Chapter

Environmental and Education Trials for Mangrove Ecosystem Rehabilitation in China

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Abstract

Based on Chinese ecological policy, we have been studying mangrove ecosystems in southern China, especially from the perspective of pollutants deposition in mangrove wetlands, physiological ecology of mangrove species on the impact of heavy metal pollution and seeking ecosystem restoration. For these, we explored in three aspects: 1) pollutants distribution and ecological risk in main distribution of mangrove, China, 2) eco-statistics and microbial analyses of mangrove ecosystems (including shellfish) in representative locations where mangrove plants are well developed, especially in Shenzhen, a rapid developing economic city in Guangdong Province, 3) ecophysiological experiments on a representative species of mangrove for evaluating combination effects of major nutrient elements and heavy metal pollution on growth and physiological responses of the seedlings. Based on the results, we proposed how to rehabilitate mangrove ecosystem in China under rapidly changing environmental conditions, with a view to our future survival and to provide nature-based solution as well as the public with more ecosystem services.

Keywords: ecosystem, wetland, pollution, restoration, subtropical mangroves, nature based solution

1. Introduction

Well-developed mangrove forest in southern China has increased their values of environment, eco-tourism resources, and conservation of biodiversity, etc. [1–3]. Mangrove ecosystems are also expected to provide many ecological services: (1) provisioning, (2) regulation, (3) culture, and (4) basic service [4, 5]. Basic service, i.e., means primary productivity of plants, soil formation and nutrient cycling, etc. The rest services are depending on basic services. Therefore, ecophysiology of mangrove is the most fundamental and essential information for this chapter.

In terms of ecological functions, mangroves can provide (1) many foods including fish, shellfish via offering their habitats, dye materials, wood and materials for high quality charcoal, etc., (2) maintain marsh ecosystems: soil conservation, reduction of storm disasters, wave attenuation, acceleration of reclamation, contaminant degradation, clean the atmosphere and marine environment, (3) eco-tourism, culture, scientific resources, etc., (4) CO_2 fixation and O_2 evolution, biomass production, nutrient circulation [6]. However, an increase of anthropogenic activities in coastal areas reduced mangrove cover and functions, with environment deterioration to be important factor, such as pollution caused by heavy metals. Recent degradation of mangrove functions, such as offering habitat for many living organisms is also reduced by persistent organic pollutants (POPs) including microplastics (MPs), etc. [7–9].

In China, large area of mangroves mainly distributed in six provinces (Zhejiang, Taiwan, Fujian, Hainan, Guangxi, and Guangdong), and two special administrative regions (Hong Kong and Macao). There were 37 mangrove species, representing 20 families and 25 genera, with thermophilic eurytopic species being the dominant components [10]. Mangrove could accumulate various pollutants derived from rivers and tidal waters due to its unique properties, such as high productivity, organic-rich matter scrap, fine grains of wetland soil, and anoxic environment [11, 12].

Pollutants like heavy metals and organic contaminants are generally toxic and persistent in mangrove ecosystems. In estuarine mangroves of New Zealand, the soils were characterized with lower Eh and currents upstream trapped more macro-nutrients and heavy metals compared to downstream [13]. In Southeast Sulawesi of Indonesia, mangrove species significantly bioaccumulated heavy metals (such as Cu, Hg, Cd, Zn, and Pb), with different partitioning and uptake capacity of heavy metals to be detected in tissues of mangrove species [14]. Marchand et al. (2011) explored the relationships between heavy metals and organic matter cycling in mangrove sediments of Conception Bay, New Caledonia [15]. Currently, various pollutions caused by anthropogenic activities are well recognized in mangrove in Shenzhen, the most rapidly developed city in China [16, 17]. Especially, Futian mangrove in Shenzhen has been recognized as one of the most typical urban mangroves located in a big city (**Figure 1**), which has been receiving more and more attention. Shenzhen municipal government has decided to keep their environment in order to achieve the sustainable development goals (SDGs) and adopt mangrove as the iconic plant.

Figure 1.
Futian mangrove located in the center of Shenzhen, China (http: //mcf.org.cn/mobile/).

In this chapter, first, we briefly summarized the history of studies in East Asia; then, we take China as an example to explore current progress in mangrove management and research: i.e. heavy metal distribution and ecological risk in mangrove sediment, as well as POPs (such as polybrominated diphenyl ethers). POPs could affect photosynthesis via belowground root vigor and function, and transfer along food chain/web to bio-accumulate [18]. Thirdly, the status of education effect of mangroves in China, especially for Shenzhen was stated. At last, the future perspective of mangrove research in China was provided. These mangrove functions under current and rapid environmental changes in China may provide a hint of conservation and restoration of mangrove ecosystems in the rest of the world.

2. Brief history of mangrove studies in East Asia

In recent years, intensively research have been conducted on the productivities of mangrove forests in tropical and sub-tropical areas of southeast Asian countries, including Indonesia, Philippines, Thailand, and southern Japan, etc. [19–22]. As a contribution to the IBP (International Biological Program), we globally estimated the biomass productivity of different types of vegetation and ecosystem. This IBP is dedicated to human survival from the perspective of biomass production as well as conservation of biodiversity including local people's lives [23–25]. In this project, general empirical models for estimating above-ground biomass, especially universal equation for root biomass was developed (**Figure 2**) [26].

Mangrove plants are characterized by their unique growth characteristics [28]. They can grow and develop along with brackish region of estuaries, wetlands and sea-shores, and are well-known as "marine forest." Furthermore, the growth of mangrove plant would be affected by other climate factors. For example, from dendrometer monitoring of the diameter growth of *Avicennia alba* growing at brackish region, a pioneer species in east Thailand, diameter growth increased with flooding of fresh water during rainy season [26]. In fact, "annual" ring was found in this species even though *A. alba* grows in western Mahachai bay, Thailand (tropical region without any clear dry season) [29] . This species may use intensively fresh

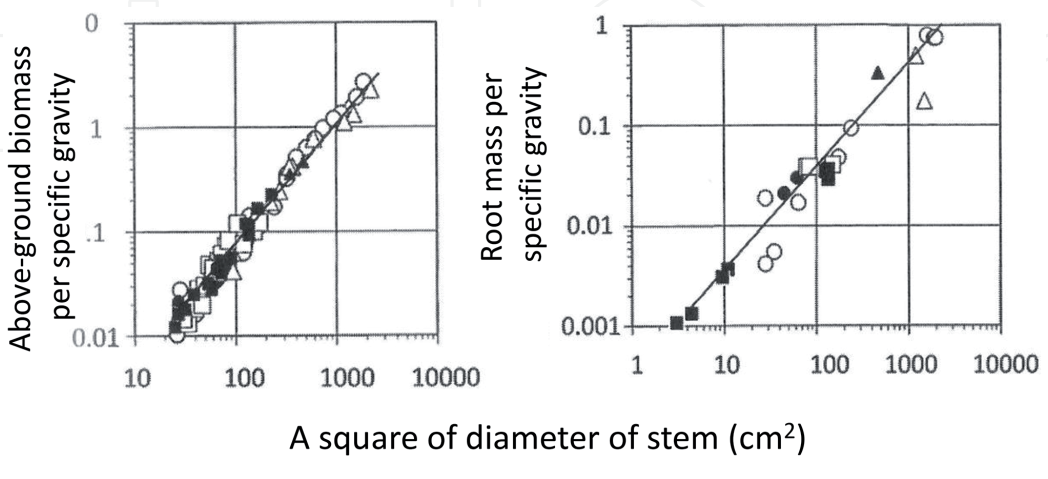

Figure 2.
Universal allometry equation of above- and below-ground biomass of mangrove forests in Asia (Adopted from Komiyama 2017 [26] modified Komiyama et al. [23] and Komiyama et al. [27]. Sampling; ○: Rhizophora *sp. at south Thailand ● n of above- and below-ground bioma △:*Rhizophora *sp. at east Indonesia, ▲: The other species at east Indonesia, □:* Rhizophora *sp. at east Thailand, ■:* Rhizophora *sp. in east Thailand.* $W_{top} = 0.251\ sD^{4.46}$; $W_{root} = 0.199\ sD^{2.22}$.

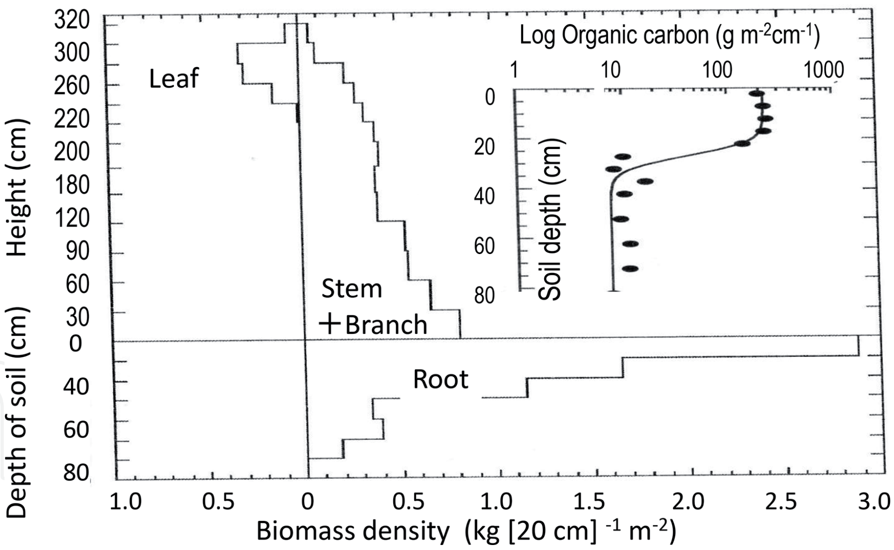

Figure 3.
The stratification diagram of a mangrove stand at the northern boundary in the Ryukyu islands, south Japan (Adopted from Hagihara [35]).

water for its growth. These areas are usually zoned by different species of mangrove depending on their adaptive traits in salt tolerance [30–33] and light utilization characteristics of each species [34]. Mangrove species grow in the front of seashore are light demanding type while a component of well-developed stands is low-light utilization type based on chlorophyll fluorescence.

Hagihara (2006) reviewed production ecology and carbon cycling of mangrove stand (*Kandelia obovata*) in the Ryukyu Islands (**Figure 3**): i.e. northern limit for the distribution of mangrove plants in Japan [35]. This species is very popular in China for ecological study [26, 32]. Hoque et al. (2011) found that Top/Root (T/R) ratio of *K. obovata* in Manko wetland, Okinawa, Japan was around 1.87 [36].

Generally, T/R ratio of mangrove stands was around 1.0 [26, 37] whereas it is ranged between 3 ~ 4 for most forests. From the stratification diagram, estimated value of the extinction coefficient (K_F) including branches for *K. obovata* stand was 0.50. The K_F was 0.56 ~ 0.69 for *Bruguiera gymnorhiza* stands in Ryukyu Islands, 0.54 ~ 0.57 for *Rhizophora apiculate* in Thailand. K_F values of deciduous conifer larch (Larix kaempferi), evergreen oak (*Quercus phillyraeoides*) and Hinoki cypress (*Chamaecyparis obtusa*) were 0.31, 0.36, 0.67 and 0.37, respectively. Thus, compared with other plants, *K. obovata* stand can make good use of incident sunlight in their canopy with their photosynthetic capacity [37].

People recently have again recognized that mangroves have played an important role in preventing Tsunami tide wave after earthquakes in Indonesia, which lead to tsunami in Southeast Asia and cause huge losses and casualties to Southeast Asian Countries, particularly Indonesia [38, 39]. In fact, the mangrove stands along with seacoast of Indonesia protected and lessened destructive power of tide wave at the time [4]. In China, though very few typical examples were available for weaken effect of mangrove on tsunami, the storm prevention of mangrove is one important aspect of mangrove ecosystem services, which have been evaluated to be 10473.3×10^4 RMB in terms of energy value [40].

Recently, due to our concern that global warming will cause rapid rise in sea level, new aspects of salt resistance (tolerance and avoidance) of mangrove species has been studied intensively [33, 41–43]. Sea level rise would increase tidal inundation period and make mangrove species beyond the specific thresholds of flooding tolerance [44, 45]. With intense environmental change, the related knowledge about mangroves have also been systematically summarized through publish of revised editions of botanical books on mangroves as well as ethnobotanical books [31, 32, 46, 47]. On the other hand, researchers recognized the impact of polluted water caused by anthropogenic activities on growth of mangrove plants, without paying much attention to negative impact of heavy metal pollution on mangrove ecosystems [26, 31, 46, 48].

The exploration on heavy metal pollution in mangrove wetlands would understand the source, history, and status of heavy metals, and obtain the relationship between heavy metals and mangrove ecosystem, which is important for coordination between economic development and environment protection. With positive leadership of Chinese ecological policy [49], we have been studying on heavy metal pollution, such as mercury (Hg), cadmium (Cd), copper (Cu), and its counter effects on physiology and growth of the representative mangrove plants dominated around southern China. A typical example of pollution is an intensive study on mangrove ecosystems in Shenzhen city where is located north of Hong Kong, one of the most dramatically developed cities in China. Shenzhen City has decided to adopt mangrove plants as the symbolic trees and well organized ecological and environmental education by establishing mangrove museums and field education parks [7]. Environmental education trail will also be briefly discussed in latter part of this review.

3. Mangrove management and research in China

3.1 Mangrove management

Mangrove species in China belong to the Indo-Malaysia Northeast subgroup of East group and covered >50,000 ha in 1950s [47]. Before 1990s, mangroves in China had been degraded and the areas greatly reduced, with only 22,752 ha remained [47]. Furthermore, mangrove ecological exploitation in China existed many problems, including imbalance between protection and utilization, simple ecological development mode, low economic benefit of ecological development, planning management and related policies and insufficient regional cooperation. Since then, increased government investments have greatly improved the research on mangroves in China.

In 1995, China's Biodiversity Conservation Action Plan included the action plans, which called for "Increasing mangrove conservation areas". As a result, majority of the national mangroves have been protected as a part of the national wide mangrove nature reserves (**Figure 4**). On the announcement of the leader Mr. Xi Jinping, one of the Chinese ecological policies orients us how to conserve mangrove forest as an ecological unit [49]. Based on this statement, conservation of mangrove ecosystem is one of the national key projects, especially at Fujian and Guangdong Province, especially Shenzhen city government, the most rapid developing economical city in China.

Over the past decades, large number of studies have significantly improved our understanding of structure and function of the mangrove ecosystems, however, there are still many areas needed to be strengthened: (1) The construction of sea walls plus many skyscrapers behind natural mangrove wetlands may prevent migration landward into areas of higher elevations in response to sea level rise; (2) Biological invasions such as those of *Spartina alterniflora* may compromise habitats. Their invasive mechanisms and efficient measures for controlling such invasion is still unclear; (3) There is still a lack of universal standard system for evaluating the efforts and achievements of mangrove afforestation and restoration in China; (4) Cooperation among related mangrove research institutions should be strengthened to ensure successful conservation, restoration of mangroves in China.

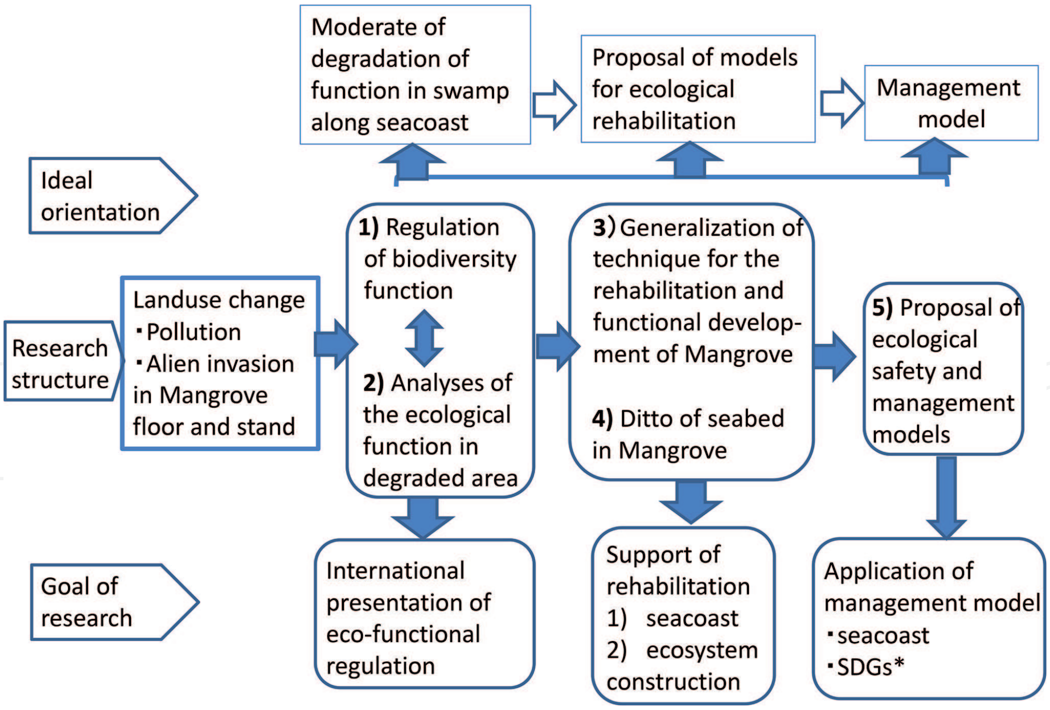

Figure 4.
A Flame work of conservation strategy of mangrove ecosystem in China proposed by Dr. Hailei Zheng at Ningde, China in 2019 [49].

3.2 Mangrove researches

Since 1970s, mangrove researches in China have mainly focused on taxonomy and ethno-botanical view point, medical use and practical use of mangrove plants [6, 50, 51]. According to uncompleted statistic, China researchers have published 24 monographs or proceedings related with mangrove, including comprehensive basic research, ecological restoration, macro-benthos, birds, pest control, and ecological location, remote sensing monitoring and evaluation, resource management, and popular science [52]. The Shenzhen City Office strongly supports researches and education in mangrove ecosystem (see education section).

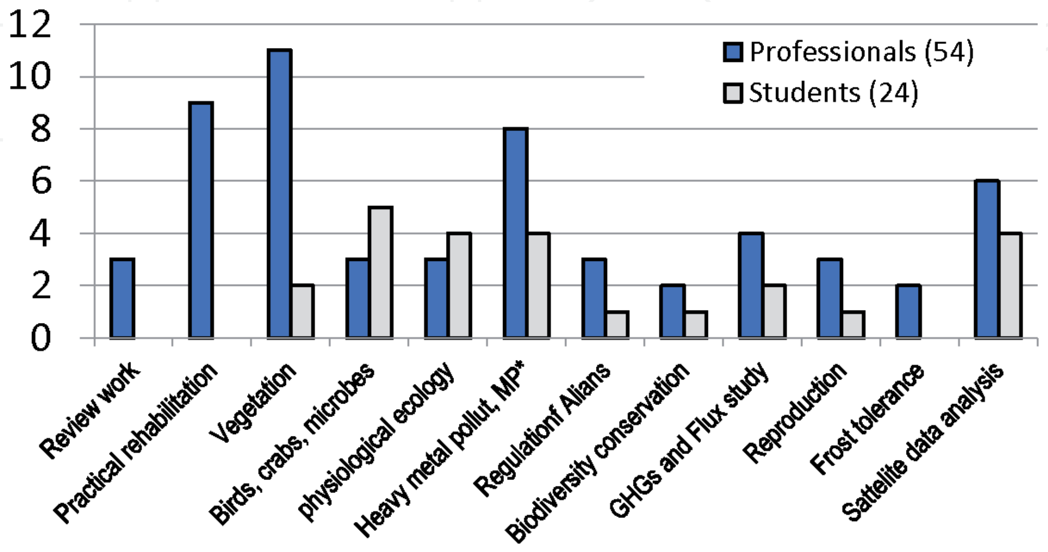

Figure 5.
Research topics on mangrove forests in Chinese Ecological Society (CES) in 2019 (Adopted from program leaflet of the meeting of CES [49, 53]).

Chinese mangrove ecologists hold workshop every two years to make further progress in mangrove researches and practical works. For most researchers, they are engaged in the topics such as remote sensing, biodiversity in mangrove ecosystems, physiological ecology, heavy metal pollutions, etc. These topics are relatively regarded as short-term target compared to those topics more professional (**Figure** 5).

At the 9th workshop in Ningde 2019 (in Fujian Province) [53], the recent ecological efforts on mangrove conservation in accordance with the SDGs (Sustainable developmental goals) was summarized as follows (**Figure 6**) [49].

The contents were: i.e. policy making, scientific review, practical forestry, and frost resistant researches, which were mainly reported by national and regional research institutes. Among them, one unique research is how to increase mangrove's frost tolerance and freezing avoidance research (**Figure** 7) [56, 57]. In 2010, sudden snow-fall caused death of newly planted mangroves because they were originally grown in sub-tropical and tropical, where there would not be a severe

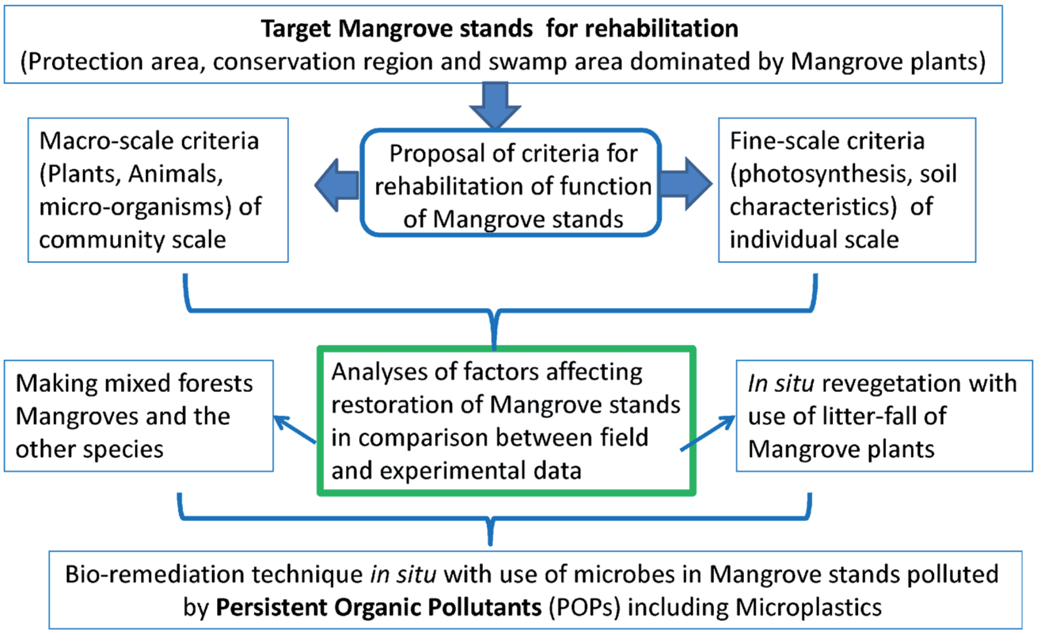

Figure 6.
Rehabilitation strategy of mangrove forests under pollution, (Adopted from the statement by Dr. Hailei Zheng, 2019) [52–54].

Figure 7.
Photos of snow on mangrove seedlings planted in Zhejiang Province, China in 2010. Left photo was offered by Dr. Jianbiao Qiu of Zhejiang Mariculture Research Institute. And right photo at nursery was offered by Dr. QiuXia Chen of Zhejiang Sub-tropical research institute [55].

low temperature environment. Glycine-Betaine was employed as a target chemical for species selection and breeding, as this compound is also common in relation to increase of desiccation and frozen tolerance [57]. Clearly, more work is needed to perform practical applications in the future.

4. Ecological statistics and diagnoses of heavy metal pollution in China

The current situation of heavy metal pollution of the southern part of China from ecological statistics was reported by Shi et al. [58]. As the first integrated analysis of heavy metal pollution in mangrove sediments across China, this study covered whole mangroves in China by selecting 6 sites including Hainan Island and near the border of Vietnam. If we focus on common mangrove species of these regions, *Avicennia marina* (characteristics: this species has pneumatophores [looks like young shoot of bamboo] for respiration in few centimeters from muddy soil) [59], the heavy metal pollution of this species shows very strong correlations in polluted condition of tideland soil (**Figure 8**).

From data of heavy metal pollution at the 6 sites, the pollution level in Futian district of Shenzhen city has higher pollution level. We detected representative heavy metal pollutants cause by high concentration of zinc (Zn), chromium (Cr), lead (Pb), nickel (Ni), arsenic (As) and relatively low concentration of molybdenum (Mo), cobalt (Co) and cadmium (Cd). Although proportion of Cd in the total heavy metal concentrations was low (based on evaluation of geo-accumulation index, contamination factor, potential ecological risk coefficient, pollution load index, and potential ecological risk index), Cd is a cause of the “Itai-itai” disease in Japan [60] and was detected as 0.66 ~ 3.30 μg/g at Futian district of Shenzhen city [61].

The factor affecting capture of heavy metal is particle size of soil with different specific surface areas and adsorption capacities [60, 61]. In fact, the heavy metal concentration was lower at Fangchenggang in Guangxi province where sand is dominant, while it was higher at Dong fang, Yunxiao and Futian district of Shenzhen where silt (between sand and clay) is dominant [62, 63]. We regarded mangrove stands, coral-reef and seaweed fauna as three major inshore marine ecosystems [1, 64, 65]. Furthermore, we explored the heavy metal pollution in Futian mangroves of Shenzhen, China. Futian mangrove is a mangrove forest area of 304 ha located in the Guangdong Province, and is the only mangrove forests located in the middle of Shenzhen, China. Futian mangrove was adjacent to the Mai

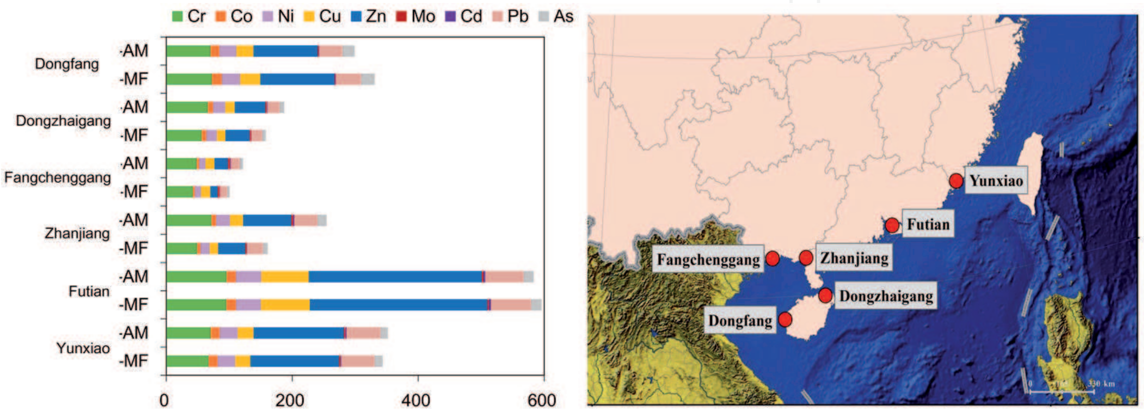

Figure 8.
Ecological statistics of heavy metals pollution in south China (AM, Avicennia marina a kind of mangrove; MF, mudflat) (Adopted from Shi et al. [58]).

Po Nature Reserve, Hong Kong, and has suffered serious heavy metal pollution since the early 1990s [62].

In order to systematically explore ecological risk of heavy metal contamination in Futian mangrove forest, being important for designing management and conservation policy, we quantify the concentrations of heavy metals (Cd, Cr, Cu, Pb and Zn) in mangrove sediments, assess the potential ecological risk and sources of heavy metals, and identify the speciation of heavy metals [66]. The results showed that heavy metal concentrations in surface sediments (0–20 cm depth) varied greatly along the coastline, demonstrating the heterogeneity of sediment to some extent. As for different heavy metal species, the concentrations reduced in the order of Zn > Cr > Pb > Cu > Cd [66]. Furthermore, the combination of studied metals had a 21% probability of being toxic, based on analysis of mean probable effects level quotient. Similarly, high heavy metal contamination was also revealed in term of potential ecological risk index and geo-accumulation index. Among all heavy metals, Cd has higher potential for adverse biological effects, being of primary concern. Take into account the sediment characteristics, clay and silt were important in raising deposition/accumulation of Cr, Cu, and Zn. As for different speciation of heavy metals, the percentage of mobile heavy metals was relatively higher than other fractions; while, no considerable ecological risk to the biota was detected in terms of the risk assessment code. The mobile heavy metals referred to the sum of acid-soluble, reducible, and the oxidizable fractions in terms of heavy metal speciation [67].

5. Ecophysiology of heavy metal resistance for mangrove plants

Mangrove plants have specific nutrient balance for growth and survival because they grow in very special environment (i.e. high NaCl, flooding environment, etc.).

Therefore, response of mangrove plants to various environmental stresses is a key information of rehabilitation of degraded regions. Cadmium (Cd), a non-essential element, can easily be taken up by plants and cause chlorosis [69], wilting [70] and cell death [71]. Heavy metals and large amounts of nutrients including nitrogen from domestic sewage also accumulate in mangrove sediment, and change its oligotrophic state [72] and pH [73]. We quantified the effects of ammonium nitrogen on the accumulation, subcellular distribution, and chemical forms of cadmium (Cd) in *K. obovata* [68]. The concentration and total amounts of Cd in leaves, stems and roots increased with NH_4^+-N supply (**Figure 9**).

In terms of subcellular distribution, Cd in roots of *K. obovata* was mainly deposited on cell wall, and the largest chemical forms of Cd was pectate and protein integrated form in all treatment. Under Cd treatments of 1 and 5 mg/L, 50 mg/L NH_4^+-N enhanced the transfer of root cell wall-combined Cd into cell, improved bioaccumulation of pectate and protein integrated Cd in cell to reduce toxicity caused by Cd. Under 10 mg/L Cd treatment, NH_4^+-N addition improved bioaccumulation of Cd on root cell wall, and limited enter of Cd into cell, which were also verified by decreased bioaccumulation of pectate and protein integrated Cd in root cell to some extent. Thus, under Cd stress, NH_4^+-N supply improved Cd immobilization in roots of *K. obovata*; the results of subcellular distribution and chemical forms showed that root cell wall combination and integration with pectate and protein acted as the mainly detoxification strategies of *K. obovata*. Plant transpiration transfer coefficient performed well in indicating the water and high temperature stress conditions plants experienced [74].

The use of chlorophyll florescence for diagnose of plant health status under stress, especially for mangrove plants is important in the rapid non-destructive

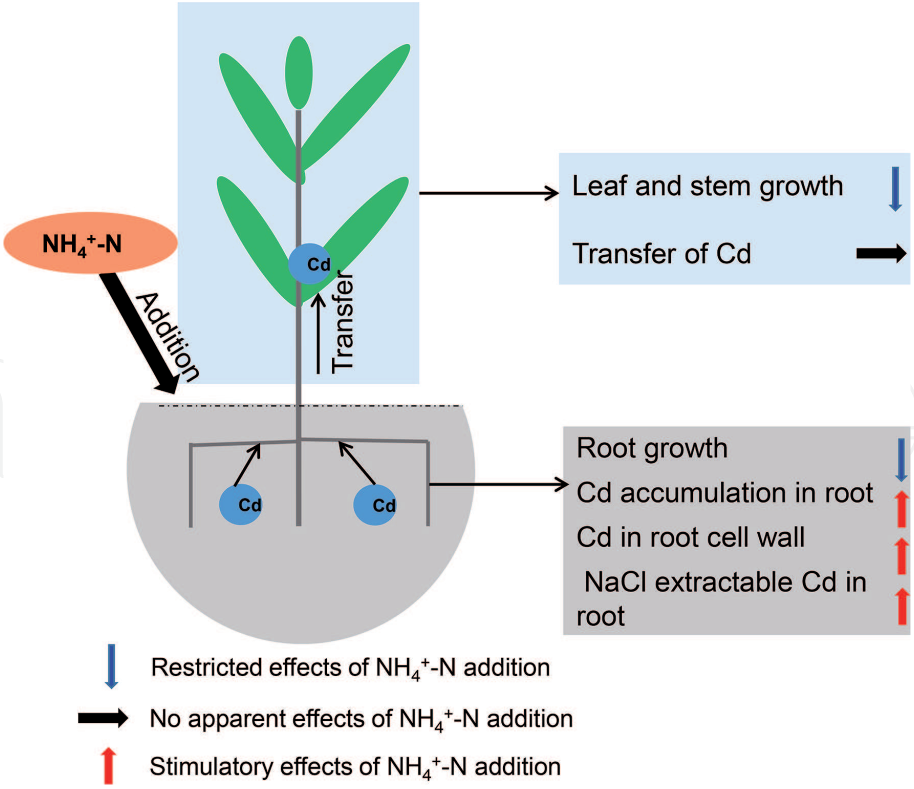

Figure 9.
The distribution of cadmium (Cd) in Kandelia obovata under nitrogen addition (Adopted from Chai et al.) [68].

assessment [34]. Physiological activity of coastal mangrove species is evaluated based on a three-temperature (3 T) model using high-resolution thermal infrared remote sensing. This evaluation method is based on growth evaluation of the representative mangrove species, *K. obovata* seedlings treated with different concentrations of Cd and nitrogen input as a simulation of environment at estuary of Shenzhen, China [75].

The cultured *K. obovata* seedlings were promoted for their photosynthesis due to the application of nitrogen, which brought a decrease leaf temperature detected by remote thermometer. In contrast, leaf temperature of *K. obovata* seedlings treated Cd increased due to stomatal closure with Cd toxicity [75]. The toxicity of Cd may be moderated by the existence of nitrogen addition, which can be clearly detected by the images from thermometer. The high-resolution thermal infrared remote sensing +3 T model is practicable for diagnosing plant health status. We should always consider synergy and antagonism in each element including heavy metals and nutritional elements [76]. Generally, the information in single metal contamination research does not reflect the biological toxicity when multiple metals are present together, with their combination toxicity having complicated mutual interactions on plants [77].

Furthermore, the interactive effects of multiple heavy metals (Cu, Pb, and Zn) on growth of *K. obovata* were studied, including plant biomass, photosynthetic parameters, lipid peroxidation and compatible osmolytes [78]. The results showed no significant reduction of biomass under heavy metal stresses, except for decreased root biomass under higher Pb + Cu treatment. This evidence indicates that *K. obovata* is highly tolerant to heavy metal stress. With increasing heavy metal stress (except for Pb + Cu and Pb + Zn + Cu), the photosynthetic parameters detected by a potable porometer (LI-6400; NE, USA) (net photosynthetic rate [Pn], transpiration rate [Tr], and stomatal conductance [Gs]) decreased at ambient CO_2 concentration (about 400 ppm) [75].

Compared to external binary metal treatment, trinary treatments (Pb + Zn + Cu) improved plant biomass and the photosynthetic capacity. As for root of *K. obovata*, binary treatment reduced biomass and soluble sugar content compared with ternary treatment. These results showed that in Pb combined treatments, the combination of Zn and Cu improved alleviating toxicity than each of them alone. Malondialdehyde (MDA) can reflect the degree of cell membrane lipid peroxidation and plant response to stress conditions [79, 80].

In leaves of *K. obovata*, Zn-containing combined treatments significantly reduced MDA, soluble sugar, and proline content under low concentration, demonstrating antagonistic effects; while, Pb + Cu treatments significantly promoted these parameters, indicated synergistic effects. Furthermore, there were negative correlations between leaf MDA and proline content with Zn concentration ($P < 0.05$). Leaf MDA content was positively correlated with the osmotic parameters, indicating co-existence of osmotic stress and lipid membranes oxidation under multiple heavy metal stresses. Thus, as for *K. obovata*, the toxicity caused by multiple heavy metals could be indicated by responses of leaf biomass, Tr, leaf MDA, leaf proline and soluble sugar [75, 78].

6. Evaluation of mangrove ecosystem: microbes and shellfish

6.1 Microbe in mangrove sediments

At the ecosystem level, mangrove plants, microbes in the soil, any other living organisms, and their natural environment cooperated with each other [3, 81, 82]. There are many places in mangrove stands producing sulfate compounds (e.g. hydrogen sulfide, H_2S). We can identify the smell of H_2S, implying importance of sulfate producing microbe activities. In the field conditions, heavy metal accumulation is important environmental factor regulating bacterial communities [83, 84]. Sulfate-reducing bacteria (SRB) could utilize sulfate as an electron acceptor in the dissimilatory reduction of sulfate [85]. How about the impacts of heavy metals pollutant on SRB? The effects of heavy metal contamination on sulfate-reducing bacteria (SRB) with both field survey and experimental approaches have been revealed [3]. SRB communities were investigated in mangrove sediments (0–30 cm depth) from 3 districts of mangrove wetlands in Shenzhen with different heavy metal contamination levels.

The results revealed that SRB community abundance was correlated with depth of mangrove sediments, especially significant correlation was found in soil concentration of Cd and Ni concentrations. From 1980 to 1990s, almost no analysis was done from the view point of biodiversity [81]. The α-diversity index of SRB community was significantly correlated with Cd level in mangrove sediments. Dominant 3 SRB groups (Desulfo-bacteraceae, Desulfobulbaceae, Syntrophobacteraceae) were isolated in the mangrove sediments of Shenzhen mangrove, China [3]. Among these families, Syntrophobacter-aceae was most sensitive to heavy metal contamination. The Unifrace clustering analysis revealed that SRB community structure was influenced by heavy metal stress. Moreover, redundancy analysis (RDA) indicated that Cd and total phosphorus were the major element affecting the SRB structure in the mangrove sediments [3].

Generally, the structure of mangrove sediment bacterial community could be affected by various factors, including plantation species [86], sediment depths [87], physico-chemical properties of sediment [88], and anthropogenic activities [87]. Different mangroves might reveal the specific biogeographic distribution pattern of bacterial community [89]. We explored the biogeographic distribution of sediment bacterial community in six mangroves across China, including two mangroves in Hainan Province, two in Guangdong Province, one in Guangxi Province and one in Fujian Province [90]. Among all six mangroves, the sediment bacterial demonstrated different characteristics in terms of bacterial abundance, bacterial richness and diversity, and bacterial community structure. Compared with intertidal mudflat, *A. marina* planted zone improved sediment bacterial abundance, richness, and diversity. Furthermore, *Proteobacteria* acted as the largest bacterial phylum in sediments in both intertidal mudflat and *A. marina* planted zone. Therefore, the biogeographic distribution of bacterial community across six mangroves in China was driven by variable wetland tropic status and other physicochemical factors (such as salinity) [90].

In mangrove sediment, *Archaea* sp. played important role in biogeochemical processes, such as ammonia oxidation [91] and methanogenesis [79]. Understanding biogeographic distribution pattern can be helpful to increase the knowledge of microbial function and to predict ecosystem responses to environmental variability [89]. We explored the effect of geographic location on mangrove archaeal community in six mangroves of China [92].

In different geographic location, mangrove archaeal have different community characteristics, which might be related to various environmental factors, including pH, carbon, and nitrogen contents in sediment. Furthermore, the main archaeal communities in mangrove sediments were genus *Thaumarchaeota* and *Euryarchaeota*, with their percentages to be 54.7–85.2% and 11.8–43.9%, respectively. This work would be useful for understanding the characteristics of archaeal community in mangrove ecosystem, which may provide new insight for exploring microbial function and ecosystem responses to variable environment.

6.2 Shellfish as food resources

Shellfish is an important component in mangrove ecosystems similar to well-known crabs [32]. Recently, people have eaten more shellfishes as healthy food than before; however, the bio-accumulation of heavy metals in the shellfish can endanger the health of consumer [93]. Shenzhen is a fast-developing city in south China, and has been developed from a small fishermen village to a modern metropolis with about 12 million populations since the reform and opening policy in 1978 [94].

A case study on 3 markets of Shenzhen has received increasing attention. Arsenic (As), Cd, Cu, Hg, and Pb in 10 popular shellfish species and associated health risks were analyzed for Shenzhen's consumers by evaluation of estimated weekly intake (EWI), non-carcinogenic and carcinogenic health risks to the 3 stages in a human life-cycle (children, adolescents, adults) [95]. Based on 50 shellfish samples in each site of market there, they found that the levels of inorganic arsenic (iAs) in *Babylonia areolata* exceeded the maximum permissible-limit decided by the food safety guidelines (0.5 mg/kg), while other elements were below the limit of the guidelines as shown in Ministry of Health of the PR. China: GB 2762–2012. EWI values of the 3 stages of human development were lower than provisional tolerable weekly intakes (PTWIs) of all shellfish species. Analysis of the total target hazard quotients (TTHQ) showed that the consumption of *B. areolata* in all stages of people would cause non-carcinogenic risks; as for children (< 10 years old), the ingested *Argopecten irradians* and *Chlamys farreri* were at non-carcinogenic risks. As for children, adolescents, and adults, the bioaccumulation of Cd caused by shellfish consumption (*A. irradians, B. areolata, C. farreri*, and *Crassostrea ariakensis*) would lead to cancer risk during life-time, with Pb and iAs to be toxicity acceptable or negligible [96].

From the perspective of species, the concentration of Zn and Cu in the *C. ariakensis* was the highest, the concentration of Cd in *C. farreri* was the highest, and the concentration in the *Sinonovacula constricta* was relatively low. From the regional differences, Cd content in *C. farreri* of Dandong was the highest; the overall concentration of heavy metals in Qingdao was relatively low; Cu and Zn concentration in *C. ariakensis* and Cd concentration in *C. farreri* of Zhoushan were relatively high; Zn and Cu content in *C. ariakensis* of Shenzhen was the highest. The calculated daily intake-limit-results show that the feeding rate in the *C. farreri* only is 0.04 ~ 0.15 kg/d to reach the limit of Cd, and the feeding rate of Zn, Cu and Cd in the *C. ariakensis* is less than 1 kg/d can reach the limit value.

The results of the risk assessment showed that the weekly intake of heavy metals by eating shellfish did not exceed the provisional tolerable weekly intake set by Joint Expert Committee on Food Additives (JECFA*, *JECFA, 2010. Joint FAO/WHO Expert Committee on Food Additives, Summary and Conclusions by the JECFA.), and there was no non-carcinogenic risk to the human body. However, in terms of the long overdose of all sampling points of the *C. farreri* and *C. ariakensis* in Dandong, the accumulated Cd has a potential carcinogenic risk to the human body.

7. Persistent organic pollutants (POPs) in mangroves of China

Overuse of POPs like plastic bags pollutes mangrove stands and POPs are hardly decomposed in mangrove ecosystems and consequently degrade habitat for most living organisms in a mangrove stand. The value of mangrove environment is getting worse by accumulation of the POPs, therefore, we should know the effect of POPs on mangrove plants as well as ecosystem for improvement of rehabilitation strategy of degraded mangrove stands.

7.1 Microplastics

Microplastics (MPs) researches have been mainly investigating on food-web and bioconcentration in Japan [97]. For example, in Tokyo Bay, the bowel of several kinds of seabird, sardine, etc. contains huge amount of MP. In detail study on a kind of seabird (*Puffinus tenuirostris*), this bird cannot eat foods due to full with MPs in the bowel. Much worse, the accumulated MPs in their stomach gradually release toxic substances [98], such as PCB. Now, if we eat such polluted sardine, our health condition would not be injured. However, we cannot deny the harmful effects of PCB and related toxic substances in MPs.

MPs are now worldwide serious problem [97, 99]. MPs have a long life-span in ecosystem and become smaller in size of less than 5 mm over time, and deposit toward deep sea [9]. The existence form of MPs in south China was classified as fiber, film, and fine particle with several colors of original products [99]. At the 6 mangrove stands located along the coast of Southern China, the top 3 MPs were detected as health safety substance, including polypropylene (PP), polyethylene (PE), and polystyrene (PS). In terms of shape, color and size, MPs were mainly fibrous, white-transparent and 500 μm-5000 μm, respectively. MPs pollution in mangroves was significantly linked to surrounding socio-economic development. The TOC and silt content of mangrove sediments also affect the deposition of MPs [99]. Based on a comprehensive evaluation using the potential ecological risk factor, potential ecological risk, polymer risk index and pollution load index, MPs showed highest ecological risk in Futian mangrove of Shenzhen, China. These fundamental data on MPs occurring in mangroves of Southern China could support further studies of the ecological consequences of MPs on mangrove macro-fauna, shrimp, fish and even human.

7.2 Polybrominated diphenyl ethers (PBDEs)

Unfortunately, polluted condition with MPs of mangrove forest is getting worse in Shenzhen. As harmful MPs, PBDEs (polybrominated diphenyl ethers) have recently been detected. PBDEs are structurally similar to PCBs and other polyhalogenated compounds. Exposure to PBDEs would cause problems in the hormone system, liver and kidney morphology, neuro-behavioral and sexual development [100, 101]. The health risk of PBDEs and PCBs are increasing, and these chemical compounds have been shown to reduce human fertility to some extent [97]. The amount of PBDEs in a mangrove ecosystem increases with increasing amount of organic matters in soil [95, 102]. Concentration [unit: ng/g-dw] of PBDE-209 in mangrove stands of Hong Kong was 0.5 ~ 5.4 except for Mai Po mangrove (47.2–112.0) opposite to Futian district of Shenzhen [103]. These values were lower than those of Shenzhen (2.1–1987.6) [102].

In Shenzhen mangroves, the levels of PBDE-209 [unit: ng/g-dw] were 2.1 ~ 110.0 in mangrove sediment and 180 ~ 600 in the leaves. The highest value was detected as 3600 in bark of the avenue trees in Beijing [104]. We found that PBDE-209 was the dominant PBDE congener in all six mangroves in China, including Yunxiao, Futian, Zhanjiang, Fangchenggang, Dongzhaigang and Dongfang [5]. Futian mangrove in Shenzhen was seriously polluted by PBDEs (in particular PBDE-209), compared to the other 5 mangrove wetlands. Total organic matter acted as an effective factor in affecting spatial distribution and ecological risk of PBDEs in sediment of mangroves. In 6 mangroves, sediments may pose low/moderate risk of exposure to penta- and deca-BDE congeners for sediment-dwelling organisms, with penta- and deca-BDE congeners to be major drivers of ecological risk. Furthermore, we explored PBDEs contamination in 4 urban mangroves of Shenzhen, including Shajing mangrove (SJM), Xixiang mangrove (SJM), Futian mangrove (FTM) and Baguang mangrove (BGM) [102]. Regarding urban functional zoning, urban mangroves were featured with industry district (SJM and XXM), central business district (CBD) (FTM), and ecological preserve (BGM) [105–107]. Our result showed that the ranking order of PBDEs contamination in urban mangroves was BGM ≈ FTM < XXM < SJM.

Compositions of PBDEs were complex in SJM, XXM, and FTM, with surface runoff to be the main source apportionment of PBDEs. Thus, in urban mangroves with different urban functional zonings, PBDEs accumulation in mangrove sediment and their bioaccumulation in mangrove plants were different. In the future, much work should be done to decrease e the input of PBDEs into the urban mangrove, such as the inspection of the illegal waste recycling sites and promotion of sewage treatment capacity of PBDEs-related enterprises.

7.3 Other POPs

Levels of polycyclic aromatic hydrocarbons (PAHs: unit: [ng/g-dw]) in mangrove sediments of China ranged from 15 to 11,098 and decreased in the order of Hong Kong (56–11,098) > Fujian (171–1074) > Guangdong (15–726) > Hainan (31–63) > Guangxi (24) [11, 12, 108]. Higher levels of PAH s in Hong Kong mangrove might be attributed to the intense anthropogenic activities. Levels of PAHs in mangrove sediments of China (24–11,098) were far below effects range mean (ERM) (44,792), with levels of PAHs in Hong Kong to be lower than effects range low (ERL) (4022), indicating that PAHs in Hong Kong may pose little risk to biota in mangrove ecosystems [63, 108]. Li et al. (2014) explored PAH pollution in sediments of three mangrove swamps of Shenzhen, China, namely Futian, Baguang and Water-lands, and found that the mean concentrations of PAHs in Futian (4480) was higher than that in Baguang (1262) and Watersheds (2711) [109]. The higher levels of PAHs in Futian mangrove may be related to various anthropogenic activities, such as continuously discharges of domestic sewage from households and Fengtang River, effluents from industrial processes, construction of highways and heavy traffic [48].

In China including Hong Kong, Guangdong, Guangxi, Hainan and Fujian, levels of polychlorinated biphenyls (PCBs) in mangrove sediments ranged from 0.1 to 47 ng/g dry weight [110–113]. In general, PCB concentrations in mangrove sediments from Hong Kong, Shenzhen, and Zhuhai were relatively higher, indicating heavily PCBs-polluted mangrove sediments in the Pearl River Estuary to some extent [114]. The higher PCB levels in sediments from Pearl River Estuary could be linked to high density of electronic/electrical industries and electronic waste recycling activities [110].

Other organic pollutants in mangrove sediment were limited. Total petroleum hydrocarbons (TPHs) in sediments were reported to be 32–579 mg/kg-dw and a higher level was observed in the Pearl River Estuary, China [82, 115], which mainly derived from vehicle exhausts and incomplete combustion [82, 88]. Tam et al. (2008) reported that the levels of dichlorodiphenyltrichloroethanes (DDTs) and hexachlorcyclohexanes (HCHs) were 28 and 0.07 ng/g-dw in Leizhou Peninsula [116].

8. Education effort

8.1 General effort

Although Chinese ecological policy was proposed, ecological and environmental education should be made for conservation and increasing ecological services of mangrove forests [31, 98, 117]. In China, the environmental education mainly focused on the popular science and propaganda of mangrove reserve and park [97, 118–120]. Since there are multiple education stations in China, we show an example of Shenzhen because mangrove species are applied as the symbolic woody plants for the city. The City Hall shows SDGs (sustainable developmental goals) to the public with both ordinal (indoor type) museum as well as field museum (outdoor type). The former exhibits basic information of mangrove ecosystem by indoor exhibition. The latter mainly shows 2 parts; one is a practical method of how to rehabilitate mangrove stand at water front and the other is to conduct ecological research, including pollination biology, vegetation, etc.

8.2 Indoor and outdoor exhibition

Shenzhen shows all aspects of mangrove conservation and the latest advances in natural education at the city museums. The museum is unique in interactive exhibits, such as many educational quizzes about how to develop mangrove forests as well as to conserve the ecosystem. There are two field museums on the coast of Shenzhen: (1) one is a kind of park to walk in mangrove stand along with the interior experience of different species of forest stands, and (2) the other is to show the ecological rehabilitation of mangrove stands (**Figure 10**).

Figure 10A showed the rehabilitation of mangrove stands in Futian mangrove in Shenzhen. In order to improve ecological function of mangroves [121], the rehabilitation of Geiwai pond in mangrove ecosystem was conducted (**Figure 10B**). Among

Figure 10.
Example of mangrove ecosystem rehabilitation in south China. (A) Rehabilitation of mangrove stand; (B) Rehabilitation of Geiwai pond of mangrove ecosystem; (C) Typical example of mangrove ecosystem plantations by Prof. Changyi Lu of Xianmen University.

these trails, a distinguish exhibition for both tourists and education of mangrove park was established and popular trees were provided to the public near Xiamen, Fujian province, southeast China (**Figure 10C**). The star shaped mangrove restoration indicated that suitable mangrove species selection and planting design would create a beautiful landscape. This is a park showing a symbol of restoration success with mangrove.

8.3 Non-Government Organization in education effect of mangrove

The protection of mangrove in Shenzhen was closely related with large amounts of non-governmental organization (NGO) and volunteer groups. In 2017, the number of professional volunteers registered in Mangrove Conservation Foundation (MCF) exceeded 300, with 198 newly trained volunteer in one year, and 100,000 people participated in relevant activities in three years. In Shenzhen, China, the above-mentioned citizen acted as the volunteer labor group for Futian mangrove ecological park. These volunteers mainly come from enterprise, residence community and school, and took part in various environmental improvement activities,

Figure 11.
Activities carried out by nongovernment organizations. (A) Marine protection activity; (B) vein painting of popular science education; (C) display board of natural education. All photos were offered by RL Li and MW Chai.

including cleaning of invasive plants, collection of marine garbage, replantation of plant, and construction of ecological floating island, etc.

The implication of these activities increased volunteer number of mangrove protection in Shenzhen. Furthermore, there were also a certain number of volunteers in Overseas Chinese Town (OCT) wetland, Shenzhen Green Fund Association, Shenzhen Spring Environmental Protection Volunteer Association. Some activities related with mangrove education was implicated to improve protection awareness of mangrove protection (**Figure 11**).

9. Future perspective

Anthropogenic pollution in mangrove ecosystems has been intensively studied (including heavy metals and POPs, etc.) and consequently we can obtain many phenomena of current situation, such as sea level-rise [27, 122–124]. Based on the data of mangrove ecosystems in China, we should make further progress in increasing ecological services and forest rehabilitation. In the future, we believe that several aspects should be further explored to improve mangrove afforestation and restoration: (1) Ecological adaptation mechanism of mangrove species under various environmental stresses; (2) The development of mangrove plant breeding and colonization techniques; (3) The remediation of degraded mangrove ecosystem; (4) Digital technology research and development in mangrove ecological engineering.

Ecological exploitation of mangrove would create better ecological environment, economic and social benefits, being important for sustainable development of mangrove resource in the future. Several countermeasures are included to engage ecological exploitation of mangroves: coordinating development and alleviating the contradiction between protection and development; promoting diversified ecological development based on local conditions; improving the economic benefits of ecological development by scientific evaluation; improving relevant policies and plans while promoting regional cooperation and scientific research. We hope our data may contribute for improving restoration practices in the rapid economic development regions.

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