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Coastal wetland loss, consequences, and challenges for restoration

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Abstract: Coastal wetlands mainly include ecosystems of mangroves, coral reefs, salt marsh, and sea grass beds. As the buffer zone between land and sea, they are frequently threatened from both sides. The world coastal wetland lost more than 50% of its area in the 20th century, largely before their great value, such as wave attenuation, erosion control, biodiversity support, and carbon sequestration, was fully recognized. World wetland loss and degradation was accelerated in the last three decades, caused by both anthropogenic and natural factors, such as land reclamation, aquaculture, urbanization, harbor and navigation channel construction, decreased sediment input from the catchments, sea level rise, and erosion. Aquaculture is one of the key destinations of coastal wetland transformation. Profound consequences have been caused by coastal wetland loss, such as habitat loss for wild species, CO_2 and N_2O emission from land reclamation and aquaculture, and flooding. Great efforts have been made to restore coastal wetlands, but challenges remain due to lack of knowledge about interactions between vegetation and morphological dynamics. Compromise among the different functionalities remains a challenge during restoration of coastal wetlands, especially when faced with highly profitable coastal land use. To solve the problem, multi-disciplinary efforts are needed from physio-chemical–biological monitoring to modelling, designing, and restoring practices with site-specific knowledge.

Key words: coastal wetlands, functionalities, loss, consequence, restoration.

Introduction

The world's wetlands have been diminishing since the 19th century. Many wetlands were reclaimed for other use (e.g., agriculture) before their significance was recognized. Coastal wetlands, which lie between the land and the ocean, are threatened from both human activity and natural hazards, such as climate change, sea level rise, local subsidence, decreased sediment supply, and acidification.

According to the Ramsar Convention (Ramsar Convention Secretariat 2010), coastal wetlands include mangroves, salt marshes, seagrass, coral reefs, beaches, estuaries, and coastal water bodies within −6 m depth. Of these, mangroves and salt marshes are the most prominent. Mangroves are mainly distributed along tropical muddy coasts, with a total area of 150 000 km^2, while salt marshes dominate the muddy coasts from subtropical, temperate to sub-polar and arctic zones, with a total area of 45 000 km^2 (Scott et al. 2014, see also http://www.ramsar.org). But a century ago, the area of mangroves and salt marshes used

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to be at least 100% larger (Scott et al. 2014). The latest global coral reef assessment estimated that 19% of the world's coral reefs are dead, with warming sea-surface temperatures and expanding seawater acidification as major threats (Worldwatch Institute 2016). The exact area loss of seagrass is not clear because their distributions are not clear yet in many places. But the consequences of coastal ecosystem loss were obvious.

Lotze et al. (2006) divided human influences on coastal ecosystems into seven periods: prehuman; hunter gatherer; agriculture; market-colonial establishment; market-colonial development; global market 1900–1950; and global market 1950–2000. With the development of human economic stages, the status of marine mammals, coastal birds, fish, reptiles, invertebrates, vegetation, water quality, and invasive species have all faced serious deterioration, and the trend has accelerated since the global market economy began in the 1900s. The general deterioration trend continued after year 2000 with limited restoration efforts scattered at different sites. It is a critical time to stop depletion of this vulnerable ecosystem and make efforts to restore the coastal wetlands wherever possible.

The purpose of this paper is to provide a comprehensive understanding of the importance of coastal wetlands, their current status of losses and consequences at different regions, and challenges faced for restoration. Some recommendations are also proposed for consideration in the future conservation and restoration practices.

Importance of coastal wetlands

Coastal wetlands provide important services, such as food and bio-materials as direct resources, habitat for wildlife, carbon sequestration, protection against storm surges, and sediment accumulation for land accretion. They also provide water purification, tourism resorts, and other functionalities.

Bioproductivity and habitats

Although the area of coastal wetlands is rather small compared to many other terrestrial ecosystems, their productivity is comparable to the most productive ecosystems. For example, the average net primary productivity of mangroves is as high as that of the tropical rain forest (2.2 $kgm^{-2}year^{-1}$), while the productivity of algal beds and reefs (2.5 $kgm^{-2}year^{-1}$) is even higher (Whittaker 1975). The net primary productivity of temperate salt marshes (1.7 $kgm^{-2}year^{-1}$) is also higher than that of temperate forests (1.2–1.3 $kgm^{-2}year^{-1}$) (Whittaker 1975; Bertness 1999).

As key habitats for many terrestrial and marine species, vegetated zones and tidal creeks provide diverse shelter and food sources for a large variety of wild animals, resulting in high biodiversity and unique food webs. About two-thirds of marine animals, such as fish, shrimps, crabs, mollusks, and turtles, have to spend some time at coastal wetlands during their life history, and over 90% of marine fisheries are sourced from coastal zones, either through harvesting of wild organisms or mariculture (Hinrichsen and Olsen 1998). In the meantime, the coastal wetlands provide food sources and habitats for millions of waterbirds.

Carbon sequestration

In terms of carbon sequestered in the soil or sediments of different ecosystems, the mean long-term rates of carbon sequestration for salt marshes, mangroves, and seagrasses (>100 g C $m^{-2}year^{-1}$) are more than 20 times higher than that of the forest (<5 g C $m^{-2}year^{-1}$) (Mcleod et al. 2011). That is why "blue carbon" has become a great concern in the last decade (Duarte et al. 2005; Laffoley and Grimsditch 2009; Vaidyanathan 2011; Howard et al. 2017). Although freshwater wetlands are often considered a source of greenhouse gas emissions (Schlesinger 1997), coastal wetlands produce less greenhouse gas because sulfate-reducing bacteria in the saline water can inhibit the methanogens by outcompeting them for energy sources, especially in polyhaline tidal marshes (salinity >18) (Bartlett et al. 1987; Poffenbarger et al. 2011).

Carbon sequestration by mangroves, salt marshes, and seagrass beds is highly variable with estimations of combined global rates ranging between 0.23 and 0.77 Pg CO_2 year^{-1}, which is about 10%–13% of the global ecosystem CO_2 uptake (Hopkinson et al. 2012), while the total emission is estimated as 0.14–1.02 Pg CO_2 year^{-1}, equivalent to 3%–19% of the CO_2 emission caused by global deforestation (Pendleton et al. 2012). Overall, it is considered that there is a net uptake of CO_2 by the coastal vegetated wetlands.

Like the organic carbon in terrestrial ecosystems, most of the organic carbon in coastal wetlands is stored underground and insufficiently investigated (Schorn 1997). Donato et al. (2011) found that more than 90% of the organic carbon in the mangroves is stored in the soil and sediments, which is also the case for salt marshes (Lü et al. 2006). Carbon stored in the top 1 m of sediments was estimated as 1800–40 000 g C m^{-2} for seagrasses, 9000–54 000 g C m^{-2} for salt marsh, and 28 900–55 100 g C m^{-2} for mangroves, which are all much higher than that in the forests (Lavery et al. 2013; Ninan 2014).

Coastal protection

Mangroves and salt marshes protect the coasts and invaluable lives and treasures behind them. Dahdouh-Guebas et al. (2005) showed the significant difference between damage with and without mangroves after the Indian Ocean tsunami occurred in December 2014. Areas behind true mangroves were largely unaffected, while the cryptically degraded area dominated by associate species was destroyed. Villages protected by wider mangroves on the coast had significantly fewer deaths than ones with narrower or no mangroves (Das and Vincent 2009). When waves penetrate into the mangrove forest, they are diminished quickly (Massel et al. 1999), and the reduction of tsunami pressure can be 90% within 100 m in dense mangrove stands (Tanaka et al. 2007). According to a study at the Florida coast, a 7 km wide strip of mangroves can reduce more than 70% of wave height during hurricanes (Zhang et al. 2012). In salt marshes, the wave height decreased exponentially with the landward distance from the marsh edge (Yang et al. 2012).

Under storm surge conditions, marsh vegetation can reduce wave energy by 60% (Möller et al. 2014). However, the spatial pattern of marsh distribution and species attributes affect the wave attenuation substantially. For example, the marsh die-offs directly connected to tidal channels have a much greater effect on increased landward flood propagation than their counterparts at inner marsh locations (Temmerman et al. 2012). According to a plume experiment, flexible low-growing plant canopies have high resilience to storm surge conditions, while more rigid and tall plant canopies experience stem folding and breakage (Rupprecht et al. 2017).

The vegetated zone can also trap enormous amount of sediments, helping survival of salt marshes with land accretion horizontally and vertically (Mudd et al. 2010). At East Chongming Island, Yangtze Estuary, the vertical accretion rate in the *Spartina alterniflora* zone was as high as 108.7 ± 80.6 mm year^{-1}, while in the pioneer zone of *Scirpus* spp., it was 57.0 ± 47.0 mm year^{-1} during 2008–2012 (Li et al. 2014). The grain size of sediments become finer from tidal flats to inner vegetated zones (Yang 1998), while the total suspended solid concentrations tend to decrease logarithmically with distance from the canopy edge in dense vegetated areas (Leonard and Croft 2006).

The functions and services presented here demonstrate the indispensable value of coastal wetlands. However, the global coastal wetlands have diminished rapidly during the past century, especially in the last 50 years, at a rate of 0.5%–1.5% per year (Scott et al. 2014). Apart from direct land reclamation (see the following sections), decreased sediment input due to reservoir construction and degradation at the estuaries and coasts are also

Table 1. Coastal wetland loss in some of the regions.

Type	Region	Area lost	Period	Source
Mangroves	Thailand	>50%	1960~	Scott 1993
	Philippines	75% (from 448 000 to 110 000 ha)	1920s–1990	Scott 1993
	Ecuador	20%–50% overall, 90% in Muisne region	—	Mangrove Action Project 2015
	Singapore	97%	—	Yee et al. 2010
Salt marshes	Bohai Bay, China	73% (from >100 km^2)	2000–2010	Li et al. 2013
	South Korea	>1500 km^2	—	Worldatlas 2017
	The Netherlands	~7000 km^2	—	Worldatlas 2017
	Venice Lagoon, Italy	>70% (from ~180 to 50 km^2)	1811–2002	Roner et al. 2016
	Mississippi Delta, US	4900 km^2	Since 1930s	Environmental Defense Fund 2015
	San Francisco Bay, US	2000 km^2	—	Gedan et al. 2009
Coral reefs	Caribbean Sea	80%	—	The Guardian 2013
	Western Pacific	50%	—	Bruno and Selig 2007

driving factors for the loss. Projected sea level rise is another potential factor threatening the vulnerable coastal wetlands (Nicholls and Cazenave 2010). IPCC estimated that as much as 33% of the coastal wetland habitats would disappear in the next hundred years if the sea level rise keeps the current rate (Meehl et al. 2007).

Coastal wetland loss and degradation: a global problem

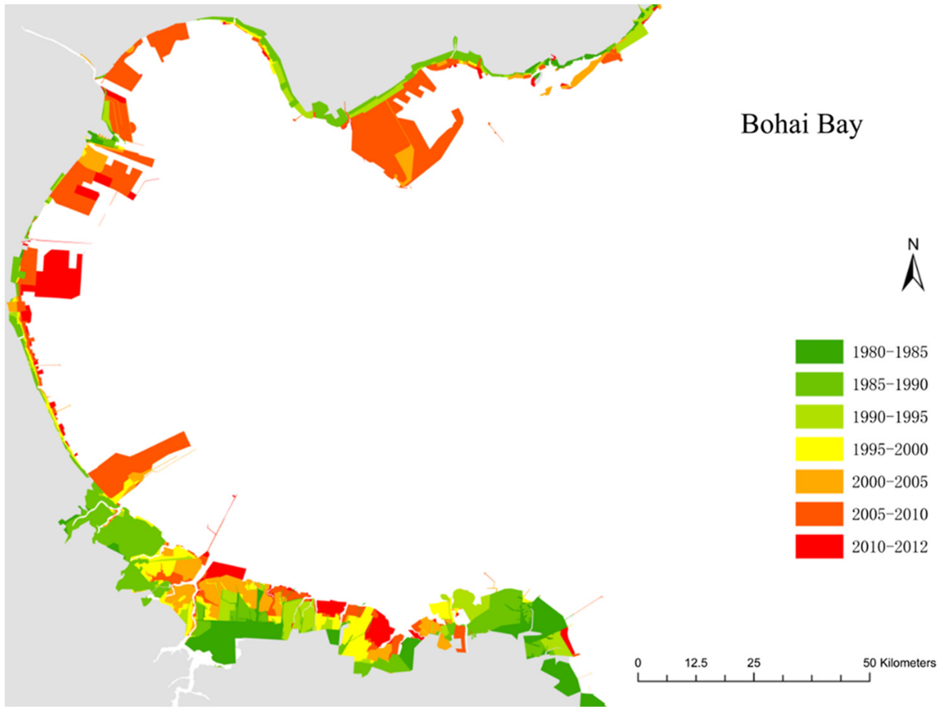
Mangroves faced a global loss of about 50% in the last decades (Table 1), most of which was transformed into mariculture ponds (Valiela et al. 2009). Ecuador, Indonesia, and many other countries are also witnessing a transformation from tidal wetlands to other more apparently profitable land uses in the eyes of the local people, such as aquaculture, harbors, paddy fields, and even parks. Along the coast of Puttlama Lagoon, Srilanka, the area of shrimp farm increased by 2777% from 1994 to 2012, while the area of salt farms increased by 60%, with the area of mangrove deceased by 34% during the same period (Jil et al. 2015). This is just an example of rapid transformation from coastal wetlands to other land use types. Like the mangroves, coral reefs are also under threat of loss or degradation in the Caribbean (~80%, The Guardian 2013) and Western Pacific region (~50%, Bruno and Selig 2007).

According to the Worldatlas (2017), China, the Netherlands, and South Korea ranked as the top three countries with the most land reclaimed from seas and wetlands (Table 1). Some countries still have plans to reclaim more land in the near future (Valiela et al. 2009; Worldatlas 2017). The Venice Lagoon also faced an over 70% marsh loss in the last 200 years due to land subsidence and low sediment input (Brambati et al. 2003; Roner et al. 2016).

Land reclamation has been the main reason of coastal wetland loss in China in the last decades. Surrounding the Bohai Sea, Northern China, more than 2000 km^2 were reclaimed between 1980 and 2012 (Fig. 1). Using new technology for land reclamation, muddy water can be pumped into the levee and new land can be created within a few months. This has happened along almost all of the Chinese coast wherever muddy subsurface is available, driven by rapid economic development.

Between 1780 and 1980, the United States faced extensive loss of its wetlands across the continents; some states lost more than 80% of their wetland coverage (Yuhas 2013). However, the most extensive wetland loss happened in the southeastern coastal states in the 1970s (Mitsch and Gosselink 2007). The Mississippi Delta alone has lost 4900 km^2 of land since the 1930s (Environmental Defense Fund 2015).

Fig. 1. Land reclamation around the Bohai Bay, China, between 1980 and 2012 (Courtesy of Dr. Bo Tian).



Dams and reservoirs constructed in rivers have prevented 20% of the global sediment inputs from reaching the coast (Syvitski et al. 2005). But for some large rivers, the situation has been more serious. For example, the Nile Delta has lost 98% of its sediment input, the Indus Delta lost 94%, and the Mississippi lost 69%, compared to the sediment input from when the first dam was built in the catchment (Syvitski et al. 2009; Giosan et al. 2014). By 2004, the Yangtze River lost 65% of its sediment input load of average between 1951 and 2004 (Yang et al. 2006), and was estimated to decrease further to ca. 110 Mt year^{-1}, which is only 20% of its level in the 1960s (Yang et al. 2014). This has induced "sediment starvation" in large estuaries (Kondolf et al. 2014), and resulted in erosion in some parts of the large deltas (Syvitski et al. 2009). On the other hand, levees have been built along the main river channels to protect populated areas from flooding, which have reduced the number of tributaries that can migrate at river deltas and maintain the ground surface level. Levee construction may reduce flooding risks in the short term, but may increase strong risks in the future (Temmerman and Kirwan 2015).

Subsurface mining of oil, gas, and water often accelerate ground compaction and delta sinking, causing frequent flooding. In fact, 80% of the world's large deltas have experienced severe flooding in the last decades (Syvitski et al. 2009).

Moreover, degradation caused by saltwater intrusion, drought, and pollution are also threatening the health of coastal wetlands (Howard and Mendelssohn 1999; Dai et al. 2013). Eutrophication in coastal waters can influence the coastal wetland ecosystem by changing the structure of biotic communities, as well as the relationships between different species (He and Silliman 2015).

Invasive species often cause coastal wetland degradation. *Spartina alterniflora*, a native salt marsh species in the southeastern US, was introduced to China in 1979 for coastal

Table 2. Major consequences of wetland loss.

Consequence	Examples	Source
Habitat loss for marine species	Indus River Estuary, Bohai Sea coast, Florida coast	Scott 1993; Iftikhar 2002; Tang et al. 2015
Habitat loss for migratory birds	China coast	Ma et al. 2014
Saltwater intrusion	Indus River Delta, Mississippi River Delta, Pearl River Delta	Rasul et al. 2012; Zhang et al. 2013; Environmental Defense Fund 2015
CO_2 and N_2O emission	All coastal wetlands replaced by aquaculture	Hu et al. 2012
Flooding	Mississippi River Delta, Chao Phraya River Delta, Ganges River Delta	Syvitski et al. 2009; Tessler et al. 2015
Erosion	Mississippi River Delta	Martinez et al. 2009

protection. Now it has spread almost all along the Chinese coast from the north to the south. It out-competes native species (such as the *Suaeda* spp. and *Scirpus* spp.) in the temperate and subtropical coasts, and in some of the mangrove communities in the tropical zone, resulting in habitat degradation for birds, with its dense, hard, and tall cohorts. In contrast, the common reed widely distributed in the old world turned out to be an invasive species in many sites of the US (Valiela et al. 2009).

Sea level rise is thought to be one of the potential threats for coastal wetlands; it is still controversial because wetlands can migrate landward if no seawall or steep relief exists behind the wetlands, but this is often not the case. "Coastal squeeze" is the concept proposed to describe coasts without retreating space facing sea level rise (Doody 2013). However, if relative sea level rise rate is slow (<4 mm year^{-1}), salt marsh can still establish, and biophysical feedbacks can even allow established marshes to survive at conditions of rising 7 mm year^{-1} if suspended sediments in the coastal water are high enough (e.g., ≥1 mgL^{-1}) (Kirwan et al. 2011; Kirwan and Megonigal 2013). But sediment availability and tidal conditions are often critical restrictions for the marsh survival (Marani et al. 2007; D'Alpaos et al. 2011). It was predicted that marshes can adapt to fast relative sea level rise of a few centimetres per year at tidal ranges >1 m and suspended sediment concentrations >30 mgL^{-1} (Kirwan et al. 2016). On the other hand, marshes can be drowned where available suspended sediment concentrations are very low (1–10 mgL^{-1}) and tidal range is very small (<1 m) (Kirwan et al. 2016).

Wind waves also play an important role in the erosion and loss of salt marshes worldwide, especially at boundary zones (Marani et al. 2011; Leonardi and Fagherazzi 2015). Low-wave-energy conditions can even result in large portions of marsh loss (Leonardi and Fagherazzi 2015). Still, short-term extreme conditions, such as storm surges, droughts, or saltwater intrusion may cause diebacks of brackish and fresh tidal water wetlands with more serious influence than slow sea level rise, and need further investigations under different conditions (Elmer et al. 2013).

Consequences of coastal wetland loss

Loss of wetland area means the loss of its corresponding ecological services for human beings (Table 2), with economic gain only for a special group of people making profits from aquaculture or other land use forms. Profound changes have been caused by conversion of coastal wetlands into other land use forms with damage from flooding or other indirect influences (Worm et al. 2006).

Flooding and storm damage

In southeastern Asia, great destruction has been caused by flooding with reduced or no protection from mangroves and salt marshes, as seen in Bangladesh, Thailand, the Philippines, and Indonesia (NASA-Earth Observatory 2013). Flooding is reported almost every year in this region. Many people have migrated out of the Indus River Delta, Pakistan, due to saltwater intrusion and reduced fishery output from the reduced mangroves (Iftikhar 2002). Similarly, in New Orleans, the population in 2010 had dropped by 24% since 2005, following hurricane Katrina, where coastal wetland protection had been falling since the 1930s (The Guardian 2010). The annual damage caused by coastal flooding will reach $1 trillion by 2050, with the most vulnerable cities located in North America and Asia (Hallegatte et al. 2013). Although the flooding damage cannot be attributed to coastal wetlands loss alone, their buffering function must play a vital role for some of the area.

Fishery structure change and biodiversity loss

The world fishery capture and aquaculture production has been increasing steadily since the 1950s, among which, the contribution from China has been prominent since the 1980s. But the production of Chinese fishery is mainly from aquaculture (>70%) (FAO 2016). The Chinese aquaculture not only produces fish, shrimp, and shells but also sea cucumbers, crabs, and a wide variety of algae. Within 1 km from the coastline, 80% of the sea surface has been used, mostly by aquaculture (Liu et al. 2015). To ensure a high harvest, the farmers have to use feedstuff and antibiotics, which may result in excessive nutrient discharge, food chain accumulation of pollutants, and antibiotic resistance effects in microbes (Romero et al. 2012). The structure of breeding sites also changes the hydro-sediment-biochemical dynamics in the coastal water.

Coastal wetland reclamation often results in the destruction of spawning and nursery ground for many marine species, while birds lose their food and shelter with more disturbed habitats. The buffer function for pollutant degradation, erosion, and land subsidence will be lowered, with increased risk from storm surge and flooding. In the Bohai Bay of Northern China, a sharp decline of fishery resources has been witnessed as a result of wetland loss and pollution from inorganic nitrogen and phosphorous, oil, and heavy metals, which greatly decreases the food available to migratory birds (Tang et al. 2015).

China's coastal wetlands have an area of 5.8 million ha, supporting 230 waterbird species, which is about 25% of the global total. They are also on the migration routes of 19% of the globally threatened migratory bird populations. Unfortunately, the vast coastal wetlands are seriously threatened by the 11 000 km long "Great Seawall", or 60% of the Chinese coast line (Ma et al. 2014). Since the 1980s, land reclamation along the coast has been increasing steadily to 400 $km^2 year^{-1}$ in 2010, and the projected reclamation speed will reach nearly 600 $km^2 year^{-1}$ by 2020. The migratory bird populations in eastern Asia are greatly endangered due to the "hostile shores" in China, Korea, and Japan (Larson 2015). Although the "armored seawall" favors some rocky shore organisms (Huang et al. 2015), it is incomparable to the ecological value lost during reclamation. Fortunately, new laws have been established to stop this trend, accompanied with restoration efforts supported by the central and local government.

The losses of biodiversity result in the damage of some critical coastal ecosystem services, such as fishery, nursery habitats, and filtering and detoxification services, which further contribute to the decline of water quality and increase of harmful algal blooms, oxygen depletion, and mortality of benthic and nekton fauna (Worm et al. 2006). Invasion of exotic species may enhance productivity, but could not compensate for the services bourne by the native taxa (Lotze et al. 2006).

Fig. 2. Newly established salt marsh between the high and low levees along the Shanghai Coast (Courtesy of Linjing Ren, 2014).

Climate change feedbacks

Clearing of mangroves and subsequent excavation of the substrates for aquaculture ponds could result in the potential oxidation of 1400 t C ha^{-1}. If half of this becomes oxidized over 10 years, then 70 t C $ha^{-1}year^{-1}$ is estimated to be returned to the atmosphere. This is some 50 times the sequestration rate, and would contribute to increased atmospheric CO_2 concentrations, leading to climate change and sea level rise (Ong 2002; Mcleod et al. 2011). Moreover, aquaculture is also an important source of N_2O due to addition of feed and wastes (Hu et al. 2012). Therefore, transformation of coastal wetlands into aquaculture will result in the increase of greenhouse gases in both CO_2 and N_2O emission. Pendleton et al. (2012) estimated that about 0.04–0.28 Pg C $year^{-1}$ can be released from these systems caused by conversion into non-wetland types and degradation. However, few land owners would consider the potential climate warming effect when constructing aquaculture ponds from coastal wetlands.

Restoration efforts and challenges

While coastal wetlands are facing loss, many countries have started taking measures to rebuild marshes with dredged sediments, or divert the river channels to elevate ground surface. Some new concepts, such as "building with nature" (De Vriend et al. 2015), "living shore lines" (Rose et al. 2014), or "blue forest" (Norwegian Blue Forest Network 2015), have also been proposed and implemented in different parts of the world to support practices for coastal wetland restoration.

Efforts of coastal wetlands restoration at different regions

Yangtze Estuary, China

Along the Shanghai coast, to facilitate salt marsh restoration out of the strongly armored seawall, a low levee near the 0 m elevation was constructed and muddy water was pumped into the space between the two levees, so that natural vegetation can establish and eventually encroach into the tidal flat outside the low levee (Fig. 2). This narrow vegetation zone can act as a buffer to protect the seawall, but whether this is wide enough or not under storm surges is as yet unknown. The time taken for vegetation to disperse over the low levee is also different among different sections of the coastline due to hydro- and morphodynamic differences at local sites.

Atlantic coast, US

In the Mississippi River Delta, a project called the "Coastal Wetland Planning, Protection and Restoration Act" has been implemented since the 1990s (CWPPR 2015). It combined sediment dredging with marsh restoration and recreation, and tried to divert sediment-laden river water back onto the delta plain (Temmerman and Kirwan 2015). Assisted with vegetation planting, they tried to stabilize the bank and protect the shoreline. The cost is high and measures are only effective within a limited area. Much more efforts are still needed to prevent the marsh from sinking.

An example of "living shorelines" is to use shellfish aquaculture as a management strategy for nitrogen reduction and bank protection (Rose et al. 2014), with removal rate at 100–1300 g N $m^{-2}year^{-1}$. Now the technique has been widely used across the US coastal states and by several countries.

San Francisco Bay, US

The first project of wetland restoration in San Francisco Bay was enacted in 1972, after losing 90% of its marshes from the beginning of American colonization (Williams and Faber 2001). With a series of restoration experiments evolved from vegetation planting to providing the right physical conditions, manipulating wetlands, and restoring physical processes, it has become a laboratory for testing different restoration techniques that can be considered by other parts of the world (Williams and Faber 2001).

The San Francisco Bay restoration efforts provided a series of lessons, such as (Williams and Faber 2001): (*i*) the need for explicit restoration objectives; (*ii*) understanding of restored salt marshes as evolutionary systems that have changing functions with time; (*iii*) the need to incorporate morpho-dynamics, or interaction of key physical processes in restoration; and (*iv*) the need to integrate long-term monitoring into the restoration plan.

The Netherlands

The Dutch people have implemented the approach of "building with nature" for years by nourishing the coast with sediments from the North Sea (Sonneville and Van der Spek 2012), creating oyster reefs to protect the coast from erosion with natural reproduction and some economic benefits, and implementing a managed retreat allowing for potential sea level rise along the River Rhine valley (De Vriend et al. 2015). These efforts will provide invaluable supports for the coastal protection from continual erosion and periodic storm surges.

Other areas

Restoration of mangroves with plantations has been achieved in Thailand, Vietnam, China, and other countries. Measures were also taken to control *S. alterniflora* along the Chinese coastline. However, compared to the wetland area already lost, the restoration efforts are quite limited and often fail.

Challenges for coastal wetland restoration

Lack of comprehensive understanding of coastal ecosystems

Knowledge gaps still exist for successful coastal wetland restoration. Geomorphic units where coastal wetlands can develop are often complicated, from high tidal zones to low lands, lagoons, and tidal creeks. They are ever-shifting due to human activities and natural processes, and there is insufficient real-time monitoring for critical processes, such as water and sediment redistribution, subsidence, or ecosystem dynamics. Sediment budgets and ratios of mud, sand, and organic matter in the soil of deltaic plain are generally unknown, yet are crucial for preventing drowning (Giosan et al. 2014).

From an academic point of view, the challenge for coastal wetlands restoration is also a great opportunity for landscape ecologists to transfer their knowledge into practice. For example, how to compromise between the different functionalities of coastal wetlands, such as *S. alterniflora*? Its functions for coastal protection and sediment trapping are considered to be positive along the Chinese coastline (Yang et al. 2008, 2012), but as an invasive species, it has negative effects on the native organisms (He et al. 2012), especially in southern China (Gao et al. 2014). In contrast, in the middle Atlantic coast of the US, the invasive *Phragmites australis* proved to be more effective in combating sea level rise with higher mineral and organic sediment trapping ability than the local *S. alterniflora* (Rooth and Stevenson 2000).

Lack of knowledge about site-specific bio-morphological interactions

For vegetation restoration in the tidal zone, it is necessary to consider how the ecosystem will interact with the physical environment. Waves and sediments will be redistributed and attenuated differently by different species, also depending on their density and biomass, thus changing the landforms, which, in turn, will affect the vegetation diversity and distribution (Leonardi and Fagherazzi 2015). Yet the knowledge for the mechanism of bio-morphological interaction is rather limited, and is often site-specific in terms of tidal ranges, wave energy, salinity gradients, suspended sediment contents, morphological conditions, and species structure. General interpretations of marsh mechanisms obtained at large scale also need site-dependent data input to support successful rehabilitation (Marani et al. 2011).

Coastal wetland restoration practice should also be "site-specific". The location, species, size, and spatial orientation of the wetland must be carefully considered according to the tide and substrate conditions. Successful restoration requires both semi-natural vegetation structure and a high diversity of fauna groups, to ensure multi-functionality of the restored ecosystem. More importantly, when restoring the ecosystem occupied by aquaculture, the income of local people should not be reduced. New benefits for those people must be explored, such as ecotourism, apiculture, and horticulture. Incorporating ecosystem services into coastal planning will achieve greater returns from coastal protection and tourism than from achieving conservation or development goals only (Arkema et al. 2015).

Moreover, while faced with quick economic development along the world coast zones, we also need to make room for potential sea-level rise. By combining conventional engineering with ecosystem-based engineering, we may mitigate potential big flooding risks in the long run (Temmerman and Kirwan 2015; Tessler et al. 2015), and provide important habitats for numerous wild and commercial species.

Conclusion and recommendations

The world coastal wetlands are faced with great pressure of being "squeezed" by human land use and sea-level rise. Serious consequences have already been caused by the coastal wetland loss, such as coastal flooding, erosion, and biodiversity decrease. It is a critical time to take actions to avoid further loss of this precious ecosystem with many important functionalities, and to restore it wherever possible. However, more efforts are still needed to understand the site-specific relationship between coastal wetlands and hydro-sediment dynamics, or the bio-physical conditions for pioneer species establishment. Social-economic effects must also be fully considered for successful restoration of coastal wetlands in the future.

Here are some suggestions for the ecological restoration of coastal wetlands:

1. *Right species at the right place*. Site selection is critical for successful coastal wetland restoration, while local species are of first priority. Most of the species' establishment needs a critical threshold of hydro-dynamics, such as flow speed and direction, inundation period and depth, even suspended sediment content. These critical conditions for different species should be studied first before taking actions.
2. *Make use of ecosystem's self-organization strength*. Once the vegetation community is established, a positive feedback between sediment accumulation and vegetation expansion and succession will be formed. It will be much more cost-effective to build small patches than to plant seedlings at large scale.
3. *Probe reliable economic benefits for the local society*. For example, the high biomass of *S. alterniflora* can be used to extract bio-mineral liquid while the residua with high crude protein can be used as forage or organic fertilizer (Qin et al. 2016). The harvested area can provide habitat for birds if cutting is planed carefully. Ecotourism and apiculture are other well-known alternatives that are economically profitable and can stimulate the protection and restoration of coastal wetlands.

Conflict of interest

The authors declare that they have no conflict of interest.

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