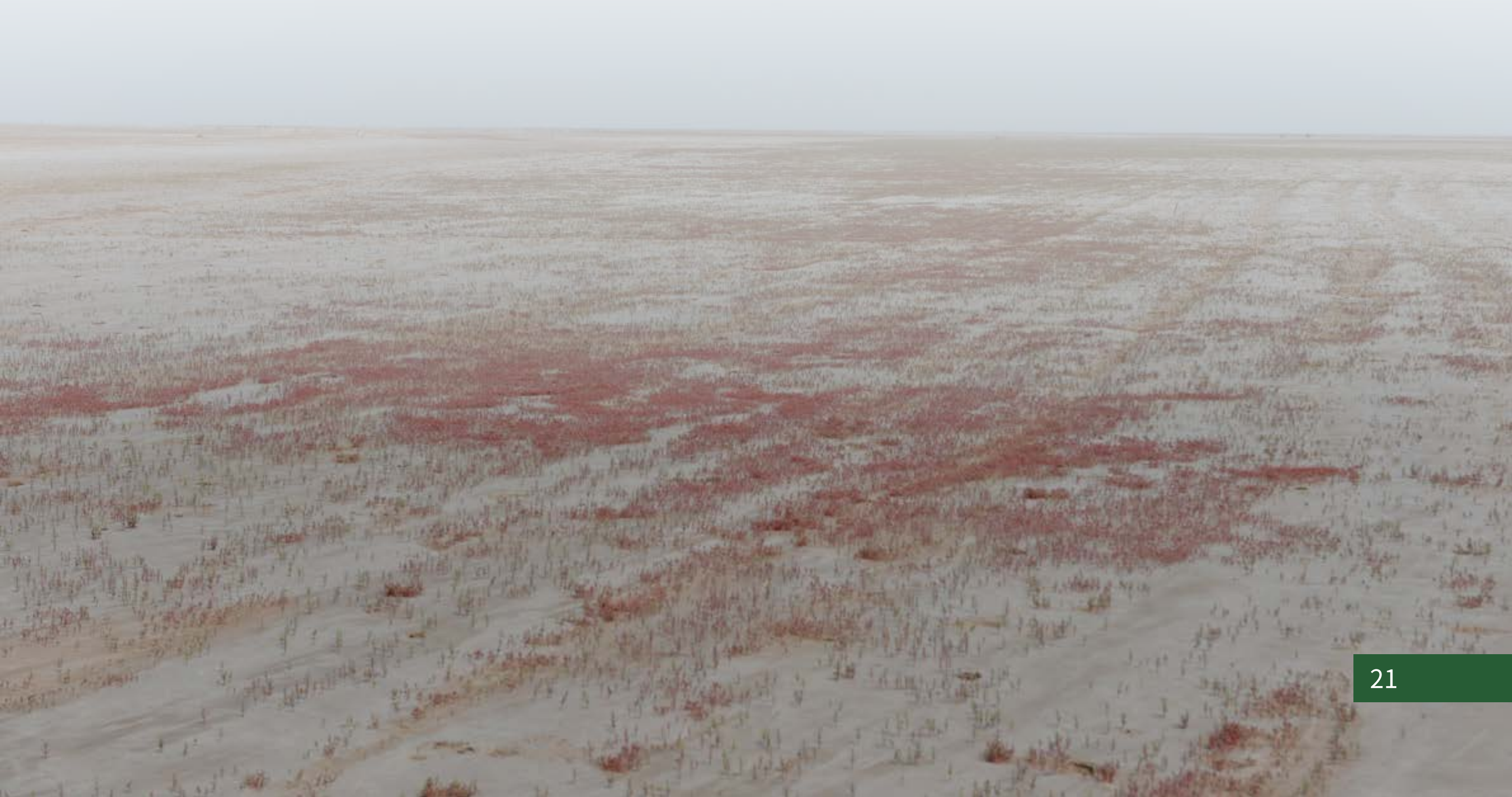
Analysis of hydrological environment suitability: Through field investigations and numerical simulations, the potential impacts of factors such as temperature, salinity, tides, waves, and currents on the growth of salt marsh vegetation are analyzed to assess the restoration area’s hydrological suitability.

Analysis of topographical and geomorphological suitability: The analysis examines whether the area’s topographical and geomorphological conditions—either naturally occurring or artificially created—support the growth of salt marsh plants.

Analysis of water quality and substrate suitability: This involves assessing whether the water quality and sediment conditions in the restoration area meet restoration requirements, as well as evaluating the impact of restoration activities on ecologically sensitive targets and the broader regional ecosystem’ s evolution.

7.Restoration Goals

The overarching objective of coastal salt marsh restoration is to systematically rejuvenate the structure and functionality of degraded wetland ecosystems using suitable technical approaches, ultimately reinstating them to a self-sustaining state. The goals of coastal salt marsh restoration should be derived from a thorough analysis and diagnosis of the primary issues causing ecological degradation in the restoration area. These goals should also consider regional characteristics, economic conditions, and other pertinent factors, while fully contemplating the recovery trajectory of ecosystem parameters and setting incremental objectives. The focal points and requirements of restoration goals for degraded wetland ecosystems vary across regions. Typically, these goals encompass medium- to long-term objectives as well as short-term goals, reflecting different anticipated states and levels of restoration.



7.1 Medium- to Long-Term Goals

The medium- and long-term goals represent the envisioned state and quality of coastal salt marsh ecosystems following a period of restoration. These goals should encompass the natural environment, biological communities, critical ecological processes, and the restoration of vital ecological services like disaster prevention and mitigation. When establishing these goals, it is essential to define the relevant ecosystem parameters and quantify the extent of restoration. Typically, the implementation period for medium- to long-term goals related to the natural environment and biological communities in coastal salt marshes ranges from 3 to 5 years. Concurrently, the restoration of crucial ecological processes and ecological service functions is usually achievable within 5 to 10 years.

The following can serve as a reference for setting medium- and long-term goals:

(1) Restoration of biological communities: This includes the recovery of various biological communities such as vegetation, benthic organisms, birds, microorganisms, and fish;

(2) Restoration of important ecological processes: This involves the restoration of processes like sedimentation, primary production, vegetation regeneration, turnover of litter material, and the exchange of biological and chemical substances with the surrounding aquatic environment;

(3) Restoration of important ecological service functions: This includes the restoration of functions such as maintaining biodiversity, purifying the environment, enhancing disaster mitigation capacity, and carbon sequestration and sink enhancement;

(4) Sustainable regional socio-economic development: This should fully consider public requirements and policy rationality to achieve mutual promotion and sustainable development of ecological, disaster mitigation, social, and economic factors.

7.2 Short-term Objectives

Short-term objectives should provide further clarity on specific restoration targets to be accomplished in the short term, based on the medium- to long-term goals. These objectives typically outline the expected levels to be achieved by specific objects and elements of the ecosystem within the restoration project’s implementation period or the initial stage post-restoration. Short-term objectives should primarily focus on habitat conditions, vegetation restoration, and threat elimination. The implementation period for achieving short-term objectives in coastal salt marsh restoration projects should be 1 to 2 years, with specific objectives based on the restoration implementation’s specific content, including:

(1) Vegetation restoration: This includes the area, patches, species number, cover, density, and height of naturally restored or restored coastal salt marsh vegetation;

(2) Habitat condition restoration: This encompasses hydrodynamic conditions, water and substrate environments, sediment nutrient status, and elevation;

(3) Elimination of threat factors: This involves addressing anthropogenic destructive activities in the restoration area, coastal engineering impacts, pollutant discharges, invasive species, pests and diseases, fouling organisms, and marine-drifting debris.

8.Restoration Methods

(1) Habitat Restoration

Habitat in coastal salt marshes refers to the ecological environment where organisms live and inhabit in wetlands. Habitat restoration aims to improve the quality of water and substrate environments, enhance habitat heterogeneity and stability, provide suitable living conditions for wetland organisms, and promote the stable operation of salt marsh ecosystems through various technical measures. Habitat restoration in coastal salt marshes includes the restoration of wetland hydrological and hydrodynamic conditions, micro-topography modification, substrate restoration, and water quality improvement.

(2) Vegetation Restoration

Vegetation restoration in coastal salt marshes mainly involves natural and artificial methods, depending on the specific degradation status of coastal salt marsh vegetation. Natural restoration includes measures such as removing external pressures or disturbances and beach closure for conservation to promote natural vegetation recovery. If the restored area cannot achieve natural vegetation recovery through natural regeneration capacity, plantation establishment and other methods can be used to restore salt marsh vegetation.

(3) Control of Invasive Species

Spartina alterniflora is the most threatening invasive species in China’s native coastal salt marshes. Due to its broad ecological niche and diverse reproductive methods, it is continuously expanding in some coastal areas. The rapid expansion of Spartina alterniflora has led to the continuous loss of native coastal salt marsh plant habitats and bird habitats in some areas. Integrated measures should be taken to control invasive species, particularly Spartina alterniflora, in conjunction with habitat and vegetation restoration methods to further the restoration of coastal salt marshes.

9.Restoration Measures

9.1 Habitat Restoration

Habitat degradation and loss in coastal salt marsh areas often result from blocked tidal exchange channels, changes in substrate types, coastal erosion, and alterations in tidal flat landforms. When habitat conditions fail to meet the needs of organisms for habitat and survival in coastal salt marsh areas, habitat restoration becomes necessary to enhance the habitat conditions in the restoration area. Habitat restoration measures primarily involve restoring wetland hydrological and hydrodynamic conditions, modifying micro-topography, restoring substrate, and improving water quality. These measures promote the natural restoration of salt marsh vegetation or are used in combination with artificial restoration to carry out coastal salt marsh restoration. Specifically, one or more habitat conditions should be restored to match the requirements of the restoration area's habitat conditions and the species targeted for restoration.

9.1.1 Techniques for Restoring Wetland Hydrological and Hydrodynamic Conditions

Techniques for restoring the hydrological and hydrodynamic conditions of coastal salt marsh wetlands include enhancing water system connectivity, regulating brackish and freshwater inflows, and implementing wave attenuation and shoreline protection measures. These techniques should be selected based on the current hydrological and hydrodynamic conditions of the restoration area.

Habitat Conditions for Coastal Reed Plants:

Phragmites australis is typically hydrophytic or hygrophilous. In China’ s coastal wetlands, Phragmites australis planting areas are typically muddy estuarine areas and intertidal flats with weak tidal dynamics, situated above the local average sea level. Soil salinity significantly impacts the growth and development of Phragmites australis, with an optimal salt content generally not exceeding 4-9g/kg. Phragmites australis exhibits strong temperature adaptability, thriving under various climatic conditions, but they generally grow best at temperatures between 15° C and 30° C. Phragmites australis has loose requirements for soil pH, typically growing well in neutral to alkaline soil with a pH between 6 and 8.

Habitat Conditions of Bolboschoenoplectus mariqueter:

Bolboschoenoplectus mariqueter is a perennial herbaceous plant belonging to the family Cyperaceae and the genus Bolboschoenoplectus, typically standing 25cm to 40cm tall. It exhibits strong adaptability to saline-alkali soil, tolerating high salt concentrations and humid environments.

Habitat Conditions of Suaeda Salsa in Coastal Areas:

Suaeda salsa in coastal areas primarily thrives in the intertidal zone, typically reaching an average height ranging from 20cm to 50cm, with a density of generally 100 to 1000 plants/ m^2. This species exhibits high salt tolerance, with soil salinity levels generally ranging from 0.5 to 20g/kg. It experiences an average daily inundation time of about 2 hours and demonstrates strong temperature adaptability. Adequate sunlight is beneficial for the growth and photosynthesis of Suaeda salsa.

Habitat Conditions of Cyperus malaccensis Lam.var.brevifolius Bocklr:

Cyperus malaccensis Lam.var.brevifolius Bocklr, a member of the family Cyperaceae and the genus Cyperus, thrives in tidal flat areas with weak tidal dynamics. It grows to a culm height of 80cm to 100cm, and the substrate can range from sandy to muddy. This species prefers a warm and humid climate, with a germination temperature range of 8° C to 10° C and an optimal growth temperature range of 24° C to 28° C.

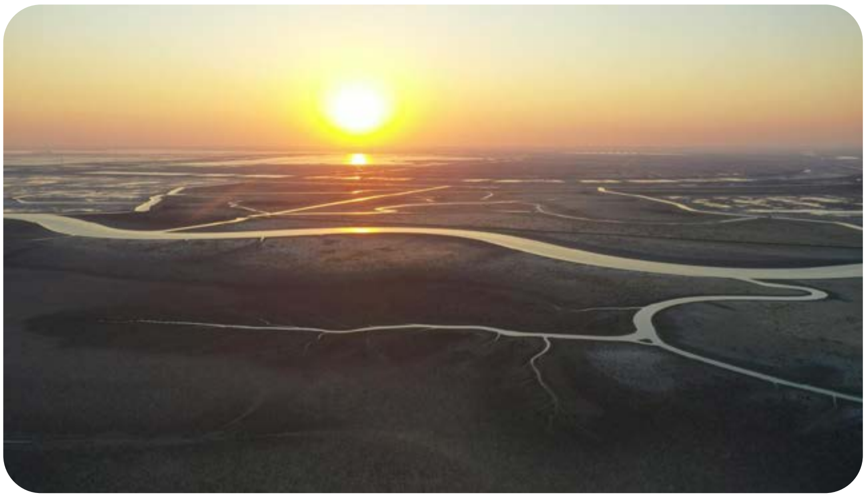
(1) Water System Connectivity Technique

Water system connectivity in coastal salt marsh areas primarily relies on tidal channels to connect numerous material flows between two or more geographical units based on the degree of circulation exchange of hydrological factors. It promotes interaction between water and land, regulates wetland water flow distribution, increases wetland water retention time, accelerates the exchange of water flow, vegetation, organisms, soil sediment, and nutrients in the region, and constitutes the cyclic transfer process of the overall salt marsh ecological environment system.

In implementing water system connectivity measures, the hydrodynamic conditions of the wetland, such as tides, currents, and waves, should be fully considered. Based on existing tidal channels, ditches, and tributaries, tidal channels of different levels, such as Grade I and Grade II, should be designed according to local conditions. If necessary, hydrological models can be used to determine the planform, cross-section, grade, density, and other characteristics of tidal channels. Dredging tributaries and ditches can improve water system connectivity, enabling effective restoration of tidal water systems in coastal salt marsh wetlands.

① Design of Tidal Channel System Planform

The planform of a tidal channel system primarily includes different forms such as parallel, dendritic, distributary, braided, and connected. During actual restoration, the planform of the intended restored tidal channel should be determined based on the current or historical planform of tidal channels in the restoration area and nearby areas.



② Design of Tidal Channel Cross-section

The cross-sectional shape of a tidal channel is usually "V"-shaped (wedge-shaped) or "U"-shaped. During actual restoration, the cross-section of the intended restored tidal channel can be designed as a trapezoidal cross-section combining the two shapes. This shape balances stable slopes and a certain capacity for tidal water inflow. Generally, there is a certain relationship between the depth and width of a tidal channel (width-depth ratio). The width-depth ratio of tidal channels in coastal salt marsh wetlands is generally 5-8 (the width-depth ratio of tidal channels varies for different regions and different salt marsh plant species). The width and depth of the tidal channel can be determined based on the average width of healthy tidal channels at various levels within the tidal channel system during actual restoration.

③ Design of Tidal Channel Hierarchies

The grading of tidal channels in coastal salt marsh areas can consider the largest main channel as the first-level tidal channel, with tributaries flowing into the main channel as second-level tidal channels, and so on. During actual restoration, the grading of the intended restored tidal channel should be determined based on the current or historical grading of tidal channels in the restoration area and nearby areas. Generally, the larger the wetland area and the stronger the hydrodynamic conditions, the greater the number of tidal channel grades it will have. However, it is advisable to avoid designing too many levels of tidal channels. The main tidal channels can be designed according to the actual situation, while smaller tidal channels can be allowed to naturally restore later through the self-restoration ability of coastal salt marsh wetlands.

④ Design of Tidal Channel Density

The density of tidal channels in coastal salt marsh areas is usually related to factors such as tidal influx, tidal range, tidal flat vegetation, and clay content of sediments in the region. When designing the density of tidal channels, it should be assessed based on the current environmental conditions such as tidal flow and tidal range in the restoration area. The density of the intended restored tidal channels can be determined based on the current or historical density of tidal channels in the restoration area and nearby areas.

(2) Brackish and Freshwater Regulation Technique

Wetland brackish and freshwater regulation technology is employed to regulate the water quality and quantity of coastal salt marsh wetlands, with the goal of enhancing the ecological environment and biodiversity of wetlands. This technique primarily involves adjusting the mixing ratio of freshwater and brackish water to achieve optimal ecological conditions for water quality and quantity in wetlands. The key advantage of this technology is its ability to improve the stability of water quality and quantity in wetlands, thereby enhancing their ecological environment and promoting the growth and reproduction of wetland vegetation.

In areas where the brackish and freshwater habitat conditions are unsuitable for the growth of coastal salt marsh plants, the supply ratio of freshwater and brackish water should be determined based on the characteristics and needs of degraded salt marsh wetlands, including the types of wetland plants (such as Phragmites australis, Suaeda salsa, etc.). If necessary, hydrological models can be utilized to simulate processes such as hydrodynamics, freshwater volume, and salinity gradient in the restoration area. This helps in designing brackish and freshwater regulation methods and implementing necessary technical measures to achieve a suitable state after restoration.

During the actual restoration process, techniques such as diverting and storing freshwater, restoring surface runoff of freshwater, and altering the salinity ratio of water sources can be employed. These actions enhance the water quality purification and water-sediment regulation capacity of wetlands, thereby improving the habitat quality and water environment of wetlands. This approach effectively restores degraded coastal salt marsh wetlands.

9.1.2 Wetland Microtopography Remodeling Technique

The microtopography of coastal salt marsh wetlands determines the depth, frequency, and duration of inundation within the wetland, significantly impacting the growth of wetland plants and other organisms. Targeted measures can be implemented to change the elevation of local areas, such as dredging tributaries and ditches, based on the water system connectivity and brackish and freshwater regulation of coastal salt marsh wetlands. This ensures that the restored local area’s topography remains consistent with the overall regional topography, enhancing habitat heterogeneity, stability, and the resilience of restored wetlands. The microtopography remodeling of coastal salt marsh wetlands can generally be approached from two aspects: elevation and slope. Specific technical methods include:

(1) Elevation Modification and Restoration Technique

The relationship between topographic elevation and tide level in the restoration area is crucial for plant growth in coastal salt marsh wetlands. During practical restoration, the topographic elevation threshold required for the growth of salt marsh plants is compared with the current topographic elevation of the wetland to determine whether measures to uplift or lower the elevation of the salt marsh are necessary.

Figure 3 Design Measure the Elevation of the Land Parcel (Source: the authors)

When the current elevation is lower than the suitable topographic threshold required for the growth of target salt marsh plants, backfill can be used to raise the marsh elevation. The selected backfill soil should meet the growth requirements of the target salt marsh plants, including particle size, nutrient content, and heavy metal indicators.

When the current topographic elevation is higher than the suitable elevation threshold required for the growth of target salt marsh plants, ecological dredging and other techniques can be used to lower the salt marsh elevation. Ecological dredging mainly includes wet dredging and dry dredging. Wet dredging is suitable for areas where the dredging equipment’s draft depth can be reached. It uses environmentally friendly cutter suction dredgers to dredge, which has high dredging precision and minimal environmental impact, but poor control and complex process. Dry dredging is suitable for wetland reconstruction or situations where wet dredging is not feasible. It can lower the marsh elevation by setting cofferdams and draining the water inside them. This method is easy to control, easy to operate, convenient for reshaping remodeling the topography, but improper operation may affect the native wetland ecosystem.

(2) Slope Modification and Restoration Techniques

Terrain slope is a critical factor in the microtopography remodeling of coastal salt marsh wetlands. Setting and modifying slopes can reshape the natural tidal flat slope, meeting the elevation requirements for various wetland plants to grow on narrow flats.

The principles of slope modification align with those of elevation modification. Determining the most suitable slope threshold for the growth of target salt marsh plants is essential. Under appropriate conditions, the suitable slope can be determined based on factors such as hydrodynamic conditions, elevation, vegetation types, and the slope of surrounding wetlands. However, for practical engineering applications and construction convenience, in areas with strong natural dynamics (where tides frequently reach), a zero-degree slope can be initially designed. Over time, the slope will naturally form. For areas with weaker natural dynamics (where tides are less likely to reach), a certain slope can be designed as needed.

9.1.3 Substrate Restoration Techniques

The substrate environment, including sediment, plays a crucial role in the formation of coastal salt marsh wetlands, serving as a foundation for the growth and reproduction of wetland plants and microorganisms. Therefore, substrate restoration is vital in coastal salt marsh wetland restoration efforts. This restoration is based on the hydrological, hydrodynamic, and microtopographic conditions of coastal salt marsh wetlands, primarily driven by hydrodynamic forces and supplemented by human intervention, aiming to restore the basic physicochemical properties of wetland substrates to a state similar to that of the reference ecosystem.

During substrate restoration, a survey and assessment of various physicochemical indicators of the current substrate conditions (such as particle size, total soluble salt content, pH value, organic carbon, total nitrogen, total phosphorus, etc.) should be conducted. These indicators should be compared and analyzed against the suitable substrate conditions required for the growth of target restoration plants. This comparison helps determine the substrate environmental issues of coastal salt marsh wetlands, leading to corresponding measures to transform them, making them approach the substrate environmental conditions of the pre-degraded (or reference ecosystem) salt marsh wetlands to meet the growth needs of restoration plants. In practical restoration processes, physical or biological methods, such as deep plowing and sun-drying, surface elevation adjustment, saline-alkali soil improvement (including chemical, plant, and engineering improvement measures), and nutrient improvement of substrates, can be employed to enhance the substrate structure and nutrient conditions of coastal salt marsh wetlands.

9.1.4 Water Quality Improvement

Maintaining good water quality in coastal salt marsh areas is essential for the growth and reproduction of organisms. Deterioration of water quality can negatively impact biological populations' survival and reproduction, threatening the entire ecosystem's stability. Therefore, improving water quality is crucial for the health and stability of the coastal salt marsh wetland ecosystem, representing a key aspect of habitat restoration.

Improving water quality involves a combination of natural regulation and artificial purification technologies to restore water quality conditions to a state similar to that of the reference ecosystem. To achieve this, measures should firstly be implemented to limit the discharge of pollutants into the sea, enhance environmental protection supervision of coastal industries and cities, and promote the adoption of more environmentally friendly production methods and wastewater treatment technologies. Additionally, large-scale beach cleanup activities can help remove garbage and pollutants, reducing their impact on the marine ecosystem. Secondly, techniques such as filtration devices, hydrological regulation measures, and microbial agents can be employed to improve water quality. Properly adjusting water flow and mixing can reduce pollutant concentrations and promote the growth and reproduction of beneficial microorganisms, further enhancing water quality. Strengthening monitoring and management practices is also crucial to ensure continuous improvement in water quality conditions.

9.2 Plant Restoration

Restoration of coastal salt marsh plants primarily relies on natural recovery and plantation establishment, tailored to the degradation status of coastal salt marsh vegetation. Natural recovery involves removing external pressures or disturbances and closing off salt marshes for conservation to facilitate natural vegetation recovery. If natural regeneration is insufficient in the restoration area, plantation establishment methods can be employed to restore salt marsh vegetation.

Plantation establishment should consider different plant types in coastal salt marshes, utilizing methods such as root, stem, and seed reproduction for planting or transplanting. Key techniques include species selection, planting methods, and timing.

When selecting plant species in coastal salt marshes, local species should be prioritized, chosen based on the restoration area's natural geographical conditions. Typically, plants with well-developed root systems, adaptation to saline-alkali environments, and the ability to stabilize soil and improve water quality are preferred.

In terms of planting techniques, suitable seasons and methods should be selected based on the characteristics and tolerance of different coastal salt marsh plants to salinity and inundation, facilitating salt marsh vegetation restoration.

China's native dominant plant types in coastal salt marshes mainly include Phragmites australis, Suaeda salsa, Bolboschoenoplectus mariqueter, and Cyperus malaccensis. Due to their different characteristics, corresponding planting techniques vary. The specific planting techniques and key points are introduced as follows.

9.2.1 Phragmites australis Planting

Phragmites australis planting in China’s coastal areas generally utilizes the transplantation method, which includes several techniques such as transplanting reed clumps with soil, transplanting rhizomes, transplanting rhizome seedlings, transplanting green reeds with rhizomes, and stem cutting propagation and transplantation.

Transplanting reed clumps with soil: This method involves transplanting reeds dug out with soil. The transplanting time is typically from late April to early May each year, although this can be adjusted based on temperature conditions in different regions and years. Before planting, trenches or pits larger than 30cm should be dug, with a density of about 1m x 1m. The reed clumps should then be placed in the trenches or pits and covered with soil, which should be compacted by stepping on it.

Transplanting rhizomes: This method is suitable for areas with higher terrain in coastal salt marsh restoration. It is usually carried out from April to May each year, when the shoot buds on the rhizomes begin to germinate. Good rhizomes can be selected for propagation, typically segments containing 4 to 6 buds and rhizome lengths of 30cm to 40cm from naturally grown coastal reed communities. Water should be sprayed in time to keep the rhizomes moist. The planting method involves digging holes and pits for planting, with a planting density of 3 to 4 reed rhizomes per hole. Each rhizome segment should have at least one bud exposed above the ground. The spacing between rows should be between 50cm x 50cm and 100cm x 100cm, with a planting depth of 5cm to 10cm.

Transplanting rhizome seedlings: Typically conducted from March to April each year, this method involves digging out reed roots and cutting them into small 30cm sections, which are then planted in nutrient-rich containers. When the seedlings reach a height of about 30cm, they are transplanted into field pits, which are approximately 30cm deep and spaced 1m apart. During transplantation, the seedlings should be transplanted with soil and the soil should be compacted.

Green reed transplanting with rhizomes: This method is suitable for coastal salt marsh restoration areas with lower terrain. During the growing season, green reeds with rhizomes measuring 30cm to 100cm in height are dug up and transported to the field for planting, ensuring that the rhizomes are fully inserted into the soil during planting.

Stem cutting propagation and transplantation: This method is suitable for areas with low total salt content in the soil. One-year-old stem cuttings are suitable for all types of coastal saline soil areas. Typically, from June to August each year, well-developed reed plants are selected, and the middle part is cut into 30cm segments, each containing about 2 to 3 sections. When planting, it is recommended to select a suitable plot with a total salt content of less than 0.5%, perform rotary plowing before planting, and maintain a 3cm to 5cm water layer on the field surface. The cut reed sections should be inserted diagonally into the seedling field with a spacing of 30cm x

30cm and can be transplanted at any time after the reed plants have sprouted roots.

During the planting period, attention should be paid to reed care, considering local climatic conditions and reed growth characteristics. Factors such as the germination period, deep-water irrigation period, reed maturity, as well as disease and pest control, should be comprehensively considered.

9.2.2 Suaeda Salsa Planting

Suaeda salsa planting in China’s coastal areas involves stages such as seed preparation, sowing, irrigation, fertilization, and rsowing.

Seed preparation: Suaeda salsa in China’s coastal areas typically matures from September to October each year, with seeds collected during this period. In some areas, seeds are collected in early November to increase the seed’s germination rate. Seeds should be collected from plants growing in environments similar to the planting location and preferably from the mudflat, then dried for preservation.

Sowing: The optimal planting dates are usually from mid-February to late April each year, depending on specific conditions and when the local temperature is above 15℃. Seeds can be sown manually or broadcasted by machine, depending on the salt marsh's characteristics. After sowing, the area can be covered with a net—either vegetable insect-proof nets or permeable non-woven fabrics—and the net can be secured with soil blocks before the first tide. During the sowing process, it may be necessary to loosen the soil in the designated area and create trenches based on the specific conditions. Additional measures, such as compacting the soil after sowing, may also be required.

Irrigation: Suaeda salsa in coastal areas typically germinates 7-10 days after sowing. During germination, soil moisture should be maintained, and irrigation should be carried out when necessary based on soil moisture conditions. The frequency and amount of irrigation should be determined according to the situation. Generally, irrigation with a small amount of water can be applied 1-2 times. In case of drought, an appropriate amount of water should be irrigated promptly.

Fertilization: Typically, one month after germination, topdressing should be applied according to the growth stage.

Replanting: Usually conducted from late October to early November each year (timing may vary in different regions and years), this involves selecting the best-growing plants to collect seeds with full grains for sowing. In the following year, areas with low Suaeda salsa coverage (such as bare areas with coverage below 80%) should be timely resowed.


Pelletized Seeds for Planting Suaeda salsa

Pelletized seed technology is an innovative seed treatment method that modifies the shape and size of seeds by coating them with a mixture of fillers, adhesives, nutrients, protectants, growth regulators, coloring agents, and other materials. This coating enhances seed protection, promotes germination, and supports seedling growth under adverse conditions. By using this technology, seed resistance is improved, seed mobility is enhanced for mechanized sowing, the likelihood of seed predation by birds is reduced, and seedling survival rates in challenging environments are increased. In this project, the wetland vegetation is predominantly Suaeda salsa, covering a large planting area that requires mechanical seeding rather than manual planting. However, due to the small size of Suaeda salsa seeds, retaining them after spraying is difficult, particularly in areas influenced by water flow. To address this, the project introduced the innovation of pelletizing Suaeda salsa seeds. The pelletized seeds are larger, making them less susceptible to being washed away, while the coating provides nutrients and protection, thereby increasing the germination rate and seedling survival in high-saline environments. This technique enhances the quality of seedling growth and improves the success rate of seed planting in saline soils.

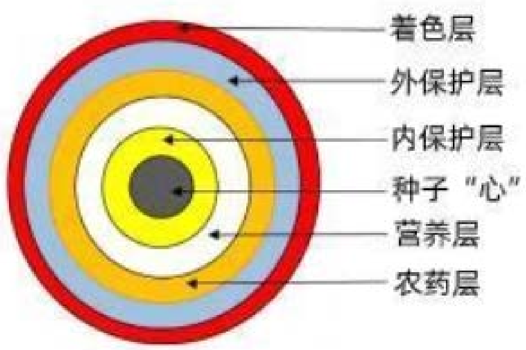


Figure 4 Seed pellets cross-section (left), seed pellets construction site drawing (right)
(Source: the authors)

Bamboo Tubes for Planting Suaeda salsa

The use of bamboo tubes as containers for growing Suaeda salsa represents an innovative cultivation method that leverages the bamboo’s natural air permeability and moisture retention to create an optimal growth environment for the plant. When selecting bamboo tubes, thicker tubes should be chosen to accommodate the root growth of Suaeda salsa. Although bamboo tubes provide some natural drainage, additional drainage holes should be drilled at the bottom of the tubes to prevent waterlogging and root rot. The bamboo tubes should also be filled with a substrate suitable for Suaeda salsa to ensure the plant’s growth needs are met. Cultivating Suaeda salsa in bamboo containers not only improves the quality of plant growth but also contributes to reducing soil salinity, yielding both ecological and economic benefits.

9.2.3 Planting of Bolboschoenoplectus mariqueter

The cultivation of Bolboschoenoplectus maritimus typically involves two phases: seed preparation and sowing. Seed preparation includes collecting, vernalizing, germinating, sowing, and resowing.

Seed collection: The seed-bearing period for Bolboschoenoplectus maritimus typically bears seeds from September to October each year. During this period, it is advisable to collect full and mature seeds to ensure a high germination rate.

Vernalization treatment: Around February of the following year, the seeds are mixed with moist fine sand in a certain ratio (such as a 1:2 volume ratio) or soaked in water and stored in a refrigerator at 1° C to 4° C for about 20 to 30 days. During this period, it is necessary to regularly check whether the seeds have become moldy and wash them promptly if needed.

Germination: Vernalized seeds are moved to a greenhouse with a temperature of 20° C to 30° C for germination. The seeds are submerged in water in the greenhouse, and the germination period is generally controlled between 5 to 15 days. Once more than half of the seeds have germinated, they are ready for sowing.

Sowing: In coastal regions of China, the optimal time for planting Bolboschoenoplectus maritimus is from April to May, when the daily average temperature exceeds 15° C. The optimal sowing density is 50 seeds/m2 to 100 seeds/m^2.

Resowing: In areas where the germination rate is less than 10% of the sown amount after one month, resowing can be done at a rate of 10 to 30 seeds per square meter.




9.2.4 Planting of Cyperus Malaccensis

Planting Cyperus malaccensis in coastal areas of China involves several stages, including provenance selection, grass block collection, planting, and fertilization.

Provenance selection: In coastal areas of China, the planting method typically involves selecting natural growth areas of Cyperus malaccensis with similar habitat conditions, such as salinity, tidal conditions, and substrate, to the planting area. Healthy, pest-free grasslands with a large, continuous area and lush growth are chosen, and soil-bearing grass blocks are collected as seedlings.

Grass block collection: Above-ground stems of the plants are cut off, leaving a 30cm stubble. Grass blocks are then dug using an iron shovel or a special seedling collector. The blocks typically range in size from 15cm×15cm to 30cm×30cm, with a depth of 20cm to 30cm. Grass blocks collected on the same day should be planted on the same day.

Planting: Cyperus malaccensis can be planted during neap tides from March to November each year. Row spacing ranges from 50cm×50cm to 100cm×100cm. Dig a hole slightly larger than the grass block according to the row spacing, spray approximately 100ml of root growth-promoting hormone solution around each grass block, and then plant it.

Fertilization: Utilize slow-release fertilization by burying the fertilizer around the perimeter of the grass block. After applying the fertilizer, cultivate hole pits and compact the grass blocks. Fertilization should be conducted between March and May each year.

During the planting process, attention should be given to the tending of Cyperus malaccensis. Construct fence nets using wooden or cement stakes, with subsidiary stakes added between the main stakes and connected by nylon ropes. Hang nylon nets for additional support. Additionally, take measures to prevent and control the proliferation of enteromorpha prolifera and diseases.

9.3 Invasive Species Control Techniques

Spartina alterniflora is the dominant invasive species in China' s coastal salt marshes. Since its introduction in the 1970s, Spartina alterniflora has rapidly spread across these coastal areas. In December 2022, the Chinese government issued the Special Action Plan for the Prevention and Control of Spartina alterniflora (2022–2025), initiating a nationwide campaign to curb its spread.

The prevention and control of Spartina alterniflora are based on a scientific assessment of the local ecological community, aiming to restrict or suppress its growth, sexual reproduction, and asexual reproduction to control its spread or achieve complete eradication. The key principles guiding the prevention and control of Spartina alterniflora emphasize ecological prioritization, equal focus on prevention and management, respect for natural processes, scientific approaches, and adaptation to local conditions, and design control schemes tailored to local conditions based on factors such as the local natural environment, biological environment, construction conditions, and project investment.

The main control methods for Spartina alterniflora include physical control, chemical control, biological control, biological substitute, and integrated control.

(1) Physical Control

Physical control methods include manual removal, covering and shading, mowing, burning, and flooding. These methods generally do not cause environmental pollution and have minimal impact on organisms. However, they are time-consuming, labor-intensive, costly, and prone to recurrence. The use of physical control techniques must fully consider factors such as the reproductive period of Spartina alterniflora and the frequency and intensity of control techniques.

(2) Chemical Control

The eradication of Spartina alterniflora is generally achieved through the application of herbicides. Chemical control methods are less costly and more effective in extermination, but they pose potential ecological and environmental risks. Therefore, it is important to select low-toxicity agents and adopt the correct application method when utilizing chemical control techniques.

(3) Biological Substitute

Biological substitute is an ecological control technique that involves substiting invasive plants with competitive native plants based on the principles of plant community succession. However, identifying rapid, effective, and safe substition species and control methods in specific areas remains challenging. Currently, studies are being conducted on the use of species such as Phragmites australis, Suaeda salsa, and mangroves to substitute Spartina alterniflora.

(4) Biological Control

Biological control involves using phytophagous animals or pathogenic microorganisms with a specific host range to control Spartina alterniflora through direct feeding, gall formation, burrowing in plant tissues, or inducing plant diseases. The goal is to maintain Spartina alterniflora within a certain density and range. However, this method is difficult to completely eradicate Spartina alterniflora and often requires the introduction of other species, which can pose a risk of invasion by alien species.

(5) Integrated Prevention and Control

In practice, combining multiple control measures generally yields better results. Various methods such as mowing, mowing + flooding, mowing + deep tillage, shading, biological substitute, and herbicide spraying can be selected based on local conditions. During prevention and control, appropriate precautionary measures should be taken to avoid derivative disasters.

9.4 Construction of Coastal Integrated Protection System

Utilizing the spatial resource endowment of coastal salt marsh restoration areas, the aim is to maximize disaster mitigation and coastal protection capabilities. Design optimal parameters such as the width of the salt marsh vegetation belt and plant density, and employ comprehensive techniques such as zonal planting, gradual level-by-level wave attenuation, and spatial optimization of plant communities to construct a comprehensive coastal protection system based on salt marsh vegetation.

9.4.1 Zonal Planting for Optimal Disaster Mitigation of Coastal Salt Marshes

In most coastal areas of China, salt marsh vegetation exhibits distinct belt-shaped distribution characteristics. Various salt marsh plants, such as Phragmites australis and Suaeda salsa, are distributed in different belt-shaped areas from the sea to the land. Therefore, zonal planting can be employed in restoration method design, combining the wave attenuation and current weakening functions of different salt marsh plants to establish an integrated protection system.

Select the suitable salt marsh plant species for the planned restoration area based on the beach characteristics and habitat conditions, and by considering the varying degrees of damage caused by marine dynamic disasters and the response characteristics of plant communities to these processes during the growth period, comprehensively analyze the survival and colonization adaptability thresholds of different salt marsh plants, such as Phragmites australis and Suaeda salsa, in the spatial zone suitable for growth in the planned restoration area. This analysis helps clarify the composition and spatial distribution characteristics of plant communities in the region.

With the overarching goal of maximizing disaster prevention and mitigation capabilities in the restored area, it is essential to design optimal parameters such as vegetation belt width and plant density. This design should consider the combination and interaction of different plant types in different zones. By focusing on various salt marsh plants, including Suaeda salsa, Bolboschoenoplectus mariqueter, and Cyperus malaccensis, implementing zonal planting can help achieve this optimization goal and form a comprehensive coastal salt marsh protection system.

9.4.2 Construction of a Nature-based Integrated Coastal Zone Protection System

To maximize disaster prevention, mitigation, and coastal protection capabilities, some restoration areas may integrate ecological structures (e.g., oyster reefs), vegetation, and seawalls, among other coastal protection measures, depending on local conditions.

With the primary objective of optimizing the disaster prevention and mitigation effects of the coastal zone, it is essential to consider the topographic and geomorphological features and spatial scale of the planned restoration area. A comprehensive analysis of the evolution characteristics of marine dynamic disasters and the disaster mitigation characteristics of different coastal protection measures is necessary. This analysis should evaluate the comprehensive impact of ecological structures, vegetation, beaches, and seawalls on the evolution of marine dynamic disasters. Based on this analysis, spatial combination methods and applicable conditions for different protection measures can be proposed. This approach clarifies the spatial configuration scheme of intergated coastal protection zones and forms a natural cross-sectional spatial configuration-based coastal zone integrated protection system.

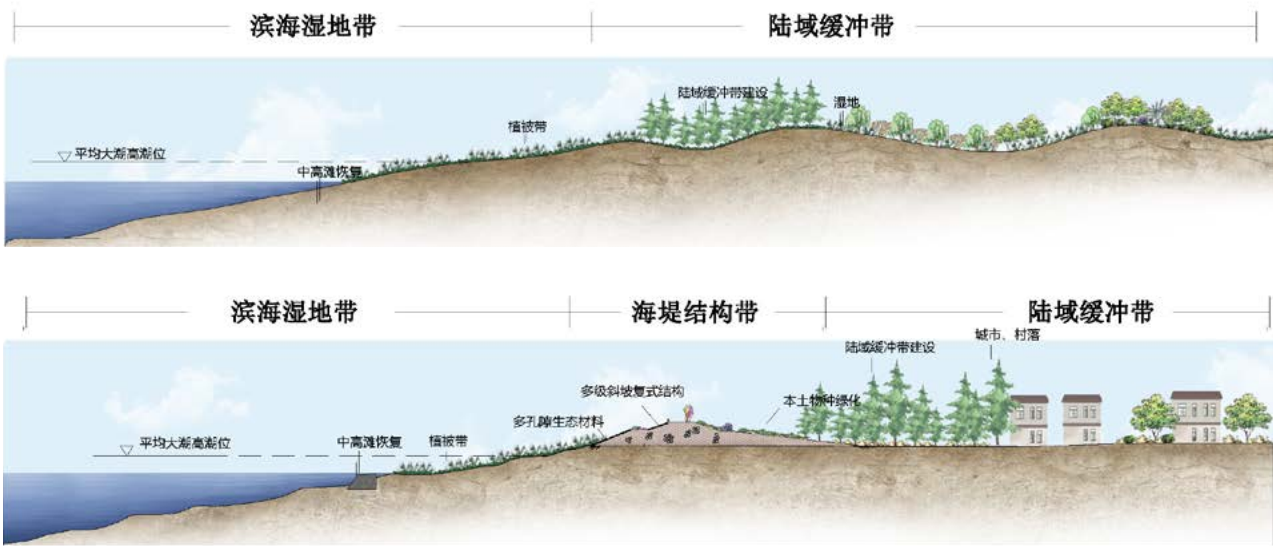


Figure 5 Schematic diagram of the Nature-based Integrated Coastal Zone Protection System

9.5 Post-restoration Stewardship

After the restoration of coastal salt marshes, a new biological community is formed. The potential risks brought by early threat factors may be strong, and interspecific competition is relatively small, making it easy to form a relatively single species community. As vegetation succession progresses, threat factors weaken, interspecific competition increases, and plant diversity gradually increases. For example, Suaeda salsa is one of the pioneer species in the community succession of coastal saline alkali land ecosystems. It is easy to form a single community in coastal wetlands. After soil modification, soil salinity decreases, which will promote the formation of secondary communities. Therefore, the management and protection of salt marsh restoration areas is a dynamic process.

In the later stage, targeted management measures need to be developed based on the ecological habits of plant community species and changes in habitat conditions. Generally speaking, it is difficult to determine the succession results of the salt marsh community in the restoration area in the initial stage after the restoration is completed. Therefore, it is necessary to combine management and monitoring of the restoration area, and the species and distribution information of the plant community provided by tracking and monitoring should be used as the basis for management and protection measures.

- During the management and protection period, regular inspections should be conducted on the growth of vegetation, and tracking and monitoring should be carried out on the growth status and environmental factors of coastal salt marsh vegetation such as salt marshes and reeds, with timely recording and analysis.
- The general maintenance period is more than 2 years. Conduct at least one routine maintenance per year. After strong typhoons, storm surges, marine pollution and other marine disasters, an additional emergency maintenance should be carried out to check the integrity and stability of the salt marsh vegetation in the repair area, and timely and reasonable repair measures should be taken for any damage that occurs.
- During the later management and protection period, reasonable irrigation and drainage can be carried out as needed. The irrigation water source should be suitable for the growth needs of plants. During the irrigation period, timely irrigation should be carried out according to the biological characteristics of plant species, soil moisture, and water salt operation rules. The number of

irrigation times should follow the principle of no drought or watering under normal circumstances, but watering should be done thoroughly. At the same time, measures such as spraying water to maintain moisture and timely drainage should be taken. Areas with salt content exceeding the growth limit of wetland plants should be irrigated and watered in a timely manner to reduce soil salt content, and monitored to control salt content.

- Determine whether to apply fertilizer based on the growth of salt marsh plants. Fertilization should be mainly based on base fertilizer, supplemented by topdressing, and the timing and amount of fertilization should be strictly controlled.
- Timely replant according to the emergence rate or survival status of plants. If necessary, supplementary planting and seedling cultivation can be adopted. For example, to meet the daily replanting needs of Suaeda salsa, containers made of biodegradable materials can be selected, usually using honeycomb seedling paper tubes.
- During the management and protection period, attention should be paid to the prevention and control of pests and diseases. The principle of disease and pest control is "prevention first, comprehensive prevention and control". Regularly conduct pest and disease testing on plants within the repair area, and promptly deal with infected and insect infested plants. Recommend using physical control measures to reduce the occurrence of pests and diseases. Strengthen inspection efforts during seasons with high incidence of pests and diseases, and implement timely prevention and control measures for various pests and diseases. At the same time, pay attention to protecting the environment and reducing environmental pollution. For plants that have died or become weak due to external reasons, timely removal and replanting can be carried out in suitable seasons for vegetation.
- Take necessary beach closure and conservation measures according to the actual situation. Arrange personnel for patrols as needed, prohibit operations

unrelated to conservation in the restoration area, take measures such as dedicated personnel to patrol and guard, and set up protective nets to strengthen protection. Regularly clean up floating garbage and weeds in the restoration area.

Figure 6 Suaeda Salsa Plant Replanting and Seedling Cultivation

(Source: the authors)

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

10.1 Follow-up Monitoring

The objective of monitoring coastal salt marsh restoration is to comprehend the ecosystem’s status and trends, providing data for analyzing the attainment of restoration goals and the comprehensive benefits generated.

Ecological restoration tracking and monitoring should encompass both implementation and post-implementation phases. Long-term continuous monitoring at fixed stations should be conducted where conditions allow. The ecological restoration monitoring program should be developed during the preparation stage of the ecological restoration plan, with a clearly defined detailed monitoring plan.

10.1.1 Monitoring Content

Based on the objectives of coastal salt marsh restoration, determine the content and parameters that need to be tracked and monitored. Ecological restoration follow-up monitoring should encompass salt marsh vegetation, biological communities, environmental elements, important ecological processes, and functions, with attention to different aspects at various stages.

For short-term ecological restoration objectives, the monitoring content before project acceptance should align with the restoration objectives and project scope. For medium and long-term ecological restoration goals, the monitoring content should emphasize relevant parameters of important species, essential ecological processes, and functions. In projects where conditions allow, in addition to the content to analyze the achievement of restoration goals, continuous comprehensive monitoring may be conducted.

10.1.2 Monitoring Areas and Stations

The tracking and monitoring of coastal salt marsh restoration should cover the entire restored area. If the restoration project involves reference and control ecosystems, the monitoring area should include not only the restored area but also salt marshes designated as reference and control ecosystems. If a baseline survey of the restoration area has not been conducted before the implementation of the restoration project, or if the ecological survey information is insufficient, a representative control ecosystem can be set up to represent the pre-restoration state of the restoration area, and synchronous ecological monitoring can be conducted. Through on-site surveys, research, and expert consultations, select salt marshes or salt marsh remnants (such as tidal flats and aquaculture ponds) in the surrounding areas of the restored coastal salt marsh that have similar habitat conditions and degradation status as the control ecosystems.

Consistent with the principles of ecological baseline surveys, follow-up monitoring should comprehensively consider vegetation and habitat conditions when setting up monitoring stations. Focus should be on setting up monitoring sections and stations based on factors such as the salt marsh restoration area, species, and tidal flat elevation. The geographic location and size of monitoring sections, stations, and quadrats should be reasonably determined based on the monitored parameters. Where conditions permit, fixed sections, stations, and quadrats should be established as much as possible, and continuous monitoring should be conducted, with an adequate number of repeat monitoring stations and quadrats.

Monitoring stations and quadrats for monitoring biological communities, environmental elements, and ecological functions should be consistent with those for vegetation monitoring. Monitoring stations for the hydrological environment, fish, birds, etc., can be set up according to assessment needs and their respective monitoring methods, reflecting the overall characteristics of the monitoring content and elements. Monitoring for the functions of coastal salt marshes in attenuating waves and weak currents should consider the characteristics of salt marsh vegetation and the marine dynamic disaster processes before and after restoration when designing the layout of sections and stations (specific methods are described in Section 5.2.6 of this handbook).

10.1.3 Duration and Frequency of Monitoring

（1）Monitoring Period

Follow-up monitoring of coastal salt marsh restoration should encompass the entire implementation process of the restoration and the different stages of the ecosystem’s status after the restoration project is implemented.

After the implementation of the coastal salt marsh ecological restoration project, to provide monitoring data for evaluating the achievement of restoration goals, the time span of follow-up monitoring should be consistent with the time of achieving restoration goals. The monitoring time for salt marsh vegetation, biological communities, and habitat conditions can be set at around 10 years, and monitoring of ecological functions is suitable for around 20 years. If the conditions for long-term follow-up monitoring are not available, the monitoring period can be set at around 5 years to meet the needs of short-term goal assessment.

(2) Monitoring Frequency

Within the first year after planting salt marsh plants, monitoring of seedling survival rate can be conducted at intervals of 1-2 months.

In the early stages of coastal salt marsh ecological restoration (<5 years), ecological follow-up monitoring should be conducted annually as appropriate. For salt marshes with a restoration time exceeding 5 years, regular follow-up monitoring can be conducted according to the actual situation, with a monitoring interval of 3-5 years for an annual cycle period being appropriate.

If the restoration work sets phased goals, the frequency of follow-up monitoring should be based on the time set for achieving the phased goals.

In each monitoring year, the survey time should be adjusted according to the phenological characteristics of coastal salt marsh plants in various climate zones, preferably during the season with the maximum plant biomass (usually scheduled between July and October). If it is necessary to reflect the seasonal changes in the characteristics of coastal salt marsh vegetation, environmental elements, biological communities, etc., a quarterly survey can be conducted, and the survey months in the same region should be consistent.

10.1.4 Monitoring Methods

In principle, the follow-up monitoring methods of coastal salt marshes are consistent with ecological baseline surveys. Based on the set monitoring content and indicators, specific monitoring methods should be determined with reference to relevant normative documents and literature. Generally, methods such as UAV survey or high-definition satellite remote sensing image analysis can be used to monitor changes in the area of coastal salt marshes. Ecological and disaster mitigation related parameter data can be obtained through on-site monitoring, and real-time continuous monitoring devices can be used to obtain information on images and ecosystem parameters of the restoration area if conditions permit. Data from social, economic, and other aspects can be collected by a combination of data collection and on-site investigation.

To visually reflect the effects of restoration, comparable image data of salt marsh habitat conditions, vegetation, and animals within the restored area can be collected regularly. For example, the growth of salt marsh vegetation can be photographed from fixed positions and angles.

10.2 Restoration Effect Assessment

10.2.1 Content of Restoration Effect Assessment

According to the short-term, medium-term, and long-term goals of coastal salt marsh restoration and the progress of monitoring implementation, stage and final assessments of the ecological system restoration effect should be conducted. The content of ecological restoration effect assessment should be selected based on the actual situation of the project and may include but is not limited to:

- Restoration of salt marsh vegetation;
- Restoration of biological communities;
- Restoration of environmental elements;
- Elimination of threat factors;
- Restoration of important ecological functions;
- Improvement of disaster prevention and mitigation capabilities.

The ecological restoration effect assessment of coastal salt marshes should set reasonable evaluation indicators in accordance with the assessment content. The evaluation indicators should correspond to the monitoring parameters and clearly specify the calculation methods. The content and indicators of ecological restoration effect assessment and monitoring should be selected with reference to Table 1.

Within 5 years after the completion of the restoration project, the focus should be on evaluating the vegetation cover of salt marshes, the restoration of salt marsh plant communities and communities of macrobenthos and birds, and the restoration of sediment environments. If the restoration project involves habitat restoration and the elimination of threat factors, the effect of habitat restoration and the elimination of threat factors should also be assessed within 5 years of the completion of the restoration work.

After the completion of the restoration project, according to the different types of coastal salt marsh plants, an assessment of the disaster prevention and mitigation capabilities of the coastal salt marsh ecosystem should be conducted after reaching maturity stage (usually within 5 years). The key assessment includes the ability of coastal salt marsh ecosystems to reduce marine dynamic disasters such as waves and weak currents based on comprehensive factors such as vegetation and topography (specific assessment methods refer to the corresponding technical standards, such as HY/T 0382-2023).

Five years after the completion of the restoration project, it is advisable to increase the assessment of the restoration of important ecological processes and ecological functions, including the maintenance of ecosystem biodiversity, carbon sequestration and sink enhancement.

10.2.2 Assessment Methods for Restoration Effects

Each evaluation indicator uses the average value of all monitoring stations as the evaluation result for the restored area. Based on the ecological restoration monitoring results, the evaluation of restoration effects can be carried out from two aspects: improvement and enhancement of ecosystem indicators, and degree of achievement of ecological restoration goals.

Assessment of improvement and enhancement of ecosystem indicators: The restoration project can assess the changes and trends of various indicators by comparing the current values of evaluation indicators with the pre-restoration values or the current values of reference ecosystems, reflecting the improvement of the ecosystem and the enhancement of its functions.

Achievement of ecological restoration goals: For evaluation indicators with clearly defined restoration target values, the achievement of ecological restoration goals can be reflected by comparing the current values of relevant indicators with the target values at the time of assessment. For evaluation indicators without clearly defined target values at the stage of setting restoration goals, the current values of evaluation indicators can be compared with the status values of reference ecosystems. When these indicators reach or approach the status of reference ecosystems, it can be considered that the ecosystem has been restored. When evaluating the degree of achievement of ecological restoration goals, for indicators that have not significantly recovered, further analysis can be conducted through expert consultation, survey, and experimentation to determine whether they are still in a degraded state or adversely affecting the restoration of the ecosystem.

10.3 Adaptive Management of Ecological Restoration

In the process of coastal salt marsh restoration, the ecological restoration goals can be appropriately and reasonably adjusted according to the long-term environmental changes and the status of reference coastal salt marsh ecosystems. Different improvement measures can be taken according to different types of restoration methods and stages of restoration.

In the process of restoration, if there are unsatisfactory ecological indicators or indicators that adversely affect the restoration of the ecosystem, the effectiveness of restoration techniques and methods should be analyzed in a timely manner. Adjustments and corrections should be made to ineffective restoration techniques and methods, as well as to restoration measures and technologies that may cause new damage to the ecosystem. New techniques and methods can be introduced to improve the effectiveness of restoration.

Based on the restoration of threat factors in the coastal salt marsh area after restoration, maintenance of terrain and landforms, degree of water exchange, sediment environment, salt marsh vegetation, and other biological communities, the effectiveness of the techniques used in restoration can be judged. For techniques that are not effective or fail to achieve restoration goals, the reasons for failure should be analyzed. Restoration measures and techniques should be adjusted if necessary, or new restoration measures and techniques should be introduced.

Natural restoration of coastal salt marshes: For coastal salt marsh restoration projects using natural restoration methods, if the number of salt marsh plants naturally growing in the restoration area does not reach the expected target, a small amount of plantation can be established for supplementation.

Artificially assisted restoration and reconstructive restoration: After planting coastal salt marsh plants, the germination of plants and the survival of seedlings should be observed regularly. Enrichment planting should be carried out when the survival rate of seedlings is less than 75%. Usually, short-term tending can end after

1 year. After the end of short-term tending, necessary enrichment planting should be carried out based on the survival of salt marsh plants until the restoration project achieves the expected goals.

11.Classic Cases of Coastal Salt Marshes Restoration

11.1 Case 1— The Coast of Yellow River Estuary, Dongying, China

I. Environmental Overview

The Yellow River estuary sits at the intersection of Bohai Bay and Laizhou Bay, home to one of the world’s most complete, representative and youngest coastal wetland ecosystems in the warm temperate zone. This region serves as a critical germplasm resource for marine life in the Yellow River and Bohai Sea areas and is considered a cradle of biodiversity. Moreover, it functions as a crucial stopover for migratory birds along the Pan-Pacific Western and East Asia-Australasia flyways. Protecting the wetland and coastal ecosystems in this area is vital for maintaining the ecological security of the Yellow River basin and the Yellow-Bohai Sea region.

In the coastal area south of the Yellow River estuary in Dongying City, the native Suaeda salsa once thrived in expansive, continuous patches, forming the renowned “red carpet” landscape. This ecosystem, rich in biodiversity, particularly birds, not only held substantial ecological value but also provided natural protection against marine disasters like storm surges, waves, and red tides.

Since the 1980s and 1990s, the development and utilization of once-deserted beaches have advanced the growth of marine fisheries, boosting local fishermen’s incomes. However, these developments have also exacerbated ecological challenges and heightened disaster risks, as natural coastlines have been damaged, increasing vulnerability to marine disasters. Since the 18th National Congress of the Communist Party of China, Dongying has embraced the concept of marine ecological civilization, shifting the region’s focus from fishery production to ecological conservation. While some ecological improvements have been observed, several ecological and disaster related challenges persist. First, many abandoned aquaculture facilities remain in the region, and tidal channels have silted up, reducing seawater exchange capacity (Figure 7). Second, coastal wetlands have been encroached upon by aquaculture ponds, leading to noticeable vegetation degradation. The once-vibrant “red carpet” has significantly receded, leaving behind vast expanses of bare beach (Figure 8). Third, human activities, including fishery production and harbor construction, have caused the gradual disappearance of oyster reefs and seagrass beds, severely threatening local ecosystems and biodiversity. In response to these ongoing challenges, Dongying has initiated multi-tiered and targeted ecological restoration efforts aimed at improving the region’s ecological conditions and bolstering marine biodiversity, disaster prevention, and mitigation.

Figure 7 Large number of abandoned aquaculture facilities left behind (Source: the authors)

Figure 8 Wetland vegetation is severely damaged (Source: the authors))

II. Restoration Targets

The goal is to enhance the environmental conditions of the coastal zone through measures such as rewetting of wetlands through aquaculture retirement, dredging of tidal channels, and microtopographic transformations. Based on these interventions, targeted restoration efforts will be undertaken, including the restoration of coastal salt marsh vegetation, the placement of oyster reefs, the transplantation of seagrass beds, and the ecological treatment of aquaculture tailing water. These initiatives aim to strengthen regional ecosystems and increase species diversity, fostering a new dynamic of harmonious coexistence between humans and the sea. Among the restoration efforts, salt marsh restoration, focused primarily on Suaeda salsa vegetation, is recognized for its significant ecological and landscape value. This section will mainly discuss the restoration of the salt marsh ecosystem in Dongying City.

III. Implementation

(1) Strengthening Technological Leadership for Local Salt Marsh Restoration

By prioritizing the development and practical application of marine ecological restoration technologies, various research institutions have collaborated to achieve significant breakthroughs, providing strong support for the successful restoration of salt marshes in local coastal regions. First, by collecting, cultivating, and preserving local germplasm resources from ecologically similar areas, issues related to seed stress resistance were resolved, significantly improving the survival rate of restored vegetation. Second, the introduction of "straw check" management practices has effectively reduced the impact of wind and waves, creating favorable micro-ecological conditions for the retention of Suaeda salsa seeds and seedlings. Third, in response to extreme weather events, emergency seawater irrigation using sprinkler systems was employed to ensure adequate water supply for the growth of Suaeda salsa, improving seedling survival rates.

(2) Establishing an Integrated Seawall-Vegetation-Tidal Flat Protection System

Over 500 hectares of wetlands have been restored by aquaculture retirement and rewetting, and 18.13 kilometers of tidal flats have been dredged and reshaped to restore the natural ecological background. Leveraging favorable habitat conditions, a three-dimensional approach to vegetation restoration was employed, adapting to local ecosystems by planting and supplementing native vegetation provenance, including Suaeda salsa, in the salt marshes. As a result, native vegetation cover has been improved, with over 1,600 hectares of native salt marsh vegetation, such as Suaeda salsa, successfully restored. These efforts have enhanced ecosystem diversity and stability, creating a gradient-based, multi-level ecosystem restoration model, resulting in the establishment of an intergrated seawall-vegetation-tidal flat protection system (Figure 9).

Figure 9 Integrated Seawall-Vegetation-Tidal Flat Protection System (Source: the authors)

(3) Innovative Construction of a Long-Term Management and Protection Model

To ensure the sustainability and long-term effectiveness of ecological restoration efforts, Dongying City has developed an innovative model for managing and protecting ecological disaster mitigation and restoration projects. Recognizing that Suaeda salsa vegetation is highly vulnerable to tidal waves and susceptible to ecosystem degradation, the city collects Suaeda salsa germplasm resources in situ each year, replanting them in the following spring. These replanting efforts are supported by timely irrigation using sprinkler systems to maintain a high seed germination rate and plant survival rate. This approach ensures that key ecological indicators—such as vegetation cover, density, and height—remain at optimal levels, promoting stable and enduring vegetation. The implementation of this management and protection model strengthens the effectiveness of marine ecological disaster mitigation and restoration, enhances the ecosystem's self-regulatory and natural recovery capacities, and ultimately fosters long-term, stable, and sustainable ecological protection in the area.

IV. Restoration Outcomes

(1) Significant Increases in Biodiversity and Carbon Sequestration

With the restoration of the region, the fragmented landscape—once dominated by aquaculture facilities—has been completely transformed (Figures 10 and 11). Coastal salt marshes, oyster reefs, and seagrass beds have been effectively restored, leading to a substantial improvement in biodiversity. In recent years, the number of bird species in the Yellow River estuary has risen to nearly 400, with national Class I protected species such as the Oriental White Stork and Black Stork, along with large flocks of geese, sea cormorants, and whooper swans, frequently observed in the restored area (Figure 12). Additionally, the impact of restoration on carbon sequestration has been pronounced. It is estimated that the annual carbon sink of the region's coastal salt marshes has increased by approximately 5,000 tonnes of carbon dioxide, significantly enhancing the region's carbon sequestration capacity.

Figure 10 Kendong Saltwater Gully before restoration by aquaculture retirement and rewetting (Source: the authors)

Figure 11 Kendong Saltwater Gully after restoration by aquaculture retirement and rewetting (Source: the authors))

Figure 12 Sea cormorants with large populations occurring in restored areas (Source: the authors)

(2) Enhancing the Synergy Between Marine Ecology and Disaster Mitigation

The 20-kilometre of Suaeda salsa-based vegetation strip, with an average width of approximately 800 metres and a plant density of 30 plants per square metre, plays a vital role in tide, wave, dike, and beach protection. This natural buffer mitigates the impact on seawalls, bolstering the coastal zone's resilience in disaster prevention and mitigation. In the high tide zone where the Suaeda salsa thrives, water depth during normal tide levels is generally less than one metre, and wave height attenuation can exceed 50%. The successful implementation of regional ecological disaster mitigation and restoration has yielded significant experience, providing a model for future marine disaster reduction efforts.

(3) Expanding Marine-Friendly Spaces and the Thriving Leisure Industry

Following the regional disaster mitigation and ecological restoration, a vast and spectacular red beach wetland has emerged (Figure 13). With its stunning combination of blue skies, white clouds, clear waters, and vibrant red beaches, the area has become a haven for photographers and birdwatchers alike. Increasing numbers of visitors come for leisure and vacations. The enhancement of the regional ecosystem has not only improved its aesthetic appeal but also expanded the public's access to marine spaces. This has significantly boosted the region's tourism and recreational fisheries, establishing it as a prime destination for eco-tourism.

Figure 13 Yongfeng River – "red carpet" formed after the restoration of the small island's riverbanks and beaches (Source: the authors)

11.2 Case 2—Restoration of coastal salt marsh ecosystem in Hangu, Tianjin

I. Environmental Context

The Tianjin Marine Ecological Protection and Restoration Project is situated in the coastal waters near Hangu, in the northern part of Tianjin Binhai New Area, located on the northern edge of the North China Plain. Facing the vast North China and Northeast China Plain, this region borders Bohai Bay to the south and connects with Ninghe District to the north. It is characterized by abundant tidal flat wetlands and oyster reefs and serves as a key site along the East Asia-Australasia migratory bird flyway. The area is also a crucial wintering ground for the Ichthyaetus relictus, an endangered species globally and a national class I protected species in China. The ecological significance of this region is substantial.

However, human development activities have severely impacted the natural wetland habitat. Intensive construction of aquaculture cofferdams has obstructed water flow, leading to significant vegetation degradation and a sharp reduction in vegetation cover. As a result, the region's biodiversity has drastically declined, rare bird migration flyways have been disrupted, and the wetland's self-purification capacity has diminished due to the accumulation of pollutants and inadequate water exchange. The aquaculture cofferdams have degraded water quality, caused ecological fragmentation and isolation, and hindered species migration and exchange, ultimately destabilizing the wetland ecosystem, which now faces serious challenges.

II. Restoration Targets

Since 2022, Tianjin Municipality has implemented Spartina alterniflora control measures, microhabitat transformation in wetlands, and the restoration of coastal salt marsh ecosystems. These efforts aim to improve the surrounding ecological environment, restore mudflat and salt marsh ecosystems, and enhance marine ecosystem services. Through these projects, the natural state of the wetlands will gradually be restored, the stability and functionality of the ecosystem will be improved, and regional carbon neutrality goals and ecological security will be supported.

In response, Tianjin has applied for central financial support in 2022 to undertake a marine ecological protection and restoration project. The project aims to enhance the surrounding ecological environment by restoring ecosystems such as silty mudflats, salt marshes, and oyster reefs, and improving the service functions of marine ecosystems. Seven specific initiatives are planned: beach restoration through aquaculture retirement, rewetting through aquaculture retirement, treatment of Spartina alterniflora, modification of seawalls for ecological functions, microhabitat restoration in wetlands, and oyster reef rehabilitation. The primary initiative, the rewetting of wetlands through aquaculture retirement, will gradually return wetlands to their natural state, improve the stability and service functions of wetland ecosystems, contribute to carbon neutrality goals, and safeguard ecological security.

III. Implementation

(1) Restoration Planning and Methods

Due to prolonged marine aquaculture activities, the natural habitat of the Dashentang mudflat wetland has been severely degraded. Large expanses of the Suaeda salsa salt marsh wetland have been converted into fish ponds and other artificial environments, leading to significant ecosystem disruption. The wetland has suffered from vegetation degradation, with the overall structure now characterized by horizontally and longitudinally connected breeding cofferdams, aquaculture ponds, and exposed mudflats. This has resulted in diminished habitat quality and reduced biodiversity.

To restore the natural attributes of the coastal wetland, the design is guided by the “Nature-Based Solutions (NbS)” approach and adheres to the core principle of “prioritizing natural restoration, complemented by targeted artificial interventions.” Based on a thorough understanding of the site’s textures and the current presence of artificial structures, the restoration strategy emphasizes respect for the existing conditions and incorporates the methods of “breaking,”“spreading,”“connecting,” and “planting.”“Breaking” refers to dismantling the cofferdams in the area. “Spreading” involves leveling the mudflats and remaining cofferdams. “Connecting” focuses on re-establishing the internal hydrological system, enabling water flow across the site. “Planting” entails re-vegetating the reshaped terrain in accordance with site conditions. By employing techniques such as restoring hydrological connectivity, reshaping micro-topography, and rehabilitating vegetation, the plan aims to gradually restore the region’s natural habitat and ecosystem integrity.

(2) Wetland Construction

Zoning and Layout: The site is divided into three main zones, from east to west: the Natural Mudflat Zone, the Wetland Restoration Zone, and the Bird Habitat Zone. The Natural Mudflat and Bird Habitat Zones are designed to provide essential spaces for bird breeding and habitation. The habitat layout is based on the specific bird species that frequent the wetland, taking into account their behaviors, habitat preferences, food sources, and breeding areas. By analyzing the spatial preferences of different bird species, we conclude that wading birds are best suited to tidal wetlands with low vegetation cover, waterfowl thrive in deep-water ponds, and shorebirds prefer areas with tall grasses for movement.

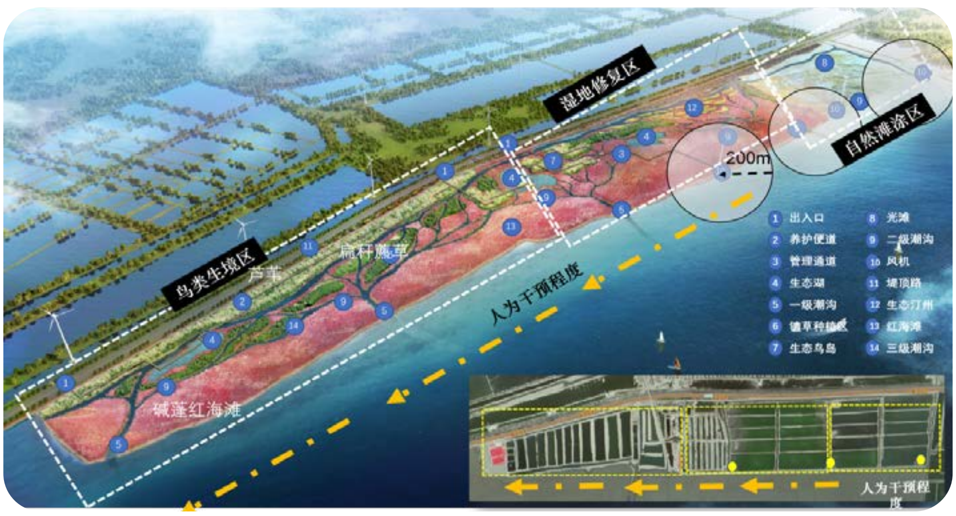


Figure 14 Schematic diagram of wetland construction zoning

Hydrological Connectivity: Dredging of the tidal channels is carried out to enhance water flow within the wetland, improving the rate of water exchange. Tidal channels are preserved and optimized to maintain nearshore hydrodynamic conditions, thereby promoting effective hydrological connectivity.

Figure 15 Photos of the construction site of tidal channel dredging

(Source: Liu Yuze, CCCC Water Transport Planning and Design Institute Co., Ltd.)

Micro-topography Modification: The high tide and nearshore beaches are reshaped by removing earth weirs around breeding ponds and salt pans, with partial backfilling of aquaculture ponds. In areas designated for wetland restoration and bird habitats, ecological high-tide beaches and tidal ponds are constructed in line with topographic features, providing suitable habitats for various species.

Vegetation Restoration: Saline-alkali tolerant plants such as Phragmites australis, Suaeda salsa, Aeluropus sinensis, Tamarix chinensis Lour., Aeluropus littoralis, Apocynum venetum L., and Salicornia europaea L. are selected for planting. Methods such as seed pellets, bamboo tube seedlings, and direct sowing are employed to enhance vegetation survival rates. Suitable plant species are cultivated in areas with varying inundation periods to ensure robust vegetation growth.

Figure 16 Seed pellets cross-section (left), seed pellets construction site drawing (right)

(Source: Liu Yuze, CCCC Water Transport Planning and Design Institute Co., Ltd.)

Figure 17 Construction drawing of bamboo tube planting site

(Source: Liu Yuze, CCCC Water Transport Planning and Design Institute Co., Ltd.)

Side slope Ecology: Ecological restoration measures were implemented on wetland side slopes, including the use of ecological stones, gabion reefs, and other materials to construct protective ecological slopes and prevent soil erosion.

IV. Restoration Outcomes

Subsequent continuous monitoring revealed that the wetland ecosystem has been effectively restored. Waterbody connectivity within the wetland was enhanced, and ecological water replenishment was successfully carried out, improving the hydrological conditions. Additionally, microtopography modifications and vegetation restoration reshaped the wetland's topography and plant cover, leading to the gradual recovery of natural habitats and enhanced biodiversity. The ecological slope modifications and berming efforts further protected the wetland's edges, preventing soil erosion and fostering diverse biological habitats. Overall, the restored wetland is regaining its natural functions, providing high-quality habitats for birds and other wildlife.

Figure 18 The restored wetland

(Source: Feng Zhe, CCCC Water Transport Planning and Design Institute Co., Ltd.)

Figure 19 Birds foraging in the restored wetland

(Source: Feng Zhe, CCCC Water Transport Planning and Design Institute Co., Ltd.)

Appendix: Knowledge of Coastal Salt Marshes

1. Characteristics and Types of Coastal Salt Marshes

Coastal salt marshes are transitional zones between marine and terrestrial ecosystems, periodically or intermittently affected by saline or brackish water bodies, with a high cover of herbaceous or low shrub vegetation on silty or peaty wetland ecosystems[1]. Coastal salt marshes differ from inland salt marshes in environmental conditions such as salinity, humidity, and temperature, despite significant similarities in plant species and vegetation characteristics. Generally, coastal salt marshes should have a high cover of herbaceous or low shrub vegetation (cover should typically be ⩾ 30%), which distinguishes them from other ecosystems in coastal areas such as mudflats, mangroves, and seagrass beds. Coastal salt marshes typically have a substrate of silt or peat[1].

In summary, coastal salt marshes typically possess the following basic characteristics:

- Located in coastal areas, subject to oceanic tidal action
- Dominated by herbaceous or low shrub plant communities, with a cover typically greater than 30%
- Tidal water bodies are non-freshwater
- Substrate is primarily silt or peat

There are several methods for classifying coastal salt marsh types. According to different vegetation types, they can be divided into Phragmites australis, Suaeda genus (Suaeda salsa, Suaeda australis, etc.), Tamarix chinensis Lour., as well as Cyperus malaccensis Lam.subsp.Malaccensis, Cyperus malaccensis, Bolboschoenoplectus mariqueter, Scirpus tabernaemontani, Carex scabrifolia Steud., and Juncellus serotinus, all belonging to the Cyperaceae family. According to different climatic zones, they can be classified into tropical, temperate, and frigid coastal salt marshes[2]. Based on the growth forms of vegetation, they can be classified into grassland salt marshes and shrubland salt marshes. According to the degree of human intervention, they can be classified into natural salt marshes, semi-natural salt marshes, and artificial salt marshes. Different types of salt marshes can be distinguished based on the prerequisite conditions for the occurrence and existence of coastal salt marshes, including lagoon-type, shore-plain-type, weir-island-type, estuary-type, semi-natural type, and artificial type[3].

2. Distribution of Coastal Salt Marshes

From a global perspective of climate zones, coastal salt marshes are mainly distributed in temperate zones, with some distribution in frigid zones[3][4]. In terms of continents and oceans, they are widely distributed along the Atlantic and Pacific coasts of North America, the southern part of South America, the western coast of Europe, Oceania, the Pacific coast of East Asia and Northeast Asia, and the southern tip of Africa[3]-[6].

In China, coastal salt marshes are distributed in coastal provinces (autonomous regions, municipalities), mainly in Shandong Province, Jiangsu Province, Shanghai Municipality, Zhejiang Province and Fujian Province, where they are mostly distributed in a strip from the shore to the sea. In other areas such as Liaoning Province, Hebei Province, Tianjin Municipality, Guangdong Province, Guangxi Zhuang Autonomous Region, and Hainan Province, the distribution area of coastal salt marshes is relatively small, mostly in scattered and punctate distribution. In addition, in estuarine areas, coastal salt marshes are more widely distributed, with relatively complete coastal salt marshes in the Yellow River Estuary and Yangtze River Estuary regions.

From a global perspective, the most significant distribution characteristic of coastal salt marsh vegetation is belt-shaped distribution. Generally, the belt distribution of coastal salt marsh vegetation refers to the different zones of growth environment at different locations and elevations on the beach, where different salt marsh plants such as Phragmites australis and Suaeda salsa are distributed in different belts from the sea to the land.

Many coastal salt marshes in China exhibit significant belt-shaped distribution of plants. For example, in the Yangtze River Estuary region, Phragmites australis, Bolboschoenoplectus mariqueter, and invasive species such as Spartina alterniflora are the main dominant plants in the region.

Before the introduction of Spartina alterniflora, the belt distribution of Phragmites australis and Bolboschoenoplectus mariqueter was the most typical in the Yangtze River Estuary, and the belt distribution of Phragmites australis and Scirpus triqueter L. still exists in areas such as the southern coast of Chongming Island[7][8]. The invasion of Spartina alterniflora has profoundly altered the distribution pattern of salt marsh plants in the Yangtze River Estuary.

In the Yellow River Delta region, the belt-shaped distribution of Phragmites australis, Suaeda salsa, and Tamarix chinensis is more typical[9]. In the Yellow River Estuary region, Suaeda salsa is widely distributed in the entire salt marsh area outside the zone of Spartina alterniflora, mainly dominated by upland plants such as Phragmites australis in areas largely free from seawater influence.

In the Liaohe River Estuary wetland, the low-tide salt marsh is dominated by Suaeda salsa, followed by reed communities or Nitraria sibirica communities, gradually transitioning to Apocynum venetum, Tamarix chinensis communities, and eventually developing into communities of Leymus chinensis and Calamagrostis epigejos[8] .

3. Diversity Characteristics of Coastal Salt Marsh Plant Communities

The height, density, and cover of plants in coastal salt marshes vary depending on the species and distribution region[10]. The high salinity, high frequency of tidal action, and high environmental instability of coastal salt marsh habitats exceed the tolerance range of most terrestrial plants. Only a few plants, such as those in the Gramineae, Chenopodiaceae, Juncus effusus L., and Cyperaceae families, have the extreme tolerance needed to survive and reproduce in coastal salt marshes[10].

4. Environmental Factors Affecting Coastal Salt Marsh Ecosystems

One of the most notable characteristics of coastal salt marshes is the sharply changing environmental gradients with elevation. Many environmental factors affect coastal salt marsh ecosystems, including tidal action, soil salinity, redox potential, sulfides, and various types of disturbances. However, tidal action (related to soil redox potential) and soil salinity are widely considered the two primary environmental factors, together determining the basic pattern of biological distribution in coastal salt marshes.

Tidal Action. The periodic or intermittent action of ocean tides is one of the most significant features of coastal salt marshes. Generally, coastal salt marshes can be divided into low-tide salt marshes, mid-tide salt marshes, and high-tide salt marshes. Low-tide salt marsh refers to the part located between the average high-water level of neap tide and the average high tide, mid-tide salt marsh refers to the part located between the average high tide and the average high-water level of spring tide, and high-tide salt marsh refers to the part above the average high-water level of spring tide[3]. When dividing different habitats of coastal salt marshes, elevation, representative species, and other factors should also be considered.

Soil Salinity. In addition to tidal action, soil salinity is another important abiotic factor affecting coastal salt marsh ecosystems. Usually, the salinity gradient is affected by tidal action, with areas where tidal action is frequent often having higher salinity, usually close to seawater salinity. Conversely, in areas where tidal action is less frequent, salinity is often lower, decreasing with the gradual increasing elevation from the sea to the land due to reduced tidal action. However, the distribution pattern of salinity in some coastal areas is different. For example, on the Atlantic coast of the southern United States and other areas, the salinity in mid- to high-tide marshes is often much higher than in adjacent low-tide marshes and uplands, forming peaks in salinity in mid- to high-tide marshes[11][12].

On temporal scales, soil salinity in coastal salt marshes often exhibits significant seasonal and interannual variations, mainly influenced by factors such as tidal frequency, temperature, precipitation, evapotranspiration, groundwater and surface water inputs, and vegetation cover. The specific patterns of salinity change also vary in different regions of coastal salt marshes or different habitats of the same salt marsh.

Topographic Changes. The surface of coastal salt marshes is not always flat or gradually changing. Due to micro-topographic changes that affect factors such as tidal action and surface runoff, it has an equally important impact on coastal salt marsh ecosystems.

These micro-topographic variations mainly include: (1) salt pans, which refer to areas in coastal salt marshes where vegetation is almost absent, usually low-lying areas that can range from a few square meters to several hundred square meters. These areas often remain waterlogged for long periods after high tides or heavy rainfalls. During the neap tide periods in dry season, these salt pans can dry up, leaving surface crystalline salt[3]; (2) Tidal channels, which are tidal water channels formed by tidal action and can be divided into primary, secondary, and tertiary channels; (3) Salt marsh cliffs, which are micro-cliffs formed by sea erosion exceeding sedimentation.

5. Ecosystem Services of Coastal Salt Marshes

Coastal salt marsh ecosystems have high biological productivity and species diversity, providing natural ecological value, social service functions for coastal protection and disaster prevention and mitigation, such as resisting storm surges and stabilizing shorelines. Coastal salt marshes are recognized as one of the blue carbon ecosystems and are important sources of ecological carbon sinks.

Maintaining Biodiversity. Coastal salt marshes are one of the most productive ecosystems in the world in terms of primary productivity, serving as crucial sources of organic and nutrient substances for many marine organisms, playing an important role in maintaining global biodiversity. Coastal salt marshes are transitional zones between marine and terrestrial environments, with rich hydrological and geographical conditions, serving as habitats for a variety of organisms. Additionally, many marine organisms use coastal salt marshes as spawning grounds, baiting grounds, wintering grounds, and migration channels, providing shelter for survival, burrowing, and breeding for wildlife, fish, and a large number of benthic organisms in adjacent habitats. Furthermore, coastal salt marshes are globally important migratory routes for many migratory bird species and have high species diversity and natural ecological value, serving important social service functions[13].

Providing Material Products. Coastal salt marsh ecosystems provide material products, including vegetation resources and a variety of benthic animal resources. Vegetation resources can be used as fertilizers, feed, fuel, etc. Various benthic animal resources (e.g., sandworms, mudskippers, and blue crabs) provide rich food and economic benefits for people, making them important economic resources in coastal areas. Studies have shown that coastal salt marsh ecosystems also have high medicinal value.

Coastal protection and disaster prevention and mitigation. Coastal salt marshes are dynamic buffer zones between land and sea, acting as natural green barriers. Most vegetation in coastal salt marshes is highly flexible with well-developed root systems, forming a soft barrier on tidal flats that can mitigate the impact of typhoon storm surges to some extent, reducing the impact and erosion of waves and currents, and allowing a large amount of sediment to be precipitated, which helps to maintain the stability of coastal terrain[13].

Carbon Sink Function. Coastal salt marshes are important carbon sequestration areas, with plants absorbing carbon dioxide through photosynthesis and storing it as organic matter. The biomass of coastal salt marsh plants can store carbon in sediment for a long time, playing a positive role in mitigating climate change[14].

Water Purification. Coastal salt marshes play an important role in water purification in the water cycle. Plant roots can filter and absorb pollutants in water (such as heavy metals, organic matter, and nutrients), helping to improve water quality and reduce pollutant levels in water[15]. As large amounts of waste residue, wastewater, exhaust gases, and other pollutants are dumped and discharged into the sea through the coastal zone, coastal salt marshes can absorb and assimilate various pollutants, and to a certain extent can mitigate marine pollution.

6. Main Threat Factors to Coastal Salt Marshes

Surveys have revealed that coastal salt marsh ecosystems in China are confronted with numerous threats stemming from human development activities, invasive species, natural disasters, and other factors.

(1) Human development activities such as coastal engineering construction and overfishing, etc.

Human development activities exert a particularly prominent impact on coastal salt marsh ecosystems. Engineering construction, tidal flat aquaculture, and other human development activities often encroach upon the growth space of coastal salt marsh ecosystems. Pollutant discharges may cause habitat destruction in coastal salt marshes. Coastal embankment projects in some areas fragment the integrity of coastal salt marsh ecosystems, leading to ecosystem degradation. Overfishing may result in changes in the benthic community structure of the coastal salt marsh ecosystem.

(2) Invasion of Invasive Species such as Spartina alterniflora

Spartina alterniflora exhibits characteristics of high adaptability and strong reproductive and spreading abilities. In recent years, it has rapidly spread in coastal areas of China, severely reducing the living space of native coastal salt marsh species and causing significant ecological invasions in most coastal areas of China. The invasion of Spartina alterniflora has profoundly altered the belt-shaped distribution pattern of coastal salt marsh plants in some regions of China, leading to the replacement of native salt marsh plants such as Phragmites australis and Bolboschoenoplectus mariqueter by Spartina alterniflora in many areas.

(3) Natural factors such as storm surges and sea level rise

Coastal salt marsh ecosystems are affected by disasters such as storm surges and sea level rise. Under the influence of sea level rise, coastal salt marsh ecosystems in some areas may gradually migrate and evolve towards the land side. However, if these ecosystems encounter artificial structures such as embankments, their migration process may be impeded, increasing the risk of degradation.

7. Coastal Salt Marsh Plants

(1) *Phragmites australis*

Family: Gramineae, Genus: Phragmites

Phragmites australis is a perennial herbaceous plant of the Gramineae family with well-developed rhizomes. The stems are hollow and smooth, with lanceolate linear leaves arranged in a biseriate fashion. The panicles slightly droop downward, with white pilose hairs between the lower branch axils. The fruit is lanceolate in shape.

Phragmites australis is a perennial aquatic or wetland herb that grows tall. Globally, 10 species of the genus Phragmites have been recorded, with three species present in China. These plants have well-developed rhizomes, allowing for robust vegetative reproduction. In natural populations, rhizomes play a vital role in reproduction and population renewal, enabling single dominant populations to form under favorable environmental conditions. The common reed typically grows over 2.5 meters in height, begins sprouting in mid-February, blooms between July and September, and bears fruit in October before gradually withering. Phragmites australi exhibits wide environmental adaptability, thriving in freshwater, alkaline, and mildly saline wetlands. They are commonly found along rivers, lakes, ponds, ditches, and low-lying wetlands. In China, Phragmites species grow across vast areas, from the eastern coastal mudflats to the inland lakes and marshes of the western mainland, and from the southern subtropical to the northern temperate cold zones. Reed wetlands provide essential ecological services, offering critical habitats and breeding grounds for birds and other wildlife.

Figure 20 Phragmites australis（Source：the authors）

(2) *Suaeda Salsa*

Family: Chenopodiaceae, Genus: Suaeda

Suaeda salsa is an herbaceous halophyte with salt-accumulating properties. Its stem is upright with reddish stripes, branching in multiple stages, and its slender branches extend obliquely. The leaves are linear and arranged oppositely. Globally, more than 100 species of Suaeda are distributed widely, with China home to 20 species and one variety. Suaeda salsa is typically found on saline and alkaline soils near coasts, lakesides, and deserts, serving as a key indicator of saline environments and acting as a pioneer species in coastal development. Suaeda salsa plants generally reach heights of 20 to 60 cm, with seedlings emerging from mid-March to early June, blooming from July to August, and producing fruit from September to October. Seeds fully mature by early November. The coastal distribution of Suaeda salsa spans Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, and other regions.

Suaeda salsa exhibits the ability to change color, with pigmentation influenced by salinity and ambient temperature. Light and temperature are the main factors affecting betacyanin levels in the coastal wetland environment, where salinity remains relatively stable. The color change in Suaeda salsa is primarily driven by the accumulation of betacyanin, which helps the plant survive in high-salinity environments by reducing light energy absorption and avoiding oxidative stress. In autumn, as temperatures drop, chlorophyll levels decrease, making the accumulated betacyanin more prominent, causing the plant to turn purplish-red as it matures.

Suaeda salsa provides important ecological services, such as improving soil nutrient content and fertility, aiding in the restoration of saline soils, and contributing to broader ecological restoration efforts. Its wide availability and low cost make it a valuable resource for environmental retsoration.

Fig. 21 Suaeda salsa seeds (Source: preparation team of this handbook)

Fig. 22 Suaeda salsa seedlings (Source: preparation team of this handbook)

Fig. 23 Left: Suaeda salsa in low salinity plot; Right: Suaeda salsa in high saline-alkali land.

Fig. 24 Suaeda salsa (Source: preparation team of this handbook)

(3) *Bolboschoenoplectus mariqueter*

Family: Cyperaceae, Genus: Scirpus Linn

Bolboschoenoplectus mariqueter is a perennial halophyte characterized by scattered culms, typically reaching a height of 20 to 100 cm. Its smooth, triangular leaf blades initially feature 2 − 3 membranous sheaths, with the uppermost sheath terminating in a leaf. The plant produces spike-shaped inflorescences, and its seeds are reversed obovate to broadly reversed obovate, plano-convex, and dark brown when mature, with a very short apex. Bulbils, which are ellipsoidal or ovate, are found within 10 cm of the ground. Germination occurs in late March, with flowering in mid-June. Bolboschoenoplectus mariqueter reproduces sexually through seed production and asexually via bulbs and rhizomes.

Endemic to China, Bolboschoenoplectus mariqueter primarily inhabits the lower intertidal zones and upper mid-tide flats. It has the widest distribution and largest biomass of a single plant among salt marsh plants in these areas. Major populations are found in the salt marsh wetlands of the Yangtze River estuary and Hangzhou Bay, with additional distributions along the Hebei and Jiangsu coasts. These wetlands are critical habitats for shorebirds and other waterfowl, and play a significant role in providing essential ecological services.

Figure 25 Bolboschoenoplectus mariqueter (Source: the authors)

(4) *Cyperus Malaccensis*

Family: Cyperaceae, Genus: Cyperus L.

Cyperus malaccensis is a perennial species in the Cyperaceae family, characterized by long, creeping, woody rhizomes and sharply trigonous, smooth culms. Typically, 1 to 2 leaves emerge from the base, with slightly shorter, flat, and spreading leaf blades. The leaf sheaths are elongated, wrapping around the lower part of the culm and displaying a brown coloration. The plant features three leafy bracts, which are shorter than the inflorescences. The inflorescences consist of long, laterally branching clusters in an umbellate arrangement, which may recur or proliferate. The nutlets are narrowly oblong, trilobed, and almost equal in length to the scales, maturing to a blackish-brown color[15].

Cyperus malaccensis can grow taller than 1.5 meters, aided by its extensive underground rhizomes and dense root systems, which contribute to its high photosynthetic carbon sequestration capacity. It is predominantly found in mid to high tidal flats. Seedlings emerge between March and May, with rapid growth occurring from June to August. Growth typically concludes between September and October, when aboveground fresh biomass peaks. From November to February of the following year, some plants wither rapidly, though many remain green. Along the coast, Cyperus malaccensis is more commonly found in Fujian, Guangdong, Guangxi, and other provinces, with particularly large populations in Guangxi’ s Qinjiang, Maoling, Dafeng, and Nanliujiang Rivers. This species plays an important role in providing ecological services.



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