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Restoring wetlands outside of the seawalls and to provide clean water habitat

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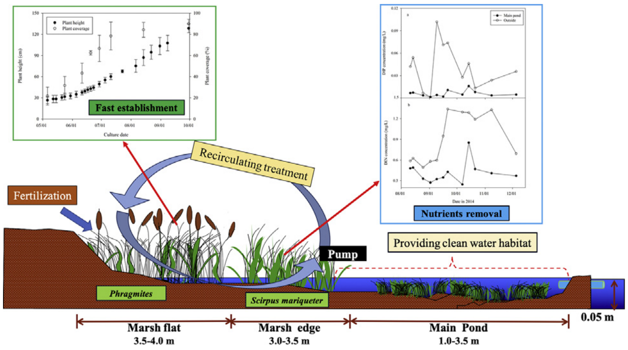
HIGHLIGHTS

- A case of restoring coastal wetlands outside of the seawalls was present.
- A fast growth of *P. australis* was achieved.
- The restored wetland can remove excess nitrogen.
- It can resist disturbances such as hurricanes and algal blooms.
- It can act as micro-habit for local aquatic organisms.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, we reported a practice at northern Hangzhou Bay, southeast China aimed at restoring coastal wetlands within the intertidal zone outside of the seawalls. The principle idea is protecting the site and helping the marsh establishment by engineering measures, and thereafter, relieving the protections to encourage the self-organization of the restored ecosystem. The results of this implementation showed the marsh reached an average vegetation cover of 70% in the first year. The excess nitrogen was removed by an ecological recirculating treatment system, which was coupled in the wetland. The long-term performance of the wetland suggested that it could resist disturbances such as hurricanes and algal blooms, and provided clean water habitat for aquatic fauna. By presenting the case of Hangzhou Bay, we call for more novel coastal restoration implementations that aim to create new boundaries with engineering features and self-organization, which benefit both human and nature.

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1. Introduction

Coastal wetlands serve as natural barriers to prevent shoreline erosion, diminish nutrient runoff, sequester carbon, and provide refuge habitat for fish and crustaceans (Gedan et al., 2011; Gedan et al., 2009; Leonardi and Fagherazzi, 2015; Sousa et al., 2012). Although coastal wetlands have been considered resilient to climate change and sea-level rise, humans abate the strength of these feedbacks by overloading nitrogen, reducing sediment subsidence rates, and reclamation (Deegan et al., 2012; Kirwan and Megonigal, 2013; Mariotti and Fagherazzi, 2013). In China, over the past two decades, coastal wetlands have been enclosed by thousands of kilometers of seawalls to create extra land for the rapidly growing economy. By building the “new great wall”, coastal wetlands were reclaimed to farmlands to produce economic benefit. However, this “new great wall” causes huge losses of ecosystem services annually, and has negative impacts on global shared ecological security, such as converting coastline from pollutant sinks to sources, alternating the coastal food web, and declining water bird populations in the East Asian–Australasian flyway (Ma et al., 2014).

In developed countries such as the USA, the Netherland, coastal wetlands have also experienced a long history of destruction and alteration by human activities (Gedan et al., 2009). Since 1980, in the USA, the loss of coastal wetlands has been restricted due to legislation and the loss must be compensated for if they are inevitable (Robertson, 2006). To address the issue of coastal wetland loss, many restoration projects have been launched in those developed countries. Mostly, this is done by returning reclaimed lands to tidal coastal wetlands, either by breaching the dikes to restore tidal flow, constructing the culverts, or lowering raised outer dike areas (Maris et al., 2007; Teal and Weishar, 2005; Warren et al., 2002). It is expected that with time, restored tides would return ecological functions and attributes characteristic of a fully functioning coastal wetland (Roman, 2012; Zedler, 2000).

For most of the developing countries, it is difficult to mimic the experience of developed countries. Avoiding the destruction of coastal wetlands is always the cheapest option. However, for the coastal areas that have been reclaimed and made for agricultural or residential use, directly returning the land to tidal coastal wetland is somehow unacceptable when considering the benefits of the local residents. Developing an effective way to restore coastal wetlands, in the presence of the “new great wall,” is urgently needed. Here we reported a practice at northern Hangzhou Bay, southeast China, which illustrates an alternative way for restoring coastal wetlands. This implementation varies from traditional restoration practices because the seawall was not directly breached to increase tidal flushing, but rather rebuilt by restoring coastal wetlands within the intertidal zone outside of the seawalls. We expected that the “rebuilding” of the “new great wall” could be achieved by coupling “ecological engineering” with “hard engineering” to facilitate the growth of tidal marshes, and provide clean water habitat for aquatic fauna.

2. Materials and methods

2.1. Study area

The study site is located at northern Hangzhou Bay, Fengxian district, Shanghai. This region is one of the most developed areas in China with high population density. Historically, coastal wetlands encompassed the shoreline of northern Hangzhou Bay. Since 1980, the coastal wetlands were repurposed to create extra land for the growing economy. Recently, the local government and citizens became aware of the important ecosystem services of coastal wetlands, and reclamation has been prohibited. However, most of the shorelines have been enclosed by seawalls, with only a few tidal marshes outside of the seawalls. These remaining tidal marshes are vanishing quickly mainly due to insufficient supply of sediment. In order to find a proper approach to restore coastal wetlands, a local site named Bihaijinsha was chosen as a pilot study (30°49′26.01″ north; 121°33′41.39″ east).

This pilot site is outside the seawall, and its total area is about 6500m^2. Previous field investigations indicated the difficulties that may arise that could inhibit outside-seawall restoration, including: ①Erosion. During the growing season, the predominant wind direction is southeast, and the wind force increases the average wave height to 0.5 m, with the maximal value of 3.9 m. Therefore, the erosion effect would induce a rapid loss of wetland sediment during restoration implementation; ②Hurricane. From July to October, hurricanes tend to disturb the North Hangzhou Bay, and destroy the newly transplanted marsh; ③ Eutrophication. Due to the excessive anthropogenic nitrogen loads, the Hangzhou Bay now is in a hyper-eutrophic state, with dissolved inorganic nitrogen (DIN) concentration approaching to 1 mg L^{-1}. It was recorded that the algal blooms occasionally occur in spring and summer.

2.2. Restoration approach

Since there is relatively little knowledge about restoring coastal wetlands outside of seawalls, we had to develop our own approach. The main idea of the design (Fig. 1) includes:

2.2.1. Recreating the wetland terrain to sustain the marsh establishment

As the Bihaijinsha site is a reprehensive seawall type shoreline, the elevation of the outside zone is low, with an average value of 2.5 m, about 1.3 m lower than the mean high tide. According to previous studies (Mendelssohn and Kuhn, 2003), we concluded that raising elevation to a suitable height could be an effective way maintain vegetation growth. However, to create a marsh platform the external soil is needed, which is an expensive resource. This problem was solved by recreating the wetland terrain as shown in Fig. 1. About 2000 m^2 wetland area was dug to 2 m deep to form a shallow pond (Main pond as shown in Fig. 1). This shallow pond, located at the lowest place of the wetland, was about 2000 m^2 in area, with 2 m deep. Meanwhile, the dredged sediment was deposited to the remaining wetland areas (4500 m^2) to increase the elevation above 3.5 m, and thus created a suitable environment for plant growth. *Phragmites australis* was transplanted as the dominant species because it is a relatively fast growing, native species. The plant was first transplanted in late April 2014.

Moreover, we expected that through the creation of shallow pools within the restored site, food availability would increase creating an important source of prey within the coastal regions (Larkin et al., 2009; Minello and Rozas, 2002). To further investigate the effect of restoration on the zooplankton biomass, we set up a fish-free enclosure (2 m × 2 m, made up of 200-mesh net) in main pond to exclude the predation effect of fish on zooplankton.

2.2.2. Constructing eco-dike to protect the wetland terrain and control water exchange

As the wetland was being restored outside the seawalls, strong wave forces would damage the wetland terrain. To maintain a stable landform, we designed an eco-dike, which was about 5 m in height (1.2 m higher than mean high tide), with the foundation made of stone blocks. Its surface layer was covered with gravel material, amounting to 40 cm deep, with grow bags buried within to facilitate plant growth through the cracks. A culvert was constructed at the lower part of the eco-dike to connect the inside wetland (with main pond), and outside water, so that the tide could reach the restored wetland. Furthermore, by controlling the valve of the culvert, we could control water exchange and maintain a desired water level. We determined that the “culvert-valve control” was crucial for outside seawall restoration because during a growing season, a low water level is essential for the survival of newly transplanted plants, which benefits the marsh establishment.

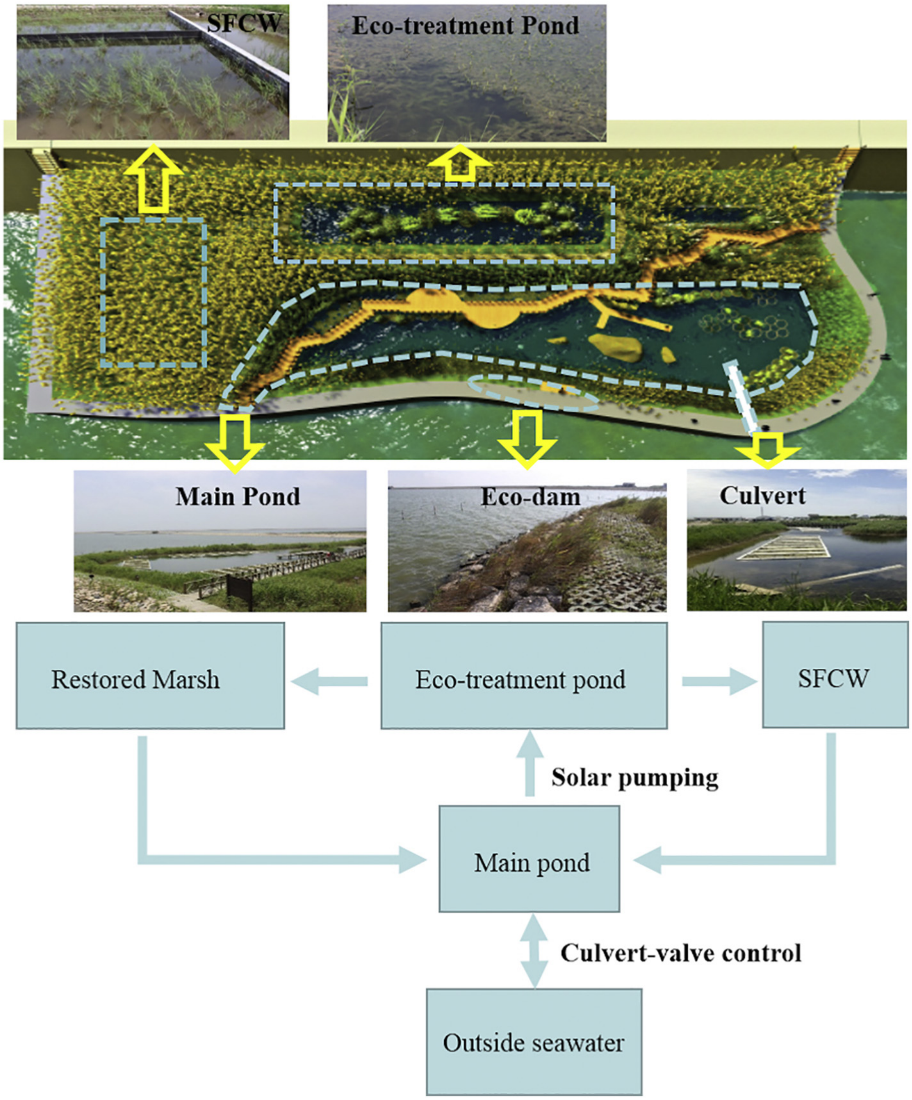

Fig. 1. The main idea of the design.

2.2.3. Fertilization and nutrient control

We hypothesized that outside-seawall restoration will lead to faster marsh establishment than normal restoration because the vegetated marsh can protect the soil from erosion, and thus help to stabilize the wetland terrain. Previous restoration cases showed that on average the marsh reached 10–20% cover the year following restoration, and 50% cover approximately 6 years after restoration (Hinkle and Mitsch, 2005; Weinstein et al., 1996). To enhance the growth of plants, the wetland was fertilized during the growing season. To our knowledge, fertilization was rarely implemented in previous restoration practices (unless experimental studies) because the nutrients would be washed away from the marsh platform by the heavy rain, and induce wetland water quality deterioration, as well as export excessive nitrogen to the nearby seawater. In our restoration plan, to reduce the nitrogen output, the culvert was closed after fertilization, and thus the washed nutrients would remain within the main pond, keeping the nutrients in the system. Moreover, an ecological recirculating treatment system was coupled into the restored wetland, based on our previous study (Chen et al., 2013). This system consisted of two units including eco-treatment pond and surface flow constructed wetland (SFCW). The eco-treatment pond was about 500 m^2 in area, with 1.5 m depth. It was located at the highest place of marsh platform, and was planted with submerged macrophytes - *Myriophyllum spicatum* to enhance its nitrogen removal capacity. The SFCW (about 500 m^2, 20 cm deep) located at the lower place of marsh platform, and was planted with *P. australis*. To remove the nitrogen, about 300 $m^3\ d^{-1}$ of water from the main pond was pumped to the eco-treatment pond by a solar pumping system. After that, about two thirds of the water flowed to the SFCW, with the remaining water flowing to the restored marsh area; after treatment all the water flowed back to main pond.

2.3. Sampling and analysis

Water samples were taken from the main pond and outside tidal area, and the influent and effluent of the eco-treatment pond and SFCW. The samples were placed in a cooler immediately after collection and were analyzed within a week. The water was filtered by glass fiber filter first, and then analyzed for NH_4^+-N, NO_3^--N + NO_2^--N, and dissolved inorganic phosphorus (DIP) in the ultraviolet and visible spectrophotometer (UV-7504, Xinmao Co. Ltd., Shanghai, China). The NO_3^--N + NO_2^--N, NH_4^+-N, and DIP were analyzed by zinc cadmium reduction method, hypobromite oxidation method, and molybdate blue colorimetric methods, respectively (APHA, 1999). Dissolved inorganic nitrogen (DIN) was the sum of NH_4^+-N and NO_3^--N+NO_2^--N. Phytoplankton containing chlorophyll *a* in a measured volume of sample was concentrated by filtration through the glass fiber filter. The photo-pigments were extracted by grinding the filter with a tissue grinder and steeping the filter slurry in 90% aqueous acetone solution overnight. The filter slurry was then centrifuged to clarify the solution, and analyzed by spectrophotometer (APHA, 1999). Dissolved oxygen (DO) was measured in-situ by a Dissolved oxygen meter (HACH LDO101, USA). To evaluate the performance of the purification system, several variables, including pollutant load (L), pollutant removal capacity (R_c), and removal efficiency (R_e), were calculated as following:

The pollutant load (L, g m^{-2} d^{-1}) was expressed as:

$$L = \frac{C_0 \times Q}{A} \times 100\%$$

The pollutant removal capacity (R_c, g m^{-2} d^{-1}) was expressed as:

$$Rc = \frac{(C_0 - C_e) \times Q}{A}$$

The removal efficiencies of pollutants were calculated as:

$$Re = \frac{C_0 - C_e}{C_0} \times 100\%$$

where C_o (mg L^{-1}) is the influent pollutant concentration, C_e (mg L^{-1}) is the effluent pollutant concentration, Q (m^3 d^{-1}) is the influent flow rate, and A (m^2) is the effective surface area of the main pond or SFCW.

At the restoration site, 4 permanent plots (1 × 1 m) were set out for long-term investigation. Plots were monitored continuously during the growing season after the first year of restoration (May 6th to September 3rd, 2014). During each survey, the average height of plants was measured and calculated. The cover of each plot was estimated as % relative to the plot's surface area. Phytoplankton, zooplankton samples were taken from water within the main pond each season in the year of 2014 and 2015. Thereafter, samples were only taken in late September for evaluation. The abundance of phytoplankton and zooplankton was manually counted with a microscope, and the diversity index (Shannon's Diversity Index) was calculated, accordingly.

3. Results and discussion

3.1. The establishment of marsh

The growth of *P. australis* is shown in Fig. 2. The results showed that *P. australis* grew well after transplantation, and the average cover achieved 70% in the first year of restoration, which was much faster than previous restoration implementation cases. The results also suggested that "Culvert-valve control" combined with fertilization could enhance marsh establishment. The restored wetland was fertilized on June 15 and 16, 2014. About 40 kg urea, equal to 18 kg N was evenly added to the field. At the same time, the culvert-valve was closed and the inner water level of the wetland was controlled to 3.3–3.4 m, about 0.1 m lower than the marsh platform. Before treatment, the height of *P. australis* increased slowly, averaged to 0.31 cm d^{-1}. After treatment, from July 17 to October 3, the height of *P. australis* increased from 40 cm to 130 cm, averaged to 0.9 cm d^{-1}. Fig. 3 recorded the overview of the wetland within the first year of restoration. The picture shows the clear marsh growth after transplantation, and on August 4 the majority of the wetland was covered by the vegetation. The fast growth of *P. australis* in our case indicated that "culvert-valve control" combined with fertilization could be a possible way to fight against extreme conditions, and accelerate restoration.

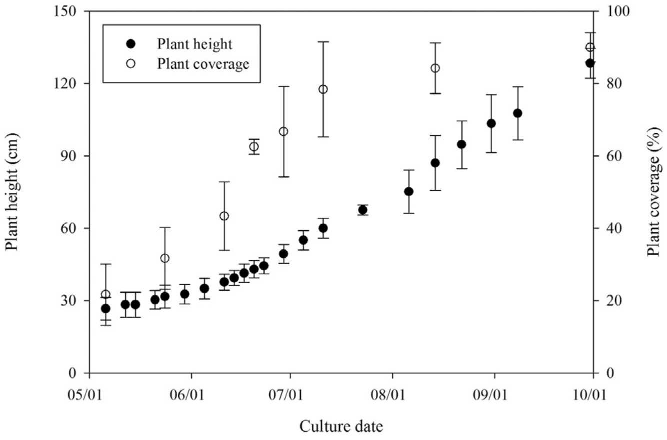

Fig. 2. The growth of *P. australis*.

3.2. Control of nitrogen

The excess anthropogenic nitrogen input is the main cause of eutrophication in estuaries and coastal waters (Jani and Toor, 2018). This study suggested that restored wetlands had the ability to mitigate external nitrogen loading. From late May to early August, the culvert was closed to maintain a low water level (3.0 m) and keep the nutrients within the system. Since August 11, the culvert was opened, connecting the main pond to the outside sea water. To maintain water quality and reduce the nitrogen output, the inner water of the restored wetland was recirculated during the experiment.

Fig. 4 shows the variation of NH4+-N, NO3–N+NO2–N, DO, DIN and DIP in main pond and outside seawater. The $NO_3^- + NO_2^-$, DIN and DIP in main pond was consistently lower than that in nearby seawater during the first year of restoration, indicating the high performance of the ecological recirculating system (Fig. 4). The NH_4^+ in main pond was always below 0.15 mg L^{-1}, and the DO was approaching to saturation condition, which indicated that the habitat was adequate for the growth of aquatic fauna. Fig. 5 shows the average removal efficiency of DIN by eco-treatment pond and SFCW. Planting with *Myriophyllum spicatum*, eco-treatment pond performed well at nitrogen removal with an average removal efficiency as high as 81.8%. The DIN removal capacity of eco-treatment pond was between 0.1 and 0.3 g N m^2 d^{-1}, with an average value of 0.19 g N $m^2 d^{-1}$. For SFCW, as the DIN in the inlet was reduced to below 0.1 mg L^{-1} by the eco-treatment pond, suggesting it had no steady nitrogen removal during the experiment.

Previous wetland restoration implementations usually focus more on vegetation growth than water quality. On the other hand, recent studies suggest that ponds within marshes have high ecosystem importance, especially for providing habitat, and supplying food for fishes and other aquatic fauna (Larkin et al., 2009; Minello and Rozas, 2002). In our restoration case, we utilized *Myriophyllum spicatum* pond and SFCW to remove nutrients and maintain water quality. Interestingly, the results of our long-term recirculating operation suggested that *Myriophyllum spicatum* pond had a substantial capacity in removing nitrogen with an average of 0.19 g N m^{-2} d^{-1}, amounting to 95 g N d^{-1}. Such nitrogen removal might be attribute to the assimilation of the plant and denitrification at sediment-water interface (Liu et al., 2016). The water quality of the system was properly maintained during the studies, despite whether outside high nitrogen water entered the system. This result suggests that *Myriophyllum spicatum* pond was a simple and useful measure to maintain the water quality, while restoring the wetlands of the eutrophic estuary. For SFCW, it showed hardly any nitrogen removal, most likely because the nitrogen removal was associated with nitrate concentrations, while the nitrogen concentration in the inlet of SFCW was low after treated by *Myriophyllum spicatum* pond. The poor performance and relatively high cost of SFCW here suggested that it could be omitted when the external nitrogen load was low, and the *Myriophyllum spicatum* pond performed well in the nitrogen removal.

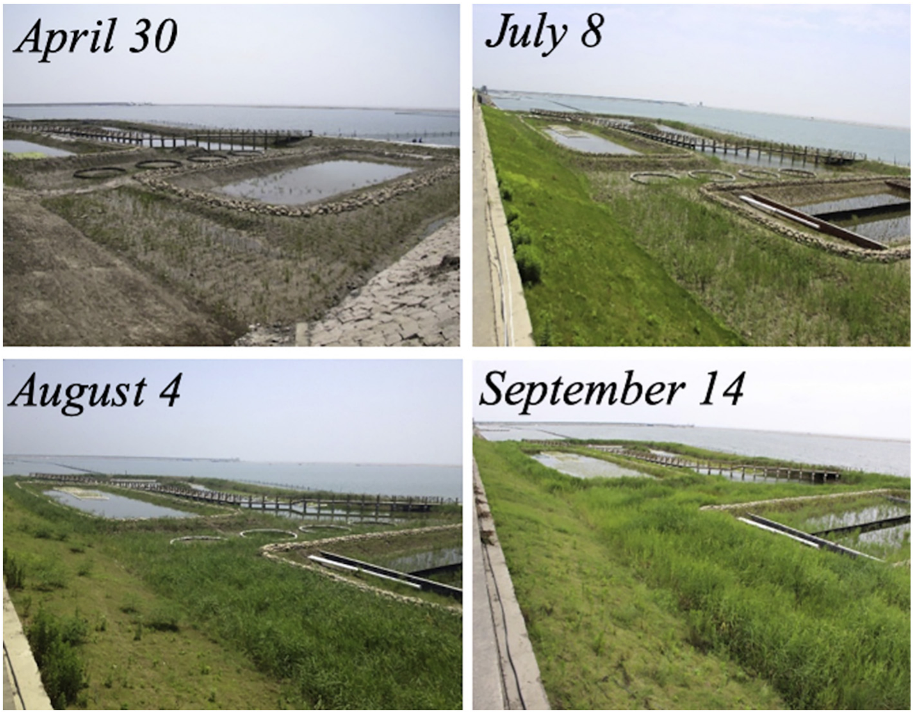

Fig. 3. The overview of the wetland during the first year of restoration.

3.3. In response to disturbance

During the study, the restored site had undergone two extreme weather events. The first event was the typhoon Fung-wong, which made landfall on September 23th, 2014. Unfortunately, the restoration site was just in the center of this typhoon (Ke and Yang, 2014). After the typhoon, we checked the site, and found minimal damage, without any loss in marsh or sediment. Fig. 6 recorded the scenes before and after the typhoon landfall. The second event occurred on October 12th–13th, 2014, when it was an astronomical tide, coming together with typhoon Vongfong. The astronomical tide and typhoon-induced storm surge slammed the wetland, and for >10 h, the whole site was flooded, with the average water level above 5.88 m, and the surface water reaching >1 m deep (Shanghai water resources bulletin, 2014). We checked the restoration site the day after the event, and saw no vegetation loss in the newly established marsh, with only a small portion of the wetland terrace being eroded (Fig. 6c). The restored site also showed its resistance to algal blooms. On September 9, 2014, an algal bloom occurred in the nearby seawater, with Chl a raised to 350 μg L^{-1}. However, the Chl a in main pond remained as low as 10.7 μg L^{-1}, and there was no obvious change in the value during the event. This result indicates that the restored wetland could become a suitable habitat for protecting the aquatic animals from harmful algal blooms.

3.4. The long-term performance of the wetland after restoration

After marsh establishment was accomplished, since August 11th, 2014, the valve of the culvert was turned off to let the tidal water circulate within the system, and to facilitate a mature, self-sustaining wetland that simulates natural tidal wetlands. Table 1 summarizes the performance of the wetland four years after restoration. It can be inferred that without manual intervention, the marsh grew well and the nitrogen and phosphorus water levels were quite low. Meanwhile, the *Myriophyllum spicatum* expanded within its areas, reaching to >70% of the main pond, and >90% of the eco-treatment pond. As the macrophytes gradually expended throughout the water body, the water quality within the system was kept at healthier levels than the outside seawater, and the restored wetland provided fine habitat for aquatic fauna. The biomass of the phytoplankton in the main pond sharply decreased from 1.93×10^7 ind. L^{-1} to 2.67×10^4 ind. L^{-1}, however, the Shannon's Diversity Index of phytoplankton increased from 1.03 to 1.6. The dominant species of phytoplankton in the main pond switched from *Peridinium minutum* (toxic algae) to *Cyclotella* sp. *and Navicula* sp., which are preferred food source for juvenile shrimps. Correspondingly, the biomass of zooplankton increased after the restoration, from 30 ind. L^{-1} to 127 ind. L^{-1}, which was about 10 folds higher than that in the outside seawater, suggesting that the restored coastal wetland could provide a more abundant food resource for coastal fish. Nevertheless, the zooplankton biomass in fish-free enclosure in the main pond was as high as 266 ind. L^{-1}, which was about 2 folds higher than that in the main pond. This result further indicated that a large portion of zooplankton biomass in this restored wetland could be utilized by fish.

Recent studies suggest that restoration propagules planted in clumps mutually benefit each other, due to positive interactions between immediately neighboring marsh plants that can alleviate physical stress, such as anoxia and erosion (O'Brien and Zedler, 2006). The larger-sized clumps experienced greater growth and survival, ostensibly because of reduced stress relative to overall patch size, and thus could enhance the restoration in high stress areas, such as the low intertidal (Silliman et al., 2015). However, for restoration within harsh environments like intertidal zones outside of seawalls, even clumping designs could not achieve successful marsh establishment due to the destructive forces of waves and currents (Sutton-Grier et al., 2015). The practice at Hangzhou Bay indicated a feasible way for coastal wetland restoration in high stress areas, which is to create large composite patches instead of small planting clumps. With the help of engineering measures, a sustainable growth and self-organization of marshes in these patches can be ensured. More importantly, we expected that these large patches might act as micro-habit for local aquatic organisms, and provide provenances for the coastal regions. The results of our four year' study suggests the feasibility of this measure. However, the change

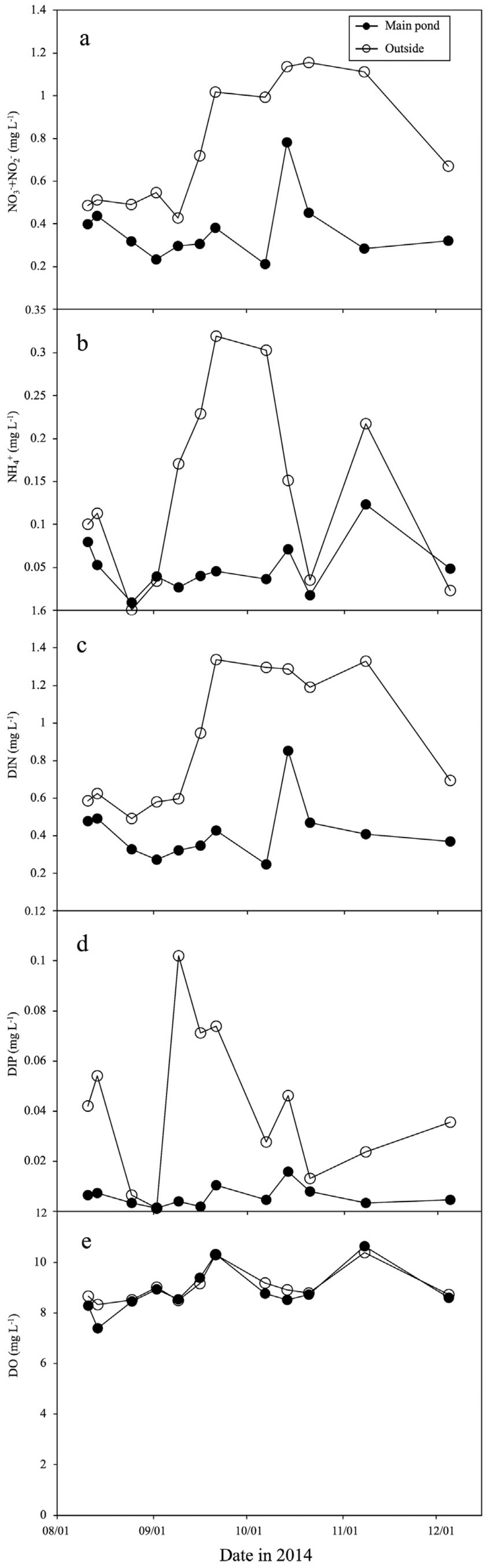

Fig. 4. The variation of the concentrations of $NO_3^- + NO_2^-$ (a), NH_4^+ (b), DIN (c) and DIP (d).

of ecosystem structures and functions of the restoration site should be more carefully evaluated by long-term investigations. The hypothesis that a composite vegetation patch, as previously described, could positively impact the biodiversity of nearby coastal regions should be verified by future studies as well.

3.5. Implication for future implementation

In developing countries such as China, within a long duration, restoring coastal ecosystem functions must deal with existing seawalls and outside intertidal areas, as space is limited due to coastal development (Ma et al., 2014; Murray et al., 2014). Divided by seawalls, the outside intertidal area usually slopes steeply downward to the deep water or sometimes slopes gently, but with a fairly high tidal range that is not suitable for marsh establishment (Li et al., 2014). The practice in Hangzhou Bay provides a feasible mean for outside-seawall restoration; that is to create a type of wetland terrain containing both marsh platform and ponds, and protect them by a semi-enclosed "eco-dike". Furthermore, by fertilization and culvert-valve control, a suitable microenvironment can be created that facilitates rapid plant growth. After marsh establishment was completed, the eco-dike was opened to enable tidal access, and thus further encourage a self-sustaining wetland to develop ecosystem functions, as well as ecosystem services.

In order to mitigate the coastal wetland losses, Chinese government recently launched a series of nationwide restoration projects along the coastal zone called "Blue Estuary Project" (Zhao, 2017). About 6 billion RMB would be spent on the coastal restoration each year from 2016 to 2020. Prior to implementations, to determine the basic principles as well as the frameworks that fit the local condition is urgently needed. The practice at Hangzhou Bay illustrates an alternative practice for future coastal restoration, with its principle idea that protecting the

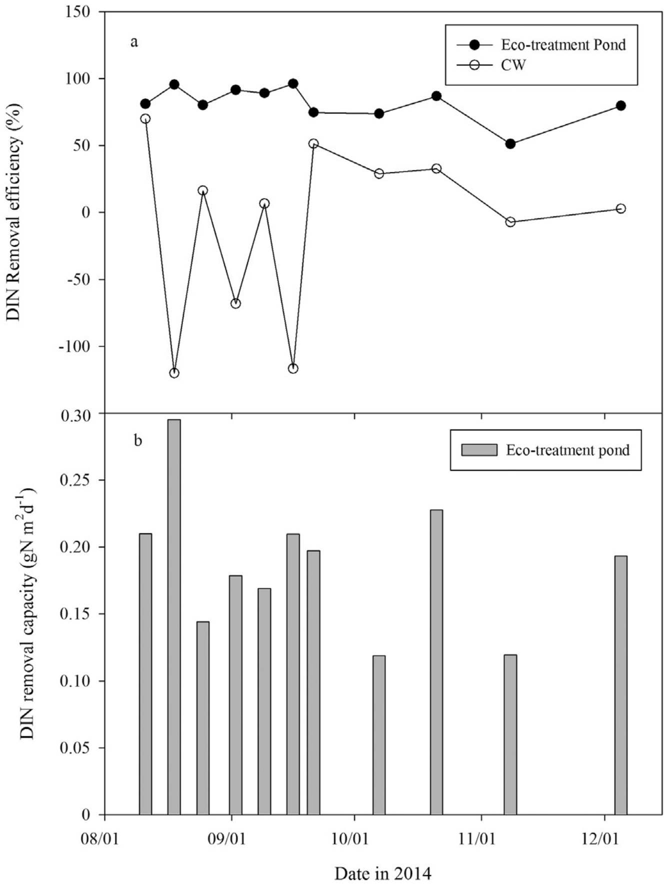

Fig. 5. The nitrogen removal efficiency by the eco-treatment pond and SFW.

Fig. 6. The appearance of wetland after typhoon landing. a) The overview of the wetland before typhoon Fung-wong; b) The overview of the wetland after typhoon Vongfong; c) Erosion caused by the tide and typhoon-induced storm surge.

Table 1
Performance of the Bihaijinsha wetland after restoration.

Values in main pond	Sampling time			
	2014, September 21th	2015, September 20th	2016, September 17th	2017, September 22th
DIN mg L^{-1}	0.43	0.12	0.041	0.031
DIP mg L^{-1}	0.011	0.0092	0.0030	0.0006
Chl-a μg L^{-1}	10.2	5.7	9.4	12.4
The abundance of phytoplankton ind. L^{-1}	1.93×10^7	6.35×10^5	2.89×10^6	2.67×10^4
The diversity index of phytoplankton	1.03	1.02	1.6	1.2
The abundance of zooplankton ind. L^{-1}	30	27	122	127
Marsh cover %	70	90	90	90

restoration site and helping the marsh establishment by engineering measures, and thereafter, relieving the protections to encourage the self-organization of the restored ecosystem. The cost of this kind of restoration is affordable for China and other developing centuries. Take Bihaijinsha case for example, it cost about 2,000,000 RMB to restore the entire 6500 m^2 area (50 m width,130 m long), averaged to 3,250,000RBM (500,000 USD) per hectare, or 16,000RMB (2500 USD) per meter coastal line. If 3billion RMB for the “Blue Estuary Project” was invested in “outside-seawall restoration” every year, it could be calculated that >180 km coastal lines could be restored, accordingly. Moreover, the performance of the Bihaijinsha wetland suggested that outside-sea wall restoration successfully brought back ecosystem services such as retaining nutrients, providing refuge habitats for the juvenile fish and shrimps, and preventing shoreline erosion.

Owing to successful restoration implementation of the Baihijinsha site, a large-scale outside-seawall restoration (43 ha) was supported by Chinese central government as a demonstration case of “Blue Estuary Project”. We designed the entire system by drawing on the experience of the Bihaijinsha site, and took it a step further to make it a wetland park for both civilians and aquatic fauna. The project was recently launched at Citizen Beach (30°42′13.94″; 121°20′10.34″), Jinshan District, Shanghai. A fast establishment of marsh was also achieved in this project, proving the restoration method was feasible. This restoration site, named as Yingwuzhou Wetland Park, was open to public in late 2017. Most importantly, in response to the challenges driven by both human activities and natural stresses, we have to think of reconstructing the boundaries between human and nature, by means of carefully designed engineering measures, coupled with the self-organization of ecosystems (Mitsch, 1993; Mitsch, 2014). These types of new boundaries are distinct from previous wall type boundaries made of concrete and steel, in that they are living systems encompassing both resistance and resilience.

4. Conclusion

The practice in Hangzhou Bay provides a feasible mean for outside-seawall restoration; that is to create wetland terrain containing both marsh platform and ponds, and protect them by a semi-enclosed “eco-dike”. Furthermore, by fertilization and culvert-valve control, a suitable microenvironment can be created that facilitates rapid plant growth. After marsh establishment was completed, the eco-dike was opened to enable tidal access, and thus further encourage a self-sustaining wetland to develop ecosystem functions, as well as ecosystem services. The results of this implementation showed the marsh reached an average vegetation cover of 70% in the first year. The excess nitrogen was removed by an ecological recirculating treatment system, which was coupled in the wetland. The nitrogen removal capacity of eco-treatment pond was between 0.1 and 0.3 g N m^2d^{-1}, with an average value of 0.19 g N m^2d^{-1}. The long-term performance of the wetland suggested that it could resist disturbances such as hurricanes and algal blooms. As the macrophytes gradually expended throughout the water body, the water quality within the system was kept at healthier levels than the outside seawater, and the restored wetland provided fine habitat for aquatic fauna. By presenting the case of Hangzhou Bay, we call for more novel coastal restoration implementations that aim to create new boundaries with “engineering features” and “self-organization”, which can benefit both human and nature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137788.

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