Handbook of Ecosystem Restoration for Coastal Hazard Mitigation: Seagrass Beds

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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 wellillustrated, 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 andexperts 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 applicable to the ecological restoration of seagrass beds in China, and can be used as a reference for other related work.

This handbook provides principles, technical processes, diagnosis and identification of restoration areas, restoration objectives, restoration measures and technologies, post restoration monitoring and evaluation, and public participation for ecological restoration of seagrass beds.

2. Terms and Definitions

(1) Seagrass

A group of monocotyledonous plant that can completely live in seawater or brackish estuaries.

(2) Seagrass bed

A seagrass community with a certain and contiguous area.

Note: It is generally recognized that when the area of a seagrass community exceeds 100 m^2, it is called a seagrass bed [1].

(3) Ramet

A new plant produced by cloning, consists of shoots, rhizomes and roots.

(4) Seagrass plug

An aggregate composed of seagrass ramets and sediment substrate.

(5) Clone growth

An asexual reproduction method in which new ramets are developed through the growth of rhizomes.

(6) Seed bank

The general term for the energetic seeds in the substrate of seagrass beds.

(7) Seedling

A young plant formed after the germination of a seagrass seed.

(8) Reproductive shoot

The shoot which can develop reproductive organs such as flowers, fruits, and seeds.

(9) Transplanting unit

The basic unit for seagrass transplanting such as plugs or ramets.

(10) Ecological baseline

The state of an ecosystem before the implementation of ecological restoration.

(11) Reference ecosystem

Specific ecosystem that serves as target or benchmark for ecological restoration.

(12) Ecological restoration of seagrass bed

The process of assisting degraded, damaged or destroyed seagrass bed ecosystems to regain their health, integration and sustainability.

3. Restoration Principles

(1)Respecting nature and prioritizing conservation

Adhere to respecting, conforming to, and protecting nature, ecological restoration follows the natural renewal and succession laws of the seagrass bed ecosystem. Adhere to prioritizing protection, with natural restoration as the main approach and artificial restoration as a supplement. For slightly damaged seagrass beds, corresponding protective measures should be taken to reduce human interference and enable natural recovery; As for severely damaged seagrass beds, a combination of artificial restoration and natural restoration should be used to restore the degraded seagrass community and improve the resilience of the seagrass bed by removing threat factors and artificially replanting.

(2)Overall planning and systematic coordination

The ecological restoration of seagrass beds should comply with the requirements of relevant laws and regulations such as national land spatial planning. Based on the overall and systematic nature of the marine ecosystem, it is advisable to comprehensively consider the interactions between various elements and components in the land, ocean, and sea land ecotone; more focus should be put on the interaction between seagrass beds and adjacent ecosystems, such as coral reefs, mangroves, other coastal or estuarine wetlands so as to avoid habitat fragmentation and islanding, and to improve ecological connectivity, diversity and stability.

(3)Adapt measures to local conditions and implement policies according to different types of species

The ecological restoration of seagrass beds should follow the strategy of adapting to local conditions and implementing policies based on classified species. In accordance with the natural conditions such as climate, landform, and hydrodynamic conditions of the restoration site, combined with the degradation status of seagrass beds, appropriate ecological restoration strategies for seagrass beds are developed, emphasizing the natural background and relying on ecological endowments. China has a rich and diverse variety of seagrass species, and target oriented restoration measures should be taken based on the differences and particularities in the morphological structure, ecological habits, phenology, and reproductive characteristics of different seagrass species so as to improve restoration efficiency and save costs.

(4)Public participation and supervision with long term mechanism

The restoration of seagrass beds should take into account of the needs of relevant stakeholders such as the residents of the community, encourage active cooperation and participation from the public and the community, and improve the public involvement. In response to the uncertainty of the ecological restoration process of seagrass beds, long-term effective management should be implemented through the entire process of seagrass bed ecological restoration, and the monitoring and evaluation of the implementation process and effectiveness of seagrass bed ecological restoration projects be strengthened; Ecological restoration plans and measures should be adjusted and optimized based on monitoring and evaluation results.

4. Overall Technical Process

The technical process for ecological restoration of seagrass beds is shown in Figure 1.

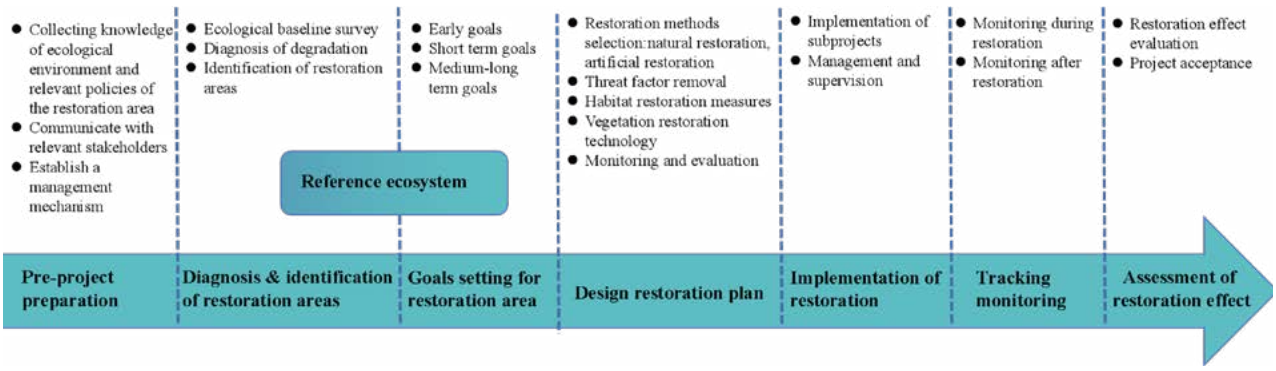

Figure 1 The technical process for ecological restoration of seagrass beds

5. Baseline Survey

5.1 Survey Objectives

The purpose of conducting an ecological baseline survey of the proposed restoration area is to understand the ecological status and degree of degradation of seagrass beds, analyze the reasons for their degradation or disappearance, and provide a basis for the development of subsequent ecological restoration plans. At the same time, the baseline survey data before restoration is also one of the benchmarks for evaluating the effectiveness of ecological restoration.

In addition to the planned restoration area, the survey scope should also include reference ecosystems.

5.2 Survey Contents and Methods

The content of the ecological survey of seagrass beds includes an overview of the restoration area, seagrass vegetation, biological communities, environmental factors, and threat factors[2]. The survey indicators contain but are not limited to the indicator elements in the table (see Table 1).Specific investigation methods refer to industry standard (HY/T 0460.6-2024) "Technical directives for investigation and assessment of coastal ecosystem status-Part 6：Seagrass beds".

Table 1 Contents and methods of seagrass bed ecological baseline survey

Content	Investigation elements	Investigation methods	Detailed methods
General situation of restoration area	Natural conditions: climate, geographical location, etc. Policies & regulations: laws and regulations, planning policies	Data collection	Collect literature, yearbooks, government reports, etc.

Table 1 Contents and methods of seagrass bed ecological baseline survey (continued)

Content	Investigation elements	Investigation methods	Detailed methods
Seagrass vegetation	Seagrass bed: area	Field investigation, aerial photography, high-definition satellite images	Execute according to HY/T 0460.6 [2]
	Seagrass: species type, coverage, shoot density, shoot height, biomass, sexual reproduction	Field investigation	Execute according to HY/T 0460.6
	Genetic information[a]: genetic diversity, gene flow, etc	Field investigation	Randomly select 10 to 30 plant samples for analysis using genomic or microsatellite markers.
Biome	Large algae: coverage and species type	Field investigation	Randomly select 10 to 30 plant samples for analysis using genomic or microsatellite markers.
	Attached organisms[a]: biomass and species type	Field investigation	Execute according to HY/T 0460.6
	Macrobenthic animals: species type, density, biomass	Field investigation	To be executed according to HY/T 0460.6
	Zooplankton[a]: species type, density, biomass	Field investigation	To be executed according to HY/T 0460.6
	Fish eggs and larvae: species type and density	Field investigation	Execute according to GB/T 12763.6

Table 1 Contents and methods of seagrass bed ecological baseline survey (continued)

Content	Investigation elements	Investigation methods	Detailed methods
Environment element	Water environment: water temperature, salinity, pH, transparency (or transmittance), chlorophyll a, dissolved oxygen, suspended solids, inorganic nitrogen, active phosphates, petroleum[a], etc.	Field investigation	The water temperature and salinity shall be implemented in accordance with GB/T 12763.2; Transparency, suspended solids, and petroleum shall comply with GB 17378.4; Other marine chemical element parameters shall be executed according to GB/T 12763.4
	Sediments: sediment type, particle size, organic carbon, sulfides, heavy metals[a], total phosphorus, total nitrogen, redox potential[a]	Field investigation	The particle size shall be executed according to GB/T 12763.8; Other parameters shall be executed according to GB 17378.5
	Terrain conditions: elevation	Field investigation	To be executed according to GB/T 17501
	Hydrodynamics[a]: flow velocity	Field investigation	To be executed according to GB/T 12763.2
Threaten Factors	Natural factors: Typhoon, storm surge, insect pest	Field survey or Data collection	Qualitative Description
	Human factors: fishery fishing (fishing volume, distribution of fishing ports); benthos capture (number of employees, capture method); seawater aquaculture (aquaculture type, aquaculture species, aquaculture area); marine engineering (type and scale); pollution discharge (number of sewage outlets)		
Notes: The elements with superscript are optional.			

5.3 Survey Time

The ecological baseline survey is generally conducted during the peak season of seagrass growth. Temperate seagrass beds are recommended from June to August, while tropical and subtropical seagrass beds are recommended from April to August.

5.4 Determination of the Reference Ecosystem

The selection of the reference ecosystem is made as follows:

a) Collect historical data of the restoration area, including routine monitoring, special investigations, literature materials, etc., and establish a reference system;

b) A relatively well-preserved seagrass bed in an area with similar environmental conditions to the restoration area.

6. Problem Diagnosis and Suitability Assessment for Restoration

6.1 Problem Diagnosis

The diagnosis of ecological degradation mainly includes the analysis of the degree and causes of seagrass bed degradation. Without skin, how can hair be attached. The most important indicator for diagnosing the degradation of seagrass bed ecosystems is the reduction of seagrass distribution area. The degree of seagrass degradation can be classified into three levels: mild degradation (a decrease of 10% to 30% in seagrass bed area within 5 years), moderate degradation (a decrease of 30% to 60% in seagrass bed area within 5 years), and severe degradation (a decrease of over 60% in seagrass bed area within 5 years).

Based on the investigation data of environmental factors and threat factors, the main causes or driving forces of seagrass bed degradation will be analyzed to serve as a basis for subsequent threat factor elimination and habitat restoration.

6.2 Restoration Suitability Assessment

At present, the main reason for the failure of seagrass bed restoration is the selection of unsuitable location of the restoration site. Priority should be given to areas where seagrass beds have existed in history for ecological restoration. Based on the data of the ecological baseline surveys, the proposed restoration area can be divided into suitable restoration areas, rehabilitation restoration areas, and unsuitable restoration areas[3].

Suitable restoration area: Environmental factors such as topography, water temperature, water quality, illumination, substrate type, and elevation meet the biological growth of seagrass. The specific conditions are shown in Table 2.

Rehabilitable restoration area: the area where the degraded seagrass bed meets the conditions of topography, hydrology, sediment type, etc., but is disturbed by human activities such as seawater pollution, fishery production, *Spartina alterniflora* invasion, etc., and the area where habitat can be improved by controlling disturbance by human activities and other artificial measures is a rehabilitable restoration area.

Unsuitable restoration area: Areas where habitat improvement is not feasible or conflicts with local planning are regarded as unsuitable restoration areas.

Table 2 Suitability analysis of the proposed restoration area

Type of restoration area	Suitable conditions	
Suitable restoration area	Environmental conditions	Topography and hydrology: It is recommended to choose bays, estuaries, sandbars, or mudflats with low wind and waves, and the average flow velocity should be less than 1.5 m/s. Elevation should be considered for seagrass in intertidal zone.
		Water quality: Meet the Class I or II standards for seawater quality in GB 3097, with relatively stable salinity.
		Light transmittance: There is no significant source of suspended sediment, and the light transmittance is generally not less than 20%.
		Sediment quality: Meet the Class I standard for marine sediment quality in GB 18668.
		Substrate type: Clayey silt, silty sand, or fine sand (shrimp shaped seagrass is a rocky reef substrate).
	Human interference	There is less interference from human factors such as seawater pollution, fishing, and marine engineering around the restoration area.

7. Restoration Goals

The ecological restoration goal should not only restore the seagrass community and its ecosystem service functions, but also consider the needs of stakeholders, balancing the social benefits. The goals of ecological restoration determine the relevant design of the content, measures, and technical methods of ecological restoration [4], as shown in Table 3.

Table 3 Relationship between restoration objectives and project planning and design[4]

Project Goals	Pre-design Objectives	Design Considerations
Offset seagrass loss at a specific site by introducing seagrass at alternative locations.	Have the environmental pressures that caused the loss been removed from the alternative site? Have the environmental pressures that caused the loss been removed from the alternative site? Is enhancement required?	Monitor the site to assess environmental conditions for sustaining target species of seagrass. Enhance site if needed. Trial methods. Undertake restoration. Monitor restoration success against previous state. Adapt methodologies if required.
Promote wider seagrass population resilience.	Assess connectivity between beds in the wider population, to identify sinks and sources of seagrass propagules (parts of the plant that become detached and go on to create new plants, such as seeds). Identify suitable habitat and past and current distribution to ascertain fundamental and realised niches. Map anthropogenic and natural disturbance.	Prioritise sites for restoration, habitat creation and enhancement, based on their position within the wider population (e.g. an important source of propagules). Assess the frequency of interventions required (e.g. maintaining an important meadow with high disturbance and poor propagule retention may require frequent facilitated dispersal, i.e. seeding).

Table 3 Relationship between restoration objectives and project planning and design[4](continued)

Project Goals	Pre-design Objectives	Design Considerations
Create seagrass beds for carbon sequestration.	Which conditions would provide highest carbon sequestration (mud, low current velocity, large dense beds, supply of organic matter)? Which locations are available? Can beds be maintained and protected in the long term?	Select habitat sites. Select species (perennial versus annual). Establish protection mechanisms. Monitor carbon sequestration, including seasonal variations.
Restore fish and shellfish nurseries and foraging habitat.	Subtidal versus intertidal? Is there a supply of larval recruits? Is there good connectivity with spawning habitats? Create a continuous meadow? Distance from other habitats? Increased edge to core (reticulated meadow design)?	Introduce regular sampling to monitor fish and shellfish populations. Adjust site locations as necessary to promote connectivity.
Enhance feeding habitat for birds.	Identify the target bird species and their prey. Does their prey utilise seagrass? Is the target species' use of seagrass impacted by water level? How might seagrass restoration impact other bird species that prefer to forage in unvegetated areas?	Monitor target bird species' populations. Monitor other non-target bird species' populations, to ensure against unintended consequences.

The ecological restoration goals include short-term goals and medium to long-term goals. The two types of goals should have a clear deadline for achievement, and fully consider the recovery trajectory of the ecosystem and its parameters, and set phased goals. The ecological restoration target parameters should be quantifiable and assessable for subsequent evaluation of ecological restoration effectiveness.

7.1 Short Term Objectives

Short term goals generally refer to specific or phased goals that are expected to be achieved for ecological restoration within 2-3 years.

Short term goals can refer to the following:

◆ Seagrass vegetation restoration: Seagrass vegetation restoration is a critical target of ecological restoration of seagrass beds. This includes the restoration area, coverage, density, biomass, etc. of seagrass beds.

◆ Restoration of habitat conditions: including the degree of improvement in remediation of substrate types, water nutrient status, sediment quality, and hydrological and dynamic conditions.

◆ Elimination of threat factors: pollutant discharge, fishery fishing, Introduced species, etc.

7.2 Medium to Long Term Goals

The medium to long-term goal of ecological restoration is to restore the structure and function of the ecosystem to a certain extent after restoration, gradually stabilizing the ecosystem and having a certain degree of resilience. The corresponding quantitative parameters of the ecosystem include biological communities, environmental factors, ecosystem functions, etc.

The medium to long-term goals can refer to the following:

◆ Restoration of ecosystem structure of seagrass bed: vegetation, macrobenthos, nekton, etc.

◆ Improvement of seagrass bed ecosystem function: maintain biodiversity, fishery function, carbon fixation and sink increase, biogeochemical cycle, water purification, etc.

◆ Implementation deadline for medium and long-term goals: The restoration of the ecosystem structure of the seagrass bed is set at 5 years, and the improvement of ecosystem function is set at 10 years.

8. Restoration Measures and Techniques

8.1 Habitat Improvement Measures

Generally speaking, if there are no seagrass in a certain area, there are two possibilities: (1) The habitat conditions in the area are not suitable for seagrass growth; (2) There were seagrass that grew in the past, but due to adverse (human or natural) factors, seagrass disappeared. In response to the latter situation, it is necessary to identify the possible reasons for the disappearance of seagrass. Once environmental conditions are significantly improved, especially in terms of water quality and sediment conditions, seagrass usually naturally recovers or gradually recovers with manual restoration. The methods for improving damaged seagrass habitats are universal (Table 4), and specific methods and technical details may vary depending on local environmental conditions [5].

In addition to the technological support for protecting or improving the habitat of seagrass beds, more ecosystem-based management of the government is required. The protection and restoration of seagrass should follow the principle of integrated land and sea planning, strictly controlling the input of land-based pollution, marine engineering, and excessive sea activities. It is one of the most effective measures to establish a seagrass special protection reserve through legislation.

Table 4 Symptoms, problem diagnosis, and habitat improvement measuresof damaged seagrass beds[5]

Symptoms of seagrass beds	Possible causes	Diagnosis of problems,	Habitat improving measures
Seasonal fluctuation of seagrass bed vegetation, Phytoplankton, macroalgae and epiphyte	Seasonal changes in temperature, light, salinity, nutrients, etc.	Diagnose changes outside the natural range and possible stress parameters	Natural phenomenon, no need to improve habitat
Outbreaks of phytoplankton, macroalgae, epiphytes or benthos	Introduced species Excessive nutritional load	Diagnose whether there are Introduced species Determination of nutrients, etc.	Eliminate Introduced species and control the introduction of invasive species Control pollution sources and improve the capacity of water exchange Removing floating large algae
Overgrazing	Outbreak of herbivorous animals, e.g. sea urchins	Investigate the population size of herbivores, etc	Regulating the population size and structure of herbivores
Erosion or burial of seagrass beds	Natural disasters such as storms, waves, and tides	Investigate the local wind and swell conditions and sediment redistribution patterns	Natural restoration or attempt to remove sediment covering seagrass vegetation

Table 4 Symptoms, problem diagnosis, and habitat improvement measuresof damaged seagrass beds[5] (continued)

Symptoms of seagrass beds	Possible causes	Diagnosis of problems,	Habitat improving measures
Sudden disappearance of seagrass bed	Catastrophic nutrient input or freshwater input	Investigation and analysis of land runoff load	Control the input of land-based pollutants and fresh water
	Dredging activities, resulting in seagrass being covered by sediment	Investigate the particle size and chemical composition of sediment	Avoid seagrass distribution areas or improve dredging methods to reduce negative impacts on seagrass beds, and supplement coarse sand if necessary to increase bottom porosity
	The modification of the coastline or seabed (such as reclamation, aquaculture ponds) so as to change the physical characteristics of hydrology and sediment	Investigating changes in hydrological and sediment characteristics Retiring the pond to be returned to grass	Construct wave buffer structures to reduce wave reflection and seabed erosion
The widespread decline and extinction of seagrass beds	Pathogenic organism	Monitoring fungal pathogens, viruses, etc. Investigating the factors causing seagrass diseases	Control the input of land-based pollution, especially industrial and Agricultural chemistry sewage and pollution

Table 4 Symptoms, problem diagnosis, and habitat improvement measuresof damaged seagrass beds[5](continued)

Symptoms of seagrass beds	Possible causes	Diagnosis of problems,	Habitat improving measures
Direct physical damage	Trawl fishing or digging sand and raking snails	Investigation and estimation of trawling or snail digging activities in seagrass habitats	Delineate sensitive areas as enclosed areas that prohibit net trawling or snail digging; Or modify fishing gear to reduce physical damage to habitats
	Propeller or wake impact	Investigation and estimation of ship activity near seagrass habitats	Block sensitive habitats to prohibit the passage of ships; Implement ship speed restrictions to minimize damage and impact of propellers on seagrass
	Anchor or drag chain	Investigation and estimation of ship anchoring activities in seagrass habitats	Blocking sensitive habitats; Delineate anchoring areas in relatively insensitive habitats
The seagrass bed is covered with a large amount of garbage	Farming or plastic waste	Investigate and analyze the types and quantities of aquaculture or plastic waste in seagrass beds	Clear the rubbish

8.2 Seagrass Restoration Technology

In the past few decades, people have tried a large number of seagrass restoration techniques and methods, and accumulated rich experiences. Foreign counterparts have published some valuable handbooks, guides, or literature for reference[4-9]. Overall, most of the data is for temperate species, and large-scale restoration areas are also concentrated in European and American countries. In particular, there are many cases of Zostera marina restoration, and the technology is relatively mature. However, the restoration of tropical and subtropical species is still in the early stage [9], and cases are relatively scarce. Developing efficient seagrass restoration techniques first require familiarity with the growth and reproductive characteristics of the target species, in order to determine the restoration method, restoration time, and corresponding management measures. There is relatively little basic research information on tropical and subtropical seagrass, making restoration difficult.

The ecological restoration of seagrass beds mainly adopts the transplantation method, which refers to the transfer of seagrass from one place to another for cultivation. With the deepening of research on the sexual reproduction of seagrass, some species of seagrass are restored with the seed method.

8.2.1 Species and Source Selection

The selection of species is crucial. At the early stage of restoration, the sea area where the restoration area is located should be investigated to clearly find out its species diversity of seagrass, and the distribution area and growth characteristics of each species should be understood to adapt to the site and grass. Generally speaking, it is advisable to choose local species that have historically existed in the restoration area. If there are significant changes in habitat conditions that no longer meet the survival needs of the original species, other local species in the area or pioneer seagrass species in nearby waters can be chosen. The distribution information of seagrass species in different sea areas in China can be found in Appendix 1.

Before large-scale restoration, small-scale trial planting should be conducted to screen or domesticate species. It should be emphasized that no unit or individual shall bring in exotic species without authorization. Species selection and source selection are closely related. Generally speaking, the selection of seed sources should abide by the following principles:

◆ The principle of sampling nearby is conducive to maintaining the vitality of the transplantation unit and saving transportation time and costs;

◆ The environmental conditions of the seed source area are similar to those of the restoration area; Or establish a seedling breeding base as a seed source;

◆ Priority should be given to selecting seagrass beds with vigorous growth, high coverage, and continuous distribution as seed sources.

8.2.2 Restoration Techniques

At present, the ecological restoration of seagrass beds mainly relies on transplantation method, supplemented by seed method. Both methods have their advantages and disadvantages (Table 5). Different seagrass species should choose different restoration techniques.

Table 5 Ecological restoration methods for seagrass beds

Restoration method	Planting unit	Planting methods	Advantages	Disadvantages
Replantation method	Substrate free transplantation method: ramets	Stone binding method, pincer binding method, grid method, etc.	Reduce transportation costs	The transplantation unit requires the use of materials such as stones, bamboo poles, nails, and metal frames to be fixed in the substrate, but the binding process requires a large amount of labor
	Substrate transplantation method: grass block	Dig out slightly larger caves than the transplantation unit during transplantation and compact them	① No binding process required ② Higher survival rate	The transplantation unit with a substrate has a large weight and the transportation cost is high. At the same time, sediment is prone to scattering during transportation, especially when the restoration site is far from the seed source.
Seed method	Sowing seeds	Direct sowing, mud block (ball) sowing, net bag sowing, etc	① Low cost, suitable for large-scale restoration ② Maintain higher genetic diversity	Depending on the seed yield, the seed germination rate is relatively low.
	Artificial seeding rearing	The method is the same as the transplantation without substrate method		

8.2.2.1 Transplantation Method

At present, most seagrass is restored by adopting transplantation methods. The important technical steps of transplantation method include transplantation time, collection of transplantation units, temporary care and transportation of transplantation units, and implantation of transplantation units.

◆ Transplantation time

The life history characteristics of different species are different, and their transplantation time is also different. The transplantation time of some dominant species is shown in Table 6.

Table 6 Ecological restoration techniques for different seagrass species

Ecotype	Species name	Restoration method	Restoration time	Seed collection time
Temperate zone	*Zostera marina*	Ramet transplantation method	April to May or September to October	June to August
		Seed method	September to October or next March	
	Zostera japonica	Ramet transplantation method	May to June	September to October
		Seed method	October to November or next March	
	Phyllosoadix iwatensis	Ramet transplantation method	October to November	-

Table 6 Ecological restoration techniques for different seagrass species(continued)

Ecotype	Species name	Restoration method	Restoration time	Seed collection time
Tropical and subtropical zone	*Enhalus acoroides*	Ramet transplantation method	March to June	September to December
		Seed method	September to December	
	Zostera japonica	Grass plug transplantation method	November to next February	-
	Thalassia hemprichii	Ramet or grass plug transplantation method	March to June	-
		Seed method	-	-
	Cymodocea rotundata	Ramet or grass plug transplantation method	March to June	-
	Halophila ovalis	Seed method	December to Next February	-
		Ramet or grass plug transplantation method	-	
	Halophila beccarii	Grass plug transplantation method	December to Next Februray	-
		Seed method	-	
	Syringodium isoetifolium	Ramet or grass plug transplantation method	April to June	-
	Halodule uninervis	Grass plug transplantation method	April to June	-

Note: *Zostera japonica* and *Halophila beccarii* have an annual growth phenomenon, and the death time of the aboveground parts varies from region to region. The restoration time is only for reference

◆ Transplantation density

The plant morphology and size of seagrass species should be fully considered for transplantation density. Recommended transplantation density of different seagrass species is:

a) The transplant density of *Zostera marina*, *Enhalus acoroides* and *Thalassia hemprichii* should be greater than 40,000 plants/ha;

b) The transplant density of Z*ostera japonica* and *Halophila ovalis* should be greater than 80,000 plants/ha.

◆ Transplantation unit collection

Common transplantation units include grass blocks, ramets, etc. When collecting transplant units, try to collect them from different areas of the seagrass bed at certain intervals to accelerate the natural recovery of the seagrass bed.

Grass blocks: use PVC pipes or shovels with a diameter of about 20~30cm to dig grass blocks with a certain shape (cylinder, rectangular cuboid, etc.) in the seagrass bed with roots and bottom material (Figure 2). The depth of the grass block should be greater than the length of the seagrass root system. The spacing between collecting grass blocks shall not be less than 1 m.

Figure 2 Grass blocks of *Halophila ovalis* (Left) and *Halophila beccarii* (Right)

(Source: Liu Songlin, South China Sea Institute of Oceanology, Chinese Academy of Sciences (CAS))

Ramet: Firstly, collect grass blocks (as described above) and wash off the accompanying substrate on site. As for most small and medium-sized seagrass, try to choose segments with 2-5 connected ramets as one transplantation unit. *Enhalus acoroides* can choose a single ramet for planting (Figure 3). Generally speaking, the survival rate of growth points (such as new shoots) in planting units is higher.

Figure 3 Transplantation units of *Enhalus acoroides*

(Source: Zhao Bin, Fourth Institute of Oceanography, Ministry of Natural Resources (MNR))

◆ Transplantation unit temporary maintenance and transportation

Seagrass plants are prone to decay, and should be transplanted as soon as possible (within 2-3 days) after the transplantation unit is collected. The transplantation unit can be temporarily stored in a sorting box, glass tank, or temporary storage tank. If conditions permit during temporary care, an air pump can be used for oxygenation.

When transporting the transplant unit to the repair area, it is necessary to keep the plants moist and fresh. If necessary, ice bags can be added to keep them fresh.

◆ Transplantation unit colonization

Different transplantation units have different methods of fixing them to the substrate. The details are as follows:

Grass block: Dig a hole slightly larger than the transplant unit in the repair area, place the grass block in and compact it. The spacing between grass block transplantation is 25-50 cm.

Ramet: To prevent being washed away by waves, the fixation of the transplantation unit requires the use of other external objects. The ramet density should not be less than 50% of the seagrass density in the source area. The specific methods include the following:

➢ Direct insertion method: Insert the transplanted unit directly into the substrate. This method is less commonly used and the transplantation unit is easily washed away.

➢ Root stem binding method: Use degradable hemp rope (which can be recycled after the planting unit has survived) to bind the root stems of the ramets to the stones, and then bury or throw them into the restoration area.

➢ The nail method: fix the rhizome with hemp rope or ties to U-shaped or V-shaped nails (similar to staples), and then fix it to the seabed of the sea.

➢ Grid method: Fix the rhizome on the mesh or grid frame with hemp ropes or ties (Figure 4), and then fix it in the restoration area. The spacing between cloned fragments on the grid is about 10 cm to 20 cm; The distance between grid frames shall not exceed 1 m.

Figure 4 Seagrass transplantation method (grid method on the Left; rope method on the Right)

(Source: Liu Songlin, South China Sea Institute of Oceanology, CAS; Yu Shuo, Fourth Institute of Oceanography, MNR)

8.2.2.2 Seed Method

・Seed collection

The seed maturity period varies among different species, and the collection time is shown in Table 6 for reference. The specific methods are as follows:

Reproductive branch collection: During the mature season of seagrass seeds, the reproductive branches are collected and placed in a net bag before being temporarily raised in a seawater pool or fixed in a sea area. When the seeds mature and fall off, remove the stems, branches, leaves, etc., and collect the seeds (Figure 5). This method is mainly applied to *Zostera marina*, *Zostera japonica*, *Zostera caespitosa*, and *Phyllosoadix iwatensis*.

Figure 5 Reproductive shoots of *Zostera marina* (Source: Zhang Peidong, Ocean University of China)

Seed collection: If the seed setting rate of seagrass is low or the reproductive branch collection is missed in that year, a sediment of about 10 cm on the surface can be excavated from the seed source area, sieved (the aperture is selected based on the seed size), washed, and the seeds selected. This method is mainly applied to species with seed bank, such as *Zostera marina* (Figure 6), *Zostera japonica*, *Halophila ovalis*, *Halophila beccarii*, etc.

Figure 6 *Zostera marina* seeds (Source: Li Wentao, Ocean University of China)

Fruit collection: As for the species without a seed bank, such as *Enhalus acoroides* (Figure 7) and *Thalassia hemprichii* (Figure 8), fruit collection is required. The fruit can be placed in a net bag and temporarily raised in a seawater pool or fixed in a sea area. When the fruit bursts, collect the seeds.

Figure 7 Mature fruits and seeds of *Enhalus acoroides*

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Figure 8 Mature fruits and seeds of *Thalassia hemprichii*

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

・Seed preservation and transportation

The seeds need to be stored in a seawater pool with similar temperature and salinity conditions to natural seawater.

The seeds of *Zostera marina* and *Zostera japonica* can be refrigerated and stored at 4 °C to 7 °C (soaked in seawater).

Seagrass seeds without dormancy period, such as *Enhalus acoroides*, *Thalassia hemprichii*, etc., shall be sown as soon as possible after seed release to prevent seed decay.

・Planting time and density

The sowing time and seed density of different species are shown in Table 6.

The seed planting density of different seagrass species should be determined by the plant morphology and the characteristics of seed germination. The planting density of *Zostera marina* and *Z. japonica* should be greater than 100,000 grains/ha.

・Planting method

Mainly including direct sowing method, mud block (ball) sowing method, net bag sowing method, mechanical sowing method, seedling transplanting method, etc.

Direct sowing method: During low tide, seeds or reproductive branches are directly sown in the restoration area. This method is low cost, but severe seed loss. It is suitable for species with sufficient seed quantity.

Mud block (shot) sowing method: Mix fine sand and clay evenly with water, use PVC pipes with a diameter of 7 cm~10 cm and a height of 3~5 cm as molds to make mud blocks, and place seeds (10~15 seeds) in the mud blocks. After drying for 1-2 days, the mud is thrown into the seagrass restoration area (Figure 9). Seeds can also be wrapped in sea mud to make clay pellets, with a diameter of 2 to 3 cm. Mud boxes or mud balls can be dug and buried, with a burial depth of 2 to 3 cm. They can also be placed directly on the seabed (Figure 10).

Figure 9 Mud block sowing method

(Source: Zhang Peidong, Ocean University of China)

Figure 10 Mud ball sowing method (Source: Xu Shaochun, Institute of Oceanology, CAS)

Net bag sowing method: Mix seagrass seeds with sediment and place them in a cotton (or hemp or other biodegradable material) net bag (the mesh size should be smaller than the short diameter of the seeds). Lay the net bag flat and fix it in the repair sea area, with a thickness not exceeding 5 cm when laying it flat (Figure 11).

Figure 11 Mesh bag seeding method[4] (Source: Gamble et al., 2021)

Mechanical sowing method: Using seagrass sowing machine to make seagrass seeds be planted in the sowing sea area (Figure 12).

Figure 12 Mechanical seeding method[4] (Source: Gamble et al., 2021)

Seedling method: The collected seeds are germinated and cultivated into seedlings, and then transplanted to the restoration sea area. This method is suitable for most seagrasses (Figures 13).

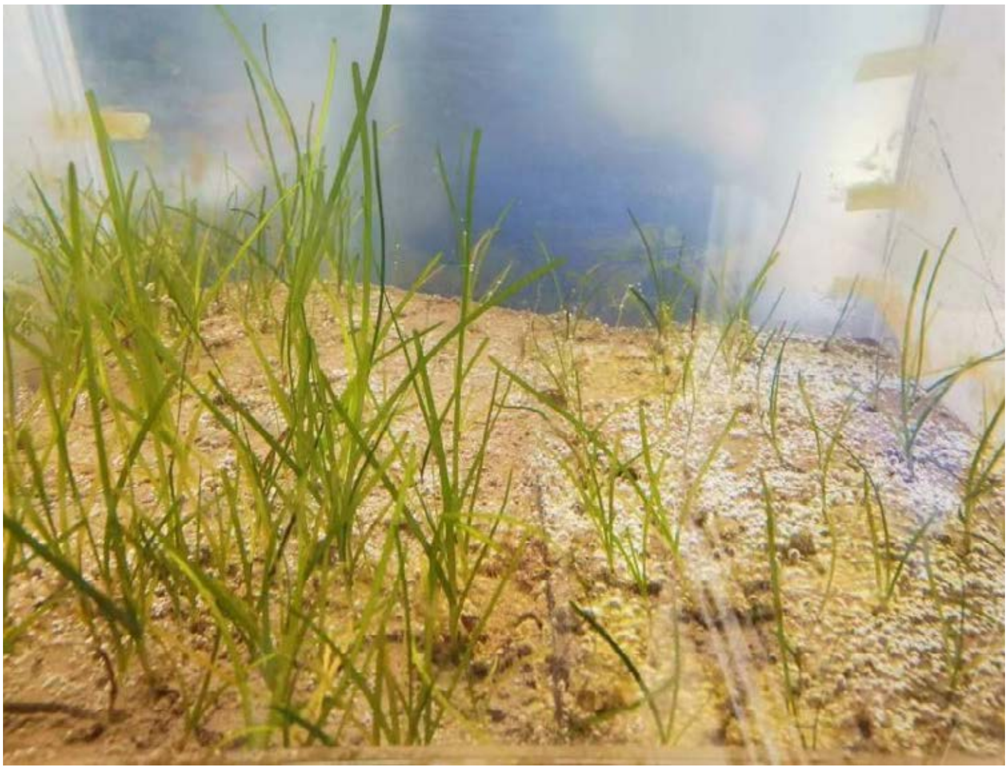

Figure 13 Indoor cultivation of *Zostera marina* seedlings

(Source: Xu Shaochun, Institute of Oceanology, CAS)

8.2.3 Management and Protection of Restoration Area

Regular management and protection are required within 2-3 years after the restoration of seagrass beds. Especially in the early stages of restoration, the planting units need to adapt to new habitats and are relatively fragile.

The seagrass restoration area requires regular patrol. A detailed patrol plan should be formulated, and the patrol route and monitoring indexes should be clearly defined. The specific patrol content includes the growth situation of seagrass, natural environmental conditions, human activities and so on.

(1) Basic environmental conditions. The weather on the day of patrol needs to be recorded. The temperature, salinity, dissolved oxygen and transparency of seawater should be measured and recorded. Clean up floating garbage in the restoration area, and the types and approximate amounts of floating garbage also should be recorded.

(2) Natural disasters. The effects of natural disasters on seagrass in the restoration area should be recorded, including tropical cyclones (typhoons), storm surges, extreme high/low temperature of seawater, etc.

(3) Human activities. Set up signs and warning tablets near the restoration area, indicating the information related to restoration, protection and management of seagrass bed. The interference of human activities in the restoration area should be avoided. It is strictly prohibited to carry out fishing activities in the restoration area and the surrounding sea area which may destroy the seagrass bed, such as trawling and picking shellfish.

(4) Abnormal conditions of seagrass bed. The phenomena of green tide (outbreak of macroalgae), red tide (large scale proliferation or high concentration of phytoplankton, protozoa or bacteria), mass death of seagrass (being eaten, uprooted, necrosis of growth end, excessive attached algae, etc.), and death of marine animals (such as fishes, shrimps and crabs) should be recorded. Clean up the large algae in the restoration area in time; Timely replanting of dead or washed away planting units and clean up pests (anemones, etc.) in the restoration area.

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

9.1 Tracking Monitoring

The systematic tracking and monitoring are a necessary component of the seagrass bed restoration project. Continuous tracking and monitoring of seagrass beds after restoration aims to get knowledge of the variation trends in survival rate of seagrass, and changes in ecosystem structure and function, etc. On one hand, timely "correction" or plan adjustment can be carried out, and on the other hand, data obtained through investigation and monitoring can serve as the basis for ecological assessment after restoration.

9.1.1 Monitoring Fequency

The monitoring of ecological restoration of seagrass beds should be conducted before, during, and after the implementation of ecological restoration projects. It is recommended to continue monitoring the ecological restoration of seagrass beds for at least 5 years. The monitoring frequency of different indicators varies (see Table 7).

a) In the first year of seagrass bed ecological restoration, intensive monitoring should be carried out on the survival and growth of transplanted seagrass plants, seed germination, and the growth and survival of seedlings. After plant transplantation, monthly monitoring is recommended for 6 months, and quarterly monitoring is recommended after 6 months to 1 year. After seed planting, it is advisable to start monitoring after seed germination, the monitoring frequency should be once every 15 to 30 days, and the monitoring should be carried out quarterly after seedling planting.

b) In the second to fifth year of seagrass bed ecological restoration, seagrass vegetation should be monitored at least once a year, and the monitoring time should be selected during the flourishing period of seagrass growth.

c) After 5 years of seagrass bed ecological restoration, the monitoring frequency of seagrass vegetation can be adjusted according to actual situations.

9.1.2 Monitoring Content and Methods

The monitoring indicators and parameters should be selected based on the initially set ecological restoration goals for seagrass beds. The monitoring indicators vary during different restoration stages.

The ecological monitoring contents include seagrass vegetation, biological communities, environmental factors, and threat factors. The specific monitoring indicators can be divided into structural indicators and functional indicators. The former includes the density and coverage of seagrass vegetation, while the latter includes carbon sequestration, cultivation of the young, and water quality improvement. The ecological function indicators are generally monitored after restoration for 5 years or more.

Genetic variation is the foundation for species to adapt to their environment. In recent years, with the reduction of genetic analysis costs, genetic monitoring of seagrass beds has gradually received attention to provide information on the population structure of seagrass in the restoration area, such as inbreeding depression (reduced adaptability caused by inbreeding), gene flow, adaptability and clonality. This information can to some extent characterize the sustainability of seagrass beds in the restoration area. In the Seagrass Restoration Handbooks UK & Ireland, genetic monitoring is incorporated in optional indicators.

The monitoring indicators of the seagrass beds after the ecological restoration can be selected according to project requirements in Table 7. For the measurement of seagrass vegetation indicators, it is recommended to choose the season of vigorous growth of seagrass beds (from April to August) for monitoring.

Table 7 Monitoring content of seagrass bed ecosystem after ecological restoration

Survey Content	Survey Elements	Survey Modality	Survey Methods	Survey Frequency
Seagrass vegetation	Planting unit: survival rate, seed germination rate, etc.	Field investigation	Set the cross-section and quadrat according to the restoration area, and calculate the survival rate. The reference for section and quadrat setting shall be carried out according to HY/T 0460.6.	Monitoring shall be conducted every two weeks in the first quarter of the first year of restoration
	Seagrass bed area	Field investigation or aerial or high-definition satellite images	Execute according to HY/T 0460.6	1-2 times per year
	Seagrass: species type, coverage, shoot density, shoot height, biomass, sexual reproduction		Execute according to HY/T 0460.6	Once every quarter in the first year of restoration and once a year for the second to fifth year
	Genetic information[a]: genetic diversity, gene flow, etc	Field sampling	Randomly select 10 to 30 plant samples for whole genome re sequencing or microsatellite molecular marker analysis.	Once in the fifth year.
Biome	Large algae: coverage and species	Field investigation	Execute according to HY/T 0460.6	Once every quarter in the first year. Once a year for the second to fifth year of the restoration
	Attached organisms[a]: species and biomass		Execute according to HY/T 0460.6	
	Macrobenthic animals: species, density, biomass		Execute according to HY/T 0460.6	Once a year
	Swimming animals[a]: species and biomass		According to GB/T 12763.6	Once in the first and fifth years of restoration respectively.
	Fish eggs and larvae: species and density		Execute according to GB/T 12763.6	

Table 7 Monitoring content of seagrass bed ecosystem after ecological restoration(continued)

Survey Content	Survey Elements	Survey Modality	Survey Methods	Survey Frequency
Environment element	Water environment: transparency, water temperature, salinity, pH, chlorophyll a, dissolved oxygen, suspended solids, inorganic nitrogen, active phosphates, petroleum[a], etc.	Field investigation	The water temperature and salinity shall be in accordance with GB/T 12763.2; Transparency, suspended solids, and petroleum shall comply with GB 17378.4; Other marine chemical element parameters shall be executed according to GB/T 12763.4	Once every quarter in the first year. Once a year for the second to fifth year of the restoration.
	Substrate environment: particle size, organic carbon, sulfide, total phosphorus, total nitrogen, heavy metals[a], redox potential[a]	Field investigation	The particle size shall be executed according to GB/T 12763.8; Other parameters shall be executed according to GB 17378.5	Once a year
	Representative cross-section: elevation	Field investigation	According to GB/T 17501	Once in the first and fifth years of restoration respectively.

Table 7 Monitoring content of seagrass bed ecosystem after ecological restoration(continued)

Survey Content	Survey Elements	Survey Modality	Survey Methods	Survey Frequency
Threaten factor	Natural factors: typhoon, storm surge, etc.	Field investigation or data collection	Quantitative and qualitative description	Once in the first and fifth years of restoration respectively.
	Human factors: fishery fishing (fishing volume, distribution of fishing ports); Benthos capture (number of employees, capture method); Seawater aquaculture (aquaculture type, aquaculture species type, aquaculture area, aquaculture time); Marine engineering (type and scale); Pollution discharge (number and flow rate of sewage outlets)			
Function index	Carbon sequestration	Field investigation	Refer to 'Coastal Blue Carbon'	Once in the first and fifth years of restoration respectively.
	Biodiversity		Same as large benthic animals, swimming animals, etc. mentioned above.	
Notes: The elements with a superscript are optional.				

9.2 Restoration Effects Evaluation

◆ Content of restoration effect evaluation

The evaluation of the restoration effect of seagrass beds can be based on the restoration goals. The content of the evaluation mainly includes the following:

➢ Seagrass vegetation: including the restoration area and coverage of seagrass beds;

➢ Animal community: including benthos, nektonic animals, etc.

➢ Environmental conditions: including water quality, sediment, etc.

➢ Ecological functions: biodiversity, carbon sequestration, etc.

Generally speaking, within 5 years of restoration, the main content of the assessment includes seagrass vegetation, biological communities, and environmental conditions. The restoration of ecological functions takes a long time, and evaluation will be conducted after 5 years of restoration[10].

◆ The reference ecosystem for the evaluation of restoration effect

The characteristics of seagrass beds vary from place to place, and the selection of reference ecosystems for evaluation should be comparable. The following two options are recommended:

➢ Areas with similar environmental conditions of the restoration area

Select the undisturbed seagrass bed as the restoration control point. The control point should be as similar as possible to the restoration area in terms of environmental conditions such as tide, water depth, elevation, and sediment characteristics.

➢ Ecological status before restoration

If it is difficult to find a control point with similar environmental conditions nearby, it is recommended to use the ecological status before restoration as the control data. It is to compare and analyze the data before and after restoration to reflect the effectiveness of ecological restoration.

◆ Evaluation method for restoration effect

In theory, when seagrass beds have a certain degree of resilience, e.g the ability of ecosystems to respond to environmental changes, the restoration of seagrass beds can be considered successful. But setting the threshold range for resilience requires long-term data accumulation and numerical simulation to obtain it.

At present, there is no unified evaluation standard for the effectiveness of ecological restoration of seagrass beds. "Technical Guidelines for Monitoring and Evaluating the Ecological Restoration of Seagrass Beds " which is a national standard has been submitted for approval and will play an important guiding role in the future[10]. The evaluation of ecological restoration effectiveness within 5 years of restoration mainly focuses on vegetation structural indicators, such as restoration area, density, and coverage. Generally speaking, the restoration area of the seagrass bed reaches 70% of the design area, and the density and coverage of shoots reach 50% of the parameters of the seagrass bed at the restoration control point. The seagrass bed has a certain degree of resilience.

9.3 Adaptive Management

According to the conventional monitoring indicators and evaluation results of seagrass bed ecosystem ecological restoration, the effectiveness and shortcomings of comprehensive ecological restoration measures should be adapted to management and timely adjustment of relevant measures. Refer to Table 8 for details.

Table 8 Explanation of assessment results and adaptive management measures

Purpose of the assessment	Assessment level	Grading explanation	Adaptive management measures
Assessment of the degree of achievement of ecological restoration goals	I	Ecological restoration measures are effective and reached its expected goals.	Continue to implement the ecological restoration projects according to the implementation plan.
	II	Ecological restoration measures are effective, but not reach its expected goals	Assessing the regular monitoring indicators and the achievement to find the reasons affecting the restoration. If the impact is not force majeure factors, ecological restoration measures will be fine-tuned and implemented after expert verification.
	III	Ecological restoration measures are not effective, and the ecological restoration project has not achieved its intended goals	Adjust the ecological restoration program and, after expert verification, submit it to the competent project department for approval before implementation.
Ecosystem Indicator Improvement and Enhancement Assessment	I	The seagrass ecosystems are better restored and moving towards stabilized ecosystems	Analyze the stability of the seagrass ecosystem. Whether it is necessary to continue the ecological restoration measures or not, decided by the expert verification.
	II	Seagrass ecosystems are better restored, but not at reference system levels	Retain and continue to implement existing ecological restoration measures.
	III	Ecological restoration measures have not worked	Adjust the ecological restoration plan and implement it after the modification by expert verification.

10. Public Engagement

Seagrass beds are mainly distributed in shallow water areas and intertidal zones, and they overlap with human activities in a large range, especially with coastal aquaculture, snail hunting in low tide, leisure tourism and ship berthing. Therefore, the site selection and implementation of seagrass ecological restoration projects involve multiple stakeholders, which may conflict with local planning and development. Obtaining the understanding, support, and direct participation of stakeholders and the public is the guarantee for the smooth progress of ecological restoration projects [4].

10.1 Communication Planning

In the early stages of a project, it is necessary to fully understand the local history, public sentiment, and ocean policy background, so that relevant stakeholders have a clear understanding of the project's basis and objectives, and to solve the concerns of specific stakeholders in the best way to ensure that the project receives support from stakeholders from the beginning. It is crucial to explore the benefits that can be brought to the local people and economy during the communication process, attracting more funds and investment, rather than just ecological benefits.

Establish a communication team: Establish a dedicated team to promptly communicate and solve problems encountered during the ecological restoration process.

Define project audience: The project audience includes funders, project teams, local stakeholders, potential beneficiaries, etc.

Clarify project objectives: What problems does the project attempt to solve and what benefits are to be achieved?

Do a good job in basic work: Understand the basic situation of the restoration site and prepare well in the early stage.

Timely tracking and summary: Summarize experience in a timely manner and evaluate the impact of communication.

10.2 Social Participation

The ecological restoration of seagrass beds is a labor-intensive activity, especially the fixation of transplant units and subsequent monitoring, which require a large amount of manpower and are costly. Involving communities, schools, and other organizations near the ecological restoration site of seagrass beds (Figure 14, 15) can not only solve the problem of manpower, but also raise public awareness of the value of seagrass beds and the challenges of conservation and restoration.

Figure 14 Primary school students participating in seagrass binding[4]

(Source: Gamble et al., 2021)

Figure 15 Management Center of Guangxi Hepu Dugong National Nature Reserve organizing villagers to plant seagrass (Source: Zhang Hongke, Conservation Management Centre of Dugong National Nature Reserve in Hepu, Guangxi)

In addition, collaborating with non-governmental organizations (NGOs), as well as attracting, training, and maintaining volunteers is an indispensable part of future seagrass bed restoration plans (Figure 16). The participation of social capital is also crucial.

Figure 16 The public welfare interactive product: *Zostera marina* planting

(Source: The Ant Forest of AliPay)

10.3 Popularization of Science

The habitat of seagrass beds is constantly being destroyed; one important reason is that people do not have sufficient understanding of the value of seagrass. Therefore, through diversified science popularization, people can better understand the value of seagrass and its close relationship with everyone, and stimulate their interest in participating in the protection and restoration of seagrass (Figure 17, 18). Importance is given to the science popularization promotion programs to focus on visual means and media interaction (Figure 19), telling good stories and motivating others. The current effective science popularization interactions include the following:

Traditional popular science lectures

Set up interactive methods such as games, painting art, outdoor explanations, etc.

Media interaction including mainstream media, scientific media, social media, etc. reporting or publishing related activities, conferences, reports, etc.

Figure 17 Seagrass sed science popularization lecture

(Source: Guan Yao, Fourth Institute of Oceanography, MNR)

Figure 18 Marine ecological protection science popularization lecture activity

(Source: Zhang Hongke, Conservation Management Centre of Dugong National Nature Reserve in Hepu, Guangxi)

Figure 19 CCTV report on Zhang Peidong's seagrass bed restoration team

(Source: Zhang Peidong, Ocean University of China)

11. Classic Cases of Seagrass Bed Restoration

11.1 Case 1-Restoration Experiment of *Enhalus acoroides* with Seed-based Method

Enhalus acoroides is a dominant species of tropical seagrass, mainly distributed on the east coast of Hainan Island in China. In the past decade or so, the distribution area of seagrass in Lingshui Xincun Port and Li'an Port Seagrass Special Protection Area has declined sharply due to the interference of intensive human activities in the coastal waters, especially aquaculture sewage and snail digging activities.

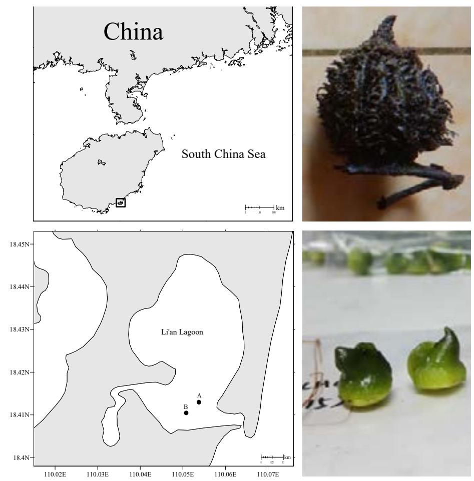

Figure 20 Planting locations (five stars), fruits, and seeds of *Enhalus acoroides*[9] (Source: Yu et al., 2019)

The fruit of *Enhalus acoroides* was first discovered in Li'an, Lingshui County, Hainan in 2017 (Figure 20), and an attempt was made to use the seed for ecological restoration in January 2018[9]. A disposable degradable paper cup is used as the planting container, with one seed and one digital label placed in each cup as a planting unit, and the seed burial depth is 2 cm. The buried planting unit is divided into two treatments：(1) Direct burial method: Burying the paper cup directly in the substrate; (2) Net bag method: Place the paper cup in a 40-mesh net bag and bury it (Figure 21). The results showed that the germination rate of *Enhalus acoroides* seeds using net bag method was as high as 96.10%, that much higher than the germination rate of 5.88% using direct burial method. This is because the net bag method can reduce bioturbation and animal predation, thereby reducing the loss of seeds. Due to the impact of water flow and animal predation, the loss rate of seeds by direct burial method is relatively high.

Figure 21 *Enhalus acoroides* planting unit

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Due to the poor seawater quality and abundant algae in the area to be restored, the seed setting rate and seedling survival rate of *Enhalus acoroides* are relatively low. The seeds of *Enhalus acoroides* do not have a dormant period, therefore, it is recommended to first germinate and cultivate them into seedlings, and then transplant them to the restoration area for better results (Figure 22).

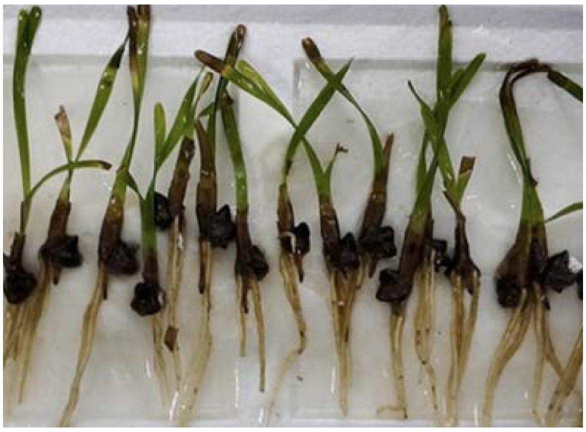

Figure 22 Seedlings of *Enhalus acoroides* which are germinated indoor[11]

(Source: Li et al., 2021)

11.2 Case 2-Transplantation Method of *Enhalus acoroides* and *Thalassia hemprichii*

The ramet transplanting method is the most commonly used method for restoring seagrass beds. The most critical step of this method is how to fix the roots of seagrass in the sediment. Hainan Academy of Marine and Fishery Sciences added fishing nets on the basis of grid method to fix them in light of coral reef flats and open waters with large tidal kinetic energy, and applied them to the restoration of *Enhalus acoroides* and *Thalassia hemprichii*, and have achieved good results.The restoration area is located in Gaolong Bay (19°29'24.91"N, 110°48'53.66"E), with a water depth of 0-2 meters, and a substrate of coral debris as well as a small amount of silt(Figure 23). The detailed restoration methods are as follows:

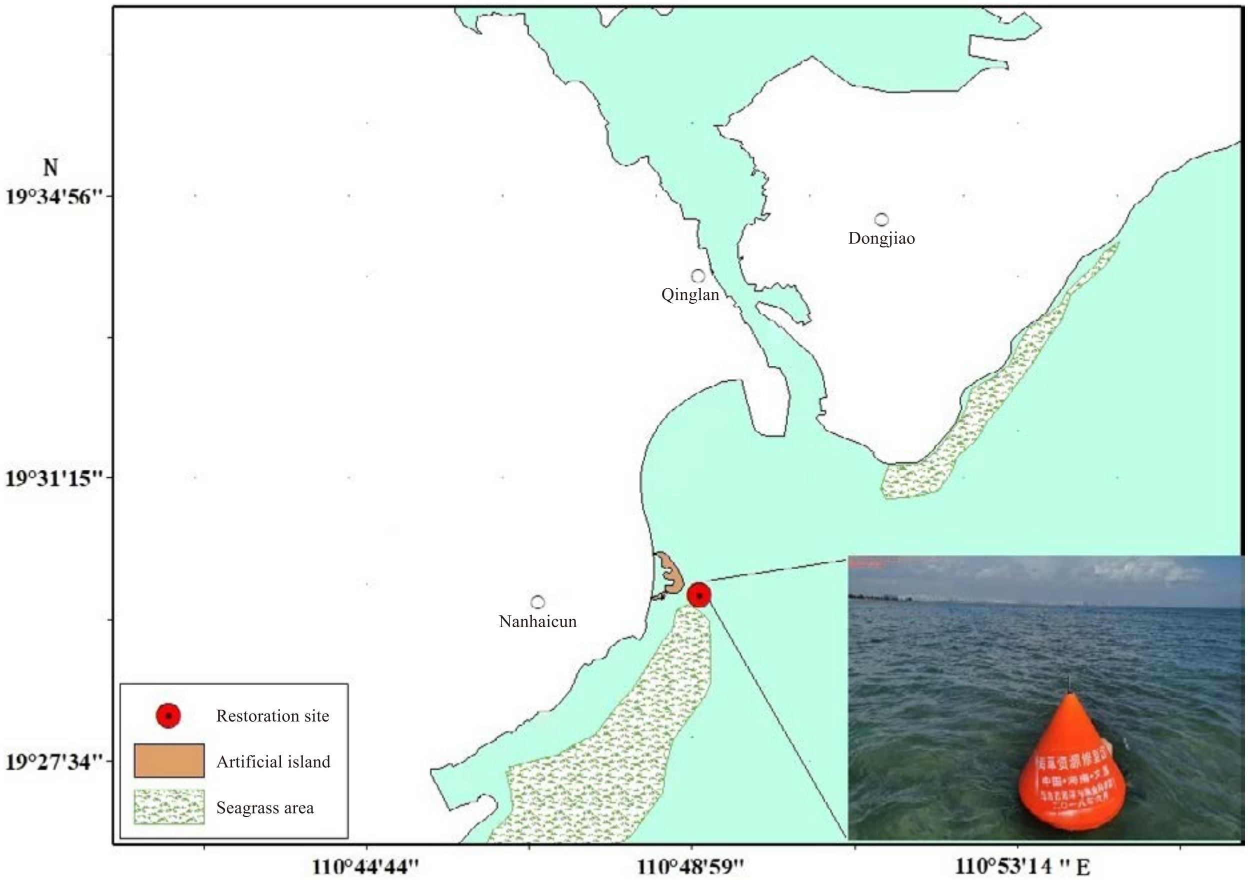

Figure 23 Restoration of seagrass bed in Gaolong Bay, Hainan[12]
(Source: Chen et al., 2021)

Units planting: Using the "seedling thinning" method to collect the seagrass planting units. There is 1 ramet in the planting unit of *Enhalus acoroides* and 2-3 ramets in the planting unit of *Thalassia hemprichii*. The interval between seagrass planting units is 20cm, forming a 1m × 1m planting patch, and interval between the patch is 50cm (Figure 24).

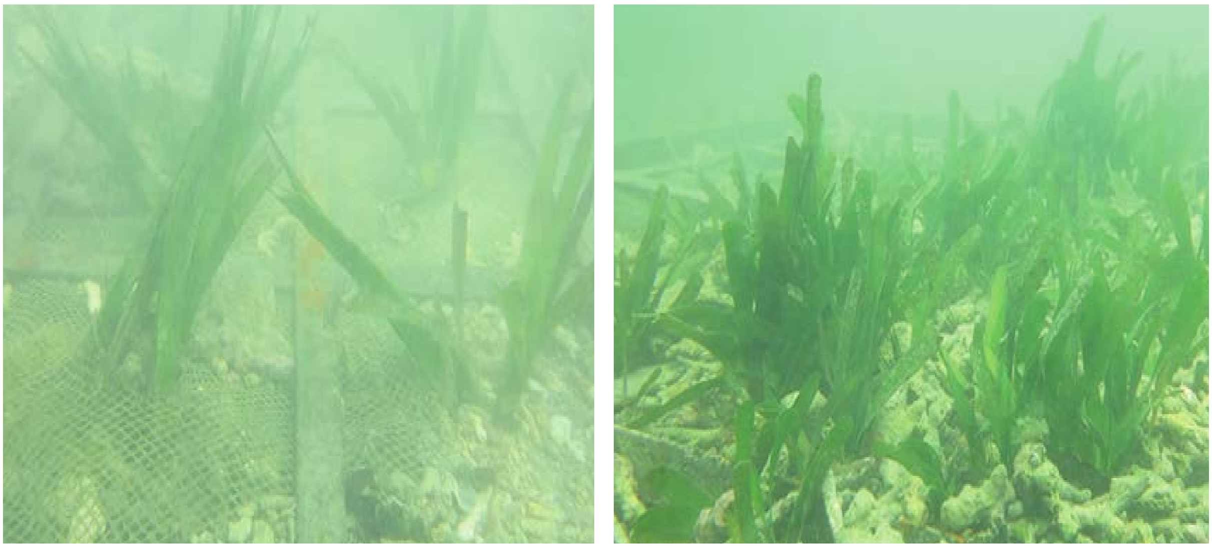

Figure 24 Restoration effect of *Enhalus acoroide* (left) and *Thalassia hemprichii* (right)[12]
(Source: Chen et al., 2021)

11.3 Case 3-Transplantation and Seed Restoration of *Zostela marina*

Zostela marina is the most widely distributed seagrass in the northern temperate zone and one of the most thoroughly studied species in terms of biological characteristics. The ecological restoration technology of *Z. marina* is relatively mature. *Z. marina* restoration includes ramet transplanting method and seed method. Zhou Yi's team from South China Sea Institute of Oceanology, Chinese Academy of Sciences and Zhang Peidong's team from Ocean University of China have developed a variety of restoration methods and achieved very good results.

The most important aspect of the ramet transplantation method is the fixation method of the ramet. According to the fixation method, it can be divided into rhizome cotton thread binding stone method, nail method, frame method (grid method), hemp rope clamping method, etc(Figure 25). At present, the widely used methods are the cotton thread binding stone method and the nail method. When using these two methods for transplantation, it is advisable to have 3 plants per planting unit[13].

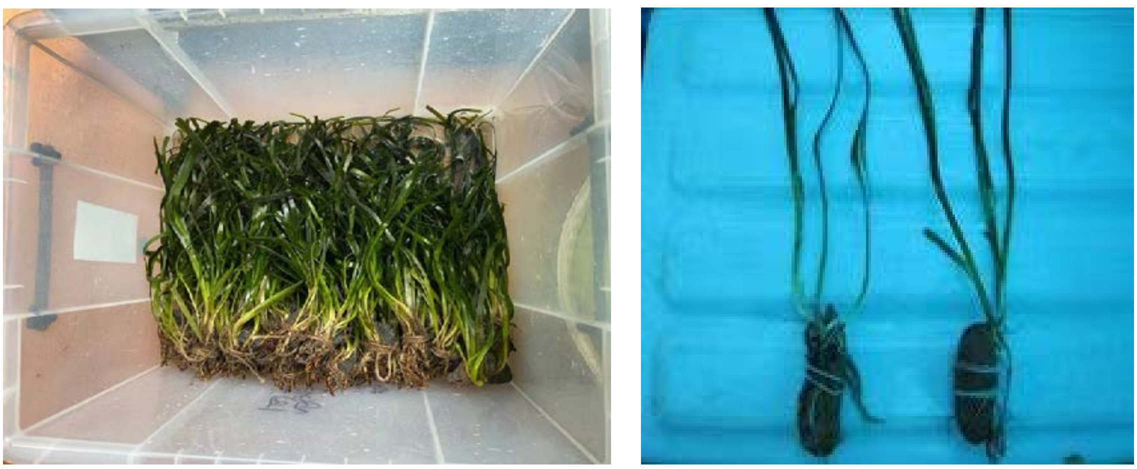

Figure 25 Rhizome cotton thread binding stone method

(Source: Gu Ruiting, East China Normal University)

Z. marina has a high seed setting rate, with a yield of over 10,000 grains per square meter. The direct sowing method has a high loss rate of seeds, and the germination rate generally does not exceed 10%. To strengthen the protection of seeds, Liu Yanshan (2015) attempted four sowing methods (Table 9, Figure 26), significantly improving the seed germination rate. Each of the four methods has its own advantages, and the best restoration method should be selected based on the actual habitat conditions of the restoration site.

Table 9 Four seeding and proliferation technologies and their costs[14]

Method	Specifications (cm)	Sowing spacing (cm)	Seed quantity/mu	Seedling completion rate	Cost (yuan/mu)
Large burlap method	120 x 90	100	64,000	25.8%	10,120
Small hemp bag method	7.5 x 15	25-75	36,000	26.5%	6,460
Mud block method	3 x 7(diameter)	25-75	36,000	32.6%	7,988
Seedling bed	85 x 70 x 60	25-75	1,080	14.8%	6,068

Figure 26 Production of seedling bed[14] (Source: Liu, 2015)

11.4 Case 4-Restoration of *Zostera japonica* based on Habitat rehabilitation

In the seagrass bed on the south bank of the Yellow River Delta, the area of *Spartina alterniflora* was only about 30 m^2 in August 2015. Yue et al (2021) found that the vegetation zone of *Zostera japonica* significantly declined from 2015 to 2019, decreasing from 550 meters to 165 meters [15]. This means that the rapid invasion of *Spartina alterniflora* has seriously encroached on the habitat of *Zostera japonica*, resulting in the inability of *Zostera japonica* bed to continue to grow and extend to the sea further (Figure 27).

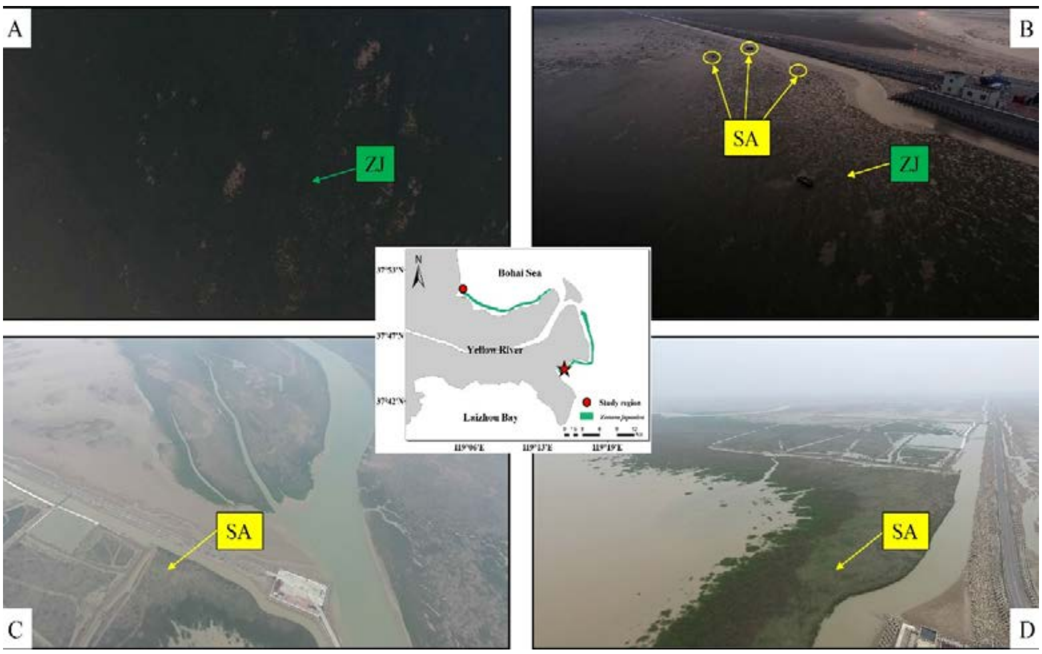

Figure 27 The phenomenon of *Spartina alterniflora* invasion in the *Zostera japonica* bed on the south bank of the Yellow River Delta (A and B: August 2015; C and D: June 2020; red star refers to the specific location of the area; ZJ: *Zostera japonica*; SA: *Spartina alterniflora*)[15] (Source: Yue et al., 2021)

Since 2020, *Spartina alterniflora* governance project has been carried out in the Yellow River Delta National Nature Reserve. By the end of 2021, 38,400 mu of *Spartina alterniflora* has been treated through the technologies as "flooding+cutting" and "cutting+tillage". After the control of *Spartina alterniflora*, Zhou Yi's team from the Institute of Oceanology, Chinese Academy of Sciences, carried out the restoration of seagrass beds in the *Spartina alterniflora* clearing area on the south bank of the Yellow River Delta from April to June 2021. 1.35 million *Zostera japonica* seeds were sown by the method of seagrass mud ball sowing, and 1.35 million *Zostera japonica* plants will be transplanted by the method of rhizome binding stones, with a total area of 20 hectares of seagrass beds restored (Figure 28). After transplanting and sowing, the rate of seed establishment is over 30%, and the survival rate of plants is over 95%, indicating significant restoration effects (Figure 29). This indicates that after the seagrass habitat is invaded by *Spartina alterniflora*, the ecological restoration of seagrass bed can still be carried out under suitable conditions through the rehabilitation of the habitat with treatment technology of *Spartina alterniflora*.

Figure 28 Restoration process of *Zostera japonica* on the southern bank of the Yellow River Delta (left side: mud ball sowing method, right side: rhizome binding stone method for plant transplantation) (Source: Xu Shaochun, Institute of Oceanology, CAS)

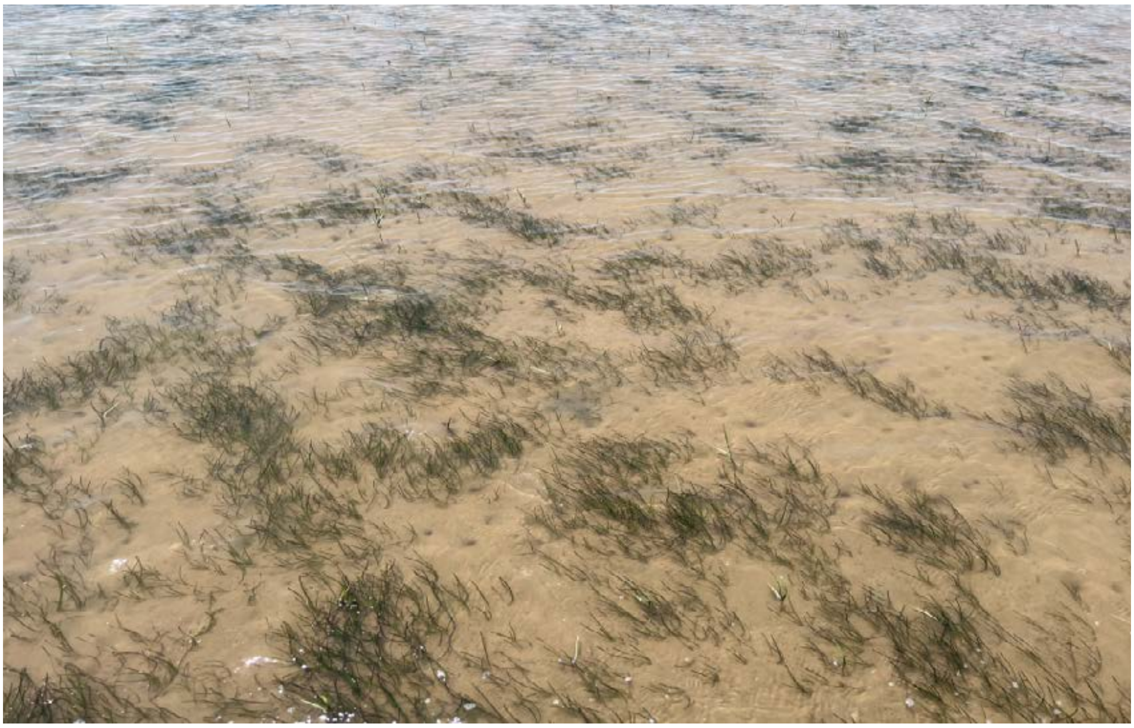

Figure 29 Restoration effect of *Zostera japonica* bed
on the south bank of the Yellow River Delta (Source: Xu Shaochun, Institute of Oceanology, CAS)

11.5 Case 5-The Snapper Program - Restoration of *Posidonia australis*

Since 1960, the seagrass area in Western Australia has decreased from 4,000 hectares to 900 hectares, affecting the population of local pink snapper, cod, herring, and other marine organisms. To this end, OzFish Unlimited organized to collaborate with scientists to initiate the restoration of *Posidonia australis*. This plan has aroused the interest of sea fishing enthusiasts and divers, and community members around the restoration area.

Posidonia australis can produce a large number of seeds, and the seeds do not have dormant period. This plan involves summoning volunteers to collect seeds, and then sown for restoration. In 2021, more than 300 volunteers participated in the restoration project and collected over 1 million fruits, greatly reducing the cost of restoration.

It has been found that the seedling establishment rate of directly sowing seeds is about 1% to 10%, but the seeds can be dispersed with the water flow to places that divers cannot reach. In some monitoring areas, seagrass seedlings have formed continuous sheets of seagrass beds (Figure 30)[16, 17].

Figure 30 Snapper Program (a) Mature *Posidonia australis* seeds; (b) Seed pretreatment; (c) Seeds used for sowing; (d) Seed sowing in the restoration area; (e) 2-year-old seedlings; (f) Sparse seagrass beds after 2.5 years[17] (Source: Sinclair et al., 2021)

11.6 Case 6-Restoration of *Zostera marina* in Virginia Lagoon, United States

Vast meadows of *Zostera marina* have once inhabited the inshore lagoon of Virginia in the United States, providing important ecosystem service functions. By 1933, a pandemic slime mold disease, in combination with a devastating hurricane, completely eradicated all *Z. marina*. The brant goose (*Branta bernicla*) and bay scallop (*Argopecten irradians*) that lost their habitat also were disappeared. In the 1990s, research found that the water quality and the light condition of the lagoon meet the growth of *Z. marina*, and sporadic *Z. marina* was also found. Based on this, it is speculated that the main reason for restricting the recovery of *Z. marina* is the limited seedling supplement, that is, lack of propagule supplement.

In 2001, a seed-based approach was established for ecological restoration of *Zostera marina*, with a total of over 74 million *Zostera marina* seeds planted in the lagoon, covering an area of 213 hectares (Figure 31). By 2018, the area of the seagrass bed had increased to 3612 hectares. The turbidity of water in the lagoon decreased, the carbon and nitrogen pool increased, and the biomass of invertebrate and fish had also increased, which promoted the recovery of *A. irradians*. The ecosystem service functions of the seagrass bed had gradually approached to the historical period.[18]

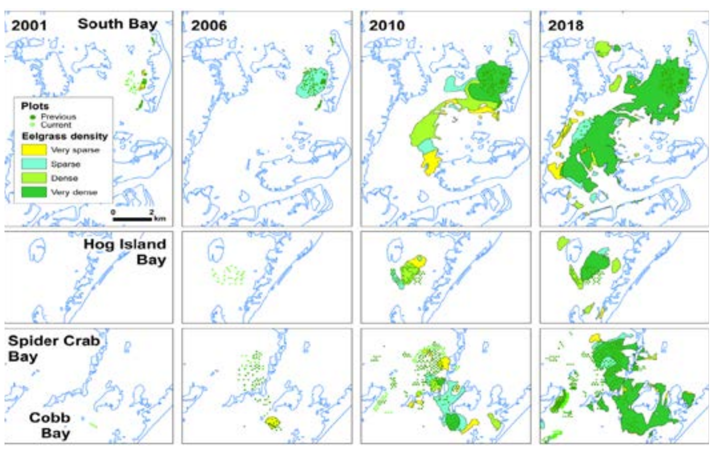

Figure 31 Changes in the area of *Zostera marina* in the lagoon[18]

(Source: Orth et al., 2020)

11.7 Case 7-Mechanical Device for Seagrass Transplantation

At present, problems still exist in the ecological restoration of seagrass beds, such as high restoration costs and low efficiency. With the development of technology, many mechanical devices for seagrass bed restoration have been developed both at home and abroad. The restoration efficiency has been gradually improved.

Zhang Peidong's team of Ocean University of China has developed a pneumatic direct seeding machine for *Zostera marina* (Figure 32). The external dimensions, net weight, and sowing depth of the machinery are 80 × 50 × 50 cm, 35 kg, and 1-3 cm, respectively. After 100 monitoring sessions, the stability rate of the mechanical seed displacement is 62.3%. This machine size is small and its operation is relatively simple, and its seeding efficiency reaches 1200 m^2/person/day, which is about 6 times that of manual seeding.

Figure 32 Pneumatic direct seeding machine for *Zostera marima*

(Source: Zhang Peidong, Ocean University of China)

The field experiment verifies that within 7 months after sowing, the seedling rate of the seeder of sowing seeds is 15%. One year after sowing, the plant density reached 72 plants/m^2 and the biomass exceeded 50 DW g/m^2. Excluding the cost of seeds, the planting cost of the seeder is about 800 yuan/mu, a decrease of 88% compared to the manual planting method.

Some effective restoration machines have also been developed abroad. Govers (2022) used an injection distributor to sow *Zostera marina* seed, but the rate of seed loss was relatively high[19].

At present, there are also devices used for seagrass transplantation, mainly for grass block and turf transplantation methods. For example, seagrass transplant ships, modified excavators and backhoes have greatly improved the efficiency of seagrass bed transplantation (Figure 33).

Figure 33 Seagrass turf backhoe[20] (Source: Suykerbuyk et al., 2016)

Appendixes 1: Distribution Status and Ecological Functions of Seagrass Beds

1. Current global distribution status of seagrass beds

Seagrass is the unique flowering plant growing in the ocean, which is widely distributed in intertidal and subtidal zones. This group evolved from marine algae into terrestrial flowering plant, then then moved back to the sea again, which has an important position and research value in plant evolution. Compared with terrestrial plant, there are fewer species of seagrasses, about 72 species in 6 families in the world. Although the species number of seagrass is relatively low, their distribution area is relatively wide with about 300, 000 to 600, 000 km2. Six global bioregions are presented: four temperate and two tropical. The temperate bioregions include the Temperate North Atlantic, the Temperate North Pacific, the Mediterranean, and the Temperate Southern Oceans. The tropical bioregions are the Tropical Atlantic and the Tropical Indo-Pacific. There are 24 species in the Indo-Pacific region, which is the region with the highest species diversity of seagrass in the world[21].

The seagrass distribution area in China belongs to the Indian-Pacific and North Pacific regions. There are both temperate seagrass beds and tropical-subtropical seagrass beds, which mainly distributed in the Yellow Sea and Bohai Sea, both sides of the Taiwan Strait, and the South China Sea , including 4 families, 10 genera, 22 species (Table 10), accounting for 30% of the world's seagrass species. Among them, there are 9 species of temperate seagrass, mainly distributed in the coastal waters of Liaoning, Hebei, and Shandong. And there are 13 species of tropical seagrass, mainly distributed in coastal waters such as Fujian, Guangdong, Guangxi, Hainan, and Taiwan.

Table 10 Species and Distribution of Seagrass in China

Family	Genus	Species	Distribution location
Cymodoceaceae	*Cymodocea*	*C. rotundata*	Guangdong, Hainan, Taiwan
		C. serrulata	Hainan
	Halodule	*H. pinifolia*	Guangdong, Guangxi, Hainan, Taiwan
		H. uninervis	Guangdong, Guangxi, Hainan, Taiwan
	Syringodium	*S. isoetifolium*	Guangdong, Guangxi, Hainan, Taiwan
	Thalassodendron	**T. ciliatum*	Guangdong, Hainan, Taiwan
Hydrocharitaceae	*Enhalus*	*E. acoroides*	Hainan, Taiwan
	Thalassia	*T. hemprichii*	Guangdong, Hainan, Taiwan
	Halophila	*H. beccarii*	Guangdong, Hongkong, Guangxi, Hainan, Taiwan
		**H. decipiens*	Hainan, Taiwan
		H. minor	Guangdong, Hongkong, Guangxi, Hainan
		H. ovalis	Fujian, Guangdong, Hongkong, Guangxi, Hainan, Taiwan
Ruppiaceae	*Ruppia*	*R. brevipedunculata*	Jiangsu, Zhejiang, Fujian, Guangdong, Hainan
		R. sinensis	Liaoning, Tianjin, Shandong, Jiangsu, Shainghai, Zhejiang, Fujian, Guangdong
		**R. megacarpa*	Shandong, Jiangsu

Table 10 Species and Distribution of Seagrass in China (continued)

Family	Genus	Species	Distribution location
Zosteraceae	*Phyllospadix*	*P. iwatensis*	Liaoning, Hebei, Shandong
		**P. japonicus*	Liaoning, Hebei, Shandong
	Zostera	**Z. asiatica*	Liaoning
		Z. caespitosa	Liaoning, Hebei, Shandong
		**Z. caulescens*	Liaoning
		Z. japonica	Liaoning, Hebei, Shandong, Guangxi, Hongkong, Guangdong, Taiwan
		Z. marina	Liaoning, Hebei, Shandong

Note: * indicates that no species were found during the latest census from 2015 to 2020

2. The ecosystem functions of seagrass bed

Seagrass beds, along with coral reefs and mangroves, are known as the three typical nearshore marine ecosystems and have extremely important ecosystem functions. Specifically, it includes the following:

(1)Maintaining biodiversity: Seagrass maintains a high level of biodiversity by providing habitats and food for animals. Seagrass is a habitat for animals such as fish, shellfish, and seabirds, and is considered as the "nursery" for fish worldwide. In addition, seagrass has extremely high productivity and can provide food sources for many animals, such as rare and endangered animals such as dugongs and green turtles.

(2)Purifying water quality: Seagrass can attach suspended particles, absorb nutrients in the water, improve the transparency of seawater, and thus purify water quality.

(3)Embankment protection and disaster reduction: The well-developed root system of large seagrass plays a role in fixing the substrate and has a certain ability to resist waves and tides, which can slow down beach erosion.

(4)Climate regulation: Seagrass beds have been proven to be the most effective carbon capture and storage system on earth, and are serving as an important global carbon reservoir and of great significance in reducing carbon dioxide emissions [3]. According to statistics, the global seagrass bed accounts for less than 0.2% of the total ocean area, but the carbon sequestered in seagrass sediment every year is equivalent to 10%-15% of the total global ocean carbon sequestration; The organic carbon storage of seagrass beds can reach 19.9 Pg C, and the annual carbon burial amount reaches 27.4 Tg C. The carbon burial rate of seagrass beds is second only to that of mangroves (Figure 34).

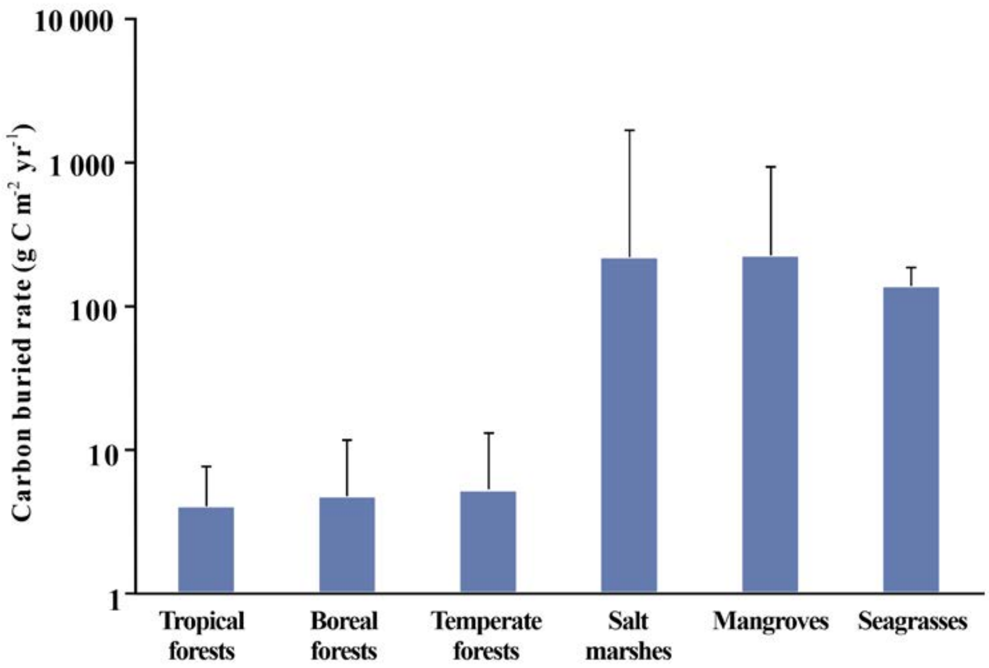

Figure 34 Carbon burial rates of different ecosystems[23]

(Source: McLeod et al., 2011)

(5)Scientific and cultural value: Seagrass groups are flowering plant that evolved from marine algae to terrestrial plant and then returned to the sea, and have an important position and research value in plant evolution. The seagrass bed ecosystem maintains a very high level of biodiversity and has a certain value for tourism and science popularization.

Appendixes 2: Atlas of Seagrass Species in China

1. Zosteraceae

1.1 *Zostera* Linn.

Zostera japonica Asch. et Graebn.

Figure 35 Photo of *Zostera japonica* specimens (Source: Zhang Xiaomei, Institute of Oceanology, CAS)

Figure 36 *Zostera japonica* habitat (Shatian, Guangxi)

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Zostera caespitosa Miki

Figure 37 Photo of *Zostera caespitosa* specimen

(Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 38 Habitat of *Zostera caespitosa* (Rongcheng, Shandong)

(Source: Li Wentao, Ocean University of China)

Zostera asiatica Miki

Figure 39 *Zostera asiatica* specimen (Source: Lee Kun-Seop, Pusan University, South Korea)

Figure 40 The habitat of *Zostera asiatica*[24] (Source: Lee et al. 2018)

Zostera caulescens Miki

Figure 41 Specimen of *Zostera caulescens* (Source: Lee Kun-Seop, Pusan University, South Korea)

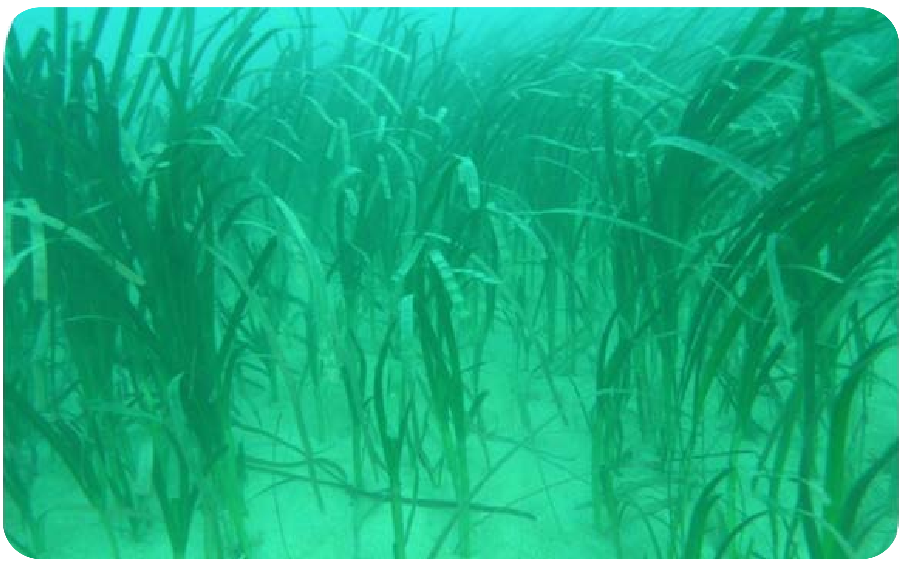

Figure 42 Habitat of *Zostera caulescens* (Gyeongsang, South Korea)

(Source: Li Wentao, Ocean University of China)

Zostera marina L.

Figure 43 Whole *Zostera marina* plant (Mashanli, Weihai)

(Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 44 *Zostera marina* habitat (Caofeidian, Hebei)

(Source: Xu Shaochun, Institute of Oceanology, CAS)

1.2 *Phyllospadix* Hook

Phyllospadix japonica Makino

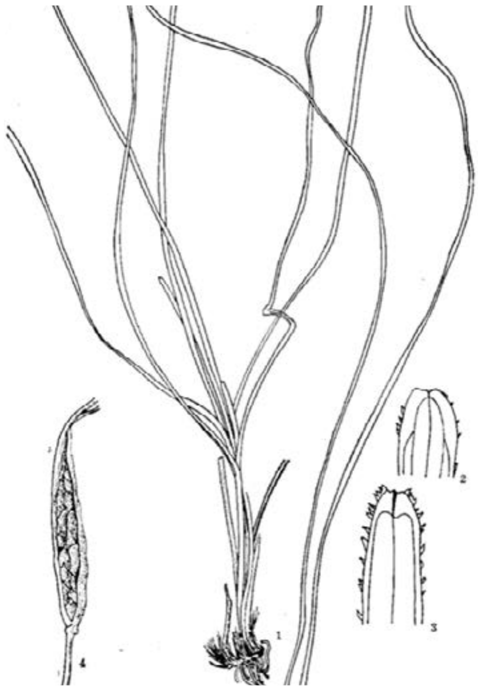

Figure 45 Hand drawing of *Phyllospadix japonica* (by Chen Baolian)[25] (Source: Sun 1992)

1. Plants, 2-3. Leaf tips of young and old leaves, 4. Young flower branches

Figure 46 *Phyllospadix japonica* habitat (Source: Lee Kun-Seop, Pusan University, South Korea)

Phyllospadix iwatensis Makino

Figure 47 Whole plant of *Phyllospadix iwatensis* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 48 *Phyllospadix iwatensis* habitat (Rongcheng, Shandong)
(Source: Li Wentao, Ocean University of China)

2. Cymodoceaceae

2.1 *Cymodocea* K. D. Koenig

Cymodocea rotundata Asch. & Schweinf.

Figure 49 Whole plant of *Cymodocea rotundata* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 50 Habitat of *Cymodocea rotundata* (Lingshui New Village, Hainan)
(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Cymodocea serrulata (R. Br.) Asch. & Magnus

Figure 51 Whole plant of *Cymodocea serrulate* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 52 Habitat of *Cymodocea serrulata* (Wenchang, Hainan)
(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

2.2 *Halodule* Endl.

Halodule uninervis (Forssk.) Asch.

Figure 53 *Halodule uninervis* whole plant (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 54 *Halodule uninervis* habitat (Wenchang, Hainan)
(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Halodule pinifolia (Miki) Hartog

Figure 55: The whole plant of *Halodule pinifolia* (Xisha, Hainan)

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

2.3 *Syringodium* Kütz.

Syringodium isoetifolium (Arch.) Dandy

Figure 56 Whole plant of *Syringodium isoetifolium*

(Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 57 *Syringodium isoetifolium* habitat (Wenchang, Hainan)

(Source: Chen Shiquan, Hainan Academy of Ocean and Fisheries Sciences)

2.4 *Thalassodendron* Hartog

Thalassodendron ciliatum (Forssk.) Hartog

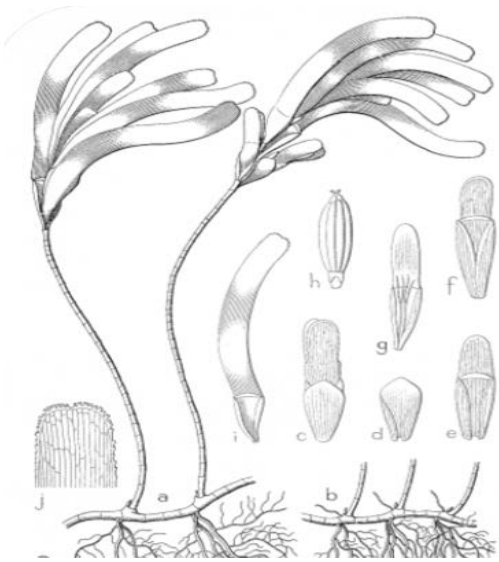

Figure 58 Hand drawing of *Thalassodendron ciliatum*[26] (Source: den Hartog 1970)

a. Flowering plants, b. Lateral stems, c. Bracts, d. Bracts I, e. Bracts II,

f. Bracts III, g. Bracts IV, h. Male flowers (including 2 pieces)

3. Hydrocharitaceae

3.1 *Enhalus* Rich

Enhalus acoroides (L. f.) Steud.

Figure 59 Whole plant of *Enhalus acoroides* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 60 Habitat of *Enhalus acoroides* (Lingshui, Hainan)

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

3.2 *Thalassia* Banks ex K. D. Koenig

Thalassia hemprichii (Ehrenb.) Asch.

Figure 61 Female plant with fruit of *Thalassia hemprichii*
(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Figure 62 Habitat of *Thalassia hemprichii* (Lingshui, Hainan)
(Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

3.3 *Halophila* Thouars

Halophila ovalis (R. Br.) Hook. f.

Figure 63 Whole plant of *Halophila ovalis* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 64 *Halophila ovalis* habitat (Shatian, Guangxi) (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Halophila minor (Zoll.) Hartog

Figure 65 Whole plant of *Halophila minor* (Source: Zhao Bin, Fourth Institute of Oceanography, MNR)

Figure 66 *Halophila minor* habitat (Gangdong, Hainan)

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Halophila beccarii Asch.

Figure 67 Whole plant of *Halophila beccarii* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Halophila decipiens Ostenf.

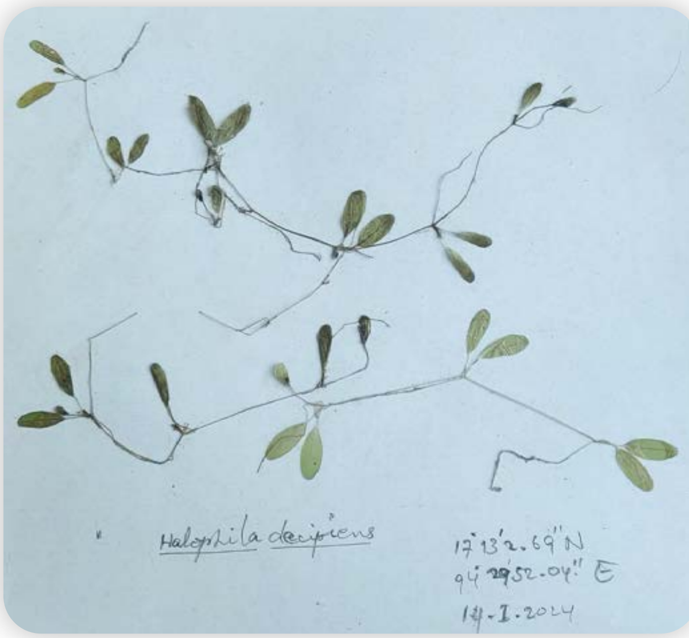

Figure 68 *Halophila decipiens*（Source: San Tha Tun，Myanmar）

4. Ruppiaceae

4.1 *Ruppia* L.

Ruppia sinensis Shuo Yu & den Hartog

Figure 69 Whole plant of *Ruppia sinensis* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Figure 70 *Ruppia sinensis* habitat (Dongying Lagoon, Shandong)

(Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Ruppia brevipedunculata Shuo Yu & den Hartog

Figure 71 Whole plant of *Ruppia brevipedunculata* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Figure 72 Habitat of *Ruppia brevipedunculata* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

Ruppia megacarpa R. Mason

Figure 73 Whole plant of *Ruppia megacarpa* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

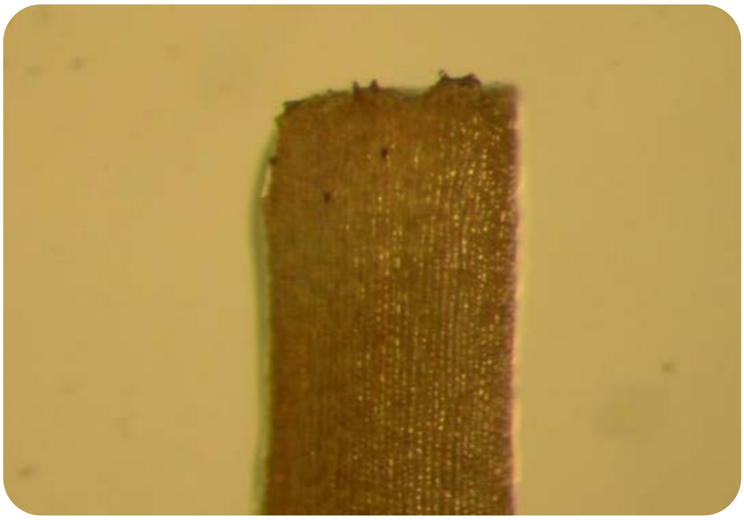

Figure 74 Young leaf tip of *Ruppia megacarpa* (Source: Yu Shuo, Fourth Institute of Oceanography, MNR)

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