Chemosphere 168 (2017) 765–776

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Hard science is essential to restoring soft-sediment intertidal habitats in burgeoning East Asia

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HIGHLIGHTS

- Soft-sediment habitats are under multiple stresses in burgeoning East Asia.
- Threats to soft-sediment habitats highlighted with four representative case studies.
- Knowledge gaps in science-based restoration of soft sediment habitats proposed.
- Lessons learned and outlook on soft sediment habitats and their restoration discussed.

ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form
24 October 2016
Accepted 30 October 2016
Available online 9 November 2016

Handling Editor: Shane Snyder

Keywords:
Hydrologic regime
Pollution
Exotic species
Mangroves
Saltmarsh
Tidal flats

ABSTRACT

Intertidal soft-sediment ecosystems such as mangrove, saltmarsh, and tidal flats face multiple stresses along the burgeoning East Asia coastline. In addition to direct habitat loss, ecosystem structure, function, and capacity for ecosystem services of these habitats are significantly affected by anthropogenic loss of hydrologic connectivity, introduction of invasive exotic species, and chemical pollution. These dramatic changes to ecosystem structure and function are illustrated by four case studies along the East Asian coast: the Mai Po Marshes in Hong Kong, the Yunxiao wetlands in Fujian, China, and the Lake Sihwa and Saemangeum tidal flats in Korea. While investment in restoration is increasing significantly in the region, the lack of key basic knowledge on aspects of the behaviour of intertidal soft-sediment ecosystems, particularly those in Asia, impairs the effectiveness of these efforts. The relationship between biodiversity and ecosystem function for relatively species-poor mangrove, seagrass, and saltmarsh systems has implications for restoration targeting monospecific plantations. The trajectory of recovery and return of ecosystem function and services is also poorly known, and may deviate from simple expectations. As many introduced species have become established along the East Asian coast, their long-term impact on ecosystem function as well as the socio-economics of coastal communities demand a multidisciplinary approach to assessing options for restoration and management. These knowledge gaps require urgent attention in order to inform future restoration and management of intertidal soft-sediment ecosystems in fast-developing East Asia.

1. Introduction

Continual coastal population growth imposes multiple stressors (e.g. pollution, invasive species) on soft-sediment intertidal habitats such as mangrove, saltmarsh and tidal flats, which have long been threatened by sustained destruction due to aquaculture, agriculture and other destructive landuses. Pressures from climate change (e.g. sea level rise) further threaten the future delivery of important services by these ecosystems (Lovelock et al., 2015). Despite recent reports suggesting slower than previously published rate of loss (Richards and Friess, 2016), mangroves in Southeast Asia are still being replaced by aquaculture ponds and other anthropogenic landscapes. Loss of less-studied habitats such as tidal flats is probably more rapid, as has been suggested by regional data, e.g. the Yellow Sea, (Koh and de Jonge, 2014; Murray et al., 2014, 2015). The transition from natural to human-dominant seascapes is expected to shift the fundamental dynamics of the nearshore environment, e.g. 'anthropogenic forcing' of nutrient quality and

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http://dx.doi.org/10.1016/j.chemosphere.2016.10.136

quantity due to the replacement of mangrove forests by cities, agriculture and aquaculture (Lee, 2016). The situation is particularly dire in burgeoning East Asia, where decades of rapid economic growth put the remnant habitats in severe competition with human settlement and other destructive landuses in the easy-to-develop flat, soft-sediment environment.

The economic prosperity of the East Asian coastal region (comprising countries/regions of China, Hong Kong, Macau, Japan, North Korea, South Korea and Taiwan) has been a major driver of estuarine habitat loss. The Pearl River delta, for example, is now the largest urban megalopolis in the world, with an estimated population of 45 million in a continuous belt comprising the cities of Hong Kong, Shenzhen, and greater Guangzhou. Parallel to this unprecedented urban growth is the rapid loss and degradation of estuarine habitats, and their capacity for services such as fishery production (see Lee et al., 2006). Exacerbated by long-term overfishing, the fish catch in the Pearl River estuary is now so depleted that seasonal closure has to be enforced to rehabilitate the dwindling stock, sometimes resulting in cross-border political disputes (Morton, 2003). One of the most common responses to the continued loss is the increase in the effort to restore these soft-sediment habitats. Mangrove restoration has received significant attention since the 2004 tsunami (Barbier, 2006), with several studies claiming less fatality and loss of infrastructure at locations protected with mangrove belts than those without such protection (e.g. Dahdouh-Guebas et al., 2005; Williams, 2005; Chang et al., 2006). Rehabilitation and restoration of mangroves is usually driven by habitat and biodiversity conservation, and provision of ecosystem services (Field, 1998; Ellison, 2000b), such as fishery production, coastal protection and support for wildlife (Lee et al., 2014a; Murray and Fuller, 2015), which are generally applicable to other soft-sediment intertidal habitats. Ecological restoration of tidal flats has received increasingly more scientific attention as well as public recognition in the East Asian countries, parallel to the increased concern about loss of coastal ecosystem services in recent years.

While much resource has been invested in restoration, many projects fail because the potential difficulties in achieving the desired outcome were ignored. Earlier views suggested that soft-sediment habitats such as mangroves are relatively resistant to disturbance while easy to restore, i.e. with high resilience (Lugo, 1998), but recent reviews highlight the challenges restoration presents, as well as the fact that most restoration projects fail (Lewis, 2000, 2005). Further, it is difficult to evaluate the success of restoration projects. For example, many recent restoration projects of tidal flats in Korea have no specific or quantitative objectives, exacerbated by the lack of corresponding assessment guidelines and/or appropriate monitoring (Nam et al., 2015). In general, simplistic approaches to habitat restoration without clear objectives or technical and ecological know-how are key reasons for failure (Ellison, 2000a; Lewis and Gilmore, 2007). Lack of post-restoration monitoring also makes assessing the success of restoration projects difficult, which contributes to bad practices being repeated (Ellison, 2000a).

Compared to vegetated habitats such as mangroves and saltmarshes, tidal flat ecosystems have been poorly studied in Asia despite their alarming rate of destruction. Twenty-eight percent of the tidal mudflats of the Yellow Sea have been lost between the 1980s and late 2000s (Murray et al., 2014). Early work on tidal flat ecology has focussed on temperate systems, e.g. the Wadden Sea (Reise, 1985). Little data on loss, let alone ecology, of the tropical tidal flats in sub-tropical and tropical latitudes, especially in Asia, is available. While tropical tidal flats are still under-studied, their flat and 'featureless' nature promotes effort to reclaim these habitats to fuel rapid coastal development, particularly in Asia. This adds to the high losses already inflicted on these tidal habitats through historical traditional landuses, such as conversion to agriculture. Such conversions are deeply entrenched in the socio-economic system of many countries, exacerbating the difficulties in reversing the threats or the loss trend.

In this review, we demonstrate the threats faced by soft-sediment intertidal habitats in East Asia by analysing four significant systems impacted by different anthropogenic stressors, and discuss the scientific knowledge base as well as solutions required to support successful rehabilitation and restoration of these habitats. While many of the drivers for loss are common to global intertidal soft-sediment coasts, Asian systems face some region-specific threats, thus prompting also a discussion of science required for underpinning restoration work in this region.

2. Threats to intertidal soft-sediment habitats in East Asia

2.1. Habitat destruction and alteration

Destruction of mangrove and saltmarsh habitats in East Asia can be traced to the historical development of urban centres on flat floodplains and the lower tidal reaches of major estuaries. Significant portions of many of the major coastal cities together with their ancillary structures such as airports and ports, in East Asia are clearly built on tidal (vegetated and unvegetated) areas. One of the pinnacles in urban development in the region, Singapore, for example, has historical turned >90% of the tropical island nation's mangroves into urban or supportive facilities, such as the Changi Airport (Hsiang, 2000). This pattern is not unique to populous and burgeoning Asia. Extension of the Brisbane airport in Queensland, Australia, in the late 1970s resulted in destruction of mangrove and saltmarsh areas that required >73,000 seedlings and transplants to restore (Saenger, 1996). Apart from urban development, conversion of tidal soft-sediment habitats for aquaculture and agriculture is a main driver for mangrove loss in Asia (Richards and Friess, 2016) and a main reason for restoration (see chapters in Field, 1996). These conversions have resulted in estimated loss rates of ~1% per annum in earlier decades (FAO, 2007), although a recent report estimated lower rates since 2000 (Richards and Friess, 2016). Notwithstanding, mangroves in most tropical Asian countries have suffered >50% loss against their extents 50 years ago.

One common consequence of reclamation of intertidal soft-sediment habitats is the construction of some barrier that would remove tidal connectivity. This is done almost exclusively as hard engineering solutions such as a concrete or stone seawall. The propensity of seawalls is such that in some countries, they have become a ubiquitous, continuous feature of the coastline, e.g. China's new Great Wall (Ma et al., 2014). Such permanent structures not only remove the hydrologic connectivity critical in maintaining the function of tidal wetlands, but also pre-dispose such habitats to future threats such as sea level rise ('coastal squeeze', Torio and Chmura, 2013, 2015; Phan et al., 2015). The full physical extent as well as the environmental impact of seawalls on soft-sediment tidal habitats deserves a global synthesis.

Coastal reclamation has long been a significant environmental issue in many populous East Asian countries such as Korea, particularly in terms of promoting loss of tidal flats and coastal diversity by blocking tidal connectivity (Koh and Khim, 2014). The embankment by the long sea-dikes in Lake Sihwa and Saemangeum on the west coast of Korea resulted in great areal loss of tidal flats followed by severe coastal pollution and ecosystem destruction (Lee et al., 2014b; Ryu et al., 2014). Although the Korean government abandoned the original plan (freshwater lake) in 2000, fortunately, due to rapid deterioration of environmental quality, the Sihwa ecosystem has not fully recovered even after 20 years (Lee et al., 2014b). The Saemangeum project has been in process since the early 1990s. In fact, land reclamation and coastal embankments in coastal areas are globally ubiquitous not only for simple extension of land area but also for coastal protection. While land reclamation may be inevitable because of land shortage for development, the environmental problems are prompted by the large-scale and rapid land reclamations without reference to coastal ecosystem capacity or resilience against catastrophic environmental changes.

2.2. Species introduction

While invasion of exotic species is a common threat to estuaries globally (e.g. the Chinese mitten crab), one threat unique to Asian soft-sediment habitats is the deliberate introduction of exotic and often invasive species. The saltmarsh grass *Spartina anglica* was introduced to China for shoreline stabilisation and tidal flat 'reclamation' in 1963, followed by *S. alterniflora*, *S. patens* and *S. cynosuroides* in 1979 (Chung, 1993; Zuo et al., 2012). The mangrove *Sonneratia apetala* was introduced into China for its robustness and rapid growth, also in attempts to restore mangroves (Ren et al., 2009). Recently this species has even been trialled as a means to control *S. alterniflora* spread (Chen et al., 2014; Zhou et al., 2015). More recently *Laguncularia racemosa* has also been introduced into China. *S. alterniflora* has since spread to as north as Liaoning in Bohai Sea (40°N) and all mangrove locations on the Chinese coast, including Hainan Island (20°N) (Zuo et al., 2012; W. Wang pers. comm). More recently, two exotic saltmarsh species (*S. alterniflora* and *S. anglica*) were found to be distributed on the south and west coasts of Korea and have become a significant issue to both local communities as well as the Korean government. Hundreds of studies, mostly in China, have been performed on the impact of these exotic species on the native species and ecosystems. Positive effects ranged from increase in coastal productivity and coastal protection to pollution abatement while negative impacts of alteration of the seascape and biodiversity have been reported (see review by Wan et al., 2009). Given their geographic extent as well as the wide-ranging ecological and socio-economic impacts, these introductions could have consequences comparable to 'text-book classics' such as the introduction of cane toad (*Bufo marinus*) to Australia.

2.3. Consumptive use

Consumptive uses such as collection of shellfish, bait, or raw materials (for building, firewood) pose significant but often undocumented threats on tidal soft-sediment habitats in populous East Asia. Apart from direct removal of foundation species (e.g. cutting of mangroves for construction material), over-exploitation of species that are functionally important may drive shifts in ecosystem state. Dramatic impacts of the latter have been demonstrated by effects of trophic cascade resulting from the removal of top predator species in aquatic ecosystems (e.g. Estes et al., 2011). Most of the data on such processes are, however, generated from hard-bottom habitats (e.g. rocky shores and coral reefs) while little information is available from intertidal soft-sediment habitats. Physical disturbance due to collection activities (e.g. trampling and turning over of sediment) can be a potent driver in the functioning of microbial communities and the ecological and biogeochemical processes they mediate (Allison and Martiny, 2008).

2.4. Pollution

Pollution and other forms of degradation are often less documented but entrenched threats on estuarine wetlands in Asia. The coastal zones in East and South Asia are the most populous regions of the world. The projection of 5 billion by 2050 in 2002 (East-West Center 2002) now seems a gross underestimate, as the latest figure suggests > 4.42 billion (http://www.worldpopulationstatistics.com/population-of-asia/). Lee (2016) estimated that between 1997 and 2010 anthropogenic influx of C and N into estuaries in the South China Sea have increased by 80% and 43%, respectively, with mangrove contributions only equivalent to ~3% of the anthropogenic N in 2010. Such a shift to 'anthropogenic forcing' of the nutrient fluxes is probably applicable to the whole of the highly urbanised coastline in East and South Asia. One consequence is the prevalence of large areas of persistent or seasonal hypoxic zones in the shallow waters around many major estuaries and embayments in the world, e.g. the northern Gulf of Mexico (Diaz et al., 2009), the Pearl River and Yangtze estuaries, China (Zhang and Li, 2010; Wang et al., 2016). More concerning is the accumulation of persistent organic pollutants in the tidal sediments of these shallow estuaries, where risks to human and wildlife health are significant (e.g. Zhao et al., 2012).

2.5. Multiple stressors

The impact of multi-stressor threats on soft-sediment tidal habitats is still poorly known. Early models have focussed on significant single stressors, such as eutrophication (e.g. Rosenberg, 1985) but the behaviour of these habitats under multi-stressor scenarios and the recovery from their release is virtually unstudied. The demanding temporal and spatial scales of such investigations are obvious deterrents. Of note, the understanding of the sources, distribution, and fate of several classic and emerging pollutants in coastal sediments in the Yellow Sea has been increasingly documented. However, the ecological responses to such pollution stressors are still poorly known to date (Khim and Hong, 2014). Most estuarine wetlands in East Asia are under multiple stresses – the intensive use of the floodplain for human settlement, agriculture, fishery production, and industry results in stressors such as chemical and organic pollution, loss of habitat, over-exploitation of biological resources as well as invasive species introduction. These multi-stressor scenarios are well exemplified by the case studies below, e.g. the Yunxiao wetlands and Lake Sihwa. The multiple lines of evidence approach addressing cause-effect relationships between stressors and ecosystem responses would be necessary in an integrated manner.

3. Case studies in East Asia: the threats and the knowledge needs

Four case studies encompassing both the temperate and sub-tropical regions of East Asia as well as a variety of principal stress types and management issues are selected to illustrate the challenges facing intertidal soft-sediment habitats in East Asia. Specifically, (1) the Mai Po Marshes, Hong Kong: conflicts between wildlife conservation and urban development in the world's largest megalopolis, and how vital knowledge about ecosystem response to management may be lacking; (2) the Yunxiao wetlands, China: the impact of exotic invasive species exacerbate pressure from multiple stressors on a heavily exploited mudflat ecosystem, with significant socio-economic implications; (3 & 4) Lake Sihwa and Saemangeum tidal flats, Korea: how management decisions such as seawall construction, reclamation and pollution as well as subsequent rehabilitation shape water quality, the biodiversity, functioning and value of diked tidal flats.

3.1. Mai Po Marshes, Hong Kong

Mai Po Marshes (MPM, 22.49°N 114.03°E) consist of a series of shallow sub-tidal to supratidal habitats in the western lower Pearl River estuary: the shallow (<8 m) Deep Bay, expansive tidal mudflats, tidal mangroves, reclaimed but tidally and traditionally operated shrimp ponds, and supratidal freshwater fish ponds. It is the largest tidal wetland in the Pearl River estuary, which is now the largest contiguous urban megalopolis in the world (>40 million). Situated on the border with mainland China, MPM conjoins the Futian Nature Reserve in Shenzhen on the northern shores of Deep Bay naturally as one connected ecosystem but are under separate jurisdictions as well as managing organisations (WWFHK for MPM; Ministry of Forestry, China for Futian). 1500 ha of the 2700 ha wetland complex in Deep Bay, including the 380-ha MPM, was declared a Ramsar wetland in 1995. While strict control over entry into the Reserve and activities permitted therein apply to the MPM, the wetlands have been threatened by cross-border fishing pressure as well as anthropogenic pressures such as pollution that permeates the whole of Deep Bay. The tidal wetlands in inner Deep Bay are, however, important habitats for bird conservation. These wetlands offer one of the series of tidal soft-sediment refuelling habitats for migratory birds along the East Asia Flyway. Up to 100,000 individuals of water birds including some endangered species, e.g. the Black-faced spoonbill (*Platalea minor*), use these habitats in winter.

Apart from the common issue of losing the mid-to upper intertidal wetlands to aquaculture, a more challenging threat to the functioning of the wetland complex is the pervasive anthropogenic pollution from the local urban centres as well as the Pearl River catchment. Untreated organic waste from animal husbandry was a major pollution source (up to 70% of total organic load) until the late-1990s. Mass balance and isotopic analyses of the carbon budget of Deep Bay indicate a significant role of anthropogenic organic matter in supporting the native and migrant bird populations (Li and Lee, 1998; Lee, 2000). In view of the rapidly deteriorating water quality due to organic enrichment that could jeopardise the wildlife conservation value of the MPM, the Hong Kong government made significant efforts to control the discharge of organic wastes into Deep Bay. Livestock pollution was gradually reduced since 1988 by progressive implementation of the Waste Disposal Ordinance. This led to decrease of total BOD_5 load (from the Hong Kong catchment) of *ca.* 125,000 kg d^{-1}in 1988 to <20,000 kg d^{-1}in 2000. However, organic pollution as indicated by the persistently declining % dissolved oxygen saturation and increasing BOD_5 did not improve even 15 years after the ban (Au, 2005). Water quality indicators eventually signalled a reverse trend in 2007, with ammonia N, total inorganic N, BOD_5, and *E. coli* values all started to decline and has remained so ever since (Environmental Protection Department, 2014).

The challenge to restoring tidal soft-sediment habitats can be illustrated by how little is known about the recovery of ecosystem function and services in response to simple indicators such as water quality parameters. The improvement in water quality indicators in Deep Bay may seem to be a simple case of successful restoration but the behaviour of the ecosystem was less easily comprehensible. The capacity of the Deep Bay wetlands to sustain the most important ecosystem service, namely, supporting wintering birds, did not have a simple relationship with restoration of water quality. The number of wintering birds in Deep Bay had a negative correlation with % DO saturation (a negative indicator of organic pollution) before 2001 but shifted to a positive correlation since then (Fig. 1). There may be a 'fundamental regime shift' in the wetland complex underpinning this phenomenon, the nature of which is poorly known. Knowledge of how degraded tidal soft-sediment systems may recover upon restoration is urgently needed to guide restoration efforts and also monitor and measure success.

3.2. Yunxiao wetlands, Fujian, China

The Yunxiao wetlands (23°53′N 117°30′E) are located at the estuary of the Zhangjiang River, Fujian Province, China. The Yunxiao mangroves (118 ha) are managed as part of the Zhangjiang Estuary Mangrove National Nature Reserve (2360 ha), established first as a provincial reserve in 1997 then upgraded as a national reserve in 2003 (Wang and Wang, 2007). The site is also a declared Ramsar site. The Zhangjiang estuary is fringed by dwarf mangrove forests comprising only three species, namely, *Kandelia obovata, Avicennia marina* and *Aegiceras corniculatum*, as extensive diking of the landward sections of the intertidal zone for aquaculture of mud crab (*Scylla paramamosain*) and razor clam (*Sinonovacula constricta*) as well as human settlement has largely eliminated landward mangrove species such as *Bruguiera gymnorhiza* and the native saltmarsh habitat. With a mean tidal range of about 2.3 m and steady supply of fine sediments from the Zhangjiang River, expansive tidal mudflats occur seaward to the mangroves. The mudflats have traditionally been supporting significant local artisanal fisheries centred on the collection of razor clams and juvenile mud crabs (for stocking the local grow-up ponds). The Yunxiao wetlands epitomise the threats many Asian wetlands encounter under a multi-stressor scenario, with the introduction of exotic species, the extensive construction of seawalls, and pressures from anthropogenic pollution and consumptive use of the habitats being the major concerns.

Codgrass *Spartina alterniflora* was introduced to the Zhangjiang estuary in 1997 (Wang et al., 2014), following its earlier introduction to China for the purposes of shoreline stabilisation in 1979. Dramatic changes to the seascape has since entailed, with large proportions of the intertidal mudflat now colonised by *S. alterniflora* (Fig. 2). The ability of codgrass to colonise mud substrates at a lower tidal position than the local mangroves has resulted in almost a complete seaward 'siege' of the mangroves. Zhang et al. (2012) found that codgrass was not only able to easily colonise the open mudflats, but also negatively affect mangrove seedling growth by significantly reducing their biomass at the meso- and polyhaline sites where human disturbance had opened up the mangrove canopy. However, mangrove forests with a closed canopy effectively suppressed codgrass establishment (Zhang et al., 2012). There is also evidence that codgrass invasion also significantly altered the macrobenthos community as well as the trophodynamics of the estuary, including carbon storage by the habitats (Feng et al., 2014, 2015; Lu et al., 2014).

While codgrass provides an additional habitat and carbon source to the macrobenthic community at Yunxiao, significant negative ecological and socio-economic impacts also occur. The ability of codgrass to spread and dominate in previous open mudflats in the lower intertidal means that mangroves in Zhangjiang estuary are now threatened with 'coastal squeeze' not only from the landward seawall but also from habitat pre-emption by *Spartina*. The ability of codgrass to expand via both vegetative propagation as well as seed dispersal, coupled with the fact that there seems to be few natural enemies, suggest that this invasive species will be difficult to exterminate. Apart from physical and geomorphologic drivers such as sediment supply and tidal asymmetry, macrophyte vegetation also influence sedimentation in estuaries, typically increasing sedimentation rate (Woodroffe, 2003). The prolific growth and ability to suppress mangrove colonisation of *S. alterniflora* means that distribution of the native mangroves will be severely restricted, resulting in a long-term change in the ecology of the estuary. If left unchecked, the invasion coupled with

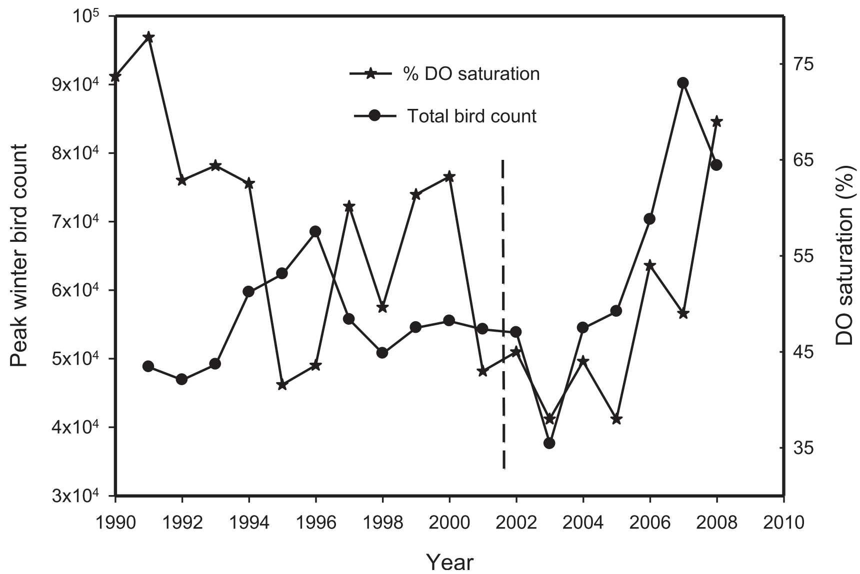

Fig. 1. Relationship between peak-winter waterbird count in Deep Bay, northwest Hong Kong, and annual mean % dissolved oxygen saturation (depth-profiled) as monitored by the Environmental Protection Department. The dotted vertical line denotes the apparent shift from a negative to positive correlation pattern pre- and post-2001. $p \approx 0.05$ for both pre- and post-2001 Spearman ρ, with a negative correlation for pre-2001 and positive for post-2001 periods. Bird data from the Hong Kong Bird Watching Society and DO data from annual water quality reports published by the Environmental Protection Department, Hong Kong SAR.

Fig. 2. Photographs of the Yunxiao mudflat taken in 2011 (left) and 2015 (right) showing the rapid colonisation of the open mudflat by introduced codgrass *Spartina alterniflora*. While some recruitment of mangroves (*Kandelia obovata*) has occurred, the codgrass has attained almost total coverage on the intertidal flat.

the ubiquitous seawall could squeeze mangroves to extinction along the Chinese coast in the face of expected significant sea level rise (Yin et al., 2011) in the future decades.

The reduction in open mudflat areas due to codgrass spread also results in significant changes in the socio-economics of the estuary. The collection of razor clam and juvenile mud crab has virtually disappeared as the open mudflat habitat of these fishery species is now occupied by dense codgrass. Even if these species may still survive in the sediments, dense codgrass growth implies that collection of these organisms will be too inefficient to support a viable artisanal fishery. Responding to this threat to their livelihood, the local fishing community has adapted by converting most of the aquaculture ponds into razor clam cultivation operations. As razor clams are filter-feeders, usually clam grow-out ponds are each accompanied by a pond merely for phytoplankton growth as feed for the clams. The ponds are heavily fertilised, with chicken manure being the preferred fertilizer. While the implication of this shift in aquaculture operation for nutrient pollution in the estuary is yet to be evaluated, recent data on sediment CO_2 emissions from the frequently drained ponds (for ease of clam harvesting) suggest this shift could result in a net increase in the carbon emission and footprint of the estuary (Ouyang, X. and Lee, S.Y., unpubl. data). A recent study comparing the carbon storage and CO_2 emission of the native mangrove and saltmarsh species (*Kandelia obovata* and *Cyperus malaccensis*) with their invasive counterparts (*Sonneratia apetala* and *S. alterniflora*) also suggest that while there may be modest increases in carbon storage capacity, the invasive species may more than offset this capacity by their high CO_2 emission rates (Chen et al., 2015). Another implication of the loss of the mudflat habitat is that fishers are pushed to collect their seeds for clam and mud crab cultivation further afield, stretching an already challenging operating environment.

There are few feasible options for rehabilitation or restoration. Eradication of *S. alterniflora* is a significant ecological as well as logistical challenge, not to mention the fact that there is to date no consensus between scientists and managers on a strategy for managing this invasion. As *S. alterniflora* has established along the Chinese coast for >40 years, and ~20 years at Yunxiao, eradication of the present codgrass stands would likely be futile as there will be a large local seed bank available for regeneration. Seed dispersal from nearby infested areas will also promote regeneration. Local mangrove seedlings also apparently cannot compete in areas with established codgrass (Zhang et al., 2012). A radical solution using the introduced mangrove *Sonneratia apetala* apparently successfully eradicated *S. alterniflora* after 12 years on an isolated island in southern China (Chen et al., 2014). The alien *S. apetala*, however, is known to cause major shifts in wetland structure and function (e.g. Liu et al., 2014) and may present its own challenges to mangrove conservation (Peng et al., 2016). Invasion by codgrass therefore causes major ecological as well as socio-economic challenges that require costly restoration or rehabilitation solutions.

The Yunxiao wetlands illustrate the rapid and large-scale impacts exotic invasive species can exert on intertidal soft-sediment habitats. These impacts could drive wholesale shifts in the ecology and thus services from and management of the wetlands. The knowledge needs in such cases include how to incorporate the established exotic species in future ecosystem management plans, and holistic analyses of the socio-economic impacts as well as management options of the introduction.

3.3. Lake Sihwa, Korea

Lake Sihwa (37°18′N 126°40′E) is an artificial lake isolated by the construction of a 12.7 km sea-dike in 1994 for providing freshwater supply to nearby industrial and/or agricultural areas (Fig. 3). Due to the lack of wastewater treatment facilities and continuing and increasing pollutant loads from the neighbouring industries and municipalities, the Lake Sihwa environment rapidly deteriorated (Khim and Hong, 2014). Earlier in 2000, the Korean government abandoned its original plan to turn Lake Sihwa into a freshwater lake and constructed a water gate allowing partial tidal circulation through the existing dikes. Although water quality parameters such as chemical oxygen demand (COD) have improved (Fig. 3), organic pollutants such as dioxins/furans, organochlorines, perflorinated chemicals, and alkyphenols, have been repeatedly found in sediments from the inner less-flushed regions of Lake Sihwa and the surrounding inland creeks in the past 10 years (Khim and Hong, 2014).

In order to examine the long-term ecological impact on Lake Sihwa, the occurrence of the dominant macrozoobenthos species analysed over a period of 20 years (Fig. 3). The result indicated that the benthic communities were apparently directly affected by the anoxic bottom condition arising from organic enrichment. For example, the dominant macrozoobenthos species before and after the dike construction were different and increased contribution of opportunistic species such as *Heteromastus filiformis*, *Pseudopolydora kempi*, and *Capitella capitata* was evident. In particular, the drastic increase of indicator species for organically polluted or enriched conditions was found only after dike construction, indicating the direct effect of embankment on the benthic habitats and/or the associated organisms. In fact, the COD in Lake Sihwa increased during dike construction and reached the maximum of 17.4 mg/L in 1997, the year following completion of dike construction (Fig. 3). Upon reinstatement of tidal exchange from 1997, COD in the 2010s rapidly declined to levels that were similar to those in the early 2000s (before the dike was completed). Water quality deterioration followed by sedimentary pollution clearly caused these benthic community changes. Meantime the occurrence of brackish water species such as *Alitta succinea* (Polychaeta: Nereididae) was consistent with the period of blocked tidal connectivity. Overall, the benthic macrofaunal assemblage in terms of the long-term changes in dominant species seemed to reflect the historical sedimentary pollution.

Of note, certain benthic species completely disappeared, whereas the number of opportunistic species significantly increased (Lee et al., 2014b). One distinct characteristic of the Lake Sihwa benthic community is the prevalence of polychaete populations after dike construction, with the number of opportunistic polychaetes species such as *Pseudopolydora kempi* and *Polydora cornuta* dominated near the dike (Lee et al., 2014b). In general, the historical anthropogenic activities and consequential environmental changes in Lake Sihwa during the past 20 years seem to be the direct drivers for the long-term changes in the benthic community. The decreasing abundance of opportunistic species and indicator species of organic enrichment in Lake Sihwa after restoration of tidal connectivity indicates apparent speedy benthic community recovery. Since 2012, a tidal power station (254 MW), the world's largest at present, has been operating in Lake Sihwa to take advantage of the large tidal range and the dike infrastructure. At present, the positive effects of tidal power station on water and/or sediment quality has not been addressed due to the lack of monitoring efforts. Further, it might be difficult to evaluate the return of “healthy” benthic community after simple restoration effort in the form of restoration of tidal connectivity, including the operation of tidal power station.

The management of Lake Sihwa demonstrates how tidal flat systems are vulnerable to seemingly simple management decisions, i.e. diking. Species dominance patterns, water quality and therefore ecosystem function and services could be dramatically altered, resulting in large and long-term environmental and socio-economic costs. However, Lake Sihwa also demonstrates the reality of demand for accommodating multiple use of these systems on populous coasts. More research in the compatibility of different uses and how to manage the same system for multiple use, while not destroying the very ecological foundation of the services, is urgently needed.

3.4. Saemangeum tidal flats, Korea

The Saemangeum (35°50'N 126°35'E) located in the Mangyeong-Dongjin estuary was one of the typical tidal flats in Korea, formerly covering ~233 km^2 of tidal wetlands with maximum extension to ~15 km offshore. However, the Saemangeum tidal flats were lost to embankment in 2006, due to the world largest continuous sea-wall (33.9 km), resulting the loss of Korea's largest estuarine tidal flat. The issue around the Saemangeum, which dates back to the late 1980s, has long been debated between government and the public until the eventual completion of the sea-dike, but the environmental deterioration that ensued prompted the second phase of debate in recent years (Nam et al., 2014). One important issue among the debates centres on the change of land development plans to building a new industrial complex and harbor, which deviates from the original plan of farmland and lake creation, thus modification of the original plan would be necessary. Notwithstanding, the recent documented widespread environmental damages and ecological threats clearly indicate failure of the original plan (Ryu et al., 2014).

One of the important consequences of the Saemangeum sea-wall would be the loss of significant ecosystem services such as the high biodiversity and productivity provided by the tidal flats. For example, 232 microphytobenthos taxa were reported in 1988, before the dike construction. A comparable number of 194 species was found from the Saemangeum tidal flat in 2003-05, during the reclamation period (Park et al., 2014a). However, one recent review of the macrozoobenthos of Korean tidal flats documented a total of 173 macrozoobenthos species in the intertidal and subtidal areas of Saemangeum, which indicates the Saemangeum fauna contribute ~30% of the total species occurring on the west coast of Korea (Park

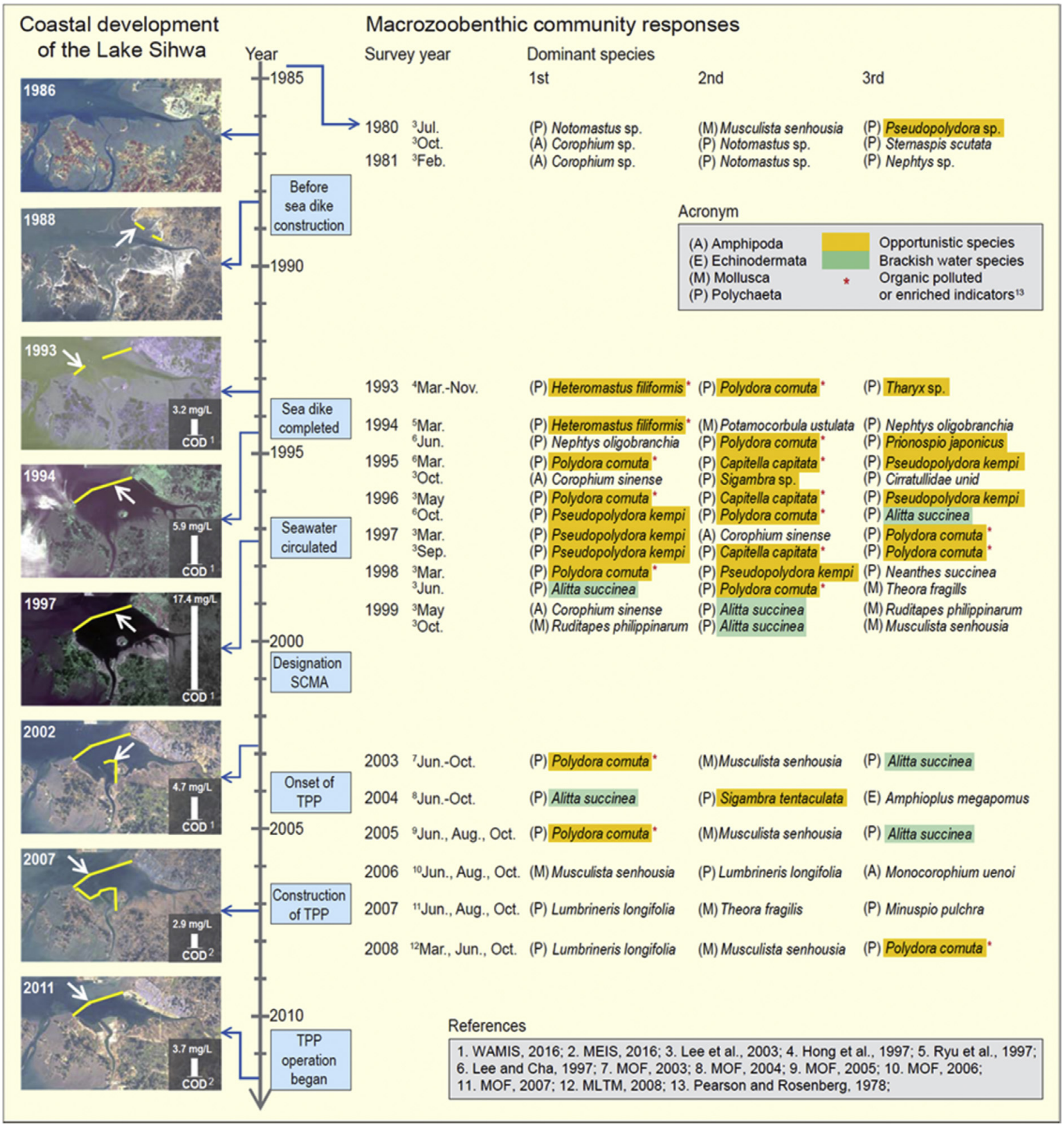

Fig. 3. The top three dominant macrozoobenthos found in Lake Shihwa since during the Lake Shihwa reclamation project, over the past 30 years (meta-data extracted from 12 references given), listed the spices belonging four taxonomic groups with highlights of the opportunistic species, brackish water species, and organic polluted or enriched indicators occurred in Lake Shihwa. Brief summary for the history of the Lake Shihwa reclamation project highlighting historical embankment activities with basic water quality data of COD in the inside of the Lake Shihwa (WAMIS, 2016; MEIS, 2016; Lee et al., 2003; Hong et al., 1997; Ryu et al., 1997; Lee and Cha, 1997; MOF, 2003, 2004, 2005, 2006, 2007; MLTM, 2008; Pearson and Rosenberg, 1978).

et al., 2014b). These results clearly indicate relatively high biodiversity of the Saemangeum flora and fauna among the Korean tidal flats (total area of ~2500 km^2) and thus this area is a hot spot in terms of productivity.

As part of a review, we collected macrozoobenthos data from Saemangeum and analysed the temporal occurrence of dominant species in order to describe the long-term benthic community change during the Saemangeum reclamation periods (Fig. 4). In general, the macrobenthic faunal composition showed two clear temporal trends: 1) increasing proportion of polychaetes, particularly in the subtidal zone; and 2) increasing proportion of opportunistic species and/or organic polluted or enriched indicators. The abundance of some numerically dominant species, e.g. the mollusc *Laternula rostrata* and brachiopod *Lingula anatina* dramatically decreased in the intertidal zone after dike construction (Ryu et al., 2011a, 2011b, 2014). Temporal changes of the dominant species in the subtidal zone was pronounced, with rapid variations in species composition, which may reflect more dynamic environmental changes in subtidal areas close to the dike.

Indeed, the direct effect of the dike in the Saemangeum area was reduced tidal flow and period, which further drove changes in geochemical conditions (Park et al., 2014c). For example, the rapid increase of COD inside the dike in 2004 after the Sector IV dike (northern part of Saemangeum) had been completed (2003),

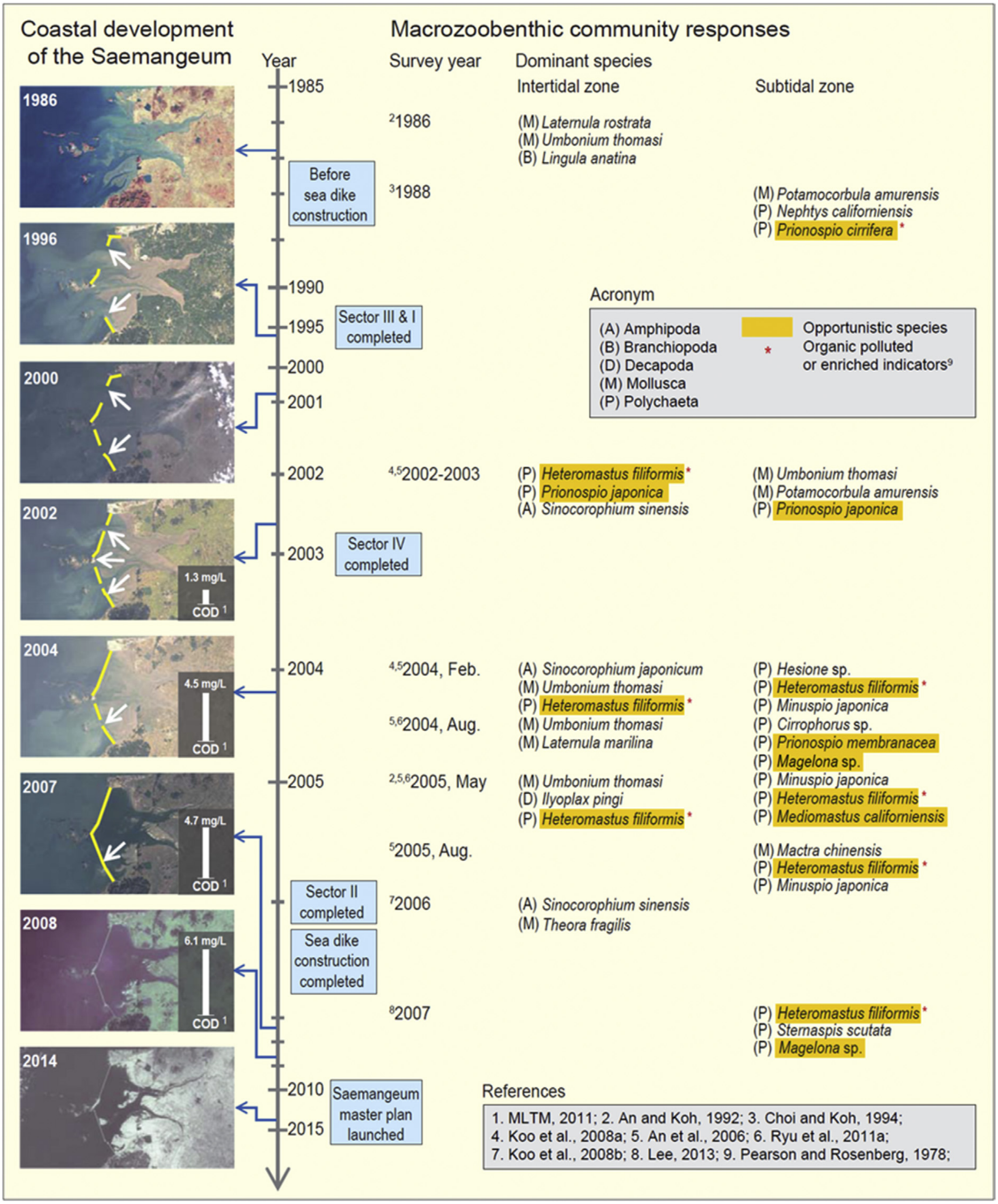

Fig. 4. The dominant macrozoobenthos found in Saemangeum tidal flats since during the Saemangeum reclamation project, over the past 30 years (meta-data extracted from 8 references given), listed the spices belonging five taxonomic groups with highlights of the opportunistic species and organic polluted or enriched indicators occurred in the intertidal and subtidal zones of Saemangeum area. Brief summary for the history of the Saemangeum reclamation project highlighting historical embankment activities with basic water quality data of COD in the inside of the Saemangeum area (MLTM, 2011; An and Koh, 1992; Choi and Koh, 1994; Koo et al., 2008a; An et al., 2006; Ryu et al., 2011a; Koo et al., 2008b; Lee, 2013; Pearson and Rosenberg, 1978).

indicated a severe pollution event in the water column due to the change of tidal flow by the embankment (Fig. 4). Also, the changes of physicochemical properties of bottom sediment, e.g. increasing finer sediments with higher organic content, observed in the Sandong area (close to Sector IV) during this period were apparently associated with the reduction of tidal energy, particularly in the subtidal zone (Ryu et al., 2014). Accordingly, the rapid alteration in zonal distribution of the macrozoobenthos along the Sandong transect, with a complete change of dominant species, was observed in 2003-05 (Ryu et al., 2014). COD continued to increase in the following years and reached a maximum of 6.1 mg/L in 2008, two years dike completion. Altogether, long-term changes in benthic community structure reflected the population and/or community level impacts arising from the physical and biogeochemical changes caused by sea-dike construction.

It is obvious that a loss of the valuable ecosystem services of the tidal flats caused by the series of major reclamation projects in Korea should caution against reclamation as a means for increasing land supply. The recent policy shift to protect and restore the tidal wetlands in Korea owes to the past (or current) environmental damages and ecological threats resulting from the grand-scale tidal wetland reclamations, such as those occurred at Lake Sihwa and Saemangeum. In Korea, about 2400 km^2 of the coastal areas have been embanked by reclamation in the past 40 years, almost on par (~2500 km^2) with the current tidal flat areas (Koh and de Jonge, 2014).

The Saemangeum tidal flat data highlight the urgent need to assess and document the biodiversity associated with similar habitats in East Asia. Knowledge on the flora and fauna of tidal flats to date is dominated by studies in Europe, e.g. the Wadden Sea. Without this baseline information, not only would it be difficult to assess the threat to biodiversity due to development or management decisions, but also the efficacy of rehabilitation or restoration efforts. With extensive anthropogenic destruction and impact already inflicted on intertidal soft-sediment habitats in East Asia, this baseline information may have already been lost but should nonetheless be a top priority in the race against time.

4. What science will inform restoration of soft-sediment habitats in East Asia?

4.1. Species diversity and ecosystem function/services

Few theories and paradigms in ecology originated from tidal soft-sediment ecosystems. While some early work on species interaction such as competition and facilitation (e.g. Levin, 1981) or bioturbation effects of the benthos (e.g. Brenchley, 1981), relatively little context-sensitive theoretical advance or empirical data are available to guide restoration and rehabilitation of soft-sediment habitats. One of the key shortcomings of mangrove restoration efforts is the establishment of monospecific plantations as a replacement of damaged natural multi-species forests. While this practice may be cost-effective in terms of resources and time required to establish a forest (especially when easy-to-plant species such as *Rhizophora* are used), questions remain as to how these monocultures may compare with natural diverse forests in terms of function and their capacity for ecosystem services. Mangrove (~70 species globally), and seagrass (~50 + species) are typically relatively species-poor systems compared to terrestrial forests so it is of great interest how function of these soft-sediment systems may respond to changes in species diversity. Saltmarshes support a more diverse flora but still with limited taxonomic diversity, e.g. the small number of genera of plants. The relationship between thresholds for functional redundancy and stand and regional diversity needs to be clarified for these species-poor systems in order to evaluate the implications of monospecific plantations as an endpoint for restoration.

4.2. System properties of tidal soft-sediment ecosystems and recovery trajectory

A large area of darkness in the ecosystem properties of soft-sediment habitats – their properties relevant to change and recovery: system inertia, stability, and resilience. Tidal soft-sediment ecosystems, especially those in populous Asia, have a long history of significant anthropogenic perturbations, the impacts of which are relatively well documented. There is, however, a dearth of information let alone knowledge about how these systems recover either naturally upon removal of perturbation, or when assisted under restoration and rehabilitation efforts. Subtidal soft-sediment systems are comparatively better studied in this respect, particular with reference to the impact of and recovery from disturbances such as fishing (e.g. Kaiser et al., 2006; Shephard et al., 2010; Verissimo et al., 2012). Borja et al. (2010) reviewed 51 cases of recovery of coastal and estuarine ecosystems from five main types of stressors (not including invasion by and subsequent removal of exotic species) and concluded that long-term degradation would require at least 15–25 years for return of the original biotic components, with recovery of diversity requiring much longer time frames. While restoration is one of the main drivers for recovery, most restoration projects either lack or have only low intensity monitoring to generate a perspective of ecosystem recovery under human intervention. The relatively short history of coastal and estuarine restoration also means that the temporal scale of data availability is far inadequate for formulating patterns on recovery trajectories. A perspective of ecosystem recovery trajectory will also benefit ecosystem conservation as the likelihood as well as scenarios of recovery will help caution against the costs of damaging the ecosystem in the first place.

The lack of long-term data on the performance of restored systems may be circumvented by drawing parallels from some human-maintained systems, e.g. plantations, with a long history. The managed *Rhizophora apiculata* plantation at Matang, western peninsular Malaysia, follows a 30-year rotation cycle, which offers parallels to the monospecific plantation approach of many mangrove restoration projects. The extensive plantation area offers replicate plots of different age since clear cutting and re-planting; the existence of some 'virgin' forests that have remained untouched for over a century also provides reference sites for comparison. Similar establishments are available in other Southeast Asian countries (e.g. Vietnam, Thailand), albeit with less meticulous management regimes. These human-managed settings could play a significant role in enabling rigorous investigations on how mangrove ecosystems behave over time in response to restoration efforts and help establish recovery trajectories. Long-term studies or monitoring are vital in informing future restoration effort as estuarine ecosystems are expected to demonstrate non-linear pattern in function and the delivery of services (Barbier et al., 2008). This non-linearity is expected to occur also in time, e.g. the ability of replanted mangroves to store carbon or support faunal biodiversity is expected to grow non-linearly with time and peak at a certain age. System response to multi-stressor situation also requires particular attention.

4.3. Region-specific data on soft-sediment tidal ecosystems

Paradigms in soft-sediment habitat ecology mostly originated from studies in European (seagrass and tidal flats) and American (sandy beach, saltmarsh, and mangrove) systems. Asian ecosystems differ from their European and American counterparts in several fundamental aspects relevant to their response to stress as well as recovery. The west Pacific supports a distinctly higher level of species richness of mangroves, corals, as well as seagrass compared to the West Atlantic or Caribbean systems. The full implication of this difference is yet to be explored, but it is expected that ecosystem resilience will be affected. The species-rich systems also present a greater challenge to complete restoration, although restoration of function may not require the full return of all component species.

Ecosystem-level syntheses on the fundamental aspects such as the productivity and resilience of Asian soft-sediment systems are still lacking. Early research on these systems has focused on the structure of plant and animal assemblages, with little management-relevant work. Long-term studies that may circumvent sporadic variations as well as provide information on system resilience and recovery are particularly needed in these rapidly changing environments. Difference in the biology of key foundation species may also be different, with implications for the impact of introduction and strategies for restoration. For example, saltmarsh species along the East Asian coast occupy a higher tidal position that the introduced *S. alterniflora,* providing a vacant niche for this species in the mid to low intertidal. Urgent ecological knowledge specific to East Asia on key foundation species as well as key ecosystems is required to inform restoration effort in the region.

4.4. Multi-disciplinary approach to restoration

The goal of restoration is usually defined by the return of ecosystem services through the re-establishing the fundamental biotic and abiotic elements of ecosystems, e.g. the foundation species (trees in a mangrove forest) or the sediment supply and hydrology of a tidal flat. However, many restoration projects terminate as soon as re-establishment of these fundamental elements is achieved, without progressing to evaluating if and how the intended ecosystem services are returned. Ecosystem services are by definition an anthropocentric concept, thus demanding restoration efforts to incorporate the socio-economic outcomes as a component of success evaluation. The link between different options (e.g. difference in restoration 'intensity') of restoration and their capacity for sustaining ecosystem services, and thus the implications for sustaining local and wider communities, requires attention. Most restoration projects either have no plans for evaluating success or have time spans too short to go beyond the re-establishment of the fundamental elements. Little knowledge is therefore available on the socio-economic benefits of the restoration.

With increasing efforts in valuating ecosystems including tidal wetlands (e.g. Costanza et al., 1997, 2014; Barbier et al., 2011), the actual socio-economic benefits of restoration options should be evaluated. The Yunxiao example illustrates the challenges of habitat restoration when significant socio-economic implications exist for different restoration options, e.g. do nothing vs complete eradication of *Spartina* vs use of *Sonneratia apetala* as biological control. Each option presents different ecological and engineering challenges but also carries different ecological and socio-economic consequences. The prime value of reclaimed land in densely populated estuaries in Asia also begs a sustainable socio-economic model for tidal wetland conservation and restoration. Some form of 'life-cycle analysis' (Finnveden et al., 2009) of each of these scenarios would benefit decision making on the restoration options.

Many restoration projects fail because they were simply managed as community projects without the necessary scientific backing. Conversely, approaches with little reference to socio-economic goals may prove irrelevant to, and therefore not supported by, local communities. Successful and cost-effective restoration of tidal soft-sediment habitats require the cooperation of scientists in disciplines such as hydrodynamics, ecology, geomorphology to work with engineers and social scientists. The Korean case studies illustrate that as expected and evidenced, the loss of biodiversity and productivity on tidal flats continuously increased. Further reclamation, say including another type of coastal infrastructure such as a tidal power station that requires a tidal barrage, would indebt the future generation again with a huge environmental and/or socio-ecological cost. In this respect, the future directions for research and policy should emphasize sustainable coastal ecosystem management with an integrated perspective that incorporates the biological (e.g. biodiversity and ecosystem services), environmental (e.g. water quality, public health), and socio-economic (e.g. demand for flat development land) imperatives rather than a simplistic landfilling approach.

Acknowledgments

SYL thanks Seoul National University for the invitation and financial support towards participating in the 2nd Korea-China Yellow Sea Symposium. This study was supported by the projects entitled "Integrated management of marine environment and ecosystems around Saemangeum" and "Development of integrated estuarine management system" funded by the Ministry of Oceans and Fisheries, Republic of Korea, given to JSK.

References

Allison, S.D., Martiny, J.B.H., 2008. Resistance, resilience and redundancy in microbial communities. P. Natl. Acad. Sci. U. S. A. 105, 11512–11519.
An, S.M., Koh, C.H., 1992. Environments and distribution of benthic animals on the Mangyung-Dongjin tidal flat, west coast of Korea. J. Oceano. Soc. Korea 27, 78–90.
An, S.M., Lee, J.-H., Woo, H.J., Koo, B.J., Lee, H.-G., Yoo, J.-W., Je, J.G., 2006. Benthic environment and macrofaunal community changes during the dike construction in Saemangeum subtidal area, Korea. Ocean. Polar Res. 28, 369–383.
Au, D.W.-K., 2005. The Change of Marine Water Quality in Hong Kong in the Past Ten Years. Master of Environmental Management thesis. The University of Hong Kong, Hong Kong, 183pp.
Barbier, E.B., 2006. Natural barriers to natural disasters: replanting mangroves after the tsunami. Front. Ecol. Environ. 4, 124–131.
Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.
Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319, 321–323.
Borja, A., Dauer, D.M., Elliott, M., Simenstad, C.A., 2010. Medium- and long-term recovery of estuarine and coastal ecosystems: patterns, rates and restoration Effectiveness. Estuar. Coasts 33, 1249–1260.
Brenchley, G.A., 1981. Disturbance and community structure - an experimental-study of bioturbation in marine soft-bottom environments. J. Mar. Res. 39, 767–790.
Chang, S.E., Adams, B.J., Alder, J., Berke, P.R., Chuenpagdee, R., Ghosh, S., Wabnitz, C., 2006. Coastal ecosystems and tsunami protection after the December 2004 Indian Ocean tsunami. Earthq. Spectra 22, S863–S887.
Chen, H., Liao, B.W., Liu, B.E., Peng, C.H., Zhang, Y., Guan, W., Zhu, Q.A., Yang, G., 2014. Eradicating invasive *Spartina alterniflora* with alien *Sonneratia apetala* and its implications for invasion controls. Ecol. Eng. 73, 367–372.
Chen, Y.P., Chen, G.C., Ye, Y., 2015. Coastal vegetation invasion increases greenhouse gas emission from wetland soils but also increases soil carbon accumulation. Sci. Total Environ. 526, 19–28.
Choi, J.-W., Koh, C.-H., 1994. Macrobenthos community in Keum-Mankyung-Dongjin estuaries and its adjacent coastal region, Korea. J. Kor. Soc. Oceanogr. 29, 304–318.
Chung, C.H., 1993. 30 years of ecological engineering with *Spartina* plantations in China. Ecol. Eng. 2, 261–289.
Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., ONeill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., vandenBelt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Change-Human Policy Dim. 26, 152–158.
Dahdouh-Guebas, F., Jayatissa, L.P., Di Nitto, D., Bosire, J.O., Lo Seen, D., Koedam, N., 2005. How effective were mangroves as a defence against the recent tsunami? Curr. Biol. 15, R443–R447.
Diaz, R.J., Rabalais, N.N., Levin, L.A., 2009. The coastal dissolved oxygen squeeze: future interactions of land and ocean processes, and consequences for ecosystem services. Geochim. Cosmochim. Acta 73. A289–A289.
Ellison, A.M., 2000a. Mangrove restoration: do we know enough? Restor. Ecol. 8, 219–229.
Ellison, A.M., 2000b. Restoration of mangrove ecosystems. Restor. Ecol. 8, 217–218.
Environmental Protection Department, 2014. Marine Water Quality in Hong Kong 2014. Hong Kong Government, Hong Kong.
Estes, J.A., et al., 2011. Trophic downgrading of Planet Earth. Science 333, 301–305.
FAO, 2007. The World's Mangroves: 1980-2005. Rome, Italy, 89pp.
Feng, J., Guo, J., Huang, Q., Jiang, J., Huang, G., Yang, Z., Lin, G., 2014. Changes in the community structure and diet of benthic macrofauna in invasive *Spartina alterniflora* wetlands following restoration with native mangroves. Wetlands 34, 673–683.

Feng, J.X., Huang, Q., Qi, F., Guo, J.M., Lin, G.H., 2015. Utilization of exotic Spartina alterniflora by fish community in the mangrove ecosystem of Zhangjiang Estuary: evidence from stable isotope analyses. Biol. Invas. 17, 2113–2121.
Field, C., 1996. Restoration of Mangrove Ecosystems. International Tropical Timber Organisation and International Society for Mangrove Ecosystems. Okinawa, Japan. 250pp.
Field, C.D., 1998. Rehabilitation of mangrove ecosystems: an overview. Mar. Poll. Bull. 37, 383–392.
Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1–21.
Hong, J.-S., Jung, R.-H., Seo, I.-S., Yoon, K.-T., Choi, B.-M., Yoo, J.-W., 1997. How are the spatio-temporal distribution patterns of benthic macrofaunal communities affected by the construction of Shihwa dike in the west coast of Korea? J. Korean Fish. Soc. 30, 882–895.
Hsiang, L.L., 2000. Mangrove conservation in Singapore: a physical or a psychological impossibility? Biodivers. Conserv. 9, 309–332.
Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M.C.V., Somerfield, P.J., Karakassis, I., 2006. Global analysis of response and recovery of benthic biota to fishing. Mar. Ecol. Prog. Ser. 311, 1–14.
Khim, J.S., Hong, S., 2014. Assessment of trace pollutants in Korean coastal sediments using the triad approach: a review. Sci. Total Environ. 470–471, 1450–1462.
Koh, C.H., de Jonge, V.N., 2014. Stopping the disastrous embankments of coastal wetlands by implementing effective management principles: Yellow Sea and Korea compared to the European Wadden Sea. Ocean. Coast Manage. 102, 604–621.
Koh, C.H., Khim, J.S., 2014. The Korean tidal flat of the Yellow Sea: physical setting, ecosystem and management. Ocean. Coast Manage. 102, 398–414.
Koo, B.J., Kwon, K.K., Hyun, J.H., 2008a. Effect of environmental conditions on variation in the sediment-water interface created by complex macrofaunal burrows on a tidal flat. J. Sea Res. 58, 302–312.
Koo, B.J., Shin, S.-H., Lee, S., 2008b. Changes in benthic macrofauna of the Saemangeum tidal flat as result of a drastic tidal reduction. Ocean. Polar Res. 30, 485–495.
Lee, C.H., Lee, B.Y., Chang, W.K., Hong, S., Song, S.J., Park, J., Kwon, B.O., Khim, J.S., 2014b. Environmental and ecological effects of Lake Shihwa reclamation project in South Korea: a review. Ocean. Coast Manage. 102, 545–558.
Lee, J.-H., Cha, J.-H., 1997. A study of ecological succession of macrobenthic community in an artificial lake of Shihwa on the west coast of Korea: an assessment of ecological impact by embankment. Ocean. Res. 19, 1–12.
Lee, J.-H., Park, J.-Y., Lee, H.-G., Park, H.-S., Kim, D.-S., 2003. Environmental assessment of the Shihwa lake by using the benthic pollution index. Ocean. Polar Res. 25, 183–200.
Lee, J.-H., 2013. Spatial and Temporal Variation of Benthic Polychaetous Community in the Offshore Area outside Saemangeum Dike since Saemangeum Dike Construction (Ph.D. thesis). Chonnam National University, South Korea.
Lee, S.Y., 2000. Carbon dynamics of Deep Bay, eastern Pearl River estuary, China. II: trophic relationship based on carbon- and nitrogen-stable isotopes. Mar. Ecol. Prog. Ser. 205, 1–10.
Lee, S.Y., Dunn, R., Young, R.A., Connolly, R.M., Dale, P.E.R., Dehayr, R., Lemckert, C.J., McKinnon, S., Powell, B., Teasdale, P.R., Welsh, D.T., 2006. Impact of urbanization on coastal wetland structure and function. Aust. Ecol. 31, 149–163.
Lee, S.Y., 2016. From blue to black: anthropogenic forcing of carbon and nitrogen influx to mangrove-lined estuaries in the South China Sea. Mar. Poll. Bull. 109, 682–690.
Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., Record, S., 2014a. Ecological role and services of tropical mangrove ecosystems: a reassessment. Glob. Ecol. Biogeog. 23, 726–743.
Levin, L.A., 1981. Dispersion, feeding-behavior and competition in two spionid polychaetes. J. Mar. Res. 39, 99–117.
Lewis, R.R., 2000. Ecologically based goal setting in mangrove forest and tidal marsh restoration. Ecol. Eng. 15, 191–198.
Lewis, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24, 403–418.
Lewis, R.R., Gilmore, R.G., 2007. Important considerations to achieve successful mangrove forest restoration with optimum fish habitat. Bull. Mar. Sci. 80, 823–837.
Li, M.S., Lee, S.Y., 1998. Carbon dynamics of Deep Bay, eastern Pearl River Estuary, China. I: a mass balance budget and implications for shorebird conservation. Mar. Ecol. Prog. Ser. 172, 73–87.
Liu, L.N., Li, F.L., Yang, Q., Tam, N.F.Y., Liao, W.B., Zan, Q.J., 2014. Long-term differences in annual litter production between alien (*Sonneratia apetala*) and native (*Kandelia obovata*) mangrove species in Futian, Shenzhen, China. Mar. Poll. Bull. 85, 747–753.
Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L.X., Triet, T., 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature 526, 559–U217.
Lu, W., Yang, S., Chen, L., Wang, W., Du, X., Wang, C., Ma, Y., Lin, G., Lin, G., 2014. Changes in carbon pool and stand structure of a native subtropical mangrove forest after inter-planting with exotic species *Sonneratia apetala*. Plos One 9, e91238.
Lugo, A.E., 1998. Mangrove forests: a tough system to invade but an easy one to rehabilitate. Mar. Poll. Bull. 37, 427–430.
Ma, Z.J., Melville, D.S., Liu, J.G., Chen, Y., Yang, H.Y., Ren, W.W., Zhang, Z.W., Piersma, T., Li, B., 2014. Rethinking China's new great wall. Science 346, 912–914.
Marine Environment Information System (MEIS), 2016. Available online at: http://www.meis.go.kr/rest/main.
Ministry of Land, 2008. Transportation and Maritime Affairs (MLTM). In: Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MLTM, Seoul.
Ministry of Land, 2011. Transportation and Maritime Affairs (MLTM). In: Saemangeum Coastal System Research for Marine Environmental Conservation. MLTM, Seoul.
Ministry of Maritime Affairs and Fishery (MOMAF), 2003. Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MOMAF, Seoul.
MOMAF, 2004. Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MOMAF, Seoul.
MOMAF, 2005. Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MOMAF, Seoul.
MOMAF, 2006. Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MOMAF, Seoul.
MOMAF, 2007. Study on Improvement of Marine Environments in the Shihwa Coastal Reservoir. MOMAF, Seoul.
Morton, B., 2003. Fishing for diplomacy in China's Seas. Mar. Poll. Bull. 46, 795–796.
Murray, N.J., Clemens, R.S., Phinn, S.R., Possingham, H.P., Fuller, R.A., 2014. Tracking the rapid loss of tidal wetlands in the Yellow Sea. Front. Ecol. Environ. 12, 267–272.
Murray, N.J., Fuller, R.A., 2015. Protecting stopover habitat for migratory shorebirds in East Asia. J. Ornithol. 156, S217–S225.
Murray, N.J., Ma, Z.J., Fuller, R.A., 2015. Tidal flats of the Yellow Sea: a review of ecosystem status and anthropogenic threats. Austral Ecol. 40, 472–481.
Nam, J., Son, K.H., Khim, J.S., 2015. Multiple implications of the restoration of coastal wetland ecosystem and the establishment of a strategic restoration framework. Ocean. Polar Res. 37, 211–223.
Park, J., Kwon, B.O., Kim, M., Hong, S., Ryu, J., Song, S.J., Khim, J.S., 2014a. Microphytobenthos of Korean tidal flats: a review and analysis on floral distribution and tidal dynamics. Ocean. Coast. Manage. 102, 471–482.
Park, J., Song, S.J., Ryu, J., Kwon, B.-O., Hong, S., Bae, H., Choi, J.-W., Khim, J.S., 2014b. Macrozoobenthos of Korean tidal flats: a review on species assemblages and distribution. Ocean. Coast. Manage. 102, 559–571.
Park, Y.G., Kim, H.Y., Hwang, J.H., Kim, T., Park, S., Nam, J.H., Seo, Y.K., 2014c. Dynamics of dike effects on tidal circulation around Saemangeum, Korea. Ocean. Coast. Manage. 102, 572–582.
Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Annu. Rev. 16, 229–311.
Peng, Y., Zheng, M., Zheng, Z., Wu, G., Chen, Y., Xu, H., Tian, G., Peng, S., Chen, G., Lee, S.Y., 2016. Virtual increase or latent loss? A reassessment of mangrove populations and their conservation in Guangdong, southern China. Mar. Poll. Bull. 109, 691–699.
Phan, L.K., de Vries, J.S.M.V., Stive, M.J.F., 2015. Coastal mangrove squeeze in the Mekong delta. J. Coast. Res. 31, 233–243.
Reise, K., 1985. Tidal flat Ecology. An Experimental Approach to Species Interactions. Springer-Verlag, Berlin.
Ren, H., Lu, H.F., Shen, W.J., Huang, C., Guo, Q.F., Li, Z.A., Jian, S.G., 2009. *Sonneratia apetala* Buch. Ham in the mangrove ecosystems of China: an invasive species or restoration species? Ecol. Eng. 35, 1243–1248.
Richards, D.R., Friess, D.A., 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000-2012. Proc. Natl. Acad. Sci. U. S. A. 113, 344–349.
Rosenberg, R., 1985. Eutrophication - the future marine coastal nuisance. Mar. Poll. Bull. 16, 227–231.
Ryu, J.-S., Choi, J.-W., Kang, S.-G., Koh, C.-H., Huh, S.-H., 1997. Temporal and spatial changes in the species composition and abundance of benthic polychaetes after the constuction of Shihwa Dike (West coast of Korea). J. Korean Soc. Oceanogr. 2, 101–109.
Ryu, J., Khim, J.S., Choi, J.-W., Shin, H.C., An, S., Park, J., Kang, D., Lee, C.-H., Koh, C.-H., 2011a. Environmentally associated spatial changes of a macrozoobenthic community in the Saemangeum tidal flat, Korea. J. Sea Res. 65, 390–400.
Ryu, J., Kim, H.-C., Khim, J.S., Kim, Y.H., Park, J., Kang, D., Hwang, J.H., Lee, C.-H., Koh, C.-H., 2011b. Prediction of macrozoobenthic species distribution in the Korean Saemangeum tidal flat based on a logistic regression model of environmental parameters. Ecol. Res. 26, 659–668.
Ryu, J., Nam, J., Park, J., Kwon, B.O., Lee, J.H., Song, S.J., Hong, S., Chang, W.K., Khim, J.S., 2014. The Saemangeum tidal flat: long-term environmental and ecological changes in marine benthic flora and fauna in relation to the embankment. Ocean. Coast. Manage. 102, 559–571.
Saenger, P., 1996. Mangrove restoration in Australia: a case study of Brisbane International airport. 36–51. In: Field, C.D. (Ed.), Restoration of Mangrove Ecosystems, International Tropical Timber Organisation and International Society for Mangrove Ecosystems. Japan, Okinawa.
Shephard, S., Brophy, D., Reid, D.G., 2010. Can bottom trawling indirectly diminish carrying capacity in a marine ecosystem? Mar. Biol. 157, 2375–2381.
Torio, D.D., Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. J. Coast. Res. 29, 1049–1061.
Torio, D.D., Chmura, G.L., 2015. Impacts of sea level rise on marsh as fish habitat. Estuar. Coasts 38, 1288–1303.

Verissimo, H., Bremner, J., Garcia, C., Patricio, J., van der Linden, P., Marques, J.C., 2012. Assessment of the subtidal macrobenthic community functioning of a temperate estuary following environmental restoration. Ecol. Ind. 23, 312–322.
Wan, S.W., Qin, P., Liu, J.N., Zhou, H.X., 2009. The positive and negative effects of exotic *Spartina alterniflora* in China. Ecol. Eng. 35, 444–452.
Wang, H.J., Dai, M.H., Liu, J.W., Kao, S.J., Zhang, C., Cai, W.J., Wang, G.Z., Qian, W., Zhao, M.X., Sun, Z.Y., 2016. Eutrophication-driven hypoxia in the East China Sea off the Changjiang Estuary. Environ. Sci. Tech. 50, 2255–2263.
Wang, M., Gao, X., Wang, W., 2014. Differences in burrow morphology of crabs between *Spartina alterniflora* marsh and mangrove habitats. Ecol. Eng. 69, 213–219.
Wang, W.Q., Wang, M., 2007. The Mangroves of China. Science Press, Beijing, China.
Water Resources Management Information System (WAMIS), 2016. Available online at: http://www.wamis.go.kr/.
Williams, N., 2005. Tsunami insight to mangrove value. Curr. Biol. 15. R73–R73.
Woodroffe, C.D., 2003. Coasts: Form, Process and Evolution. Cambridge University Press, Cambridge, 623pp.
Yin, J., Yin, Z-e, Hu, X-m, Xu, S-y, Wang, J., Li, Z-h, Zhong, H-d, Gan, F-b, 2011. Multiple scenario analyses forecasting the confounding impacts of sea level rise and tides from storm induced coastal flooding in the city of Shanghai, China. Environ. Earth Sci. 63, 407–414.
Zhang, H., Li, S.Y., 2010. Effects of physical and biochemical processes on the dissolved oxygen budget for the Pearl River Estuary during summer. J. Mar. Syst. 79, 65–88.
Zhang, Y., Huang, G., Wang, W., Chen, L., Lin, G., 2012. Interactions between mangroves and exotic *Spartina* in an anthropogenically disturbed estuary in southern China. Ecology 93, 588–597.
Zhao, Z.Y., Chu, Y.L., Gu, J.D., 2012. Distribution and sources of polycyclic aromatic hydrocarbons in sediments of the Mai Po inner Deep Bay Ramsar site in Hong Kong. Ecotoxicology 21, 1743–1752.
Zhou, T., Liu, S.C., Feng, Z.L., Liu, G., Gan, Q., Peng, S.L., 2015. Use of exotic plants to control *Spartina alterniflora* invasion and promote mangrove restoration. Sci. Rep. 5.
Zuo, P., Zhao, S.H., Liu, C.A., Wang, C.H., Liang, Y.B., 2012. Distribution of *Spartina* spp. along China's coast. Ecol. Eng. 40, 160–166.