Global
Environmental Institute
北京市朝阳区永续全球环境研究所

Address: Room 032, unit 1, foreign affairs office building,
tower garden, No. 14, South Liangmahe Road,
Chaoyang District, Beijing
Postcode: 100600
Telephone: 86-10-8532-5910
Fax: 86-10-8532-5038
E-mail: gei@geichina.org
Website: http://www.geichina.org

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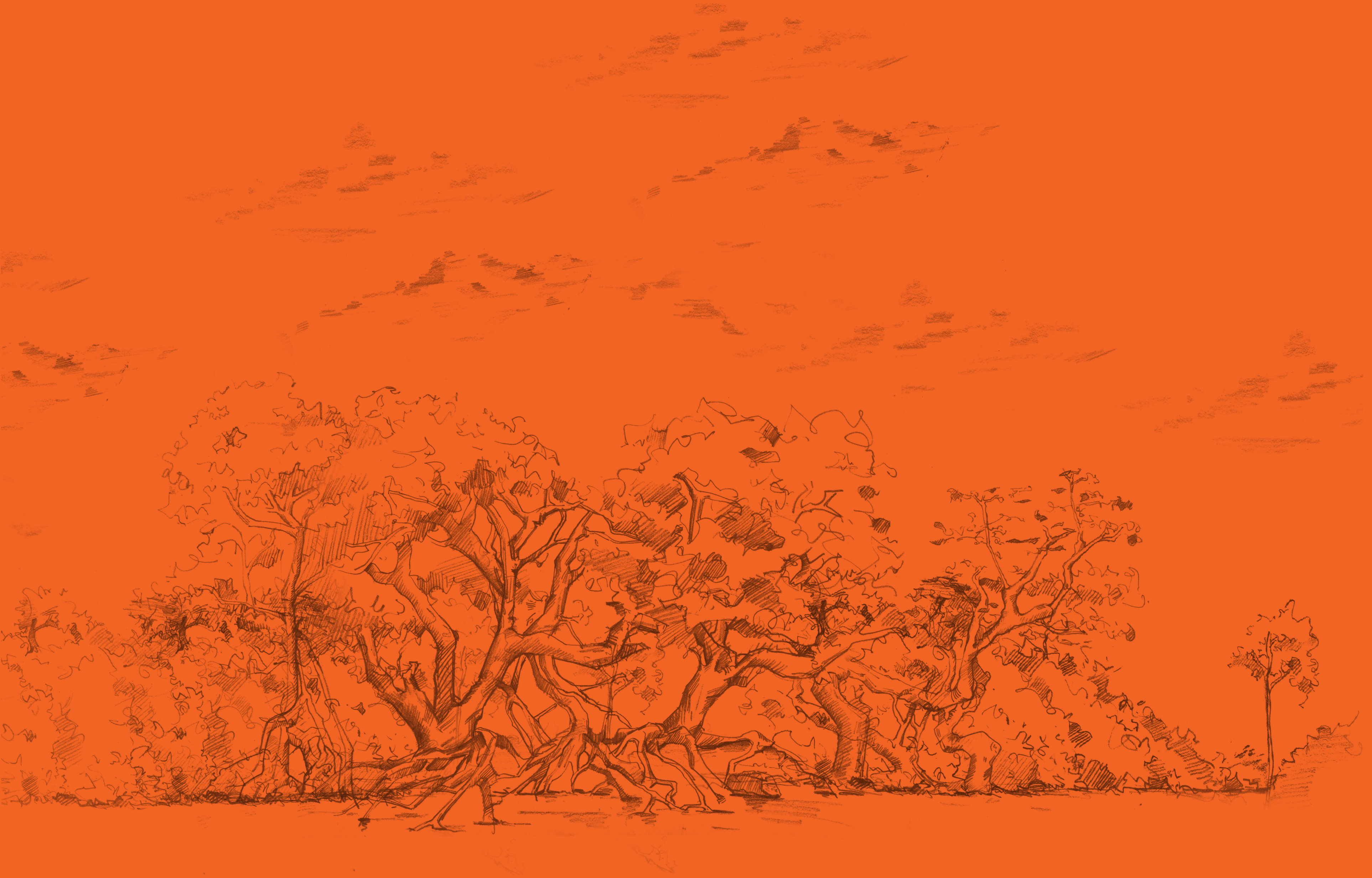
Mangrove Ecosystem Restoration Guide

Overview of Mangroves in China



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Author: WANG Wenqing , WANG Jing , ZHONG Cairong
Proofreading: FAN Min , JI Lin , ZHANG Yamian

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PREFACE

Mangrove ecosystems serve as a transitional zone between territorial ecosystems and marine ecosystems, where freshwater meets with seawater. They are among the most productive and complex ecosystems on the planet, providing numerous ecological functions and services to both marine environments and to people.

Globally, mangrove forests are distributed across tropical and subtropical areas (usually within a 20-degree isotherm). About 42% of all mangrove forest area is located in East and Southeast Asia, totaling over 5 million hectares. In these regions, mangrove forests provide a primary habitat for many species of seabirds and waterfowl, in addition to some terrestrial animals. They host thousands of endangered species, ranging from *Eretmochelys imbricatae* (CR), *Panthera tigris tigris* (EN) to 50 million migrating bird species, and enable migrating birds to fly between East Asia and Australia.

Over two billion people inhabit in East and Southeast Asia; among them, two thirds live in coastal areas whose food, water and livelihoods are dependent on mangrove forests. According to the National Marine Hazard Mitigation Service, 36% of typhoons originate from the area near East and Southeast Asia in the Pacific Ocean, and 10% of typhoons originate from the Bay of Bengal. With their rich biodiversity, mangrove systems not only support coastal residents' livelihoods but also serve as a buffer to protect shorelines from extreme climate disasters, including tropical storms, typhoons and tsunamis.

Mangrove ecosystems are also highly effective as carbon sinks. Their carbon storage efficiency per unit area is much higher than that of rainforests, which have the highest carbon storage efficiency among territorial ecosystems. It is estimated that if mangrove forests are damaged or cut down, their carbon emission are 5-10 times higher than those of rainforests.

Nevertheless, the development of human society and exploitation of coastal belts have caused unprecedented destruction to the planet's mangrove ecosystems. Since the 1940s, we have lost over 35% of global mangrove forest area, and the areas remaining are disappearing at an alarming rate of 1-2% per year. Mangroves in East and Southeast Asia are currently facing a similar set of threats that contribute to their deforestation. According to research conducted by the United States National Academy of Sciences, major causes for the loss of mangrove forests in East and Southeast Asia from 2000 to 2012 were the expansion of aquaculture, rice planting, palm oil production and wood cutting.

In China, owing to effective policies and actions, mangrove forest coverage increased from 22,000 hectares in 2001 to 30,000 hectares in 2017, making China one of the few countries that has increased its mangrove forest coverage. The Chinese government has placed great importance on the protection of mangrove forests, and as of 2018, over two-thirds of natural mangrove forest has been included within nature protected areas. However, there are still over 48.6% local mangrove plants under threat of extinction in China, and mangroves in China still face a series of problems, such as invasive species and pesticides.

The Global Environmental Institute (GEI) is a Chinese environmental NGO that endeavors to address global environmental issues through informing policymaking and developing market-based mechanisms. In 2018, GEI launched its Marine Conservation program with an aim to prevent the mangrove corridor in East and Southeast Asia from suffering further fragmentation, to protect and restore over 42% of the world's mangrove forests, and to provide nature-based solutions to address climate change. Currently, GEI has carried out community-based mangrove and forest conservation pilots in two communities in China's Guangdong Province and twenty-seven communities in Myanmar.

During the implementation of our projects thus far, we have found that frontier mangrove protection staff are in urgent need of concise and clear instructions to guide their restoration and protection work. In many cases, they pay too much attention to restoration instead of focusing on how to ensure that restored mangroves areas evolve into stable and healthy ecosystems. To meet this gap, Mangrove Ecosystem Restoration Guide, developed in collaboration with Professor WANG Wenqing of Xiamen University and his team, intends to guide frontier staff to turn their concentration from mangrove forests themselves to the whole mangrove ecosystem, to scientifically restore and protect mangrove ecosystems and to support future protection actions, so as to promote the protection and restoration of mangrove forests in the regions of East and Southeast Asia. The handbook also summarizes the current status of mangrove forests in China and major issues/challenges linked to mangrove afforestation, with an aim to provide reference for mangrove forest conservation efforts in China.

I would like to thank the Third Institute of Oceanography of China's Ministry of Natural Resources, Guangdong Zhanjiang Mangrove National Nature Reserve and Dongzhaigang National Nature Reserve for their guidance and support during the writing of this handbook. I would also like to express my gratitude for the financial support from Global Environmental Innovation Fund and SEE Foundation, without which this handbook would not have been possible to create.

We hope you enjoy reading it and find the contents useful.

Jin Jiaman

Jin Jiaman
1st August 2019

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01

Terminology

1. Mangroves

Woody plants growing in tidal flats of tropical and subtropical areas, mainly composed of evergreen shrubs or trees and subject to cyclical tidal flooding.

2. Mangrove wetland

Coastal wetland with a certain area of mangroves. Major geomorphological units of coastal wetland include mangrove forest, bare mudflat outside mangrove forest, tidal creek and waters with depth no more than six meters at low tide.

3. Mangrove ecosystem

Organic integrated system composed of producers (including true mangrove species, mangrove associates, associated plants, benthic algae and phytoplankton), consumers (including fishes, benthos, zooplankton, birds, insects and mammals), decomposers (microorganisms) , and inorganic environment.

4. Mangrove plant

True mangrove and mangrove associates.

5. True mangrove (exclusive mangrove)

Woody plants and two herbaceous species (*Acrostichum aureum* and *Acrostichum speciosum*) that only grow in coastal intertidal zones.

6. Mangrove associate (semi-mangrove)

Amphibious woody plants growing in intertidal zones, but not as dominant species. Mangrove associate species can also grow in land non-saline soils.

7. Intertidal zone

The coast zone between average highest tide line and average lowest tide line, that is, a zone extending from the underwater area covered by the highest tide to the area exposed by the lowest tide.

8. Mudflats outside mangrove forest

The exposed area outside the mangrove forest at low tide.

9. Pond conversion to forest

One of mangrove wetland restoration measures, mainly targeting on aquaculture ponds (fish ponds, shrimp ponds, etc.). To convert aquaculture ponds into mangrove forests through artificial or natural methods, so that to restore the original landscape of mangrove wetland.

10. Pond conversion to wetland

One of mangrove wetland restoration measures. Different from pond convestion to forest, it restores mangrove wetland by opening only the dyke of fish pond, allowing hypocotyls, seeds or fruits of mangrove plants to enter with water flow and then settle down. Mangrove seedlings can be artificially planted to speed up the recovery of mangroves.

11.Intertidal-breeding conversion to mudflat

One of mangrove wetland restoration measures. It restores the functions of tidal flats and shallow waters by removing aquaculture from mudflats outside mangrove forest and shellfish farming from shallow waters (*e.g., Tegillarca granosa, Sinonovacula constricta, Meretrix meretrix, Paphia undulata,* oysters).

12. Land suitable for mangrove afforestation

The area where environmental conditions meet with the basic requirements for the growth of mangroves. These conditions include temperature, water quality, salinity, tidal elevation, sediment and hydrologic conditions, among which the most important one is tidal elevation.

13. Alien species

Species distributed outside their native ranges because of migration, diffusion and human activities.

14. Ecological restoration

The process of re-establishing self-regulating and self-organizing ecosystems for orderly evolution by lifting human interference to reduce load pressure, or the process of assisting the gradual recovery or virtuous-cycle development of damaged ecosystems with artificial means as a supplement to self-recovery.

02 Restoration objectives

The major objective of mangrove wetland restoration is to restore its ecosystem function. Apart from the mangrove forests coverage, the composition of mangrove species and its population genetic diversity as well as animal diversity (fishes, birds, benthos, and animals with important economic value) should also be considered as restoration objectives. In particular sites, such as severely eroded coastal areas, coastal areas with discontinued shelter forests, and planned urban green spaces, the restoration objectives can include breakwater and landscape features. In certain regions, the production and living support for local residents should also be a restoration goal. Mangrove wetland restoration should concentrate more on the overall functional recovery of mangrove ecosystems, rather than a simple vegetation recovery.

03 Restoration principles

a. Ecology and protection should be the priorities. The integrity of mangrove ecosystem should be mantained. Biodiversity and ecosystem's functional recovery should be important criteria for restoration effectiveness;

b. Natural restoration should be highlighted, supplemented with artificial restoration, to substantially reduce the cost of restoration and post-restoration maintenance;

c. Restoration objectives, strategies and technologies should be set according to the integrity, typicality, rarity/vulnerability, and damage degree of mangrove ecosystem;

d. Effectiveness should be underlined and subject to strict evaluation, post-restoration tracking, monitoring and effectiveness assessment should also be part of restoration tasks;

e. Improvement of local residents' production and living standard should be fully considered in making restoration objectives, methods, proceedings and effectiveness assessment.

Restoration targets 04

4.1 The choosing of restoration targets should be compatible with the regional development planning and neighboring community's marine development activities, and be supported by the local government and community;

4.2 Restoration targets can be divided into four categories: degraded woodland, bare mudflat, fish pond and aquaculture area outside mangrove forest.

a. Degraded woodlands: Areas where part of mangrove forest die from pests and diseases, pollution, felling and pruning, as well as extreme weather. In degraded woodlands, plant species and density can be increased through regeneration, tending and transplanting;

Death of mangroves, caused by concentrated sewage discharge from fishponds (Wenchang, Hainan, China, April 2016, © Zhou Zhiqin)

Death of mangroves, caused by concentrated sewage discharge from fishponds (© Wang Wenqing)

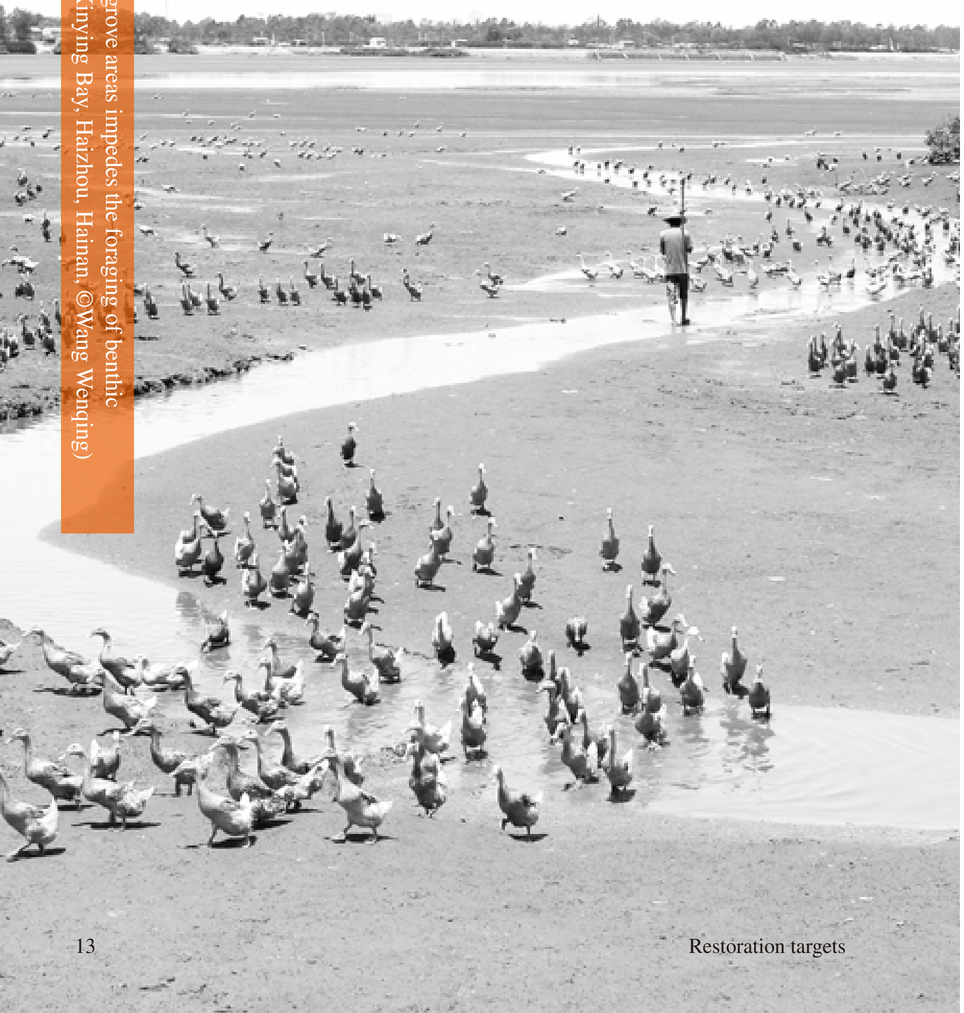
Death of mangroves, caused by Typhoon Rammasun in July 2014 (Dongzhaigang, Hainan. Provided by Zhong Cairong)

Restoration of degraded woodland where pests (Sphaeroma spp.) caused the death of mangroves (Dongzhaigang, Hainan, © Wang Wenqing)

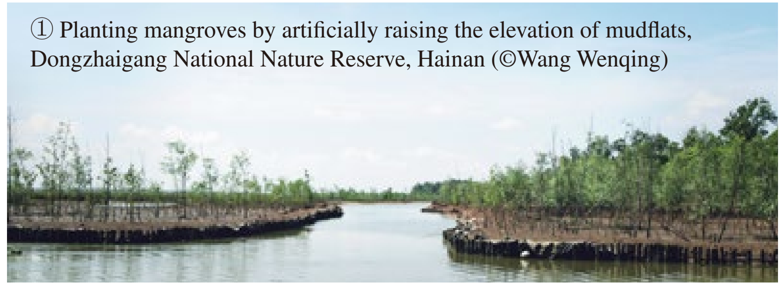
Remaining mangroves, after cutting activities by villagers in Xinying Town, Danzhou, Hainan (©Wang Wenqing)

b. Bare Mudflats: Exposed tidal flats with no mangrove plants, including the existing mudflats outside mangrove forest and the surrounding mudflat area where no mangroves distribute in the periphery. Mangrove coverage and forest belt width can be expanded through artificial afforestation methods. However, strict argumentation is demanded to these methods concerning whether they meet the requirements of natural restoration. Historical usage of bare mudflats should also be taken into account.

Shellfish farming in bare mudflats not only interferes benthic animals, but also affects the foraging of water birds (Zhangjiang Estuary, Fujian, ©Wang Wenqing)



Poultry cultivation in mangrove areas impedes the foraging of benthic animals and water birds (Xinying Bay, Haizhou, Hainan, ©Wang Wenqing)



① Planting mangroves by artificially raising the elevation of mudflats, Dongzhaigang National Nature Reserve, Hainan (©Wang Wenqing)

② Afforestation in suitable tidal flats in Sibi Bay, Dongfang City, Hainan Island (©Wang Wenqing)

C. Fish ponds and farmlands: Fish ponds previously built by destroying mangrove forest can turn into mangrove forests through pond conversion to forest and pond conversion to wetland.

Farmland that cannot be used due to soil acidification and salinization after reclamation of mangroves (Dongzhaigang, Hainan, ©Wang Wenqing)

Farmland that cannot be used due to soil acidification and salinization after reclamation of mangroves (Zhanjiang, Guangdong, ©Wang Wenqing)

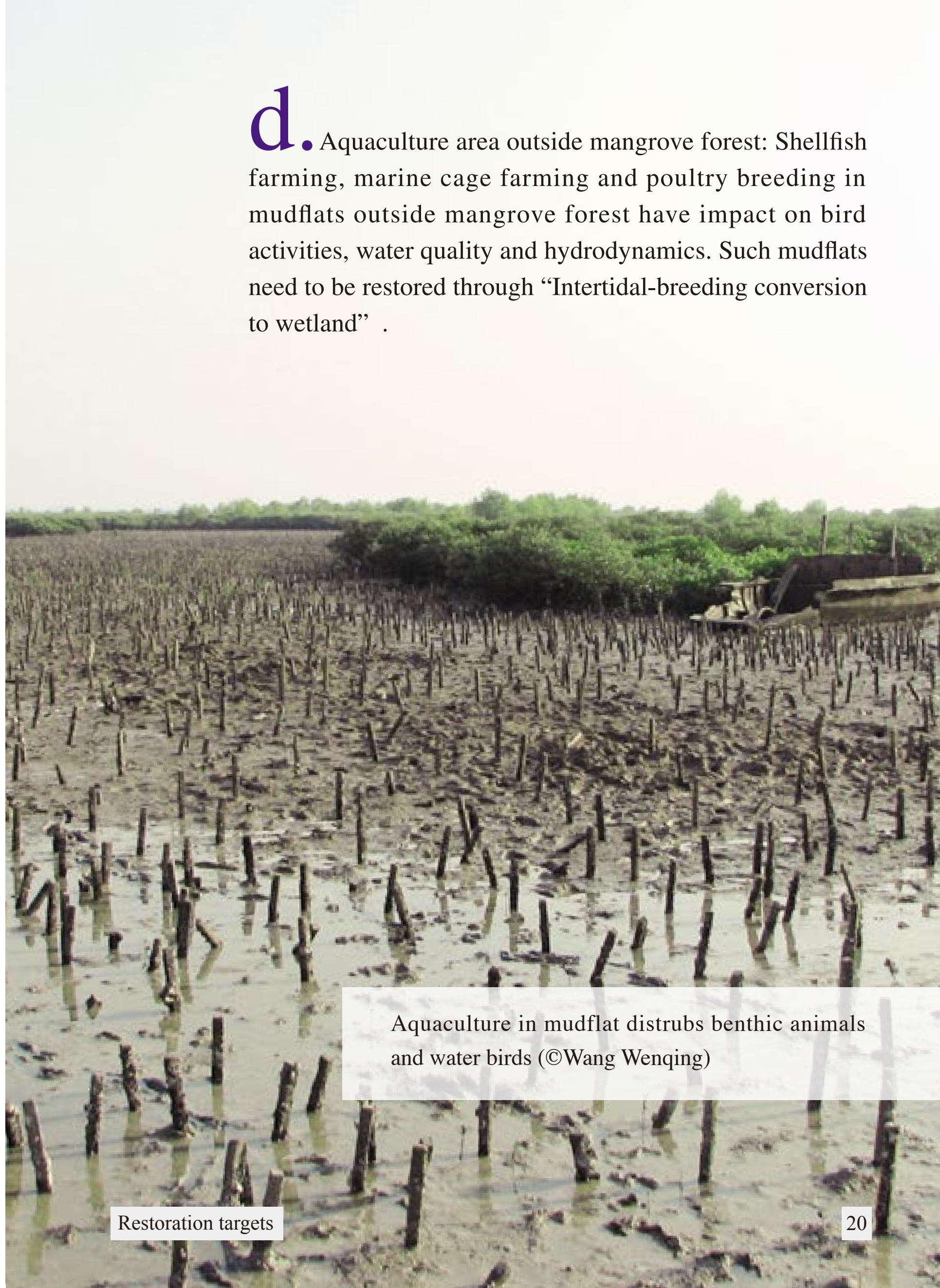
Deforestation for aquaculture is mainly responsible for mangrove destruction in Southeast Asia (Ponds in inner side of Dongzhaigang mangrove forests, Hainan, ©Wang Wenqing)

Deforestation for aquaculture (Zhangjiang Estuary, Fujian, ©Wang Wenqing)

Naturally restored mangrove forest after conversion from fish pond (Dongzhaigang, Hainan, ©Wang Wenqing)

Artificial restoration in fish ponds in Bali Island, Indonesia (© Wang Wenqing)

d. Aquaculture area outside mangrove forest: Shellfish farming, marine cage farming and poultry breeding in mudflats outside mangrove forest have impact on bird activities, water quality and hydrodynamics. Such mudflats need to be restored through “Intertidal-breeding conversion to wetland” .



Aquaculture in mudflat distrubs benthic animals and water birds (©Wang Wenqing)

05

Selection of mangrove species

Mangrove species should be selected according to the conditions of the proposed restoration site.

Basic criteria for species selection as shown in the following aspects:

5.1 Regional aspect

Before implementing restoration project in a proposed site, field investigation and document research to the native mangrove plants in the site and its surrounding area should be conducted to sort out a concrete list of mangrove species living within. Species used in the restoration project are selected from the list. True mangrove species in China and their distribution are as shown in Table 1. The distribution of Mangrove species in one region of a province may differ from another due to differences of regional microclimates. For example, *Lumnitzera littorea* is only naturally distributed in southern Hainan, and it suffers cold damage after being introduced to northern Hainan. The northest distribution area of *Ceriops tagal* is southern Leizhou Peninsula, and it dies from low temperature after being introduced to eastern Guangdong. Meanwhile, illustration of mangrove plants should be edited with the following contents:

- **Name:** Common name (local name) and scientific name;
- **Distribution:** Distribution and status;
- **Habitat and salinity tolerance:** Basic morphological characteristics, ecological adaptation (salinity tolerance, tidal level, temperature), etc.;
- **Features and usages;**
- **Reproduction:** Propagation methods, and phenology (time of propagule maturity);
- **High quality photos.**

An example is provided below:

Kandelia obovata Sheue, Liu et Yong

Common name: Shuibizai
mangrove shrub or small tree up to 10 meters tall, with buttress root, simple leaves opposite, elliptic or subobovate, entire with wide petiole and stipule, and fall early. Inflorescence is a single flowered pendulous cyme and axillary in position. Flowers are white. Fruits are oval in shape. The hypocotyls are spindle shaped or cylindrical, smooth, reddish brown after maturity. The flowering period lasts from July to August, and the fruiting period lasts from December to next May.

Distribution: It is the most widespread mangrove specie in China. It is distributed in Fujian, Guangdong, Guangxi, Hainan Province, and Hong Kong, Macao, and Taiwan China. It has been introduced to southern Zhejiang Province as well.

Habitat and salinity tolerance: This typical mangrove plant mainly grow in middle tidal flats and middle outer tidal flats. It is commonly found in the inner edge of *Avicennia marina* and *Aegiceras corniculatum* forest. As one of the species at the middle stage of succession, *Kandelia obovata* is more saline tolerant than *Aegiceras corniculatum*, but less than *Avicennia marina*. Under natural conditions, it grows luxuriantly in upper and middle muddy tidal flats with a soil salinity of 7.5–21 mg/g (Lin Peng et al., 1981). In Hong Kong and other places, it can grow normally in areas with seawater salinity of 30 mg/g.

Features and usages: It is highly adaptable and easy to be cultivated. *Kandelia obovata* is the most cold-resistant mangrove plant on the west coast of the Pacific Ocean. It is the only mangrove plant that has been successfully introduced into Zhejiang Province, and that has the northest distribution in China. It is one of the mangrove species that are widely used for greening tidal flats in the subtropical coast of China. Its hypocotyl is rich in starch and edible after appropriate processing. Its Leaves can feed livestocks, and barks, rich in tannin, can be used as an astringent.

Reproduction: It can be planted by inserting the hypocotyl.


Flowers


Hypocotyls


Fruits


Buttress roots

Kandelia obovata forest (Jiulong River Estuary, Longhai, Fujian)

Kandelia obovata introduced into Ximen Island, Yueqing, Zhejiang in 1957

Table 1. True Mangrove Species in China and Their Distribution

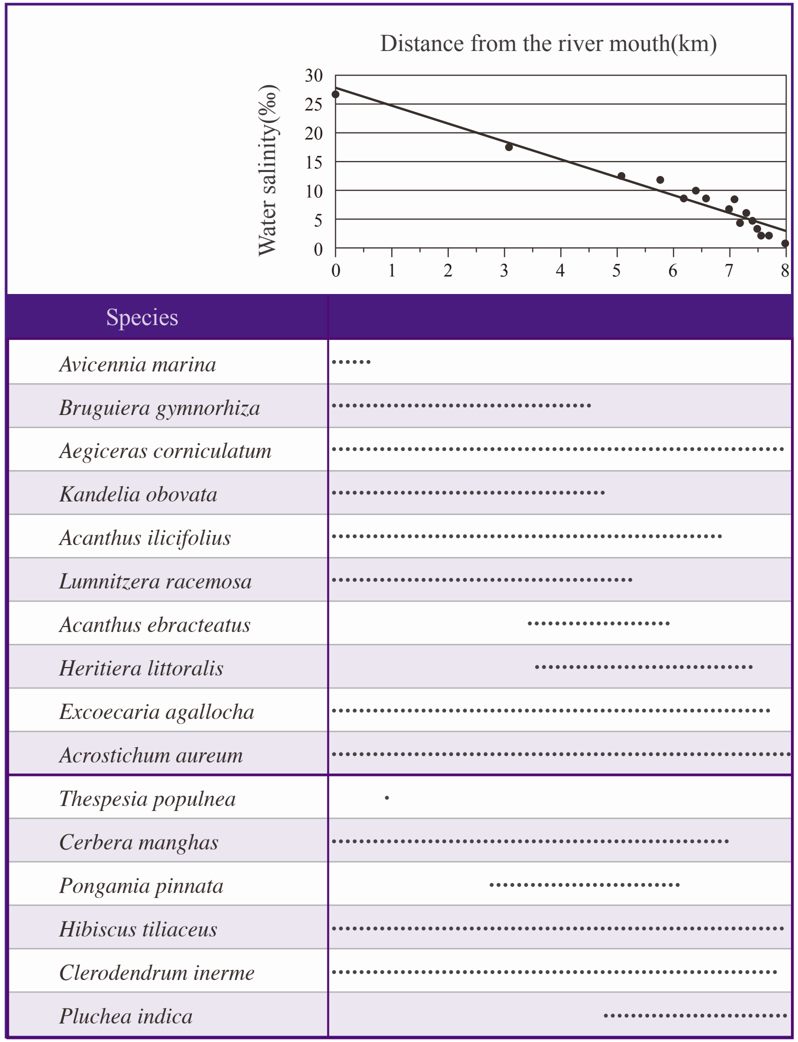
Species	Zhe jiang	Fujian	Guang dong	Guang xi	Hai nan	Hong Kong	Tai wan
Kandelia obovata	Intro.	√	√	√	√	√	√
Bruguiera gymnorhiza		√	√	√	√	√	Ext.
Bruguiera sexangula		Intro.	Intro.		√		
B. s. var. rhynchopetala		Intro.	Intro.		√		
Rhizophora stylosa		Intro.	√	√	√	Ext.	√
R. apiculata					√		
R. ×lamarckii					√		
Ceriops tagal			√	Ext.	√		Ext.
Sonneratia caseolaris		Intro.	√		√		
S. ×gulngai					√		
S. ×hainanensis					√		
S. ovata					√		
S. alba					√		
Xylocarpus granatum			Intro.		√		
Lumnitzera racemosa		Intro.	√	√	√	√	√
L. littorea					√		
Acanthus ilicifolius		√	√	√	√	√	√
A. ebracteatus			√	√	√		
Scyphiphora hydrophyllacea					√		
Acrostichum aureum		Ext.	√	√	√	√	√
A. speciosum			√		√		
Nypa fruticans					√		
Avicennia marina		√	√	√	√	√	√
Aegiceras corniculatum		√	√	√	√	√	
Excoecaria agallocha		Ext.	√	√	√	√	√
Pemphis acidula					√		√

5.2 Estuary and bay aspect

For a particular bay or estuary, a list of native mangrove species should be sorted out on the basis of field investigation and document research. The mangrove species used for restoration should be selected from the list. If the list can not be confirmed, select from the regional species list, but the suitability of environmental conditions of the proposed site should be carefully examined. If there were no mangroves historically distributed in the proposed site, it is necessary to re-examine the restoration objectives and investigate local environmental conditions in more details.

In general, the upper tidal limit from river mouth is the upper boundary of natural mangrove distribution. River sections with mangrove distribution are usually divided into upper, middle and lower sections. Mangrove species vary along the river due to the differences in salinity tolerance, competitiveness and floating capability of propagules. Generally speaking, *Avicennia marina*, *Sonneratia alba* and other highly saline-resistant species only grow in lower section; *Kandelia obovata* and *Bruguiera gymnorhiza* grow in lower and middle sections; *Sonneratia caseolaris*, with low salinity tolerance, can only be found in upper and middle sections; and *Aegiceras corniculatum* , adapt to various degrees of salinity, can be distributed all along the river. Figure 1 shows the distribution of mangrove plants along Huangzhu River in Fangchenggang City, Guangxi Province.

Figure 1. Relationship between mangrove species distribution and water salinity along Huangzhujiang River, Fangchenggang City, Guangxi, China



5.3 Intertidal aspect

Mangrove forests grow in the intertidal zone of tropical and subtropical coasts, because periodic tidal flooding is a necessary condition for growth of mangroves. The environmental gradients formed by tidal flooding and immersion decide the overall distribution and population structure of mangroves in tidal flats (Figure 2).

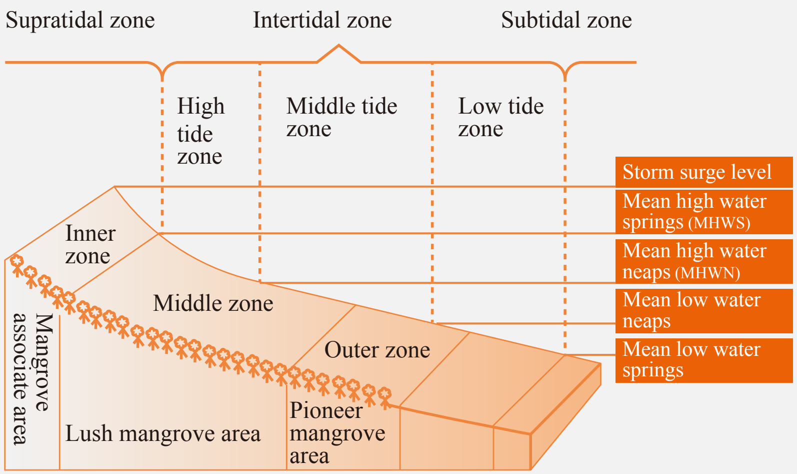


Figure 2. Schematic diagram of mangrove tidal flats

The distrbution of mangrove species, which have different degrees of tolerance to seawater inundation, appear perpendicular to the coastline from low tide zones to high tide zones in intertidal flat.

Before implementing a restoration project in a proposed site, the waterlogging flooding tolerance of mangrove species should be rated, and the elevation of tidal flats in the site should be measured. Take the mangrove afforestation in China' s Hainan Island for example: In recent years, common species found in the seedling market include *Rhizophora apiculata*, *Rhizophora stylosa*, *Bruguiera gymnorhiza*, *Bruguiera sexangula*, *Bruguiera sexangula* var. *rhynchopetala*, *Sonneratia caseolaris*, *Avicennia marina*, *Aegiceras corniculatum*, *Kandelia obovata*, *Excoecaria agallocha*, *Heritiera littoralis*, *Thespesia populnea*, *Hibiscus tiliaceus*, *Pongamia pinnata*, and alien species such as *Sonneratia apetala* and *Laguncularia racemosa*. When selecting specific species for restoration project, it can be decided according to the tide zones and sediment types in the proposed site. For details, please refer to Table 2 below.

Table 2. Mangrove species in Hainan Island, China and tidal flat areas sutible for their growth

Tide zones	Types of sediments	Mangrove species for afforestation
Low tide zone	Sandy and sandy- muddy sediments	*Avicennia marina, Rhizophora stylosa, Sonneratia alba*
	Muddy and muddy-sandy sediments	*Aegiceras corniculatum, Sonneratia alba, Kandelia obovata, Sonneratia caseolaris, Sonneratia apetala, Rhizophora stylosa*
Middle tide zone	Sandy and sandy- muddy sediments	*Avicennia marina, Rhizophora stylosa, Rhizophora apiculate, Sonneratia alba*
	Muddy and muddy-sandy sediments	*Aegiceras corniculatum, Kandelia obovata, Sonneratia caseolaris, Sonneratia apetala, Nypa fruticans, Rhizophora stylosa, Sonneratia alba*
High tide zone	Sandy and sandy-muddy sediments	*Bruguiera gymnorhiza, Lumnitzera racemosa, Bruguiera sexangula, Excoecaria agallocha, Bruguiera sexangula* var. *rhynchopetala, Thespesia populnea, Hibiscus tiliaceus, Pongamia pinnata, Xylocarpus granatum, Cerbera manghas,* and species in middle and high tide zones
	Muddy and muddy-sandy sediments	*Bruguiera gymnorhiza, Lumnitzera racemosa, Bruguiera sexangula, Cerbera manghas, Bruguiera sexangula* var. *rhynchopetala, Excoecaria agallocha, Heritiera littoralis, Thespesia populnea, Hibiscus tiliaceus, Pongamia pinnata, Xylocarpus granatum,* and species in middle and high tide zones

Among them, some species growing in low-tide zone can be planted in middle tide zone and high tide zone, and some species in medium-tide zone can be planted in high tide zone. Species' resistance to salinity and their sensitivity to salt-free habitats should be considered, because seawater and sediment salinity vary among sites.

5.4 Alien species

When selecting species for mangrove afforestation, one should take into account laws, regulations and ecological development needs. For example, most mangrove forest in Hainan Province have been included in the scope of nature reserves. Article 37 of the *Regulations on Natural Reserves in Hainan Province* stipulates that it shall be forbidden for any organization or individual to introduce or apply genetically modified organisms and alien species into nature reserves. In this case, attention should be paid to alien species when selecting species for afforestation in protected areas.

In addition, mangroves, in China, belong to forests for special use, whose functions are mainly embodied in ecological benefits in currect time. Therefore, collocation of different species should be underlined in the selection for the sake of both short-term and long-term ecological benefits. When selecting species for afforestation outside nature reserves, should also consider its impacts on nature reserves, because seeds of alien species may spread into protected areas with seawater as a result of tidal changes.

Sonneratia apetala introduced into Dongzhaigang National Nature Reserve, Hainan (©Wang Wenqing)

Sonneratia apetala naturally spread into Dongzhaigang National Nature Reserve, Hainan (©Wang Wenqing)

Elimination of alien *species Sonneratia* apetala from Shankou Mangrove National Nature Reserve, Guangxi (Photo provide by: Guangxi Shankou Mangrove National Nature Reserve Administration Burea)

For example, in 2011, alien species *Laguncularia racemosa* was planted on the sides of artificial river channels in Haitang Bay, Sanya, Hainan Province. It has spread widely in nearby Tielu Bay Mangrove Nature Reserve since 2014, which seriously threatens native plant species. Similiar case is the plantation of *Sonneratia apetala* and *Laguncularia racemosa* in Dongfang and Danzhou, western Hainan in 2014. These two highly adaptable species grow much faster than native species. Although it remains unclear whether they will cause biological invasion, but it's highly possible for them to threaten native species. In this light, constant attention to alien species' eclological impact is needed.

Laguncularia racemose, high invasiveness owning to its strong adaptability, rapid reproduction, and easy spread of fruit (©Wang Wenqing)

Natural spread status in the third year after *Laguncularia racemosa* planted in Qingmei Bay Mangrove Nature Reserve, Sanya (©Wang Wenqing)

06 Seedlings

6.1 Nursery selection

To improve seedling adaptability and survival rate, large-scale mangrove restoration project (more than 50 hectares' coverage) should establish temporary nurseries near the proposed site.

Temporary nurseries may be located in the site or in nearby places with similar site conditions, such as sparse woodland in the high tide zone, grassland, and salinized farmland that is subject to seawater but not suitable for other crops. Abandoned aquaculture ponds may also be reconstructed into nurseries. This way of choosing temporary nurseries can reduce seedling loss during transportation, minimize transportation cost, and increase seedling survival rate.

Rhizophora stylosa seedlings

Rhizophora stylosa seedlings

Fixed nurseries should be located in coastal wetlands convenient for transportation and close to residential areas, thus accessible to water and electric facilities. These locations are also good for the procurement, sale and transportation of seedlings and related production materials.

Nurseries should be established in plots with no or little vulnerability to storms. In general, the slope of nurseries should not be greater than three degrees, because fast-flowing water on steep slope is likely to cause soil erosion and wash away fertilizers, seeds and seedlings.

Aegiceras corniculatum seedlings

Ceriops tagal seedlings

The best location for mangrove nurseries is in open high tide zones that can be flooded by seawater. Nurseries can be submerged by seawater, preferably, 15 to 20 times per month. Frequent seawater inundation has considerable effect on seedling raising, thus seawater drainage in nurseries could also be under manual control by setting up valves. Inadequate seawater inundation is not beneficial to seedling hardening, and given low moisture capacity, more freshwater needs to be added to accelerate seedling growth, which will increase the cost of cultivating seedlings.

The seawater salinity of nurseries should range from 15 ‰ to 20 ‰ . High salinity is not conducive to seedling growth, while low salinity is not conducive to hardening. The survival rate of seedlings is often low when they are transplanted from low-salinity nurseries to high-salinity sites, which has happened frequently in China.

In addition to seawater inundation conditions, it's better for mangrove nurseries to be equipped with freshwater irrigation facilities. Freshwater irrigation facilities can moderately control the seawater salinity of different areas in favor of seedling growth, and wash away mud adhering to seedlings during high tide, which increases the survival rate of seedlings and the rate of qualified seedlings.

Mangrove nursery in Daoxi forest farm, Hainan Province

6.2 Seed collection

To maintain the genetic background stability of local mangrove plants, the propagation materials (seeds, fruits and hypocotyls) used for seedling raising should be collected nearby. In other words, locally derived propagules should be adopted. Long-distance transportation of propagation materials and afforestation seedlings across provinces/regions are not recommended.

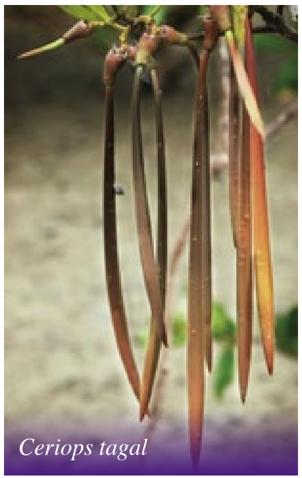
The appropriate time for seed collection is determined by species-specific phenological data.

For viviparous species, such as *Bruguiera gymnorhiza, Bruguiera sexangula, Rhizophora stylosa, Rhizophora apiculate* and *Ceriops tagal*, their propagules are seedlings without roots, often referred to as hypocotyls. They can be collected from trees by shaking the trunk, or on the ground after natural falling. In Hainan, the best time to collect the propagules of *Bruguiera gymnorhiza* is from October to December, and for Bruguiera sexangula, the best time is from August to December.

Hypocotyls of viviparous mangrove plants

Kandelia obovat

Bruguiera gymnorhiza



Ceriops tagal

Rhizophora stylosa

Seeds released from rotten berries of *Sonneratia*

- Fruits of *Sonneratia* species are berries containing numerous seeds. They fall naturally upon ripe. Collect mature fruits, take out the seeds after they are rotten fruits, and wash clean the seeds for planting;

- For *Lumnitzera racemosa*, *Heritiera littoralis* and *Scyphiphora hydrophyllacea*, fruits can directly be used for seeding; For *Heritiera littoralis*, whose germination takes long time, partial peeling of seeds can greatly promote seed germination;

- For *Excoecaria agallocha* and *Xylocarpus granatum*, seeds can be taken from cracked fruits for planting;

- For crypto-viviparous *Nypa fruticans*, seeds spread out from ripe spherical fruits;

- For crypto-viviparous *Avicennia marina* and *Aegiceras corniculatum*, collect ripe fruits, soaking them till peeled off before sowing;

- For *Acanthus ilicifolius*, collect branches (10–20 cm, with leaves cut partially) and plant for propagation, or take out crypto-viviparous seeds (actually seedlings) from cracked ripe fruits for sowing.

Please note that for the majority of mangrove plants, the propagation materials (including hypocotyls, seeds and fruits) are recalcitrant and intolerant to low temperature and dryness, and need to be sowed immediately after collected.

6.3 Seedling culture

Except for viviparous species, such as *Bruguiera*, *Ceriops*, *Kandelia* and *Rhizophora* whose hypocotyls can be directly inserted for afforestation, most of mangrove seedlings need to be cultivated in nurseries before planting.

6.4 Seedling hardening

If the water salinity in afforestation site exceeds 25‰, seedlings need to be hardened before being moven out of the nursery.

07

Seedling transportation and preservation

The cultivation of seedlings in nurseries near the afforestation site not only substantially increases the survival rate of planted seedlings, but also sharply reduces costs. Unless necessary, long-distance transportation of seedlings is not encouraged.

Seedlings can be transported according to the general transportation standards. Soil used for seedling cultivation is with high water content, and the bumping in long-distance transportation may loosen seedlings' soil balls. Therefore, when loaded, seedlings should be placed in layers separated by planks and not pressed against each other. After unloaded, seedlings should be kept from direct sunlight and planted as soon as possible.

Transportation of Seedlings (©Wang Wenqing)

Planting

8.1 Planting methods

a. Planting methods should be mainly based on natural propagation and supplemented by artificial methods. Support every possible natural spread of propagules, and give priorty to hypocotyls over seedlings in nourishment-bags;

b. In order to reduce costs and increase survival rate, it is forbidden to use large-sized seedlings (three or more years old seedlings for true mangroves) in mangrove wetland restoration project;

c. If there is a large area of mangroves near the restoration area, give way to natural spread and settlement of mangrove seedlings, such as opening fish ponds and the water gates;

d. In areas with bad conditions, such as with high salinity and low tidal elevation, appropriately increase seedling density to enhance seedlings resilience to adverse environmental conditions.

8.2 Afforestation density

Afforestation density refers to the number of seedlings planted per unit of area in an afforestation site, also known as initial planting density. In general, terrestrial afforestation density is not related to seedling survival rate. However, most of experienced technicians in mangrove afforestation believe that high afforestation density serves to high seedling survival rate. In this view, appropriate afforestation density is an important guarantee for a succesful mangrove afforestation.

① Afforestation density in suitable tidal flats

Afforestation in suitable tidal flats is usually implemented in areas rarely subject to storms and tidal scour, with no or slight need to raise the beach face. The Research Institute of Tropical Forestry of the Chinese Academy of Forestry conducted research on afforestation techniques for native slow-growing mangrove species in middle and high tidal flats with small storms, such as *Bruguiera gymnorhiza, Bruguiera sexangula, Rhizophora stylosa, Kandelia obovata* and *Aegiceras corniculatum*. The research concluded that the ideal afforestation density range is from 0.5m*1.0m to 1.0m*1.0m, adding that higher density leads to thin and small stems and seedling lodging, while lower density impedes canopy closure and forest growth. Afforestation experiments were also carried out in Sanjiangwan tidal flats where the wind and waves are smaller than other areas in Dongzhaigang National Nature Reserve. Five types of planting density were applied to fast-growing species:1.0m*1.0m, 2.0m*2.0m, 2.0m*3.0m, 3.0m*3.0m and 3.0m*4.0m. Among them, the later three types of density are beneficial to the natural regeneration of native species in forest stands, such as *Kandelia obovata, Aegiceras corniculatum,* and *Acanthus ilicifolius*, and to the formation of two- or three-layered complex structure of forests. The first two types of density are unfavorable for the natural regeneration of native species, and the artificial regeneration of local species also failed due to insufficient light conditions.

Therefore, afforestation density can be appropriately reduced in suitable tidal flats. Fast-growing species can be planted with density vary from 2.0m*3.0m to 3.0m*3.0m, and slow-growing species can be planted within, density vary from 1.0m*1.0m to 1.5m*1.5m. For independent planting of slow-growing species, the density shall vary from 0.5m*1.0m to 1.0m*1.0m. Where large-sized seedlings are used, the afforestation density can be lowered correspondingly. For example, when the canopy width of seedlings reaches 30cm to 40cm, the afforestation density should not be less than 300 plants/mu for *Kandelia obovata, Rhizophora stylosa* and *Rhizophora apiculate,* 220 plants/mu for *Bruguiera,* and 400 plants for *Aegiceras corniculatum.*

② Afforestation density in tidal flats with harsh conditions

Tidal flats with harsh conditions are unfavorable for mangrove growth due to large storm, low beach face, high salinity and high sand content. We have carried out mangrove planting trials on tidal flats with harsh conditions in Fujian Province, implementing high afforestation densities: 0.3m*0.3m, 0.3m*0.5m, and 0.5m*0.5m. Pleasing results are achieved. Technical staff of Dongzhaigang National Nature Reserve planted fast-growing species with the densities of 0.5m*1.0m and 1.0m*1.0m in the flat's peripheral 10m-20m forest belt. However, no significant difference of planting effect between the two densities was found. Within the forest belt, native species such as *Rhizophora stylosa,* *Kandelia obovate* and *Aegiceras corniculatum* were planted with the densities of 0.3m*0.3m, 0.3m*0.5m, 0.5 m*0.5m, 0.5m*1.0m, and 1.0m*1.0m. In planting strips prone to tidal scour, planting hypocotyls and container seedlings with the densities of 0.3m*0.3m and 0.3m*0.5m yielded good results. While in other places, plantation with the densities of 0.5m*0.5m and 0.5m*1.0m achieved better results.

Therefore, the afforestation density can be appropriately increased in tidal flats with harsh conditions to accelerate canopy closure, so that the plant communities can be more effective in protecting the beach from the wind, which reduces the loss caused by tidal scour. Within the area 10m to 20m away from the outer edge of the tidal flat, fast-growing species should be planted preferably at the densities of 1.0m*1.0m to 1.0m *2.0m. They can be interplanted with native species such as *Rhizophora stylosa, Aegiceras corniculatum,* and *Kandelia obovata* at the densities of 0.5m*0.5m to 0.5m*1.0m. In the tidal flats, the density may vary from 2.0m*2.0m to 3.0m*3.0m for fast-growing species, and from 0.5m*0.5 m to 0.5m*1.0m when interplanted with native species. If only native species are planted, the afforestation density should vary from 0.3m*0.3m to 0.5m*0.5m. Furthermore, if large-sized seedlings are planted, the afforestation density should be moderately lowered down according to the canopy and growth of seedlings. After two or three years of growth, seedlings' canopy closure or coverage of their forest stands can exceed 60%.

8.3 Timing of planting

a. The timing of planting is determined according to planting methods, propagule maturity and climatic conditions;

b. For inserting hypocotyls, the timing depends on the maturity of hypocotyls. Hypocotyls should be sowed immediately after collected. Hypocotyls are vulnerable to low temperatures and dryness, so they are not fit for long-time storing.

c. For planting with nourishment-bag seedlings, the timing is slightly adjustable, except for summer time under high temperature and drought conditions.

09 Pond conversion to forest

Pond conversion to forest can be achieved through artificial conversion, assisted conversion, and natural conversion.

9.1 Artificial pond conversion to forest

Artificial pond conversion to forest is mainly applicable in areas that face relatively harsh environment (high salinity, poor soil conditions and many human disturbances) and need to be remedied in a short time. It includes the following steps:

（1）Site preparation

Aquaculture ponds are divided into high-elevation aquaculture ponds and low-elevation aquaculture ponds. High-elevation aquaculture ponds is relatively high in terrain with high dikes. Their surrounding and bottom sides are often covered with thick plastic membranes that are isolated from sediments, in order to prevent water leakage as well as the effect of bottom silt to the water. In some cases, bricks and concrete are used to harden pond. Low-elevation aquaculture ponds are usually located in relatively low terrain and are not isolated by plastic membranes or other materials. If a pond is converted to plant mangroves, however high its elevation is, its beach face must be higher than the average sea level.

a. If the pond's elevation is below the average sea level, the dike shall be flattened down and moved into to the pond by excavator to lift the evevation until the elevation of the pond meets the requirement for mangrove growth;

b. If the pond's evelation meets the requirement for mangrove growth, the dike can be kept;

c. If the pond's evelation is higher than the average sea level, mangrove associates can be planted on the basis that dike is kept;

d. If the elevation of a pond, after its dike is flattened, still fails to meet the requirement for mangrove growth, leave the center of the pond to the outlet intact, and fill the other parts up to the elevation required for mangrove growth. At the same time, set a drainage channel to connect the pond with the sea during site preparation, so that to ensure smooth sea water drainage and supply.

（2）Planting densit

The planting density of mangrove seedlings is determined according to site suitability and financial input. For example, the planting density is flexable in areas where storms are relatively small and mangrove growth conditions are relatively favorable. Invest more then choose high planting density, invest less then choose low density. High-density planting shortens the duration for canopy closure, while low-density planting reduces costs and avoids unnecessary waste. However, for those sites where face large storms and harsh conditions for the growth of mangrove plants, high-density planting is preferred to speed up forest growth and enhance forest resilience. Specific planting density may vary from 1m*1m to 1.5m*2m.

（3）Artificial tending and management

Artificial tending and management is necessary within a period of time after the mangroves are planted. It mainly includes seedling replanting, regular patrolling and ground clearance.

Due to low survial rate of mangrove seedlings and their complex habitat, patrolling needs to be carried out on a regular basis. New seedlings should be replanted to replace sick or dead ones in a timely manner to facilitate forest canopy closure and enhance its resilience, so as to generate greater ecological benefits.

Regular patrolling should stop unauthorized people from doing fishing operations and other actions like random trampling result in destroying seedlings in the forest land, thus to protect achievements of afforestation.

In addition to regular patrolling, garbage and debris in the forest needs to be cleaned up in a timely manner, especially in winter and spring. A lot of mosses often grow in part of low-lying areas, and attach to saplings, which affect the photosysthsis of saplings or even make the saplings fall down. Therefore, it is necessary to manually remove the mosses in time, and meanwhile, dig trenches to drain off water in the forest.

9.2 Assisted pond conversion to forest

(1) Site preparation

Similar to artificial pond conversion to forest, different measures should be taken according to the situations of aquaculture pond. If the pond's evelvation meets the requirements for mangrove growth, the dike can be kept. If not, the dike needs to be flattened to the bottom of the pond. When artificially supporting natural regeneration and site preparation, it is also necessary to keep the tidal channel to ensure a smooth connection with the sea.

(2) Species selection

In General, seed sources are abundant if there are contiguous or considerable area of mangroves around the restoration site. In this case, the seeds or hypocotyls of mangrove plants can naturally spread and grow in the site under the help of tides.

However, in sites that lack seed sources, seeds or hypocotyls should be sowed artificially to promote restoration. Seeds of native species should be the first choice for sowing. Seeds or hypocotyls of other Rhizophoraceae mangrove species, Aegiceras corniculatum or Avicennia marina are also applicable.

(3) Artificial tending and management

Artificial assisted management is important for pond conversion to forest. Warning signs can be set up to notify people not to enter the restoration area, thus to avoid seedling destruction caused by trampling and fishing. In addition, regular or irregular patrolling should be carried out to clean garbage and debris. It is particularly necessary to remove mosses in winter and spring, so as to avoid their damages to seedlings or saplings.

9.3 Natural pond conversion to forest

In general, if an aquaculture pond is located in suitable topographical areas, with sufficient seed sources nearby, no artificial measures are needed after the pond is converted. Sediments will deposit gradually in the bottom of the pond over time. Tides will bring seeds or hypocotyls of mangrove plants into the pond, which will settle down and grow. Here a mangrove community will recover on its own.

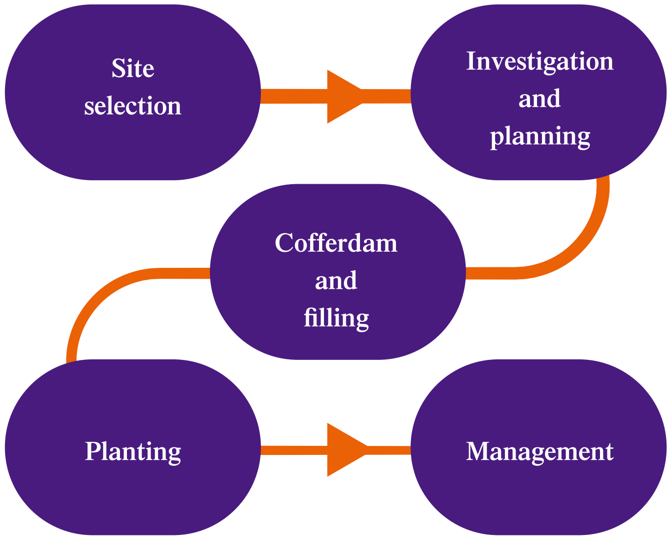
10

Tidal flat afforestation

Tidal flat afforestation, often referred to as mudflat afforestation, is the process of planting mangroves in the bare intertidal flats. It is also the process of mangrove restoration in places where mangroves are destroyed by humans or where mangroves were distributed in history. Afforestation in areas with no historical distribution of mangroves is not advised. If afforestation is really needed in such areas, sufficient investigation prior to restoration is recommended, especially investigation concerning the contribution of mudflats to other species such as water birds.

Mangroves grow in the intertidal zones and are periodically flooded by tidal water. Therefore, a large number of mangrove seeds and hypocotyls are brought to tidal flats with the flow of tidal water every year. In suitable coastal tidal flats, mangroves naturally regenerate within a certain period of time. However, most of the existing mudflats are not suitable, mainly due to its low elevation and long-time seawater immersion, which cannot meet the necessary requirements for the growth of mangrove plants. Every year, certain amount of seeds sprout in such tidal flats and grow into seedlings, but gradually wither to death due to their inability to adapt to long-time seawater immersion. Prior to afforestation tasks on these tidal flats, it’s necessary to improve the flats scientificly with artificial assistance methods. Otherwise, there would be no forest or even no tree alive despite of endless planting.

Therefore, the steps of mudflat afforestation can be summarized as follows:



10.1 Selection of sutiable mangrove forestland

A mangrove ecosystem is an organic system composed of producers (true mangroves, mangrove associates, associated plants to mangroves and phytoplankton, etc.), consumers (fish, zoobenthos, zooplankton, birds and insects, etc.), decomposers (microorganisms), and the inorganic environment. Sometimes, it is called “mangroves”. Mangroves and various coastal organisms are major components of mangrove ecosystem, and they share equal importance in this system. They coexist in the system, where they also enjoy a relatively independent space.

Therefore, the following two factors shoule be considered when selecting a sutiable mangrove forestland:

First, a mangrove afforestation site should meet the requirements of mangrove growth after improvement supported under current fianacial budget. Site factors highlighted in mangrove afforestation include salinity, weather, standing wave environment and beach face elevation. Among them, weather conditions, as region-specific inherent conditions, are difficult to change by artificial means. Changing salinity and standing wave environment requires huge fianacial investment to bring in fresh water resources and create rias coast, which is also very difficult. For intertidal zones below average sea level, their beach face elevation can be raised by artificial means, such as earth filling, to meet the requirements for mangrove growth. Comparing to others, this factor is relatively easy to be improved.

Second, mangrove afforestation coverage should match with the need to maintain biodiversity. An intact mangrove ecosystem contains not only a fixed coverage of mangrove forests, habitats for a variety of marine lives, such as tidal flats, tidal creeks and shallow waters, but also places where birds inhabit and forage. In this ecosystem, vegetated area of mangroves presents the lowest biodiversity, in contrast to forest edge, tidal flats, tidal creeks and shallow waters. Mangroves’ leading role in this habitat can not be neglected. Nevertheless, blind afforestation that encroaches on large scale of tidal flats to increase mangrove coverage will cause problems, including losing foraging habitats for birds and living spaces for other marine lives. In this case, the functions and values of mangroves will be greatly reduced.

Therefore, the selection of tidal flat afforestation sites should concentrate on the zones without mangrove distribution and the narrow zones with less mangrove distribution. For afforestation in tidal flats at the outer edge of the existing mangrove area with forest belt wider than 150 m, sufficient investigation and demonstration should be carried out in advance to ensure that afforestation will exert no or little (ignorable) effect on other organisms.

10.2 Improvement of afforestation site

Requirements for mangrove growth include temperature, salinity, standing wave environment, and tidal flat elevation. Among them, temperature and salinity conditions can be matched through species selection. Standing wave environment, usually related to topography and geomorphology, can be artificially created, though with high cost. Hence, the improvement of afforestation sites mainly intends to enable low-elevation tidal flats to meet the growth requirements of mangrove plants through engineering measures.

Beachface elevation and critical submergence duration are important

limiting factors for the growth of mangroves. Summaries concerning the relationship between the interior &exterior boundaries of mangrove belt and the tidal level have already been given in relevant studies at home and abroad, which make clear that the mangrove belt is located in tidal flats above average sea level.

Afforestation sites can be improved by engineering measures, including cofferdam and earth filling.

10.2.1 Cofferdam

Cofferdam is basic facility in the afforestation tidal flats to prevent tides from rushing or excessively draining sediments in the tidal flats. Considering the tidal scour condition of afforestation sites, cofferdam can be divided into temporary cofferdam and permanent cofferdam (often referred to as seawall or revetment).

Cofferdam is not needed if the sediments in the tidal flats, under moderate tidal scour condition, are unlikely to be washed away by waves.

(1) Temporary cofferdam

Temporary cofferdam, usually consisting of pile, plank or sandbag, is mainly built in tidal flats where sediments, under light tidal scour condition, can be kept by mangrove seedlings after six to twelve months of the plantation.

Usually, pile cofferdam and plank cofferdam’s duration is about one to two years, while sandbag cofferdam only last three to six months.

The size, length and density of pile is decided according to filling height and volume. If the fiiling depth is 50cm to 70cm, pile is required to have a tail diameter of 10cm, a length of 300cm to 400cm, and 50cm gap between each other. Plank should be 2cm thick and stitched with no or narrow seam. *Casuarina equisetifolia* is hard, tough and cheap, usually used for making piles and planks.

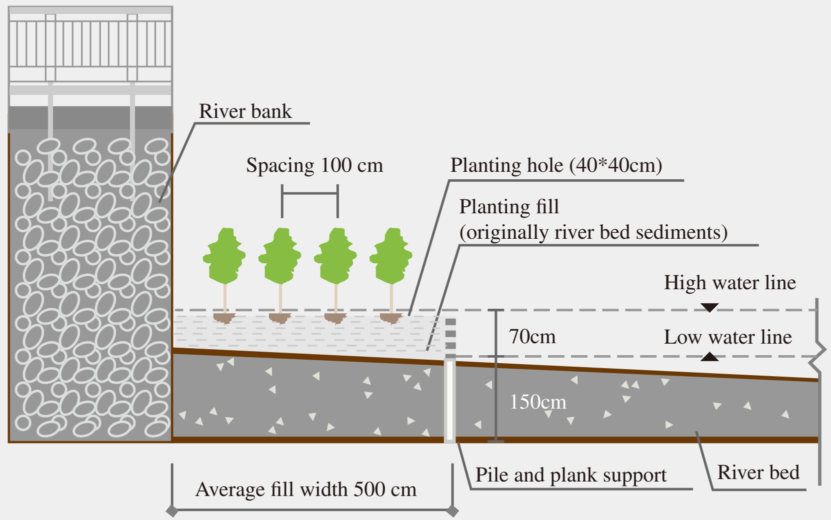
Example 1: Cofferdam built for mangrove afforestation in the upper Sanya River

Originally, there were only a small amount of *Sonneratia caseolaris* and *Rhizophora apiculate* in Jinji Bridge section of the upper Sanya River. Lack of mangrove species and poor view required landscape reconstruction by artificial planting along the river channel. In the 140m to 180m wide river channel, original sediments are sand and mud brought by sewage and flood discharge. Here, tidal flats with no mangrove plants are at low elevation and need to be raised by 70cm to 80cm for mangrove plantation. Upstreams area of the river channel is free from storms in the non-typhoon season and has no shipping traffic.

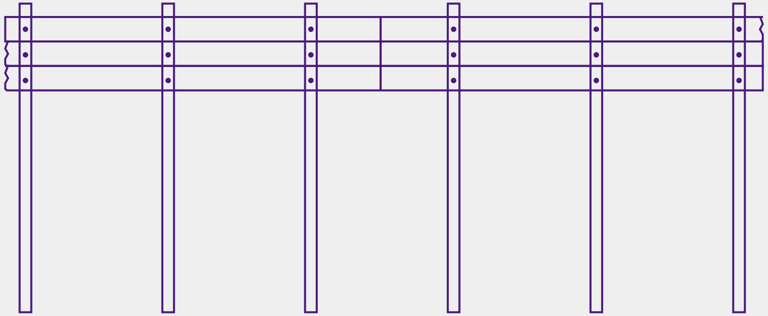
After field investigation, cofferdam building was adopted to stabilize tidal flats for afforestation. Since sediments with small viscosity are likely to be washed away by tidal water, the cofferdam need to be built before filling the tidal flats. However, the cofferdam, if not solid enough, might be squeezed by sediments under the pressure created by

filling. Therefore, piles and planks made from newly harvested *Casuarina equisetifolia* were used to make cofferdam. The piles were 10cm wide at the tail and 250cm long. The planks were 2cm to 2.5cm thick. During the operation, piles were inserted by the excavator into the mudflats, with 80cm to 90cm left above the ground; planks were neatly nailed onto the piles on one side of filled mudflats, with no or narrow seam to avoid sediment loss. After the cofferdams were placed, sediments were excavated from the river channel to occupy the planting strips. The cofferdams, if without pests, can be used for two to three years.

The design and construction drawings are illustrated as follows:



Detailed drawing of partial section of the structures for mangrove afforestation in upper Sanya River



Schematic diagram of temporary cofferdam for mangrove afforestation in upper Sanya River

Temporary cofferdam for mangrove afforestation in Sanya River

Example 2: Cofferdam built for mangrove afforestation in the tidal flats of Xinghui Village, Dongzhaigang Bay

Due to low beach face, there was almost no mangrove growing in the tidal flats of Xinghui Village in Dongzhaigang Bay. Mangrove afforestation was launched by the Dongzhaigang Nature Reserve Administration in 2011. The flat beach with no shields is subject to serious tidal scour. If there is no protection, sediments on the beach will be washed away by waves. Therefore, a 50cm-high sandbag cofferdam structure, duration for one year, was recommended.

According to the afforestation planning, the sandbag cofferdam were to be placed after filling the tidal flats. However, under outdoor dry-wet conditions with strong sunlight and high temperature, sandbags went rotten two to three months after use, which led to serious loss of sandy and muddy deposits from within. The sandbag cofferdam obviously lowered down and needed to be reconstructed. Considering the short duration of sandbags and the potential pollution of rotten sandbags, piles and planks were then applied to replace the sandbags. These piles, 8cm to 10cm wide at the tail and 2.5m long, were put with a space of 1m to 1.5m in between, and planks were 1cm to 1.5cm thick.

Compared to sandbag cofferdam, the overall costs of wood cofferdam is higher, as a result of higher material cost and lower labor cost. In this project, the piles fulfilled the cofferdam needs. The planks were not thick nor resistant enough, and after six to eight months of use, some of them were washed away, which asked for artificial mending.


Temporary sandbag cofferdam for afforestation in Xinghui Village, Dongzhaigang Bay


Temporary sandbag cofferdam for afforestation in Xinghui Village, Dongzhaigang Bay


Temporary cofferdams made from piles and planks for afforestation in Xinghui Village, Dongzhaigang Bay

Example 3: Cofferdam for afforestation in Yeboluo Island, Dongzhaigang Bay

Due to low elevation, the beach face of tidal flats was raised by 30cm to 70cm for afforestation in Yeboluo Island in Dongzhaigang Bay. Drawing on the experience in Xinghui Village, wood cofferdam with new sizes were directly applied in afforestation design and construction.The piles, made from *Casuarina equisetifolia*, had a tail diameter of 10cm and a length of 4m, and were inserted with a space of 0.5m to 1m in between, and the planks, also made from *Casuarina equisetifolia,* were 2cm thick.

The construction procedure was changed to be: filling—inserting cofferdam—filling again.

First, an initial afforestation belt was created, and then inserted pile cofferdam at its edge. Then, the tidal flats were filled again with mud. When placing the cofferdam, an excavator passage should be kept. During the second filling, mud should be occupied from both sides of the cofferdam for supporting. Sediments in the planting strips, to some extent, supported the planks, and sediments outside, in a short period of time, protected the planks by reducing the drilling and destruction by boring animals such as *Sphaeroma spp*.

The cofferdam remained intact and performed well after two years of use.

Temporary cofferdam for afforestation in Dongzhaigang Bay

Temporary cofferdam for afforestation in Dongzhaigang Bay

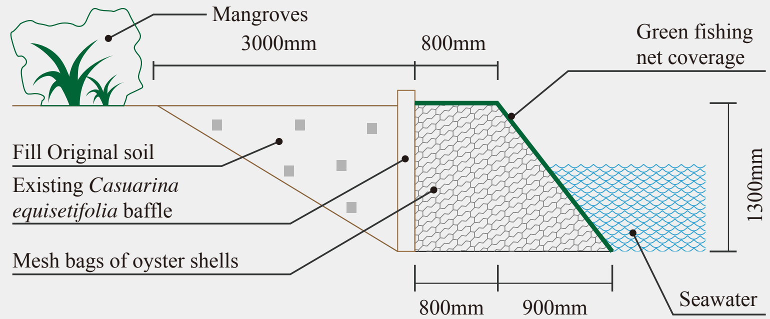
(2) Permanent cofferdam (seawall or revetment)

Permanent cofferdam (seawall or revetment) is mainly used in tidal flats where, due to severe tidal scour, the sediments are still not fixed after seedlings resume their growth. Permanent cofferdam serve as engineering auxiliary facility to protect afforestation site from waves. Materials of permanent cofferdam can be oyster shell or stone.

Similar to coastal rocky revetments, cofferdam made from oyster shell has a trapezoidal cross-section, of which the specification depend on the actual situation. In Yanfeng East River in Dongzhaigang Bay, the oyster shell cofferdam is 70cm to 110cm high, 160cm wide at the bottom and 80cm wide at the top, with the base 30cm deep under the mudflats (as shown in the Figure below). After the protective slope is built, planting strips are backfilled with mud, and the oyster shell cofferdam can be fixed under the pressure generated sinking sea mud.

Example: Oyster shell cofferdam in Yanfeng East River, Dongzhaigang Bay

On the banks of Yanfeng East River in Dongzhaigang Bay, sediments had been lost due to serious tidal scour under the long-term impact of fishing boats and cruise ships. Mangrove plants on both sides of the river continued to fall and die, and the river became wider. In order to protect the mangroves on both sides, Dongzhaigang Nature Reserve Administration Burea used wood cofferdam in 2014 to address the scouring problem. However, the piles and planks were seriously damaged within only half a year due to drilling by *Sphaeroma spp*., which undermined the protection effect. In 2015, oyster shell was built into wall and it achieved desired result. The oyster shell cofferdam, reusing the waste of local marine life, do not cause pollution. It is solid and not easy to loosen, and therefore plays an effective role in blocking the waves and protecting the tidal flats. Many pores among individual oyster shell has provided survival-facilitating habitat for various marine lives including crabs and sea frogs.



Cross-sectional view for Practice I

Notes:

1. Total length: 1,725m; Practice I construction length: 275m.
2. In the case of insufficiency of oyster shell as raw materials, a segmental construction approach may be adopted. It is recommended to complete the task of Practice I and Practice II first, and then Practice III.
3. If possible, the original ditch mouth should be retained. If the distance between ditch mouth is more than 100m, water inlets (three to four meters large) should be added artificially.

Seawall design drawing for mangrove ecosystem restoration in Yanfeng East River, Dongzhaigang Bay

Oyster shell cofferdam in Yanfeng East River, Dongzhaigang Bay

Oyster shell cofferdam in Yanfeng East River, Dongzhaigang Bay

10.2.2 Filling

(1) Determination of filling height

Mangroves can only grow above the mean sea level, so, before afforestation, low tidal flats need to be elevated by filling. Given that mangroves are distributed in all cities and counties in Hainan Island, the elevation of nearby tidal flats with mangrove distribution can be taken as a reference. The simplest method to set filling height is to measure the elevation difference between the afforestation site and the reference site. If mangrove species differ between the two sites, the filling height is subject to adjustment according to the requirements of different mangrove species for tide zones.

Level gauges can be applied to measure the elevation difference between tidal flats. Tidal range poles can also be made for measurement. Straight bamboo poles (or PVC pipe, etc.) with open bottles bound in a row are inserted in each measuring site at low tide, and the site with mangrove distribution is the reference site. When the tide rises, seawater will automatically enter into all the bottles below the water level. The height difference between bottles with water in different poles represents the elevation difference between measuring sites.

If there is a small tidal range, water depth at high tide should be measured by more personnels at the same time to determine the elevation difference. If no mangrove is distributed in the afforestation site, measure the water depth at high tide, and use data of high tides in the tide tables to calculate the elevation as well as corresponding filling height. The calculation needs to be based on average sea level.


DIY tidal range pole


Re-check if the filling height meets the requirement

Though rough and less precise, these measurement methods can meet the needs of general filling operations for mangrove afforestation. It is a little difficult to estimate the elevation of beach face based on tide table, and the simplest and most practical method to estimate the filling height is based on the elevation difference between tidal flats for afforestation and sites with mangrove distributions.

Considering the factors including subsidence and sediment loss caused by tidal scour, the final filling height should usually be 10cm to 20cm higher than measured, but no higher than 20cm below high tide level.

(2) Filling construction technology

Exotic soil or original sediments may be used to fill the tidal flats for afforestation. However, exotic soil is costly and subject to serious loss due to tidal scour. Its composition and structure may have adverse effects on marine lives. Therefore, original sediments in the tidal flats are generally preferred. On-site filling can be achieved by evacuating or dredging. Advantages and disadvantages of the two approaches are shown in the Table below.

Table 4–1 Comparison between evacuating-filling and dredging-filling

Approaches	Advantages	Disadvantages
Evacuating - filling	1.No sedimentation, low loss volume, and available for direct planting after backfilling, which is conducive to planting in planned time or urgent planting for progressive inspection and acceptance; 2.Small section and low cost on cofferdam; 3.Easy control of mud; 4.Flexible cofferdam layout; 5.Cofferdam building and excavation can be conducted in flow process.	1.Limited working time and long construction period due to tides; 2.High cost on mud; 3.Large number of vessels are required.
Dredging -filling	1.Working time guaranteed; 2.Fast operation; 3.Low cost on mud.	1.Large amount of mud loss, difficult to hold sediments that are dominated by coarse-grained sand; 2.Long sedimentation process, making the tidal flats not suitable for direct planting within a certain period of time; 3.Large section and high cost on cofferdam; 4.High risk, great damage if accident happens during the construction period, and weak ability to combat interference from surrounding constructions; 5.Two sets of processes required for dredging and filling; 6.Difficult to meet different design elevations in the same cofferdam.

According to previous afforestation practices, dredging-filling is mainly used in beaches or silts with high water content and close to slurry form, while excavating-filling applies to other conditions. In the excavating-filling process, the topsoil of more than 30cm of tidal flats should be placed on the surface of planting strips, and the other substrate should be placed on the lower layer. Excavating-filling can create a variety of habitats for marine lives, which helps to promote the conservation and development of biodiversity, and increase the fishing income of local fishermen. After afforestation through such process in the tidal flats of Xinghui Village and Yeboluo Island in Dongzhaigang Nature Reserve, a large number of *Scylla serrata* and fishes have been found in the artificial tidal creek, which attract many fishermen for fishing.

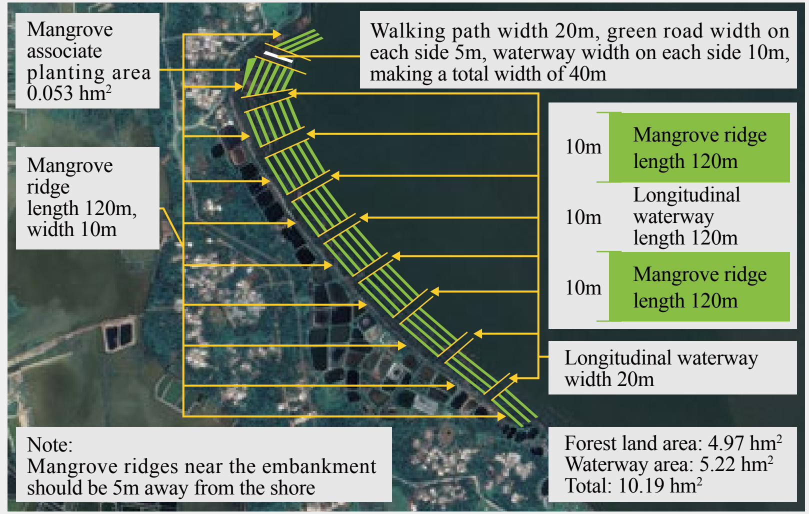
(3) Filling shape and coverage

Redging-filling is an efficient way to fill the planting area as a whole. Generally, there is no need to divide the planting area into blocks or strips. However, it should be noted that sediment extraction area should be more than 10m away from the planting area. If the sediments are taken near the planting area, the elevation difference between the cofferdam and the outer boundary of the planting area will increase, which will lead to cofferdam collapse and sediments loss.

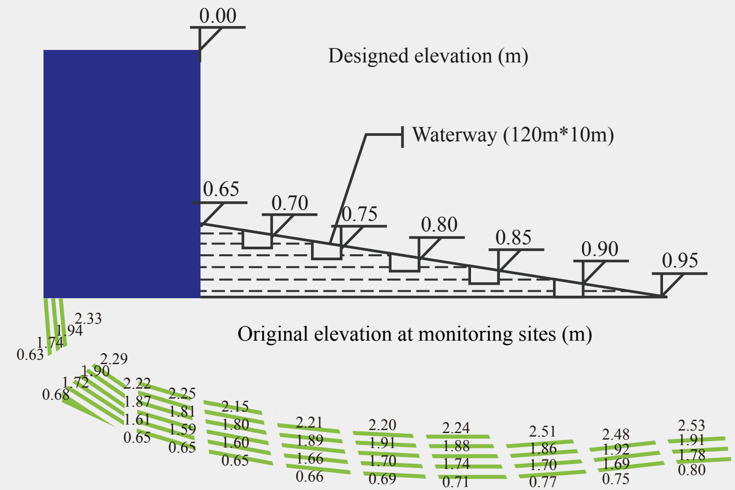
Excavating-filling approach allow the planting area to be devided into strips or block. Sediments are excavated from the non-planting area on both sides of strips. Since it's more difficult for excavators to work on tidal flats than on lands, the width of the planting strips is usually 20m to 30m and should not be too narrow. Otherwise, the sediments are likely to be washed away by tide. The wider the planting strips are, the more stable the sediments are, but the higher the cost will be due to multiple times of transportating sediments.

Filling by floating excavator in Dongwan, Dianbaishui, Guangdong Province

Filling by floating excavator in Dongwan, Dianbaishui, Guangdong Province



Layout plan for mangrove afforestation in Xinghui Village, Dongzhaigang Bay



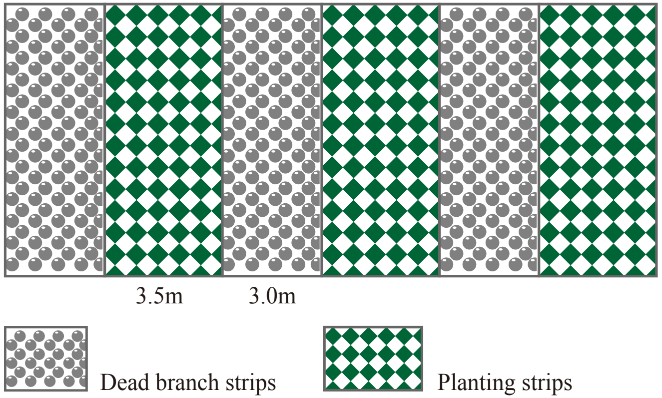
Design diagram of filling height for mangrove afforestation in Xinghui Village, Dongzhaigang Bay

11 Restoration of degraded mangroves

Before to develop degraded mangroves restoration, a comprehensive investigation should be conducted to identify the causes of degradation and then make countermeasures.

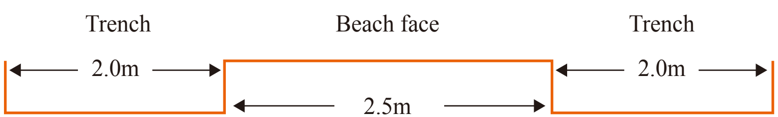
(1) Forest land improvement

If the afforestation requires to cut down and clean up dead mangrove plants, these plants could be placed in the way of strips in the forest, removing and burning them is not recommended in consideration of carbon emissions and air pollution. The Figure below shows the design diagram for dead tree strips in Luodou degraded forest in Dongzhaigang Bay, implemented in 2017.



Design diagram of dead tree strips in Luodou degraded forest in Dongzhaigang Bay

When mangroves are seriously degraded, a large number of mangrove plants die, and their roots ritten. It causes beach face elevation to lower down and water to accumulate in the forest. As a result, these tidal flats, originally suitable for the growth of mangroves, turn unsuitable, and mangrove plants cannot regenerate naturally within. Therefore, artificial land preparation should be carried out to raise the elevation of planting area and reduce the duration of seawater immersion, thus to meet the requirements of the growth of mangroves. Tidal creeks can be widened and deepened to ensure smooth drainage in the forest land. Beach face can be raised by trenching and ridging in the planting area. Ridge belts can improve the sediment structure and enhance air permeability. Tidal channels between ridges are also conducive to forest drainage. In addition, ridging can adjust the pH value of forest sediments to prevent seedling roots from high sulfur content, and trenching can reduce seedling damages caused by crabs.



Schematic diagram of artificial ridging in degraded forest stands

For degraded mangroves at higher elevation, if there are still standing trees in the forest and no obvious beach face subsidence, direct afforestation can be carried out. For tidal flats with muddy or sandy sediments, if there are intensive crab activities in the forest, afforestation can be carried out after ploughing. Ploughing, same as trenching and ridging, is conducive to improving the substrate structure, enhancing air permeability, and reducing the sulfide content in sediments.

Mechanical ridging in the forest gap of the degraded mangroves in Dongzhaigang Bay


Artificial ridging in the forest gap of the degraded mangroves in Dongzhaigang Bay

(2) Mangrove species selection

In the artificial restoration of degraded mangroves, mangrove species should be selected based on the causes of forest stand degradation. If the degradation is caused by natural disasters such as typhoon, originally distributed species are preferred. Other native species can be added. If the degradation is caused by pollution or pests&diseases, native species that are more resistant to pollution or pests&diseases should be selected.

It is not advised to select alien species including *Sonneratia apetala* and *Laguncularia racemosa*. However, if the degraded forest is dominated by *Sonneratia caseolaris*, certain amount of Rhizophoraceae mangrove plants, which adapt to the site conditions, can be planted to improve the forest stand structure and biodiversity.

(3) Protection facilities

In low-lying waterlogged lands, which are mainly composed of muddy sediments, ridges created for planting trees are likely to collapse due to wet and soft sediments. Therefore, if the forest gap is large and mechanical operation is rarely harmful to the habitat, mechanical ridging can be adopted to widen ridges to enhance ridge stability. Artificial ridging is an alternative approach if the forest land is not suitable for mechanical operation. However, artificial ridges are narrow and easy to collapse, so wood cofferdam should be built around. Cofferdam is also needed around the ridges on the edge of tidal creeks that are greatly affected by water flow. For areas have great deal of fishing, garbage, and debris, net protection and enclosure for forest cultivation should be applied. Besides, warning signs should be set up.

(4) Forest management

The post-restoration management for degraded mangroves usually last two to three years. The specific duration can be decided in the design stage based on site conditions and mangrove species selection. In forest lands with favorable site conditions and fast-growing species, the management period may be shorter. In forest lands with poor site conditions and dominant amount of slow-growing species, the management period should be longer to ensure the survival rate of plants.

Floating debris and large algae as main threats to mangrove seedlings, need to be cleaned up in time

Management tasks include patrolling, replanting seedlings, cleaning up debris and maintaining ridges. Patrolling intends to prevent unauthorized people from fishing or destroying seedlings in the forest land. New seedlings should be replanted to replace sick or dead ones in a timely manner to facilitate forest canopy closure. Debris should be removed to prevent adverse effects on seedlings. Collapsed ridges should be repaired in time to ensure the natural growth of seedlings.

Simple net enclosure can greatly reduce the damage of floating debris to mangroves

Management work should be carefully recorded, including monitoring data of saplings' growth status. All notes and files concerning degraded mangrove forest restoration work should be kept to help to make improvement in mangrove forest restoration management and summarize lessons from restoration practices.

Simple net enclosure can greatly reduce the damage of floating debris to mangroves

12 Monitoring and evaluation

12.1 Plant community monitoring

In order to know about ecosystem restoration results and its dynamic changes, and to see the structural and functional features as well as their development trends after restoration, long-term fixted sample plot monitoring of plant community in needed. Monitoring content mainly includes: species composition of plant community, changes on species' quantity, vegetation biomass, and growth status (such as growth rate and productivity). Monitoring on dominant species and key species are specially needed.

Mangroves are restored mainly through inserting hypocotyls and planting container seedlings. Quadrats should be chosen according to the growth of saplings. Afforestation effects can be evaluated based on seedling indicators in the Quadrats, such as survival rate, plant height, ground diameter, diameter at breast height and crown width.

Monitoring scope

The monitoring scope covers entirely the current afforestation area. Quadrats should be set up in the standard sample plot, and should consider the spatial relationship, including the distance from the afforested area to the natural forest and to pre-restored forest land.

Layout principles of fixed sample plots

The layout of fixed sample plots follows three principles:

Being representative: Sample plots should represent the entire afforested area, covering different tidal zones and all planted species. The plots should be typical, representative and adequate to ensure that the data of investigation and monitoring can fully reflect the overall status of afforestation and restoration.

Being typical: Rare and endangered mangrove species, and major planted mangrove species should be highlighted in the monitoring to better understand their current status and trends.

Being Exercisable: Sample plots should be stable enough for long-term investigation and monitoring. If all other principles are followed, sample plots should be arranged in areas with convenient transportation.

Layout method and quantity of fixed sample plot

The followings can be adopted for the layout method and quantity of fixed sample plot:

Transect monitoring: Transects are set on representative afforested land, extending from the edge of the afforested land at the highest water level to the edge at the lowest water level that is perpendicular or approximately perpendicular to the coast. Each transect should be 5m wide and 20m long for long-term monitoring. Based on mangrove species distribution and afforested area, a minimum of two transects can be arranged to cover all mangrove species into monitoring.

Quadrat monitoring: In the afforested land, quadrats are established in representative areas of different tidal zones and mangrove species to monitor afforestation and restoration status. The size of quadrats is preferably 10m*10m or 20m*20m, and a 3m*3m or 5m*5m quadrat can be within the above large quadrats according to afforestation density and forest stand growth. The number of quadrats is determined according to site conditions, tree species quantities and afforested coverage. In general, one to six quadrats may be set for investigation under the same conditions.

Monitoring content

The monitoring of plant community should include the following aspects:

(1)Changes in species composition and species quantity: Record changes in species composition in the quadrats during different periods, and analyze community development trends in the restored forest;

(2)Canopy closure of forest stands and coverage of understory vegetation: Record canopy closure of the arbor layer and coverage of shrubs, herbs or seedlings in the restored forest;

(3)Seedling status: Record survival rates of saplings during different periods;

(4)Plant growth: Including plant height, ground diameter (plants lower than 1.3m), diameter at breast height (plants taller than 1.3m), crown width, etc.

Frequency and time of monitoring

Monitoring should be conducted once to four times per year, flexible to different objectives. If hypocotyls are inserted or seedlings of slow-growing species are planted for afforestation, monitoring can be conducted twice in the first three years and annually after saplings are under stable growth. It is better to do monitoring during March to May, so that problems can be identified in time, post-winter growth of tree species can be recorded, and adjustments on management measures can be proposed immediately. If monitoring is required to be twice a year, the first may be done during March to May and the second during September to October.


Seedling growth monitoring

12.2 Sediment monitoring

Annual sediment monitoring should be conducted, content including the elevation of tidal flats and physical &chemical properties of sediments in the afforested land.

Monitoring on tidal flat elevation

Monitoring on tidal flat elevation can record elevation changes of tidal flats, providing necessary information for afforestation effects analysis.

Multiple monitoring sites can be set in different afforestation areas. If transects are applied, monitoring lines should be placed every 10m to 20m perpendicular to the transects, and on each line set two to three monitoring points. If quadrats are applied, one or two quadrats should be set in the high, medium and low tidal zones respectively, in each of which should evenly set two to three monitoring points. Deposition rate monitors or pre-arranged cement columns or PVC pipes can be used to measure the elevation. Elevation changes of tidal flats during a specific period can be estimated according to the measured elevation variation.

Monitoring on sediments' physical and chemical property

(1) Field sampling: The sediments to be monitored are surface sediments. When the tide ebbs or the soil is exposed to the air, use a cutting ring to collect 0cm to 20cm thick surface sediments from the sample plots or transects. Conduct the collection three times in each plot or transect. Take samples and cutting rings, placed in aluminum boxes or sealed bags, back to laboratory. Dry the samples under 105 degrees Celsius, identify the dry weight and calculate bulk density.

(2) Analyzing physical and chemical property: Major physical and chemical indicators include pH, salinity, organic carbon, total nitrogen, total phosphorus, heavy metals and sulfides.

pH and salinity should be measured with equipment on site.

Other indicators can be examined by methods specified in GB1737.5–2007 *Marine Monitoring Specifications Part 5: Sediment Analysis*. For example, the potassium dichromate oxidation-reduction capacity method is used to determine the content of organic carbon, the potassium sulfate oxidation method for total nitrogen and total phosphorus, the iodometric method for sulfides, and the flame atomic analyzer for heavy metals.

Centipede net has become a common tool do fishes monitoring in mangrove forests, because it's convenient to be placed

12.3 Monitoring on marine animal

Monitoring on marine animal can through investigating fishes and macrobenthos inside and outside the mangrove forest.

12.3.1 Monitoring on fishe

Method

Set one to three sampling points (flexble in different tidal zones) in forest interior, forest edge and artificial tidal creeks respectively to catch marine animal. Set fishing nets in the sampling points before the tide comes in and after the tide is out. Collect fish samples bring back to the lab for analysis.

●Record vegetation information (species, plant height, canopy closure or coverage, etc.) and habitat parameters (substrate, salinity, turbidity and relative water depth).

●Take three centipede nets with 8.5mm*8.5mm meshes as one unit, and deploy three units in each sampling point.

●Identify the species of captured fishes, and then measure their body length and weight.

Frequency and time of monitoring

If allowed, monitoring should be carried out monthly. Quarterly or twice per year (rainy and dry season respectively) in poorly equipped areas. It is advised to conduct monitoring during the highest tide in every month or every quarter, and collect samples three to five days continuously each time.

Centipede net has become a common tool do fishes monitoring in mangrove forests, because it's convenient to be placed

12.3.2 Macrobenthos monitoring

Method

Macrobenthos monitoring points vary according to different tidal zones, plant species distribution and terrain status. In general, monitoring points, placed at the section perpendicular to the coast, should be set in the interior and at the edge of forest respectively. If there is a huge difference in tree species at the section, monitoring points could be placed in the inner belt, middle belt and outer belt. On each point set 5 quadrats, in parallel to the coast, with a size of 25cm×25cm, a depth of 30cm, and spacing more than 2m in between. Collect all the mollusks on the surface of the quadrats. Dig out sediments till 30cm beneath the ground, and use sieve (aperture 1 mm) to sort out all animals in the sediments. All the samples obtained should be kept on site with 5% formaldehyde solution, and brought back to the laboratory for sorting, counting and weighing.

Frequency and time of monitoring

If allowed, monitoring should be carried out monthly. Quarterly in poorly equipped areas. It is advised to collect sediments on the day with long ebb tide during the monitoring period.


Macrobenthos monitoring

12.4 Water quality monitoring

Sampling site selection

In the restored forest land, sampling sites should be set every 500m along the main tidal creeks (more than 50cm deep and 1m wide). Water samples should be collected according to the *Technical Specifications for Water Sampling Design (HJ495–2009)* published by the State Environmental Protection Administration.

Use opaque wide-mouth glass bottle to collect water. Place the bottle to a depth over 20cm underwater. Lift and seal them after filling with water. Fill in sampling records carefully, make label with serial number. Sample should be kept in a 4°C incubator and sent for test as soon as possible. Sampling should be conducted once during high tide and once during low tide every month. If there is sewage outfall in the afforested site, sample should also be collected at the sewage outfall.

Monitoring indicator

The indicator for water quality monitoring mainly include pH, salinity, dissolved oxygen (DO), potassium permanganate index, ammonium nitrogen, active phosphate, chemical oxygen demand (COD), and five-day biochemical oxygen demand (BOD5). If possible, heavy metals should also be monitored, including zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd).

12.5 Monirtoring on bird

Bird is an important component of mangrove ecosystem. In particular, changes in the populations of water birds can reflect the health of mangrove wetlands.

Sample plot selection

Monitoring on water birds is usually conducted in tidal flats and ponds that support concentrated bird activities as well as areas with concentrated nests. Therefore, it is necessary to set up sampling plots in the foraging area (tidal flats, shallow ponds) reserved during artificial mangrove restoration and in tidal flats near the restored area. The plots should be wide-open, and monitoring points/routes should have a sufficient safety distance (100m) from birds or have shelter. Point method or line transect method may be chosen based on the size and traffic conditions of each afforestation site. Besides, the monitoring points/routes should be fixed.

Time and frequency of bird monitoring

According to the migratory pattern of birds, each year can be devided into critical periods from November to next April and non-critical periods from May to October. The best time for bird monitoring should be determined according to the local features of tides and bird activities. It should follow these principles: a) monitoring should be conducted in a period when species and numbers of waterbirds in the monitoring area remain relatively stable. b) monitoring should be completed in a short period to reduce duplicate records. In General,

monitoring should be conducted weekly during critical periods and monthly during non-critical periods. Monitoring should be conducted in tidal flats during low tide, and in ponds during high tide. monitoring should be conducted monthly in concentrated nesting areas during the breeding season (April–July).

Counting

Use direct counting method. If the point method is applied, all the birds observed at the sites should be recorded. When the line transect method is applied, the monitoring is usually conducted by walk or vehicles and vessels in wide-open areas with uniform habitats. Telescope or binoculars can be used for counting. If bird population is very large or in a motion state, such as flying, feeding and walking, the number of birds can be estimated by counting units of 5, 10, 20, 50, 100, and the like.

Monitoring records

Monitoring records should include investigation data (e.g. bird species and numbers, population structure, population status, habitat description, etc.) and environmental information (e.g. date, time, GPS coordinates, tide level, weather, pond water level, etc.). Species information, such as classification (Order, Family, Genus), level of protection, and distribution, should be added in the process of data consolidation.

12.6 Mangrove ecosystem restoration evaluation

Mangrove ecosystem restoration evaluation includes short-term evaluation and long-term evaluation. Short-term evaluation usually refers to afforestation project acceptance appraisal, which, according to the design requirements of afforestation operation, checks the preservation of afforested tidal flats and the survival rate of mangroves after the completion of afforestation project and appropriate management. Long-term evaluation examines mangrove ecosystem restoration based on long-term monitoring results of relevant factors, such as plant communities, sediments, water quality, marine life and birds. It may involve a comprehensive evaluation of ecological factors, ecosystem function evaluation, and landscape evaluation. A preliminary investigation on the proposed site is advised before the implementation of project.

Short-term evaluation

Short-term evaluation focuses on ecological restoration based on artificial afforestation. Currently, there is no unified technical regulation for mangrove afforestation nor unified standard for its acceptance appraisal in China. Artificial mangrove afforestation is more difficult than terrestrial afforestation, due to poor habitat, large unmber of interference factors, and low survival rate. On the basis of summing up China's experience of afforestation and acceptance appraisal over the past years, Wang Youshao put forward short-term indicators and criteria of mangrove restoration technology evaluation system, including plant survival rate and afforestation coverage, which are as shown in Table 4 (Wang, 2013).

Table 4 Short-term indicators and criteria of mangrove restoration technology evaluation system

Indicators	Good	Qualified	Unqualified
Preserved area/designed area	1.0	≥0.7	<0.7
Plant survival rate %	≥70	50~60	<50
Newly built forest (plants/hm^2)	≥3500	≥2500	<2500
Resorted forest (plants/hm^2)	≥2333	≥1667	<1667
Special forest (plants/hm^2)	≥3500	≥2500	<2500

Mangrove afforestation density is closely related to species mass growth and afforestation site conditions.Thus it is not appropriate to fix the criteria. However, in terms of afforestation coverage and plant survival rate, Wang Youshao and others objectively put forward the acceptance appraisal criteria. Based on the afforestation status in Hainan Island, the criteria are divided into four grades (excellent, good, qualified and unqualified) for acceptance appraisal two to three years after afforestation, which are as shown in Table 5.

Table 5 Criteria for mangrove afforestation acceptance appraisal

Acceptance appraisal indicators	Excellent	Good	Qualified	Unqualified
Preserved area	1.0	≥0.9	≥0.8	<0.8
Plant survival rate %	≥75	≥65	≥55	<55

Comprehensive evaluation of ecological factors

The analytic hierarchy process is applied to evaluate the effectiveness of mangrove ecosystem restoration.

The primary indicators include plants, fish, macrobenthos, water quality, sediments and birds.

The secondary indicators are specified as follows:
●Plant indicators include: species composition, coverage, forest belt width, canopy closure or coverage, growth status (height, DBH/base diameter, phenology, growth, pests and diseases) and dominant species. A comparative analysis should be conducted based on historical data and surrounding natural forest distribution.
●Marine life indicators include: species and numbers of both fishes and macrobenthos, and the distribution features of each species.
●Sediment indicators include: sediment elevation variance, sediment loss, pH, organic carbon, total nitrogen, total phosphorus and sulfides.
●Water quality indicators include: pH, salinity, inorganic nitrogen, active phosphate, dissolved oxygen, chemical oxygen demand, and biochemical oxygen demand.
●Bird indicators include: species and numbers of the birds, and their spatial and temporal distribution features.

Use the expert scoring method to weigh these indicators, the fuzzy mathematics method to do comprehensive calculation, and obtain the comprehensive evaluation value.

Ecosystem function evaluation

Ecosystem functions are evaluated by examining changes in ecosystem functions in the restored area based on the monitoring data, mainly including biodiversity conservation, soil retention, water purification, as well as air exchange and regulation. Applicable methods for quantitative evaluation and analysis are market capitalization method, fuzzy mathematics method and productivity estimation method.

Landscape evaluation

Landscape evaluation refers to the comparison and analysis of landscape processes and landscape functions, including numbers, sizes, connectivity, fragmentation, sediment loss and diversity of habitat patches. Mangrove restoration on the spatial scale should be evaluated, taking into account landscape indicators of the same mangrove community naturally distributed under the same site conditions.

Distribution

Mangroves are xylophyta communities growing in the intertidal zone of tropical and subtropical coasts. Mangrove conservation and restoration is of great importance as mangroves are one of the most diverse and productive marine ecosystems. It is also one of the ecosystems that has the highest ecosystem service on the planet. Paying high attention to mangrove conservation, Chinese General Secretary Xi Jinping visited the Golden Bay Mangrove Forest Conservation Area in Beihai City, Guangxi Province on April 19, 2017. During the visit, President Xi learnt the role of mangroves as the Ocean Guardian and Sea Forest in regulating the marine environment in detail, and instructed "We must respect science, fulfill responsibilities, and protect mangroves well."

In China, mangroves are naturally distributed in Hainan, Guangdong, Guangxi, Fujian and Zhejiang Province, as well as Hong Kong, Macao and Taiwan China (Figure 1), or more specifically, between Yulin Port (18° 09'N) in Sanya, Hainan Province to Shacheng Bay (27° 20'N) in Fuding, Fujian Province. The northernmost distribution of artificially introduced mangroves are found in Ximen Island (28°25'N) in Yueqing, Zhejiang Province. Among the mangrove species, *Kandelia obovata* is recorded to distribute in the northernmost boundary of China.

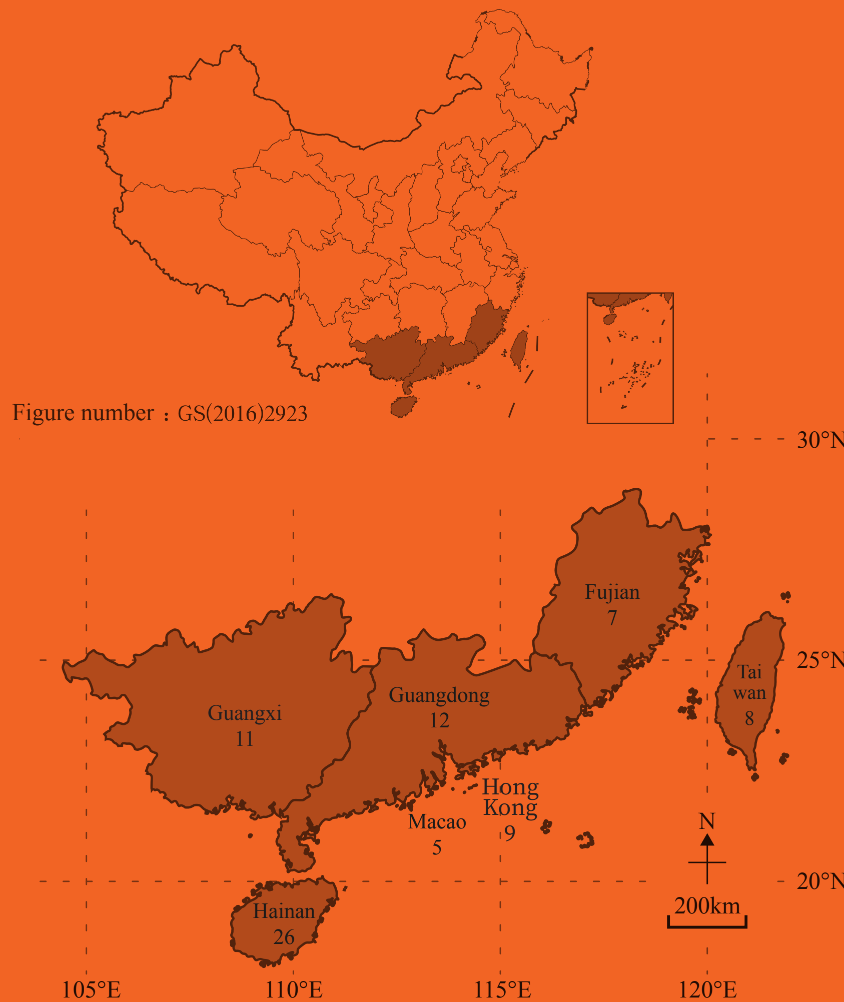


Figure 1. Distribution of mangroves in China showing the number of true mangrove species in each province

In the early 1950s, there were nearly 50,000 hectares of mangroves in China. However, the mangrove area reduced drastically due to land reclamation in the 1960s and 1970s, pond aquaculture in the 1980s, as well as urbanization and port and industrial zone construction in the 1990s. In 2001, the State Forestry and Grassland Administration (SFGA, formerly the State Forestry Administration, SFA) conducted a national wetland survey using remote sensing, geographic information system (GIS) and geographic positioning system (GPS). The results found that there was 22,024.90 hectares of mangroves in the mainland and

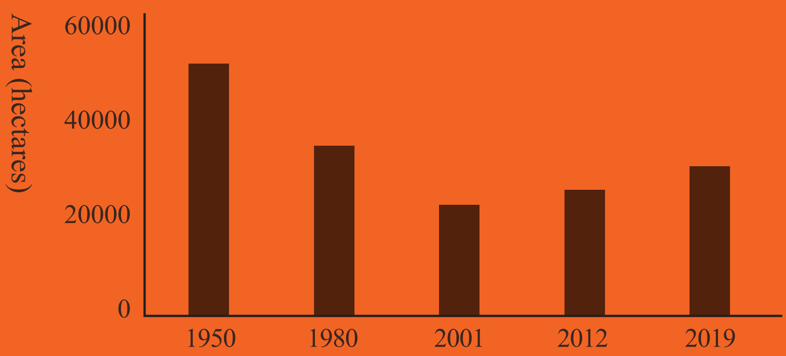


Figure 2. Changes in the area of mangroves in China

659 hectares in Hong Kong, Macao and Chinese Taipei. The mangrove area in China totaled 22,683.90 hectares, equivalent to only 45% of the mangrove area of the early 1950s (Figure 2).

Since 2001, the Chinese Government has paid intensive attention to mangrove conservation and restoration. Through strict protection of existing mangroves and large-scale artificial afforestation, the trend of sharp decline in mangrove area has been successfully curbed and the area of mangroves has gradually recovered. The area of mangroves in China increased from 22,000 hectares in 2001 to about 29,000 hectares in 2019 (excluding Hong Kong, Macao and Taiwan China), with an average annual increase of 1.8%, while the global total mangrove area decreased by 0.5% annually. China has become one of the few countries in the world with a net increase in mangrove area. However, controversies still exist because traditional remote sensing methods can not accurately determine the area of mangroves due to the wide distribution, small plate and narrow forest belt of mangroves. The difference in the specific mangrove area among studies ranges from 2,000 hectares to 34,000 hectares.

The distribution of mangroves in China are as follows:

● Hainan Island, the distribution center of mangroves in China, accommodates extensive tidal flat area and rich mangrove species with 4,900 hectares mangrove forests. Mangroves can be found in the northeast of Dongzhai Bay and Qinglan Bay, the south of Sanya Bay and the west of Xinying Bay,etc. As the coastline of the east coast of Hainan Island twists and turns, with many bays and large area of tidal flat, which informed the distribution of mangroves are wide, mangrove species are diversified and mangrove structure is complicated. In particular, Dongzhai Bay and Qinglan Port are the largest mangrove distribution areas in Hainan.

● Guangdong has a total mangrove area of 14,256 hectares, mainly distributed in Zhanjiang, Shenzhen and Zhuhai city. The Zhanjiang National Mangrove Nature Reserve, with a mangrove area of about 7,230 hectares, is the largest nature reserve with mangroves as the main protection object in China.

● In Guangxi, mangroves cover a total area of 8,922 hectares, distributed mainly in Yingluo Bay, Dandou Estuary, Tieshan Bay, Qinzhou Bay, Beilun River Estuary, Pearl Bay and Fangcheng Bay.

● In Hong Kong, mangroves mainly grow in Mai Po in Shenzhen Bay, Ting Kok in Tai Po District, Sai Kung and Lantau Island, with a total area of 380 hectares.

● In Macao, there are 64 hectares of mangroves distributed in Coloane and Taipa.

● In Fujian, mangroves are mainly distributed in the Zhangjiang River Estuary, Jiulongjiang Estuary and Quanzhou Bay, with a total area of 1,429 hectares.

● In Chinese Taipei , mangroves are mainly found in Tamsui Estuary, and from Hongmao Bay to Hsienchiaoshih Coast in Hsinchu, with a total area of 278 hectares.

● In Zhejiang, there are no natural mangroves, but only 163 hectares of *Kandelia obovata*, which was

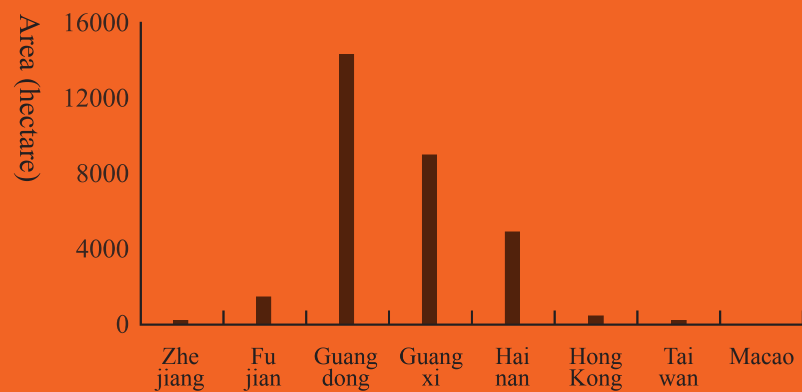


Figure 3. Mangrove area in each province of China (excluding Macao)

02 Species

There are 26 species of true mangroves (including hybrids and varieties) and 11 species of mangrove associates in China (Tables 1 and 2). In addition, *Sonneratia apetala* has been introduced from Bangladesh and *Laguncularia racemosa* from Mexico.

Table 1. True mangrove species and distribution in China

Species	Hai nan	Guang dong	Guang xi	Tai wan	Hong Kong	Ma cao	Fu jian	Zhe jiang
Acrostichum aureum	√	√	√	√	√	√	√	√
A. speciosum	√	√						
Xylocarpus granatum	√	I						
Excoecaria agallocha	√	√	√	√	√		√	
Pemphis acidula	√			√				
Sonneratia alba	√							
S. caseolaris	√	√/I						
S. × hainanensis	√							
S. ovata	√							
S.×gulngai	√							
Bruguiera gymnorhiza	√	√	√	E	√	I	√	
B. sexangula	√	I					I	
B. s. var. rhynochopetala	√	I					I	
Ceriopstagal	√	√	E	E				
Kandelia obovata	√	√	√	√	√	√	√	I
Rhizophora apiculata	√							
R. × lamarckii	√							
R. stylosa	√	√	√	√	E		I	
Lumnitzeralittorea	√							
L.racemosa	√	√	√	√	√		I	
Aegiceras corniculatum	√	√	√		√	√	√	
Avicennia marina	√	√	√	√	√	√	√	
Acanthus ebracteatus	√	√	√/E					
A. ilicifolius	√	√	√	√	√	√	√	
Scyphiphora hydrophyllacea	√							
Nypa fruticans	√							
total*	26	12	11	10	9	5	7	0

* Means that only naturally distributed species are calculated. I defines an introduced species and E means an extinct species.

Table 2. Associated mangrove species and distribution in China

Species	Hai nan	Guang dong	Guang xi	Tai wan	Hong Kong	Ma cao	Fu jian	Zhe jiang
Hernandia nymphaeifolia	√			√				
Pongamia pinnata	√	√	√	√	√	√	E	
Hibiscus tiliaceus	√	√	√	√	√	√	√	
Thespesia populnea	√	√	√	√	√		I	
Heritiera littoralis	√	√	√	√	√		I	
Barringtonia racemosa	√	√	I	√			I	
Cerbera manghas	√	√	√	√	√	√	I	
Clerodendrum inerme	√	√	√	√	√	√	√	
Premna obtusifolia	√	√	√	√	√		I	
Dolichandrone spathacea	√	E/I						
Pluchea indica	√	√	√	√	√	√	√	
total*	11	10	8	10	8	5	4	0

* Means that only native species are calculated. I defines an introduced species and E means an extinct species

Protection

Since 2000, most of the natural mangroves in China have been included within the boundary of protected areas, making direct and large-scale destruction impossible as people with increasing environmental awareness have come to realize the value of mangroves under robust rule of law. Land reclamation and deforestation have been restrained. Mangroves have been rarely fallen as fuel wood with the gradual solution of production and domestic fuel issue for coastal residents. Appropriate eco-compensation measures have been taken for mangrove damage related to port construction along with urbanization.

Nature reserves provide an important way to strengthen mangrove conservation and management. In 1975, Mai Po Marshes and Inner Deep Bay in Hong Kong was designated as a nature reserve, and in 1980, Dongzhaigang Provincial Mangrove Nature Reserve was established. Since then, the protection of mangroves in China has been increasingly improved. So far, there are approximately 30 nature reserves targeted at mangrove conservation in mainland China, including six national nature reserves (one in Hainan and Fujian each, and two in Guangxi and Guangdong each). The total area of the nature reserves is 65,000 hectares, among which, mangroves account for about 16,500 hectares, which representing 74.8% of the total area of mangroves in China. The rate far exceeds the global average of 25%. We can say that mangroves are under the most protected natural ecosystem in China. In addition, a number of mangrove wetlands were inscribed onto the List of Wetlands of International Importance, such as Dongzhaigang National Nature Reserve (Hainan), Zhanjiang National Mangrove Nature Reserve (Guangdong), Mai Po Swamp Nature Reserve (Hong Kong), Shankou Provincial Mangrove Nature Reserve (Guangxi), Beilun Estuary National Nature Reserve, and Fujian Zhangjiangkou National Mangrove Nature Reserve. All these protected areas have played a fundamental role in mangrove protection in China.

In addition, protected areas that combine mangrove conservation with development and utilization of wetland resources have gained increasing attention in recent years, such as wetland parks, marine special protection areas and marine parks. Examples of approved ones related to mangroves are Beihai Coastal National Wetland Park (Guangxi), Hailing Island National Wetland Park of Mangrove Forest (Guangdong), Leizhou Jiulongshan Mangrove National

Wetland Park (Guangdong), Yueqing Ximen Island Marine Special Protection Area (Zhejiang), and Techeng Island National Marine Park (Guangdong) etc. Besides, mangrove wetland parks of Sanjiang in Dongzhai Bay of Haikou, Bamen Bay in Wenchang, Yulin Bay and Ningyuan River in Sanya, and Xinying Bay in Zhangzhou are under planning and construction.

Restoration

Large-scale afforestation was considered to be the primary and even the only way to restore mangrove ecosystems in China. Apart from the large-scale mangrove plantation in the 1950s and 1960s, mangrove afforestation has been widely carried out in various places since the 1990s with deep understanding of the importance of mangroves. In 2001, the Chinese Government planned to recover 60,000 hectares of mangroves in 10 years, but only realized less than 7,000 hectares after 18 years,. Besides, Hainan authorities plan to add 8,500 hectares to the existing 5,000 hectares of natural mangroves.

Excessive flooding associated with low tidal elevation is responsible for the failure of mangrove afforestation in China. Mangroves can only occupy the intertidal zone because excessive high or low frequency of tidal flooding will lead to mangrove degradation, death or make natural regeneration difficult. However, the middle and high intertidal zone suitable for mangrove growth have been completely lost due to seawall construction and land reclamation, with only the low intertidal zone left for current mangrove afforestation. As a result, mangroves are mainly afforested in the low intertidal zone and mudflats. Although the mangrove ecological restoration program has yielded remarkable results overall, there are still some deficiencies that deserve attention and should be improved.

● **Unreasonable objective of afforestation area.** In 2001, SFGA (formerly SFA) scoped 58,800 hectares of tidal flats suitable for mangrove afforestation and planned to plant 60,000 hectares mangroves by 2010. However, to 2017, the actual area of successful afforestation was 7,000 hectares, equivalent to only 11.6% of the planned objective. A large number of theoretical studies and practical results have proven that not all tidal flats exposed at low tide are suitable for mangrove forestation. The failure of afforestation in lower tidal flats is mainly attributed to long and frequent flooding to great depth. There is a critical tidal elevation for afforestation, only above which mangrove afforestation is possible. In fact, tidal flats suitable for direct afforestation in southern China are very limited, due to land reclamation and urban construction. At the preparation meeting for the *Implementation Plan for National Wetland Protection Project (2016–2020)* (November 2014, Beihai, Guangxi), mangrove experts from around the country estimated there is no more than 6,000 hectares of tidal flats suitable for growing native species in harmony with China's marine functional zoning. According to the survey by Xiamen University in 2016, there is less than 300 hectares of such suitable tidal flats in Hainan Island. Therefore, it is debatable to propose a large area of mangrove afforestation.

● **Afforestation in tidal flats changed the pattern of Coastal wetlands.** Tidal flats account for more than 90% of mangrove afforestation in coastal areas, but with tidal elevation below the critical elevation, afforestation fails in most cases. For this reason, soil is artificially filled in many areas to elevate tidal flats with a view to improve mangrove survival rate. Examples of this practice can be found in Xiamen, Shenzhen, Jiangmen, Haikou and Lingshui. Xiamen has even proposed a tidal flat ecological restoration model that requires "no tidal flat after the tide ebbs." Elevate the elevation of tidal flats artificially seems necessary in some special sites, such as areas with discontinued forest belts and areas with severe coastal erosion. Nevertheless, this approach of ecological restoration aimed at afforestation has brought about negative impacts by changing the original ecological pattern of coastal wetlands. Apart from mangroves, mudflats, shallow waters and tidal creeks are also essential for the maintenance of wetland ecosystem structures and functions. Among them, mudflats outside mangrove forest provide the major places for water birds to forage, while dense mangroves can only serve for inhabitation and nesting. Located on the international migratory route of the East Asian-Australasian Flyway, coastal wetlands in China are important for migratory water birds to refuel. Transforming all mudflats into mangroves, even if successful, will also occupy the foraging habitats of water birds. In addition, this special afforestation involves complex problems of marine hydrology and plant ecology, such as tidal elevation, cofferdam engineering, and tree species configuration. Generally, a single forestry design agency and afforestation construction agency cannot be competent that afforestation and will likely end up with failure, considering high technical risk and huge capital investment.

● **Single species of afforestation.** In order to reduce costs and minimize earth fill, the tidal elevation is limited to be just slightly higher than the critical elevation. As a result, only a few mangrove species that are most resistant to flooding can grow in the artificially filled tidal flats. At the same time, in order to make afforestation simple and easy, a small number of easy-to-live species are planted in large scale, without considering the ecological structures and functions of species and especially the importance of local native species. In the long run, mangrove forests will look identical from south to north in the country. At that time, huge risks will arise from large-scale rapid spread of pests and diseases, and structural simplification and functional decline of mangrove ecosystems.

● **Risk of invasive species.** From 2000 onwards, *Sonneratia apetala* introduced from Bangladesh and *Laguncularia racemosa* from Mexico have became the main species for mangrove afforestation in China because of their rapid growth. According to a survey conducted by Xiamen University, invasive species account for 80% of the artificial mangrove afforestation in China. Among them, *Laguncularia racemosa* has the typical characteristics of invasive species, such as strong adaptability, fast growth, and quick propagation. It widely spreads and completely outcompetes native species in the Qingmei Bay Mangrove Nature Reserve and Tielu Bay Mangrove Nature Reserve in Sanya, Hainan. The latest assessment results show that 50% of the mangrove species in China are rare or endangered, far more than the average of 15–20% of higher plants in China. The dominance of alien species in afforestation goes against the original intention of ecological restoration.

While, the restoration of mangroves with native species has become more and more accepted in recent three years and has been widely adopted throughout China.

To this end,

the following recommendations are provided:

● Mangrove conservation and restoration should focus on mangrove ecosystems recovery more than on mangrove afforestation. Mangrove ecosystems, especially bare mudflats outside mangrove forest, are important habitat for water birds. Bare Mudflats should be prior reserved in the process of mangrove restoration.

● Mangrove restoration should set aside space for natural restoration. By way of natural restoration, mangroves can be restored in a natural state through effective fencing, management and protection that prohibits or minimizes human interference in the site. Natural restoration can greatly reduce the cost of restoration.

● Native species should be highlighted. Native species are species that have historically occurred in the site for restoration and the adjacent areas. When used in mangrove restoration, native species will play a fundamental role for maintaining local ecosystem health and biodiversity. Some nature reserves in Fujian, Guangdong, Guangxi, Hainan Provinces and Hong Kong, they have taken steps to remove invasive species from the protected areas, but the effect is undermined by the steady drift of seeds or fruits of nearby *Sonneratia apetala* and *Laguncularia racemosa* to the protected area. There is an urgent need to adopt a national unified protection and rehabilitation strategy. It is suggested that the relevant departments expand management to nursery, seedling transport, afforestation design, and encourage the use of native species in afforestation by offering compensations or incentives.

- Pay attention to the role and function of community in mangrove conservation and restoration. Diverse development models for surrounding communities should be explored, to facilitate effective management and protection of mangroves converted from ponds and mangroves that newly planted. For example, fishermen community cooperatives can be adopted to guide fishermen to convert fish ponds to mangroves. Eco-friendly pond aquaculture should be promoted through market supply chain, which increases the income of fishermen by reducing the farming scale and increasing the output value. The carbon trading mechanism can be introduced for mangrove carbon transactions to support the follow-up management and protection of mangroves and the diversified development of communities. Eco-tourism oriented to nature education also helps both mangrove protection and community income improvement, which truly turns ‘unsustainably use what forest provide’ into ‘lucid waters and lush mountains are invaluable assets’. If the surrounding fishermen communities can benefit from mangrove protection, the long-existing lack of management and protection forces will be addressed by expanding local forces. This will make it possible for the restored mangroves to succeed in becoming a healthy ecosystem.