Landscape Ecol Eng (2011) 7:241–250
DOI 10.1007/s11355-010-0126-z

ORIGINAL PAPER

Wetland changes and mangrove restoration planning in Shenzhen Bay, Southern China

Hai Ren · Xiaoming Wu · Tianzhu Ning · Gu Huang · Jun Wang · Shuguang Jian · Hongfang Lu

Received: 1 September 2009 / Revised: 22 July 2010 / Accepted: 22 July 2010 / Published online: 13 August 2010

Abstract Mangrove forests and associated *gei wai* (excavated ponds used for shrimp and fish farming) provide important ecosystem services in Shenzhen Bay. Much of the mangrove and *gei wai* wetlands, however, have been lost because of intensified human activities in the past 30 years. Using five-phase remote-sensing images, we describe the recent history of the spatial–temporal dynamics for the wetlands in the bay. From 1986 to 2007, mangrove area increased from 1.8 to 4.8 km^2, while the area of *gei wai* decreased from 36.6 to 17.2 km^2. Reclamation of *gei wai* mainly occurred in western and northern Shenzhen Bay, and changed the tidal water environment. The bay has five typical mangrove communities: *Avicennia marina* + *Kandelia candel* + *Aegiceras corniculatum*, *Kandelia candel* + *Aegiceras corniculatum* + *Acanthus ilicifolius*, *Bruguiera gymnorrhiza* + *Excoecaria agallocha*, *Aegiceras corniculatum*, and *Sonneratia apetala* + *Sonneratia caseolaris*. The distribution of these communities and their dominant species in the bay exhibit a spatial pattern and temporal (successional) sequence. We describe a mangrove restoration program based on the mangrove successional sequence and the interaction of mangrove and *gei wai* in the bay. We have planned six mangrove protection and restoration projects in closed areas, semiclosed areas, and open areas to reconstruct the ecological integrity of the entire Shenzhen Bay.

Keywords Multitemporal TM imagery · Mangrove · Ecological integrity · Overall planning · Shenzhen River Estuary

H. Ren (✉) · J. Wang · S. Jian · H. Lu
Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Xingke Road 723, Tianhe District, Guangzhou 510650, China
e-mail: renhai@scib.ac.cn

X. Wu
Pearl River Water Resources Scientific Research Institute, Guangzhou 510611, China

T. Ning · G. Huang
Water Environment Research Center of Chinese Urban Construction Design and Research Institute, Shenzhen 518048, China

Introduction

Mangroves, which have global distribution within coastal tropical and subtropical regions, provide many ecosystem services. They contribute organic matter to the estuary, act as filtering systems for sediments and other substances, provide habitat for aquatic organisms and birds, stabilize shorelines against erosion from storms, provide economically valuable ecosystem goods, are esthetically attractive, and are valuable for scientific investigation and environmental education (Harty and Cheng 2003; Kraussa et al. 2008). Mangroves and coastal resources are especially important for people in less-developed countries of the tropics, where use of coastal and marine resources is often the only means to meet subsistence and economic needs (Gilman 2002; Sharp and Nakagoshi 2006; Craft et al. 2008). Unfortunately, these valuable services of mangroves and salt marshes are seldom recognized by the public. Most coastal zones face serious problems of occupation/loss and degradation (Howarth et al. 2000; Tam 2004; Weinstein et al. 2007; Bosire et al. 2008). Coastal zones urgently need the development of plans for sustaining, protecting, and restoring mangroves. Such planning is difficult, however, because it must balance the interests and often conflicting objectives of multiple stakeholders (Gilman 2002; Weinstein et al. 2007; Wolanski and Richmond 2008).

Having recognized the value of mangroves, some countries and scientists have begun to develop plans for mangrove restoration in coastal regions. The integrated coastal zone management (ICZM) method provides a mechanism to ensure that the consequences of one sector's decisions on other sectors are properly considered (Harty 2009). Nieto (1993) applied the Venezuelan experience to link territorial and coastal planning. Gilman (2002) pointed out guidelines for coastal and marine site planning and examples of planning and management intervention tools. Harty and Cheng (2003) and Harty (2009) reported ecological assessment and planning strategies for mangrove management in Australia and New Zealand. Most coastal development planning involves mangrove restoration and management, and rehabilitation or restoration of mangrove ecosystems has been reviewed (Field 1999; Bosire et al. 2008; Kraussa et al. 2008; Qin and Mitsch 2009). Zhang and Sui (2001) and Chen et al. (2009) reported the progress in mangrove conservation, restoration, and research in China. Lewis (2005) discussed ecological engineering for successful management and restoration of mangrove forests.

Remote sensing, geographic information systems, and the Global Position System are commonly used in landscape inventory and planning (Jobin et al. 2003). Land classification and change were initially studied by relative radiometric normalization of Landsat Multispectral Scanner (MSS) data using an automatic scattergram controlled regression (Christopher and Ding 1995), but the precision is not high. In fact, Newkirk and Wang (1990) developed a common knowledge database for remote-sensing and geographic information in a change-detection expert system to improve precision. Li et al. (2006) used a knowledge-based system to retrieve spatial–temporal dynamics of mangrove wetlands using multitemporal remote-sensing data. China has developed remote-sensing image-processing approaches for mangrove inventory since the 1990s (Li and Tan 2003; Lee and Yeh 2009). To date, several case studies have used multitemporal remotely sensed imagery to describe changes in the mangrove wetland of the Pearl River Estuary (Li et al. 2002, 2006).

Shenzhen Bay is located in two large, modern cities (the Shenzhen Special Economic Zone of China and the Hong Kong Special Administrative Region) on the east coast of the Pearl River Estuary. The mangrove ecosystem in Shenzhen Bay is the only mangrove system located within large cities of China. It is also the resting land and habitat on the north–south flyway for migratory birds in the Eastern Hemisphere. Urbanization, in particular the establishment of the Shenzhen Special Economic Zone and the development carried out along the Bay Circuit, led to large-scale reclamation projects that changed the original structure of the estuary shoreline and significantly impacted the water environment in the bay (Cui 2007; Ren et al. 2007).

The historical mangrove area in Shenzhen Bay occupied about 10 km^2, but much of this area was lost to urbanization in the 1970s and 1980s (Wang 1998). There has been some recovery of mangrove area since the 1980s because of reclamation and *gei wai* (which literally means a pond enclosed by a bund or embankment). In Asia, people living in coastal areas have for many hundreds of years produced shrimp in *gei wai* that the farmers excavated adjacent to bays or estuaries; mangroves commonly grow in *gei wai*. In spite of reclamation and construction of *gei wai* since the 1980s, the total area of mangroves (original and restored) had not yet increased to even 50% of the historical area by 2007 (Wang 1998). In addition, mangrove distribution changed from a more extensive, continuous belt along the bay into an aggregative distribution around the two mangrove nature reserves. Finally, the current mangrove forests contain fewer species and fewer exotic species, and are dominated by plantations of *Sonneratia apetala* (Wang 2002; Li et al. 2006).

Reclamation of wetlands changed the water environment dynamic, which changed sedimentation rates in Shenzhen Bay. According to monitoring data, the natural siltation rate was 0.01–0.03 m/year in Shenzhen Bay in the 1970s. By the 1980s, however, the average siltation rate was 0.12 m/year at the north of the bay and 0.02–0.04 m/year at the other foreshore (Wang 2002). This shows that Shenzhen Bay is being greatly disturbed by human activities. In the past 20 years, seawater quality of Shenzhen Bay has been rated as national class III (Wang 2002); this rating system ranges from class I to V, and class III indicates moderate pollution (Ren et al. 2007). Nutrient concentrations of NH_3–N, total P, and total N have increased threefold. The water pollution has also led to tidal flat pollution. Because of the large waves resulting from reclamation, mangrove planting projects started after 2000 have always failed. In addition, as a result of high-intensity development and construction around the Futian Mangrove Natural Reserve, habitat quality decreased and the number of birds declined, which broke the ecological balance of the food chain and resulted in greater damage caused by mangrove pests and diseases (Wang 2002).

As indicated in the previous paragraph, the coastal zone in Shenzhen Bay faces destruction of its ecosystem structure and suffers from functional decline, water pollution, vegetation damage, loss of biodiversity, biological invasion, reduced biological productivity, and frequent red tides (Wang 2002). The environmental destruction during the early stage of urban development caused irreversible damage. However, the current government recognizes the important ecosystem services and rare wetland resources provided by Shenzhen Bay. In the last 5 years, the government has invested billions of dollars to protect wetlands and to restore degraded ecosystems while maintaining economic and social development.

The overall aim of this study is to describe and understand the changes of wetlands and mangroves in Shenzhen Bay and to identify strategies for sustainable management of mangroves. The specific objectives are to: (1) describe the changes in the distribution of mangroves and wetland in Shenzhen Bay over the past 30 years, (2) describe the vegetation structure and characteristics of the mangrove ecosystem in the bay, and (3) develop planning and management strategies for mangrove protection and restoration in the bay.

Methods

Study site

Shenzhen Bay is located on the east coast of the Pearl River Estuary in South China (about 113°53′–114°05′E, 22°30′–22°39′N) and has an area of about 75 km^2. The bay is at the mouth of the Shenzhen River (a small branch of the Pearl River) Estuary, a semi-enclosed gulf, and is directly linked with the coastal water bodies. There are more than 3 km^2 of mangroves in the bay, being one of the largest surviving mangrove forests along the coast of mainland China. The dominant species of mangrove in Shenzhen Bay are *Bruguiera gymnorrhiza*, *Kandelia candel*, *Aegiceras corniculatum*, *Avicennia marina*, and *Acanthus ilicifolius*. There is a rich benthic invertebrate fauna under the mangrove forests, and in summer several bird species nest in the mangrove trees around natural reserves (Tam 2004).

Shenzhen City established the Futian National Mangrove Nature Reserve (with an area of 3 km^2) in 1984, and the Hong Kong Government designated the adjacent Mai Po Wetland (with an area of 15 km^2) as a nature reserve in 1995 (Wang 2002). Shenzhen Bay, from west to east, is gradually experiencing an increase in human disturbance: the original mangroves have disappeared from the western bay, and the mud flat has been considerably damaged because of reclamation of the sea. The northern bay, except the Futian Mangrove Nature Reserve, is subjected to huge human disturbance. In the eastern bay, the Mai Po Wetland is well protected.

Another feature of Shenzhen Bay is *gei wai* (Fig. 1). Although shrimp are the main harvest, fish, oysters, algae, and brackish water sedges have also been harvested from the *gei wai*. The *gei wai* support large areas of vegetation, principally mangroves, reedbeds, and sedges.

Fig. 1 Photograph of the *gei wai*

Shenzhen Bay belongs to the lower subtropical marine monsoon climate zone of the East Asian monsoon region. Annual average temperature is 22.4°C (28.2°C in July, 14.1°C in January). Annual average rainfall is 1700–1900 mm (about 70% in the rainy season of April–October, 30% in the dry season). Annual average evaporation is 1500–1800 mm, and annual average relative humidity is about 80%. Wind is often strongest and most commonly from the southeast. There are two to four typhoons each year, in summer and fall. Shenzhen Bay is affected by ocean tides, with two daily high tides and two low tides. The average tidal water level is −0.33 m (with highest level of 2.66 m and lowest level of −1.56 m). Average wave height is 0.9 m (Wang 2002).

Data collection and analysis

We began a comprehensive investigation of Shenzhen Bay in 2005 by field investigation and remote-sensing techniques. In 2006, we began ecological restoration experiments and established research transects. The last field survey of all the mangrove communities was conducted in June 2008. According to Vegetation of China, there were five mangrove communities in the bay (Editorial Committee of Vegetation of China 1980). We established five transects across the whole land–sea interface zone for those five communities in the study area, and various numbers of 10 m × 10 m quadrats were placed along each transect, depending on the length of the transects. Among those five transects, three have three quadrats and two have five quadrats, only three (per transect) of which were selected for further analysis. The following data were recorded in this survey for each plant individual on the transect: species, number, height, diameter at breast height (DBH, only for trees), and growth status (alive or dead). In addition, we measured the coverage of the plant community and the mud thickness in the surface layer for each quadrat. The calculation [mean ± standard deviation (SD)] of collected data on vegetation investigation was done using Excel 2003.

We collected five-phase Landsat Thematic Mapper (TM) satellite images (30 July 1986, 2 January 1992, 8 February 1999, 10 January 2003, and 4 November 2007), a 1:250000 digital elevation model (DEM), 1:50000 vector water distribution maps, tide level data in the bay, Shenzhen and Hong Kong administrative maps, and papers related to the Pearl River Estuary. We processed the images using ERDAS IMAGINE 8.31. The process included geometric correction processing, vegetation information extraction, image classification, and area statistics (Newkirk and Wang 1990; Jobin et al. 2003; Li and Tan 2003; Lee and Yeh 2009).

During the process of geometric correction of the image, we matched TM images with the digitized 1:250000 DEM, then used the Albers projection to select 20 uniformly distributed control points, and finally used a binary quadratic polynomial for geometric correction (Christopher and Ding 1995; Li et al. 2006). The root-mean-square error of geometric registration was less than 0.5 pixels. This precision is sufficient for accurate multitemporal analysis of dynamic changes of the mangroves, *gei wai*, and tidal flats.

Based on previous research, we have developed a classification expert system method and chosen TM2, TM5, TM7, and Normalized Difference Vegetation Index (NDVI) as a basic expert classifier element. The mangrove expert classifier was established based on information in accordance with the training area for mangrove dynamic monitoring (Ren et al. 2003; Li et al. 2006). We generated the various phase images of mangrove classification by using the same expert classifier to classify multitemporal TM images.

We then overlaid and analyzed the results of these classifications. Data on area and changes of mangroves, *gei wai*, and tidal flat were obtained (Newkirk and Wang 1990; Li et al. 2006). Finally, we reused the classification map, selected the field control points to correct for the actual situation, and then overlaid the digital map of the administrative boundaries onto the statistic areas (Jobin et al. 2003; Li and Tan 2003).

Results

Changes in mangroves and *gei wai* in Shenzhen Bay in the past 21 years

From 1986 to 2007, mangrove area in the bay increased from 1.8 to 4.8 km^2, while the area of *gei wai* decreased from 36.6 to 17.2 km^2 (Fig. 2; Table 1). Reclamation of *gei wai* mainly occurred between 1986 and 1999 because of urbanization. Because *gei wai* provide valuable ecosystem services and could be colonized by mangrove, it is reasonable to consider them together as an essential wetland component that has declined from 38.4 km^2 (in 1986) to 22.0 km^2 (in 2007).

From the point of view of spatial distribution, mangrove area increased mainly around the original mangrove distribution areas and in the high-shore tidal flats around the mouth of the Shenzhen River. Minor changes in mangrove area were documented in the Futian Mangrove Natural Reserve and Mai Po Wetland Reserve. The reduction of *gei wai* occurred mainly in the west and north of Shenzhen Bay. Shenzhen City filled substantial wetland areas in the northwest bay and also rehabilitated some mangroves.

Changes of the shoreline of Shenzhen Bay in the past 30 years

We drew the coastline changes (Fig. 3) of Shenzhen Bay over the past 30 years based on the remote-sensing images described earlier and historical data (Zhang and Zhang 1997; Liu et al. 1998). After accounting for the natural siltation process, the analysis showed that Shenzhen City reclaimed substantial foreshore area and that the Hong Kong government also reclaimed a small amount of wetland. Reclamation at the “western gate” (the peninsula that forms the northwest boundary of the bay) and northern bay occupied a large number of coastal mangrove forests and tidal flats, and also affected the tidal movement of water into and out of the bay.

Relationships among mangroves, tidal flats, and *gei wai*

Mangroves, tidal flats, and *gei wai* are important components of Shenzhen Bay wetlands. These wetlands are especially important to birds. Mangroves are the “home” of birds, tidal flats are the “restaurant” of birds, and *gei wai* are the “garden and restaurant” of birds. Moreover, maintenance of appropriate *gei wai* can meet the interests of local fishermen. Therefore, a productive and stable coastal mangrove ecosystem requires appropriate proportions of these three components.

Wang (1998) and Tam (2004) found that birds in the Mai Po Wetland preferred habitats with particular spatial patterns of mangroves, tidal flats, and *gei wai*. The ratios of area occupied by these three components were also important. Based on the analysis of the pattern and land cover in the Mai Po Wetland, the ratio of area for mangroves, tidal flats, and *gei wai* is 1:2:3 (Fig. 4).

The mangrove community in Shenzhen Bay

The mangrove community in Shenzhen Bay is yellow–green and simple in appearance. The community is mainly

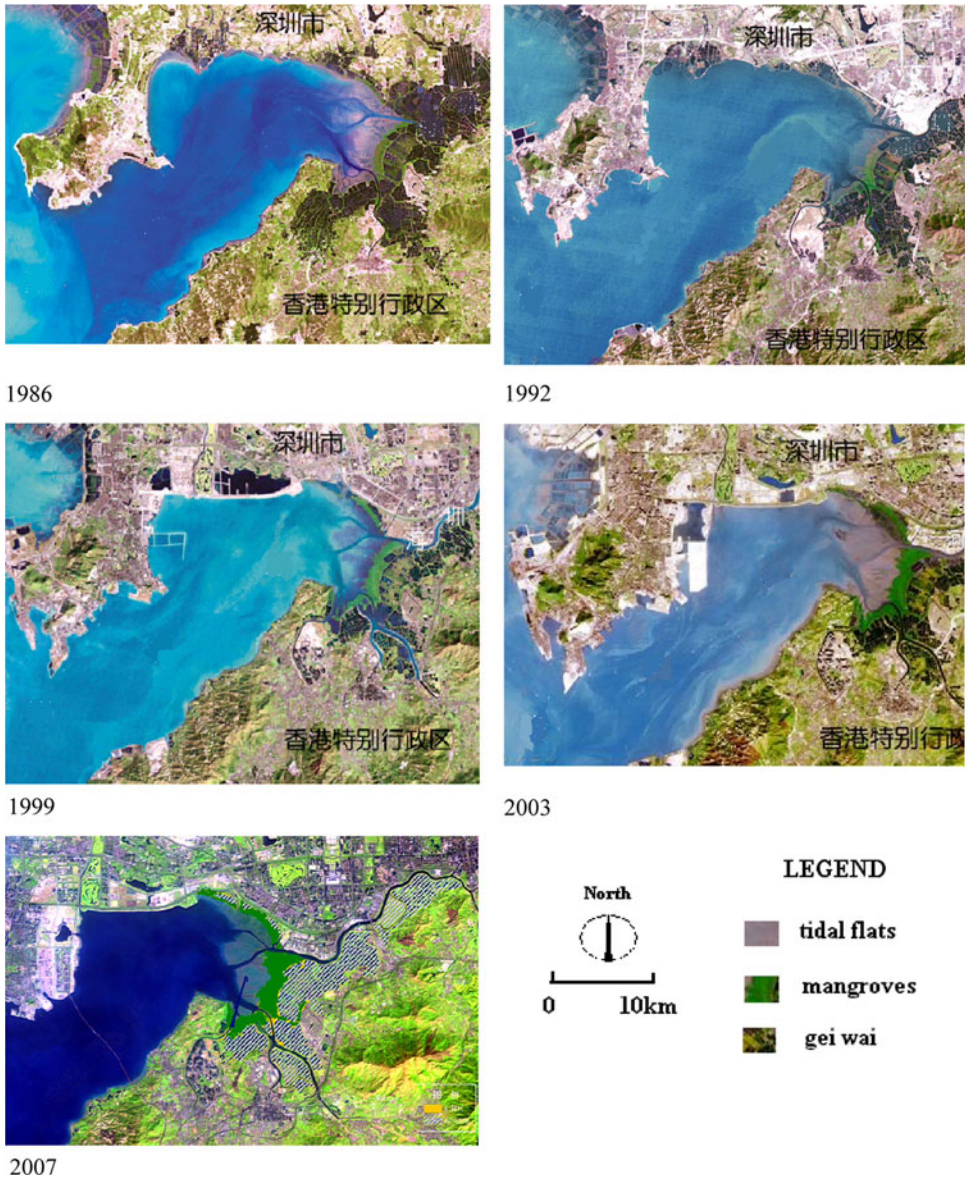

Fig. 2 Multitemporal TM imagery of Shenzhen Bay. Note: the scale in 2007 is different from the others, being 1:13 km

Table 1 Area occupied by mangrove and *gei wai* in Shenzhen Bay

	Year and area occupied (km^2)				
Landscape feature	1986	1992	1999	2003	2007
Mangrove	1.8	3.0	3.2	4.3	4.8
Gei wai	36.6	27.5	14.8	14.8	17.2

composed of herbs and small trees. The canopy of the community is continuous and uniform, and the height of the canopy is about 3–4 m but as high as 12 m. Canopy coverage is usually 80–90%. Species richness of the mangrove community is poor in Shenzhen Bay. *Avicennia marina*, *Kandelia candel*, and *Aegiceras corniculatum* are codominant species. Artificial plantations of the exotic *Sonneratia apetala*, which were established in 1993, have developed into lush communities and are approaching a

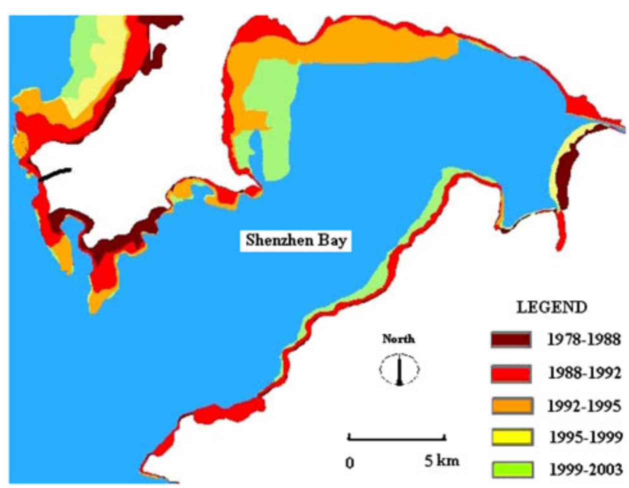

Fig. 3 Shoreline changes of Shenzhen Bay over the past 30 years

state of natural regeneration. There are five mangrove communities in the bay (Table 2):

1. The *Avicennia marina* + *Kandelia candel* + *Aegiceras corniculatum* community.
   This community is mature and has experienced less human disturbance than the other communities. The mud thickness in the surface layer is about 30–35 cm. Canopy coverage is about 80%. *Avicennia marina* has coverage of about 50%, occupies the upper canopy, and is 4.5 ± 0.5 m high, with DBH of 14.2 ± 1.0 cm. There also are a small number of *Kandelia candel* in the upper canopy; this species has coverage of about 20% and is 4.5 ± 0.3 m high. *Aegiceras corniculatum* has coverage of about 30%, occupies a lower layer than the other two species, and is about 1.5–3.0 m high.
2. The *Kandelia candel* + *Aegiceras corniculatum* + *Acanthus ilicifolius* community.
   This community is located on the high tidal flats and is dense and shrub-like. The mud thickness in the surface layer is about 20–30 cm. Coverage is about 90%. *Kandelia candel* occupies the upper canopy and is 2.5 ± 0.3 m high. *Aegiceras corniculatum* grows in a lower layer and is about 1.2 ± 0.4 m high. *Acanthus ilicifolius* is also abundant throughout this community and is 0.8 ± 0.2 m high. Some *Derris trifoliata* Lour. climb on *Acanthus ilicifolius* individuals.
3. The *Bruguiera gymnorrhiza* + *Excoecaria agallocha* community.
   This community is located between the high tidal flats and land, and is dense and tree-like. The mud thickness in the surface layer is about 20–30 cm. Coverage is about 90%. Both *Bruguiera gymnorrhiza* and *Excoecaria agallocha* occupy the upper canopy and are 4.5 ± 0.8 m high. Seedlings of *Excoecaria agallocha* grow in a lower layer to height of 2.0 ± 0.2 m. Some *Aegiceras corniculatum* individuals also grow in the lower layer.
4. The *Aegiceras corniculatum* community.
   This mature community is located in the middle of the mangrove belt and consists of only one species. The mud thickness in the surface layer is about 10–20 cm. Coverage is about 90%. The community is densely populated with individuals 2.1 ± 0.2 m high.
5. The *Sonneratia apetala* + *Sonneratia caseolaris* community.
   This community consists of plantations of *Sonneratia apetala* and *Sonneratia caseolaris* that have been colonized by other plants. The mud thickness in the surface layer is about 30–40 cm. Coverage is more than 80%. The height of *Sonneratia apetala* is 12.5 ± 0.4 m, and the DBH is about 21.2 ± 0.7 cm. The height of *Sonneratia caseolaris* is 11.5 ± 0.3 m, and the DBH is about 18.8 ± 0.5 cm.

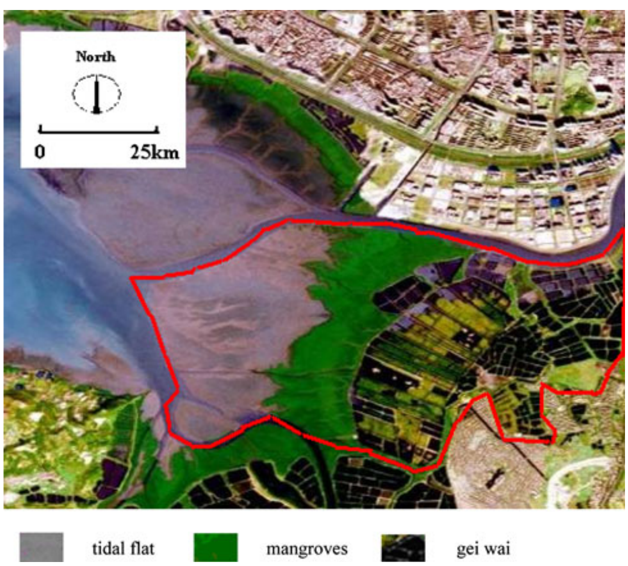

Fig. 4 Relationships among mangroves, tidal flat, and *gei wai*

The ecological series in space fully reflects the succession series in time for Chinese mangrove. The succession

Table 2 Community characteristics of the study sites with different stands

Community	Coverage (%)	Mud thickness in the surface layer (cm)	Dominant species in tree layer	Density (N/300 m^2)	Mean height of upper canopy (m)	Mean DBH of upper canopy (cm)
Avicennia marina + *Kandelia candel* + *Aegiceras corniculatum*	80	30–33	*Avicennia marina*, *Kandelia candel*	957	4.5 ± 0.5	14.2 ± 1.0
Kandelia candel + *Aegiceras corniculatum* + *Acanthus ilicifolius*	90	20–30	*Kandelia candel*	1211	2.5 ± 0.3	1.5 ± 0.2
Bruguiera gymnorrhiza + *Excoecaria agallocha*	90	20–30	*Bruguiera gymnorrhiza*, *Excoecaria agallocha*	867	4.5 ± 0.8	2.1 ± 0.3
Aegiceras corniculatum	90	10–20	*Aegiceras corniculatum*	1082	2.1 ± 0.2	1.2 ± 0.1
Sonneratia apetala + *Sonneratia caseolaris*	80	30–40	*Sonneratia apetala*, *Sonneratia caseolaris*	361	12.5 ± 0.4	21.2 ± 0.7

of these communities is closely related with their biological–ecological characteristics of dominant populations and the nature of tidal flats (Tam 2004). The spatial distribution and temporal pattern of colonization of mangroves are obvious in Shenzhen Bay: the pioneer mangrove species *Avicennia marina* usually occupies the frontier edge of the tidal flat area (the low tidal flats). After *A. marina* colonizes the low tidal flats, *Kandelia candel* and *Aegiceras corniculatum* colonize the middle tidal flats. Species such as *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, and *Acrostichum aureurm* only grow in the high tidal flat (the area close to land), and *Acanthus ilicifolius* only grows on sunny tidal flats. Some plants commonly associated with mangrove (*Heritiera littoralis*, *Hibiscus tiliaceus*, *Thespesia populnea*, and *Clerodendrum inerme*) grow on the banks of the bay. Based on the typical succession of mangrove ecosystems as described in previous studies (Wang 2002), we developed a mangrove succession model for Shenzhen Bay (Fig. 5).

Discussion

Based on the above analysis of pattern and dynamics of wetlands and community structure of mangroves, we hope to restore the ecological integrity of the entire Shenzhen Bay by developing strategies for mangrove protection and restoration in Shenzhen Bay as described in the following three sections.

The relationship between *gei wai* and mangrove

Due to intensified human activities, much of the mangrove and *gei wai* wetlands have been lost in the past 30 years in Shenzhen Bay. At the same time, *gei wai* have also been colonized by mangrove in the past 20 years. *Gei wai* are located between the mangrove and urban land. As a buffer zone, it can provide ecosystem goods to the city and increase the income of farmers in the zone. It also can support birds in the mangrove and provide suitable habitat

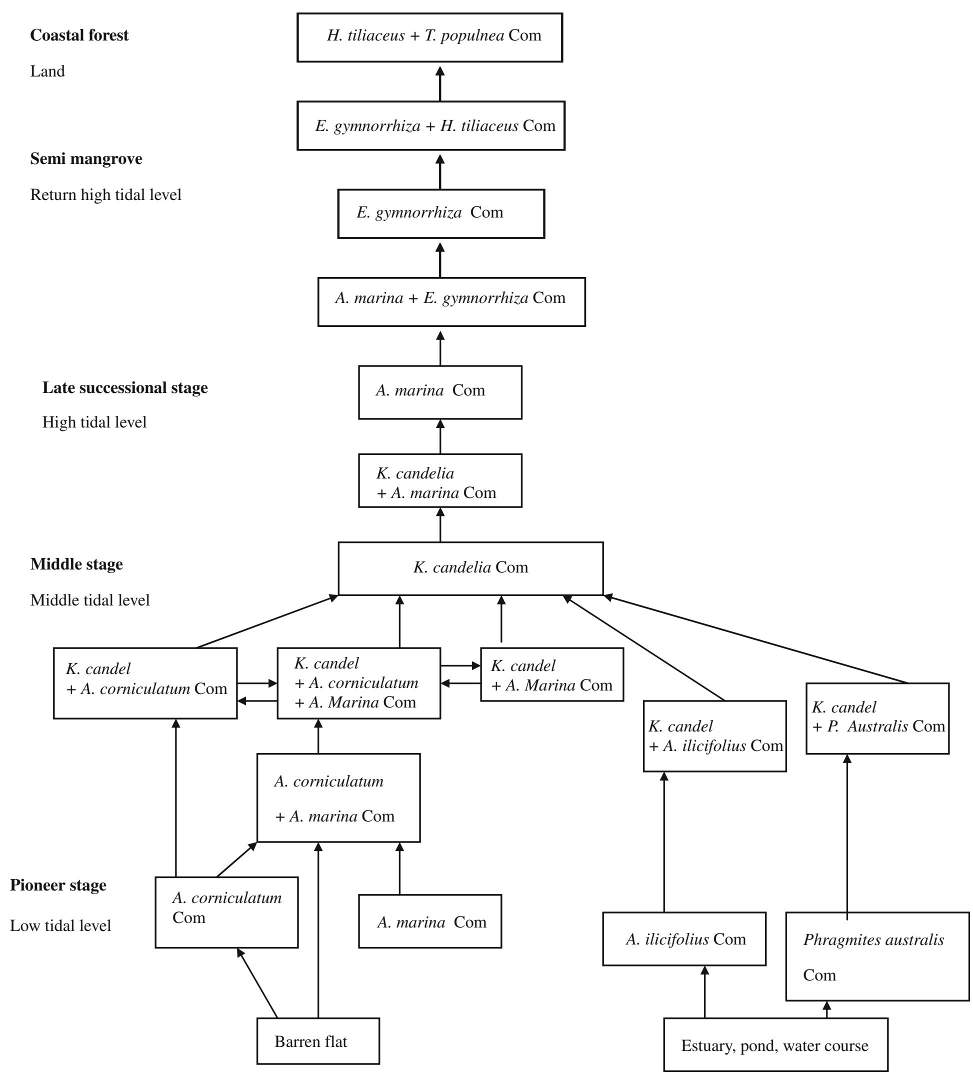

Fig. 5 Succession model of mangrove in Shenzhen Bay

space for mangrove invasion and extension. The hydrological conditions and soil of current *gei wai* in Shenzhen Bay are better than in the tidal flats (Wang 2002). Pioneer mangrove species such as *Acanthus ilicifolius* can naturally invade *gei wai*, then *Kandelia candel* will invade the *Acanthus ilicifolius* community and develop into the mixed species community after 10 years. This mixed community will succeed to middle and late successional stages in *gei wai*. One issue is that reed (*Phragmites australis*) may also invade *gei wai* and compete with *Acanthus ilicifolius*. It is important to control dispersal of reed and facilitate extension of mangrove into *gei wai*.

Conservation and restoration of mangrove forests

Considering the historical changes of the Shenzhen Bay shoreline in the last 30 years, future management of estuarine wetlands must limit the impacts of urban activities and protect vegetation by reconstructing the mangrove belt. Specific management objectives include: protection of all existing mangroves and *gei wai* to prevent further human disturbance or degradation, improvement of mangrove communities dominated by nonnative species and control of invasion by alien species at *gei wai* in the northern bay (Ren et al. 2009), and replanting of mangrove in the western bay.

Previous research has indicated that mangrove forests usually occur on a raised and sloped platform that is above mean sea level and that is inundated by tidal waters no more than 30% of the time. Attempts to establish mangroves in areas that previously did not support mangroves have often failed (Lewis 2005; Walters et al. 2008). Mangroves will not grow in locations where waves are large in the western bay, where mangrove restoration is needed. We can avoid the problem of high waves and rehabilitate mangrove ecosystems by constructing *gei wai*. The reason is that the restoration program involves reconstruction of site conditions through construction of an artificial foundation and soil remediation. In *gei wai*, temperature, tidal level, sediment, tidal flow, and salinity can be controlled. The microhabitat at *gei wai* supports the survival of mangrove seedlings (Ren 2009).

With reference to the spatial distribution of the natural mangrove sequences in Shenzhen Bay, pioneer species such as *Avicennia marina* will be planted at the external *gei wai* (those closer to the bay), followed by *Kandelia candel* and *Aegiceras corniculatum* at the middle *gei wai*, and then by *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, and *Acrostichum aureum* at the internal *gei wai*. Some native plants that naturally grow with mangrove (such as *Heritiera littoralis*, *Thespesia populnea*, *Hibiscus tiliaceus*, and *Clerodendron indicum*) will be planted on the banks of the bay. *Acanthus ilicifolius* should be planted where waves are large, and some areas with large waves should not be planted, so that residents and tourists can view sea waves (Ren 2009).

The following rules or experiences can be applied when restoring and managing mangrove forests (Wang and Wang 2007): antiwave facilities will increase mangrove colonization; high-density planting will improve the survival rate; nursing and management of seedlings are required; a protective net around the plantation will reduce problems (garbage, barnacle consumption of algae, crab and rodent hazards, pests and diseases, etc.); planting of younger seedlings will increase the mangrove survival rate; appropriate reforestation methods vary by species; and reforestation is more effective if it is done sooner rather than later.

Overall planning for mangrove protection and restoration in Shenzhen Bay

Based on the history of spatial changes and on the current status of mangroves, the overall planning for mangrove protection and restoration in Shenzhen Bay should have the following goals: to protect mangroves and birds to ensure the region's biodiversity and environment, to protect fishermen's economic interests in farming the wetland areas, and to satisfy the public's need to view mangrove forests and the sea. Given these goals, we have planned the following six mangrove projects: planting of mangroves in the western area of the bay (this project has already been proposed); improvement of the existing coastal park; protection of the Futian National Mangrove Nature Reserve; construction of the Futian Fengtang River Mangrove Restoration Demonstration Area (now underway); development of a mangrove public education park (this project has already been proposed); and protection of the Mai Po Natural Reserve in Hong Kong (Fig. 6).

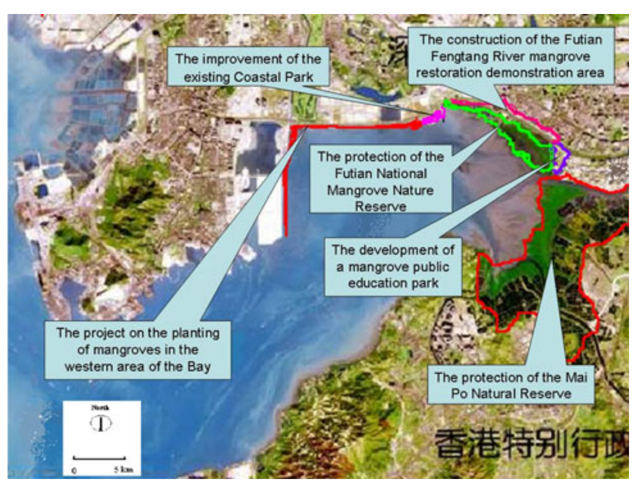

Fig. 6 The overall planning for mangrove protection and restoration in Shenzhen Bay

These projects and natural reserves should be considered together to reconstruct the ecological integrity of the entire Shenzhen Bay. Coastal flat formation, tidal dynamics, water quality, mangrove forests, and bird habitat are the most important factors affecting ecological integrity. By paying attention to these factors, we can ensure the ecological health of the bay and develop a self-healing ecosystem that will support sustainable development.

With respect to public access, we have divided Shenzhen Bay mangrove wetlands into closed areas, semiclosed areas, and open areas. The Mai Po Nature Reserve and Futian National Mangrove Nature Reserve will not be open to the public and are to be used only for scientific research. The public will have limited access to the mangrove public education park (with an area of 0.42 km^2). Finally, the mangrove restoration area in the western bay and the coastal park will be completely open to the public.

Conclusions

Shenzhen City has reclaimed a lot of wetlands such as tidal flats, mangroves, and *gei wai* in Shenzhen Bay during the past 30 years because of urbanization. Mangrove area in the bay increased, while the area of *gei wai* continued to decrease between 1986 and 2007. The suitable ratio of area for mangroves, tidal flats, and *gei wai* is important for a productive and stable coastal mangrove ecosystem in the bay. Mangrove communities had low species number and were composed of shrubs and small trees. The dominant species were *Avicennia marina*, *Kandelia candel*, and *Aegiceras corniculatum*. The distribution of mangrove communities in the bay showed a spatial pattern with continuing shifts from seaward to landward, and a temporal (successional) sequence. We can simulate the mangrove species distribution pattern in the *gei wai* to restore mangrove. To restore ecological integrity in the entire bay and increase public access to mangrove, six mangrove protection and restoration projects have been designed in closed areas (the Mai Po and Futian Nature Reserve), semiclosed areas (Fengtanghe river restoration area and the mangrove public education park), and open areas (the mangrove restoration area in the western bay and the coastal park).

Acknowledgments We thank Ms. Qianmei Zhang of the South China Botanical Garden and all staff of the Administration of Futian Mangrove National Natural Reserve for field assistance during the study. We also thank our colleagues at the Pearl River Water Resources Scientific Research Institute for image processing. Thanks are also due to Prof. Bruce Jaffee for polishing the English. We also thank the anonymous reviewers for their valuable comments on an earlier version of the manuscript. The project was supported by the Key Supporting Project of Ministry of Science and Technology of P.R. China (2007BAC28B04), the Knowledge Innovation Program of the Chinese Academy of Sciences (KSCX2-SW-132), and the Guangdong Sci-Tech Planning Project (2008A030203007).

References

Bosire JO, Dahdouh-Guebas F, Walton M (2008) Functionality of restored mangroves: a review. Aquat Bot 89:251–259

Chen LZ, Wang WQ, Zhang YH (2009) Recent progresses in mangrove conservation, restoration and research in China. Journal of Plant Ecology 2:45–54

Christopher DE, Ding Y (1995) Relative radiometric normalization of Landsat multispectral Scanner (MSS) data using an Automatic Scattergram Controlled Regression. Photogramm Eng Remote Sensing 56:1015–1026

Craft CB, Bertram J, Broome S (2008) Coastal zone restoration. Encyclopedia of Ecology, pp 637–644

Cui WZ (2007) Temporal and spatial variation of water environment and its impact on the ecosystem of the Pearl River estuary. Hehai University Doctor thesis

Editorial Committee of Vegetation of China (1980) Vegetation of China. Science Press, Beijing

Field CD (1999) Rehabilitation of mangrove ecosystems: an overview. Mar Pollut Bull 37:383–392

Gilman E (2002) Guidelines for coastal and marine site-planning and examples of planning and management intervention tools. Ocean Coast Manag 45:377–404

Harty C (2009) Mangrove planning and management in New Zealand and South East Australia—a reflection on approaches. Ocean Coast Manag 52:278–286

Harty C, Cheng D (2003) Ecological assessment and strategies for the management of mangroves in Brisbane Water—Gosford, New South Wales, Australia. Landsc Urban Plan 62:219–240

Howarth R, Anderson D, Cloern J, Elfring C (2000) Nutrient pollution of coastal rivers, bays, and seas. Issues Ecol 7:1–15

Jobin B, Beaulieu J, Grenier M (2003) Landscape changes and ecological studies in agricultural regions, Québec, Canada. Landsc Ecol 18:575–590

Kraussa KW, Lovelock CE, McKee KL (2008) Environmental drivers in mangrove establishment and early development: a review. Aquat Bot 89:105–127

Lee TM, Yeh HC (2009) Applying remote sensing techniques to monitor shifting estuary mangrove communities, Taiwan. Ecol Eng 35:487–496

Lewis RR III (2005) Ecological engineering for successful management and restoration of mangrove forests. Ecol Eng 24:403–418

Li CG, Tan BZ (2003) A study on remote sensing image processing approaches for mangrove inventory. Cent South Forest Invent Plan 22:24–28

Li TH, Zhao ZJ, Han P (2002) Detection and analysis of mangrove changes with multi temporal remotely sensed imagery in the Shenzhen River Estuary. J Remote Sens 6:364–369

Li X, Liu K, Wang SG (2006) Mangrove wetland changes in the pearl river estuary using remote sensing. Acta Geogr Sin 61:26–34

Liu YF, Han MK, Wu L (1998) Recent evolution of outlets in Zhujiang River Delta and the prospect for land reclamation. Acta Geogr Sin 53:492–500

Newkirk RT, Wang F (1990) A common knowledge database for remote-sensing and geographic information in a change-detection expert system. Environ Plan B 17:395–404

Nieto HP (1993) Linking territorial and coastal planning: the Venezuelan experience. Ocean Coast Manag 21:227–243

Qin P, Mitsch WJ (2009) Wetland restoration and ecological engineering: International Conference of Wetland Restoration and Ecological Engineering. Ecol Eng 35:437–444

Ren H (2009) The planting method on mangrove at tidal zone. Chinese patent. ZL 200610124054.4. 30 Sept 2009

Ren H, Li P, Peng SL (2003) The restoration and management of ecosystems in coastal region. Sciences, Beijing

Ren H, Shen WJ, Lu HF, Wen XY, Jian SG (2007) Degraded ecosystems in China: status, causes, and restoration efforts. Landsc Ecol Eng 3:1–13

Ren H, Lu HF, Shen WJ (2009) *Sonneratia apetala* Buch.Ham in the mangrove ecosystems of China: an invasive species or restoration species? Ecol Eng 35:1243–1248

Sharp A, Nakagoshi N (2006) Rehabilitation of degraded forests in Thailand: policy and practice. Landscape Ecol Eng 2:139–146

Tam NFY (2004) Conservation and uses of mangroves in Hong Kong and Mainland China. In: Wetlands ecosystems in Asia, function and management, pp 161–182

Walters BB, Rönnbäck P, Kovacs JM (2008) Ethnobiology, socio-economics and management of mangrove forests: a review. Aquat Bot 89:220–236

Wang SG (1998) Status quo of coastal wetlands and their protection in Guangdong Province. Chongqing Environ Sci 20:4–11

Wang BS (ed) (2002) Mangrove forest ecosystem and its sustainable development in Shenzhen Bay. Sciences, Beijing

Wang WQ, Wang M (2007) The mangroves of China. Science, Beijing

Weinstein MP, Baird RC, Conover DO (2007) Managing coastal resources in the 21st century. Frontier Ecol Environ 5:43–48

Wolanski E, Richmond RH (2008) Estuary restoration. Encyclopedia of Ecology 1422–1427

Zhang QM, Sui SZ (2001) The mangrove wetland resources and their conservation in China. J Nat Resour 16:28–36

Zhang QM, Zhang YC (1997) On biological and geomorphologic process of seashore in South China. Quat Sci 4:344–353