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March 2014

Tohoku Gakuin University

Can Gio Mangrove Protection Forest Management Board

International Society for Mangrove Ecosystems (ISME)

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Inside cover: Sunset along the scenic Dan Xay River in Can Gio by Assoc. Prof. Vien Ngoc Nam

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Contents

Foreword

Studies in Can Gio Mangrove Biosphere Reserve, Ho Chi Minh City, Viet Nam is an output of a collaborative research project between Tohoku Gakuin University in Sendai, Japan and Can Gio Mangrove Protection Forest Management Board of Ho Chi Minh City, Viet Nam. Papers presented at two workshops held in Can Gio, Viet Nam in March 2013 and in Tohoku Gakuin University, Sendai, Japan in November 2013 are included in this publication.

Prof. Toyohiko Miyagi from Tohoku Gakuin University, Mr. Le Van Sinh from Can Gio Mangrove Protection Forest Management Board and Assoc. Prof. Vien Ngoc Nam from Nong Lam University, who are coordinators of this collaborative research project, have played an active role in implementing the mangrove studies, in organizing the workshops, and in finalizing the papers of this publication.

We are most grateful to Tohoku Gakuin University for the financial and technical support, and to International Society for Mangrove Ecosystems (ISME) for the editorial support. The launching of this book will receive national and international publicity. Its posting onto the ISME website is most welcome as it becomes available worldwide.

MR. DOAN VAN SON

Vice-Chairman of Can Gio People's Committee, Ho Chi Minh City,
Viet Nam

Message

Studies in Can Gio Mangrove Biosphere Reserve, Ho Chi Minh City, Viet Nam is a joint publication of Tohoku Gakuin University in Sendai, Japan; Can Gio Mangrove Protection Forest Management Board of Ho Chi Minh City, Viet Nam; and the International Society for Mangrove Ecosystems (ISME), Okinawa, Japan.

Published as ISME Mangrove Ecosystems Technical Reports No. 6, the book provides an overview of Can Gio District and Mangrove Biosphere Reserve as introduction, and has six technical papers by scientists from Viet Nam and two technical papers by scientists from Japan.

Congratulations to Prof. Toyohiko Miyagi from Tohoku Gakuin University, Mr. Le Van Sinh from Can Gio Mangrove Protection Forest Management Board and Assoc. Prof. Vien Ngoc Nam from Nong Lam University for being the coordinators of the project and authors of this book. I am glad that ISME has contributed in editing the papers and in the design layout, under the able guidance of Prof. Shigeyuki Baba, the Executive Director. The launching of this book onto the ISME website will be well-received by mangrove scientists worldwide.

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An Overview of Can Gio District and Mangrove Biosphere Reserve

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1. Can Gio District

1.1 Geography and Climate

Can Gio (10°22′14″–10°40′09″ N; 106°46′12″–107°00′59″ E) is one of the 24 districts of Ho Chi Minh City (HCMC) in Viet Nam (UNESCO/MAB, 2000; Tuan & Kuenzer, 2012). The coastal district is 35 km in length and 30 km in width. Covering ~72,000 ha in area and located ~50 km southeast of HCMC, the district is a deltaic confluence of the rivers of Saigon, Dong Nai and Vam Co, which drain into the East Sea. The township of Can Thanh and six communes of Binh Khanh, An Thoi Dong, Ly Nhon, Tam Thon Hiep, Long Hoa and Thanh An form the human communities of Can Gio. The district has a population of ~71,000 people.

The tropical climate of Can Gio is typically monsoonal with two distinctive seasons (UNESCO/MAB, 2000; Tuan *et al*., 2002; Tuan & Kuenzer, 2012). The dry season is from November to May and the rainy season is from June to October. Wind directions are southwest during the rainy season with the strongest velocity in July and August, and northeast during the dry season with the strong winds in February and March. Rainfall, humidity, temperature and sunshine hours vary between the dry and rainy seasons. Annual average rainfall ranges from 1,300–1,400 mm with highest monthly average (300–400 mm) in September. The rainfall in Can Gio is lower than in HCMC and decreases gradually southwards. The humidity ranges from 79–83% during the rainy season and from 74–77% during the dry season. The mean annual relative humidity is 80% decreasing to less than 60% during the dry season. The annual average temperature is 25.8°C with monthly averages ranging from 25.5–29.0°C. The number of sunshine hours varies from 5–9 per day.

1.2 Topography and Hydrology

The topography of Can Gio is generally flat and low-lying with the highest elevation at Giong Chua (~10 m elevation) in compartment 14 (Tuan *et al*., 2002). The terrain is formed by alluvial deposits from the estuaries of six rivers, namely, Nga Bay, Cai Mep, Go Gia, Thi Vai, Soai Rap and Dong Tranh (Tuan *et al*., 2002; IUCN, 2013). Accretion of mud flats can be observed between the estuaries of Soai Rap and Dong Tranh, and between the estuaries of Dong Tranh and Nga Bay. Elsewhere, erosion is occurring along the banks of the Go Gia estuary.

Water salinity in the mangroves is highest in March and April when it reaches 19–20 ppt in the landward north and 26–30 ppt in the seaward south (Hong, 2004). During the rainy season, water salinity is only 4–8 ppt. The average monthly salinity is 18 ppt. Based on soil salinity, Tu (1996) classified the soils of Can Gio into hypersaline acidic soil, saline acidic soil and saline soil. Later, Tuan *et al*. (2002) classified the soils into four main types: saline soil, saline soil with low aluminium content, saline soil with high aluminium content, and soft mud with sandy soil deposits at the sea front.

The semi-diurnal tides range between 2–4 m in amplitude depending on the lunar calendar and distance from the sea (Binh *et al*., 2008). Tidal amplitudes are highest from October to November, and lowest in April and May. Five inundation classes have been identified based on frequency of inundation (Nam, 1994). They are sites inundated twice daily (0.0–0.2 m), once a day (0.2–0.5 m), once a month (0.5–1.0 m), once a year (1.0–1.5 m) and once every few years (> 1.5 m). Hong (1996) described sites as non-flooded (> 2 m), rarely flooded (1–2 m), infrequently flooded (0.5–1.0 m) and regularly flooded (0–0.5 m).

A study on waves and suspended sediment at Nang Hai in Can Gio mangroves reported that most of the energy is dissipated inside the mangrove forest due to wave-trunk interactions and wave breaking (Phuoc & Massel, 2006). The concentration of suspended sediment depends on wave intensity and tidal current velocity. Wave action is one of the main factors causing sediment transport and coastal erosion. The study concluded that establishment of mangrove vegetation can encourage the deposition of sediments.

1.3 Deforestation and Reforestation

From 1965–1969 of the Second Indochina War, the mangrove forests in Can Gio were almost completely destroyed by spraying of herbicides and other chemical agents by the U.S. air force (Nam *et al*., 2003; Hong, 2005; Hoan *et al*., 2007). Among the coastal districts of the Mekong delta, Can Gio and Camau were the most intensely sprayed (Ross, 1975). It was estimated that ~57% of the Can Gio mangroves were destroyed through deforestation.

After the war, Can Gio came under the jurisdiction of Duyen Hai District of Dong Nai Province (Hong, 2005). A decade later, the landscape of Can Gio remained highly degraded (Nam *et al*., 2003; Hong, 2005; Hoan *et al*., 2007). Some 10,000 ha were barren, 4,500 ha infested with the palm *Phoenix paludosa* and the fern *Acrostichum aureum*. Only 5,600 ha were cultivable. Mangrove trees of *Rhizophora*, *Sonneratia* and *Bruguiera* were scarce although some localised regeneration of *Avicennia* and *Nypa* palm was observed. Damage to the landscape was aggravated by the felling of trees by the local people for fuel wood and house construction. Severe erosion was observed on the bare land along rivers and canals as the area covered by water increased by ~30% (Nam *et al*., 1993). Coastal erosion increased due to the large tidal amplitude and the lack of a protective green belt.

In August 1978, the HCMC People's Committee signed Resolution No. 165/QD-UB, which transferred the management responsibility of Duyen Hai from Dong Nai to HCMC and renamed Duyen Hai as Can Gio (Nam *et al*., 2003; Hong, 2004, 2005; Hoan *et al*., 2007). Since then, a massive mangrove reforestation program was undertaken by the HCMC Forestry Department. Some 20,000 ha were planted with *Rhizophora apiculata*. From 1978–1991, the mangroves were managed as economic forests for wood production.

Several factors caused the degradation of mangrove plantations in Can Gio (Hong, 2004). They included the imbalance between demand and supply of fuel wood and poles for house construction, and the lucrative business of shrimp export encouraged local farmers and some agencies in HCMC to clear tracts of mangroves for shrimp farming. Both factors resulted in tree cutting and forest clearing by the local people.

In 1991, Can Gio was designated a coastal protection forest by the Ministerial Council Decision 173 CT. The reforestation efforts have brought ecological and environmental improvements to Can Gio. With the extensive establishment of mangrove plantations, the entire landscape turned into one of the most beautiful and extensive sites of rehabilitated mangroves in the world (Tuan & Kuenzer, 2012). These plantations serve as the "green lung and kidney" for the people of HCMC (Le, 2002).

2. Mangrove Biosphere Reserve

2.1 Declaration and Management

In January 2000, Can Gio was designated as the first Mangrove Biosphere Reserve (MBR) in Viet Nam under the Man and the Biosphere (MAB) Program of the United Nations Education, Scientific and Cultural Organization (UNESCO) (Tuan & Kuenzer, 2012). Since the declaration of Can Gio MBR, research, monitoring and training activities have been conducted. The focus of these activities is to promote international research, enhance the environmental awareness of the local people, and to demonstrate to local and foreign visitors how mangrove forests are rehabilitated and protected. As a result, Can Gio MBR has become an important research site and tourist destination.

The three main management objectives of Can Gio MBR are biodiversity conservation, environmentally-sound social, cultural and economic development, and mangrove-related training, research and education (Tuan *et al*., 2002; Le, 2008). The biosphere reserve is divided into three zones:

- The core zone (4,720 ha) is protected for long-term conservation of biodiversity. Human activities are prohibited in this zone, which is retained for conservation, research and monitoring purposes.
- The buffer zone (37,340 ha) serves as a protective buffer for the core zone. It provides a natural landscape, and functions as corridors for wildlife, and as cultural and ecological destinations for tourists.
- The transition zone (29,310 ha) surrounding the core and buffers zones is allocated for the socio-economic development.

2.2 Forest and Ecotourism

Forested and non-forested areas are the main current land-use of Can Gio MBR (HCMC People's Committee, 2012). Of the forested area (31,773 ha), 60% are planted forests and 40% are natural forests (Table 1). Of the non-forested area (39,587 ha), 55.8% are waterways, 35.3% are utilised land and 8.9% are wasteland.

Can Gio MBR comprises 24 forest compartments which vary from 1,000−2,000 ha in area each (UNESCO/MAB, 2000; Nam *et al*., 2003). The largest are Compartment 23 in the east and Compartment 24 in the north where Tam Thon Hiep is located. The smallest is Compartment 22 in the south near Can Thanh. Compartments 4a, 6, 11, 12 and 13 are designated as the core zone with the remaining compartments forming the buffer zone (Figure 1). Binh Khanh, An Thoi Dong and Ly Nhon along Soai Rap estuary, which form the western boundary, and Long Hoa and Can Thanh at the seafront, which form the southern boundary are the transition zone surrounding the biosphere reserve. The Can Gio Forest Park in Compartment 17, Vam Sat Tourist Site in Compartment 15 and the Can Gio Resort in the transition zone near Can Thanh town are major tourist attractions (Le, 2002).

Table 1 Land-use of Can Gio Mangrove Biosphere Reserve (HCMC People's Committee, 2012)

Land-use	Area (ha)	Percent (%)
1. Forested area	**31,773**	**44.5**
a. Forest plantations	18,963	26.6
b. Natural forests	12,810	17.9
2. Non-forested area	**39,587**	**55.5**
a. Waterways	22,091	31.0
b. Utilised land	13,983	19.6
c. Wasteland	3,513	4.9
Total	**71,361**	**100.0**

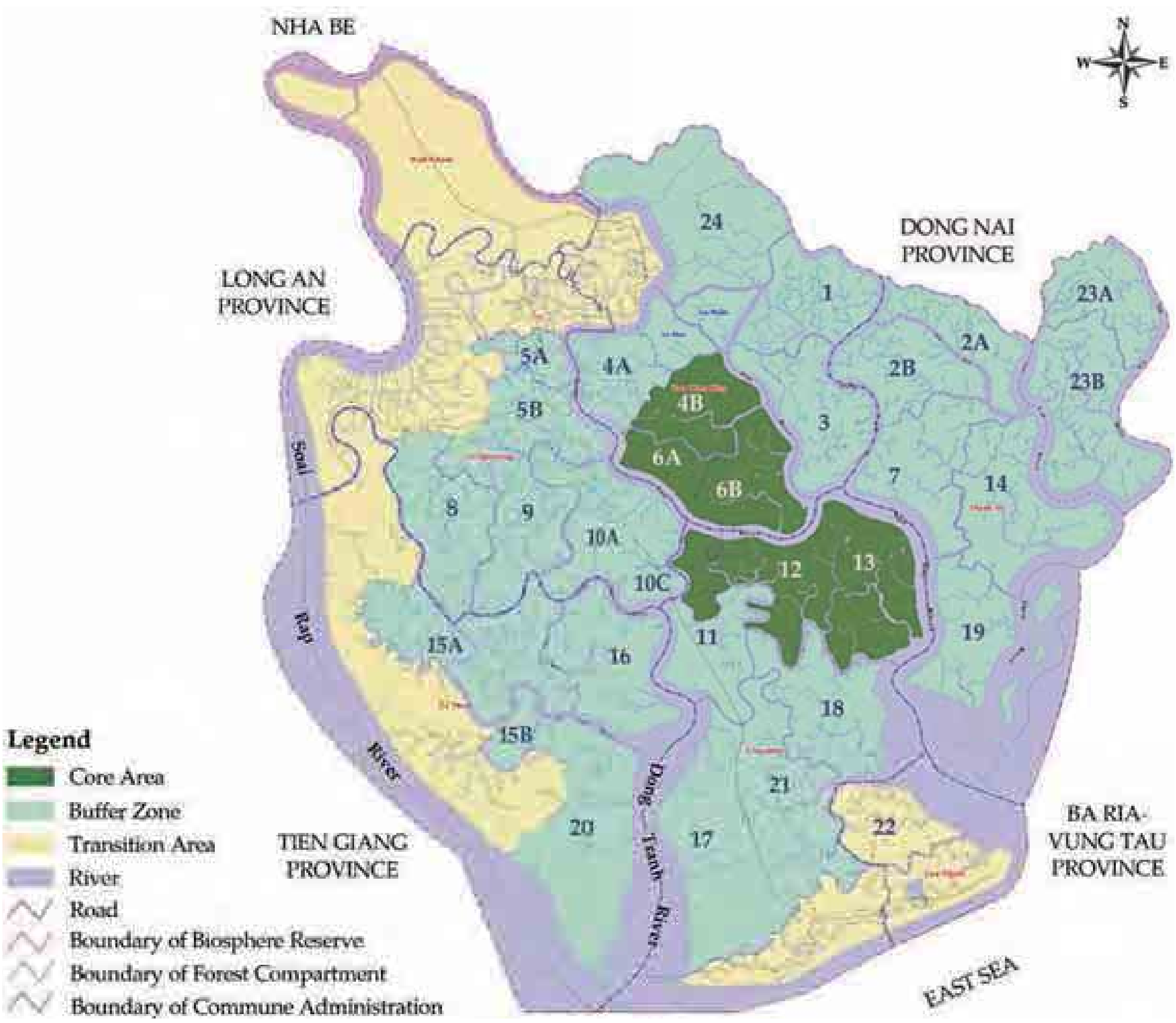

Figure 1 Zonation of Can Gio Mangrove Biosphere Reserve (HCMC People's Committee, 2012)

2.3 Flora and Fauna

Before the war, mangrove vegetation in Can Gio was categorised into salt-water and brackish-water communities (Cuong, 1964). Common plant species of these two communities are listed in Table 2.

Table 2 List of plant species found in Can Gio before the war (Cuong, 1964)

Species in salt-water community	Species in brackish-water community
Acrostichum aureum	*Acanthus ebracteatus*
Aegiceras corniculatum	*Amoora cucullata*
Avicennia alba	*Barringtonia acutangula*
Avicennia officinalis	*Clerodendron inerme*
Ceriops decandra	*Cryptocoryne ciliata*
Ceriops tagal	*Dalbergia candenatensis*
Derris trifoliata	*Derris trifoliata*
Excoecaria agallocha	*Flagellaria indica*
Flagellaria indica	*Gardenia lucida*
Heritiera littoralis	*Glochidion littorale*
Kandelia candel	*Hibiscus tiliaceus*
Lumnitzera littorea	*Melastoma polyanthum*
Phoenix paludosa	*Nypa fruticans*
Rhizophora apiculata	*Pandanus tectorius*
Sonneratia alba	*Pluchea indica*
Xylocarpus granatum	*Sonneratia caseolaris*
Xylocarpus moluccensis	*Thespesia populnea*

Table 3 gives a complete list of true mangrove species and mangrove associates presently found in Can Gio MBR compiled from Nam *et al*. (2003) and Hong (2004). A total of 35 species belonging to 19 genera are true mangroves while 24 species belonging to 22 genera are mangrove associates.

In the World Atlas of Mangroves, 30 mangrove species have been recorded for Viet Nam (Spalding *et al*., 2010). Of these, all species are found in Can Gio including *Kandelia obovata* which was introduced from north Viet Nam. In Table 3, *Lumnitzera littorea*, *Rhizophora x lamarckii* and *Xylocarpus moluccensis* are not listed in the world atlas.

The forest and aquatic ecosystems of Can Gio MBR are also rich in mangrove fauna comprising planktonic and benthic organisms, mammals, birds, fishes, reptiles, and amphibians. These animal species are listed in Hong (2004) and will not be discussed here.

2.4 Constraints and Challenges

From the forestry viewpoint, it has been a constraint not to carry out silvicultural treatments such as thinning of the planted forests. A study revealed that the rotation of *R. apiculata* is 21 years. Most of the forests are beyond its rotation age with the oldest forest being 35 years old. Trees in such old-growth forests are dying or having pest problems such as

Table 3 True mangroves and mangrove associates presently found in Can Gio Mangrove Biosphere Reserve (Nam et al., 2003; Hong, 2004)

True mangrove		Mangrove associate	
Acanthus ebracteatus	*Heritiera littoralis*	*Allophyllus cobbe*	*Premna integrifolia*
Acanthus ilicifolius	*Kandelia candel*	*Annona glabra*	*Styrax agrestis*
Acrostichum aureum	*Kandelia obovata*	*Azima sarmentosa*	*Thespesia populnea*
Aegiceras floridum	*Lumnitzera racemosa*	*Cerbera manghas*	*Viscum ovalifolium*
Avicennia alba	*Nypa fruticans*	*Cerbera odollam*	*Wedelia biflora*
Avicennia lanata	*Phoenix paludosa*	*Clerodendron inerme*	
Avicennia marina	*Rhizophora apiculata*	*Cordia cochinchinensis*	
Avicennia officinalis	*Rhizophora mucronata*	*Crinium asiaticum*	
Bruguiera cylindrica	*Rhizophora stylosa*	*Dalbergia candenatensis*	
Bruguiera gymnorhiza	*Rhizophora x lamarckii*	*Derris trifoliata*	
Bruguiera parviflora	*Scyphiphora hydrophylacea*	*Finlaysonia obovata*	
Bruguiera sexangula	*Sesuvium portulacastrum*	*Instia bijuga*	
Ceriops decandra	*Sonneratia alba*	*Hibiscus tiliaceus*	
Ceriops tagal	*Sonneratia caseolaris*	*Hibiscus macrophyllus*	
Cryptocoryne ciliata	*Sonneratia ovata*	*Lasia spinosa*	
Dolichandrone spathacea	*Xylocarpus granatum*	*Melaleuca cajuputi*	
Excoecaria agallocha	*Xylocarpus moluccensis*	*Pongamia pinnata*	

Note: Under the true mangroves, *Rhizophora x lamarckii* is a hybrid (*R. apiculata x R. stylosa*). *Ceriops decandra* is now recognized as *Ceriops zippeliana.*

termites and wood borers (Figure 2). Furthermore, some inland sites are no longer inundated by tide due to forest succession and increased elevation, and are therefore unsuitable for the growth of *R. apiculata*.

Figure 2 Trunk of an old-growth tree with termite nest (left) and showing wood borer attack (right)

The entire coast of Viet Nam falls within the typhoon belt. The Mekong delta including Can Gio is particularly susceptible to typhoons (Diele *et al*., 2013). For example, Typhoon Durian (Category 4) made landfall in December 2006. Damage affected only 28 ha of Compartment 17 (Figure 3). Thanks to the protective role of mangrove forest, no human lives and property were lost.

Lightning strikes are fairly frequent in Can Gio mangroves creating circular gaps in the forest canopy (Kautz *et al*., 2011). Standing dead trees persist for several years before they collapse, providing light and creating space for regeneration. The percentage of lightning struck areas (0.23%) is relatively low (Figure 4). However, it was suggested that lightning may not be the cause of these gaps in the mangrove canopy as no burn or scorch marks were observed on the dead trees (Ong & Gong, 2013).

Figure 3 Forest of Compartment 17 damaged by Typhoon Durian with more close-up view as inset

Figure 4 Circular gaps in the mangrove canopy of Can Gio with distant and inside views as insets

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Destruction, Restoration and Management of Can Gio Mangroves

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1. Introduction

Can Gio, a suburban district of Ho Chi Minh City (HCMC), covers an area of ~72,000 ha (Figure 1). It is the poorest district of the city with a population of ~71,000. The district has a vast tract of deltaic mangroves with a network of rivers and channels. The main waterways lead to the port of HCMC.

Figure 1 Location map of Can Gio

From 1964−1970, the U.S. Air Force sprayed the forested vegetation of Can Gio (formerly Rung Sat) with herbicides to remove enemy cover (Ross, 1975). As a result, 57% of mangrove forests in the district were destroyed (Figure 2). Dispensed by C-123 planes and UH-1 helicopters, more than 2.5 million liters of Agent Orange (2,4-D and 2,4,5-T) were used for deforestation while 186,000 liters of Agent Blue (cacodylic acid) were targeted at food crops.

Agent Orange contains dioxin, which can persist in the environment and enter the food chain. In 1971, while the war was still in progress, two scientists from Harvard University demonstrated that fish from the Dong Nai River, Saigon River and Can Gio coast, all contained dioxin at unacceptably high levels including human breast milk obtained from the local population (Carroll, 2010).

Figure 2 Can Gio mangroves before and after spraying of herbicides (Photo credit: Chicago Tribune)

In some areas, trees of *Rhizophora*, *Sonneratia* and *Bruguiera* were killed by the herbicides but in many areas, the land had become barren with no vegetation cover (Nam *et al*., 1993). Years later, weed species of the palm *Phoenix paludosa* and the fern *Acrostichum aureum* infested the more elevated degraded sites

(Figure 3). Among the mangrove species, *Avicennia* spp. and *Nypa fruticans* showed some resilience by showing some ability to recover through natural regeneration.

Figure 3 Fruits of *Phoenix paludosa* (top) and fronds of *Acrostichum aureum* (bottom)

Since 1978, a vast reforestation programme was undertaken by HCMC Forest Department to rehabilitate the mangroves, under the direction of HCMC People's Committee. More than 20,000 ha of mangrove forest have been planted, mainly with *Rhizophora apiculata*. The objectives of the plantations were to meet the demand for fuel wood and construction materials of HCMC, as well as to re-establish conditions suitable for the development of various socio-economic activities such as fisheries, aquaculture, research, education and ecotourism.

The reforestation effort brought vast ecological improvement to the mangrove environment and its associated biodiversity. The planted mangrove forests are now teeming with fauna such as monkeys, otters, pythons, wild boars, crocodiles and various birds. In 1991, Can Gio was declared an Environmental Protection Forest by the Council of Ministers. The district became one of the most beautiful and extensive sites of rehabilitated mangrove in the world, and was designated a Mangrove Biosphere Reserve by UNESCO in 2000.

2. Economic Forest Management (from 1978–1991)

After the war, the landscape of Can Gio was barren with mangrove vegetation reduced to scattered scrubs and bushes of. Due to lacking of fuel wood and construction raw material, the mangrove forest was cut for local consumption. On 7 August 1978, an extensive reforestation program was undertaken by HCMC Forestry Department with the establishment of Duyen Hai Forestry Enterprise, a unit responsible for implementation of forest restoration. Mangrove propagules were bought from Nam Can, Dam Doi and Ngoc Hien districts of Ca Mau province (formerly Minh Hai), and transported by boat to Can Gio for planting.

The Can Gio mangrove forest was divided into 24 forest compartments. Each compartment was managed by a Forest Brigade involving 140 forestry households. In addition, five Forest Ranger Stations also took part in forest surveillance against poaching and illegal cutting.

2.1 Management Objectives

The reforestation program in Can Gio, which started in 1978, was aimed at establishing mangrove plantations for sustained production of fuel wood, charcoal and poles. Major management objectives (Nam *et al*., 1993) were:

- To conserve and protect the shore and riverbanks from erosion and damage by strong winds and waves in support of inland fisheries and agricultural production
- To protect and preserve available mangrove forests through maintaining and ensuring their role as a productive ecosystem, and as a breeding and feeding ground for marine and other wildlife
- To maximize the production of construction poles and roof thatches for the housing and other construction in HCMC and its suburban districts
- To provide livelihood and employment as well as to improve the living standard of the local people
- To preserve sufficient areas for research, recreation and training, and as seed sources for forest management
- To promote social forestry, through people's participation in improved utilization and management of the forest by providing training and field demonstration
- To regulate the use of waterways within the mangroves so that their navigation will not be impaired

2.2 Plantation Activities

Large tracts of degraded mangrove land in Can Gio were rehabilitated (Nam *et al*., 1993). In the south, *R. apiculata* was widely planted. In the north, *Eucalyptus* spp. were planted on raised beds with *N. fruticans* within canals and *R. apiculata* on bed slopes. The nipa palm was planted on riverbanks to prevent erosion and in paddy fields where the yield is low due to saltwater intrusion. From 1978–2000, 21,100 ha of *R. apiculata*, 715 ha of *Eucalyptus* spp. and 281 ha of *N. fruticans* were planted (Table 1).

Table 1 Area of planting by species from 1978–2000

No.	Species	Area (ha)
1	*Rhizophora apiculata*	21,100
2	*Eucalyptus* spp.	715
3	*Ceriops* spp.	638
4	*Nypa fruticans*	281
5	*Intsia bijuga*	95
6	*Thespesia populnea*	95
7	*Rhizophora mucronata*	68
8	*Avicennia alba*	19
9	*Xylocarpus granatum*	19
10	*Kandelia obovata*	3
11	*Bruguiera sexangula*	1
	Total	23,034

Other species planted included *Ceriops tagal*, *Ceriops zippeliana*, *Intsia bijuga*, *Thespesia populnea*, *Rhizophora mucronata*, *Avicennia alba*, *Xylocarpus granatum*, *Kandelia obovata* and *Bruguiera sexangula*. Photographs of some of the planted species are shown in Figure 4. These plantations provided fuel wood, poles, chip wood and other materials for construction in Can Gio and HCMC (Figure 5).

The plantation model of *Eucalyptus* spp. on raised beds failed because of saltwater intrusion and poor soil nutrition. Up to now, the *Eucalyptus* trees were cut and replaced with mangrove species that can grow on elevated sites. Sites infested with *A. aureum* were cut, burnt and planted with *R. apiculata*. In abandoned salt pans, the embankments were breached to allow flushing of tidal water and planted with *C. tagal* (Figure 6). In the interior and elevated area infested with *P. paludosa*, site treatment was carried out by cutting, heaping and burning prior to planting *C. tagal* and *Lumnitzera racemosa*. In open swampy wasteland covered with *Paspalum vaginatum* and *Sesuvium portulacastrum*, *R. apiculata* was also planted.

2.3 Silviculture Operations

After the herbicide spraying, *R. mucronata* disappeared in Can Gio. To rehabilitate this species, 40 ha

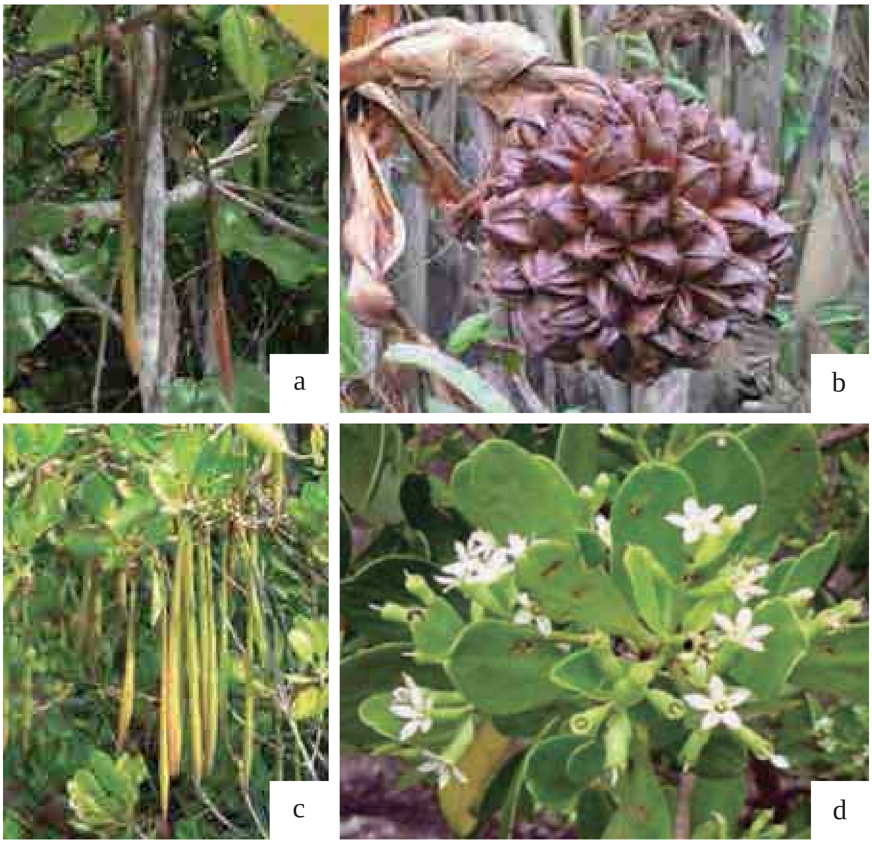

Figure 4 Propagules of *Ceriops zippeliana* (a), fruit head of *Nypa fruticans* (b), propagules of *Ceriops tagal* (c) and flowers of *Lumnitzera racemosa* (d)

Figure 5 Fuel wood (top) and construction poles (bottom) of *Rhizophora apiculata*

were planted along riverbanks and in more elevated sites to serve as seed stands for future plantations. About 142 ha of *R. apiculata* were established as seed orchards. From 1978–1989, propagules were transported by boat from Ca Mau, about 300 km south of Can Gio. Since 1991, propagules were collected locally.

A rotation age of 20 years was proposed for fuel wood plantations (Chan, 1990). As Can Gio mangroves are no longer managed for economic purposes, the rotation has yet to be considered. From 1985–1999, forest thinning was carried out, yielding a total production of 337,060 stere of fuel wood and poles. Three thinning operations were enforced for the *Rhizophora* plantations (Nam *et al*., 1993).

Thinning 1 was carried out in plantations of 5–6 years by pruning the multiple stems (3–5 cm dbh) and leaving 1 or 2 main stems/tree depending on initial density. The yield was 10–14 stere/ha of wood and thinning intensity varied from 50–64%.

Thinning 2 was carried out in plantations of 9–10 years. Thinning intensity was 25–37% with a mean distance of 1.3–1.4 m. Yields were 15–22 stere/ha of wood with 6.5–8 cm dbh. To ensure proper thinning, the District Forest Ranger of HCMC Forest Department would conduct a forest inventory and mark the trees prior to Thinning 2.

Thinning 3 was carried out in plantations of 14–15 years. Yields were 20–25 stere/ha of wood with 3–10 cm dbh. The expected tree density after Thinning 3 was 2,500 trees/ha.

On 2 June 1999, the HCMC People's Committee issued Decision No. 3172/QD-UB-CNN prohibiting forest thinning in Can Gio. Since then, the quality of the forest has deteriorated. Trees were growing slowly due to high tree density, insufficient light, and prevalence of pest problems such as termite and wood borer attack.

Figure 6 An abandoned salt pan planted with *Ceriops tagal*

3. Protected Forest Management (from 1991–2000)

On 29 May 1991, the Council of Ministers declared Can Gio mangrove forests as an Environmental Protection Forest (EPF) and thereby placing emphasis on the role of mangrove forests in coastline and riverbank stabilization, as breeding and nursery ground for marine fauna, and as habitats for wildlife. The declaration combined the protective roles of mangrove forests with organized production activities to improve living standards of the local people.

Management practices of the Can Gio EPF were as follows:

- Newly accreted forests along the coast are to be managed as strict protection areas
- Along the riverbanks, a green belt of mangrove of 10−20 m wide must be retained to safeguard against erosion caused by waves, winds and ships
- Mangrove forests in the hinterland are to be managed by the Forest Department, Forest Ranger and District People's Committee for aquaculture and forestry production.

In 1993, the State Forestry Enterprise was replaced by the EPF Management Board under the Department of Agriculture and Rural Development (DARD). In 2000, the EPF came under the jurisdiction of Can Gio District People's Committee. Part of the mangrove forest was allocated to the Agricultural Enterprise and to households for management and protection. The number of forest owners was reduced from 24 to 12 units. To mobilize reforestation, forest owners can harvest and market products from forests which they planted. Consequently, they became the real owners, fulfilling their responsibility of forest maintenance and protection.

4. Biosphere Reserve Management (from 2001)

With the designation of Can Gio into a Mangrove Biosphere Reserve (MBR) in 2000, the management was transferred from DARD to Can Gio People's Committee with the formation of Can Gio Protection Forest Management Board (PFMB). Since then, growing forests flourished with richer biodiversity, and there was better environmental protection for HCMC and its suburbs.

4.1 Management of the MBR

Mangrove forests of the Can Gio MBR comprise 24 forest compartments. Each compartment (1,000–2,000 ha) is sub-divided into plots (100 ha) and subplots (1–10 ha). Currently, Can Gio PFMB has signed contracts with 141 households (10,825 ha) and 14 local units (15,153 ha) to protect a total area of 25,978 ha. A total of 14 forest compartments are directly managed by PFMB. The annual funding for the management and protection of Can Gio MBR is 25 billion Dong (USD 1.2 million), excluding investments in building infrastructure and technology, scientific research, and communication for the environmental protection.

4.2 Role to HCMC and Surrounding Areas

Can Gio is strategically located adjacent to HCMC and four provinces (Dong Nai, Ba Ria-Vung Tau, Tien Giang and Long An). The mangrove ecosystems of Can Gio play important roles in protecting the environment of HCMC and surrounding areas. They provide large amounts of oxygen, absorb and store CO_2 (~80 t/ha/year), and contribute to the reduction of greenhouse gases. The Can Gio MBR is also the habitat for marine life aquatic species of economic value, and is the traditional fishing grounds of local residents and fishermen. The mangroves provide protection from coastal storms and erosion. This is also an ecosystem of particular interest for development of ecotourism, environmental education and extra-curricular learning for students in HCMC and adjacent areas.

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Further Study on the Mangrove Recovery Processes in Can Gio, Viet Nam

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1. Introduction

A large tract of mangrove forest occurs in the district of Can Gio, southeast of Ho Chi Min City (HCMC) in Southern Viet Nam. Most of this mangrove forest was destroyed by the spraying of defoliants during the Viet Nam War (Hong & San, 1993). Thanks to a massive reforestation program initiated in 1978 by HCMC Forestry Department, the mangrove forest was restored, and the area was designated as the Can Gio Mangrove Biosphere Reserve (MBR) under the Man and the Biosphere Program of UNESCO (UNESCO-MAB) in January 2000. Today, the MBR is managed and conserved by the Can Gio Mangrove Protection Forest Management Board. The area is one of the most successful examples of rehabilitation of damaged mangroves in the world.

This report provides an historical overview of the Can Gio mangroves. The destruction, reforestation efforts and recovery processes are discussed. Lessons learnt from the Can Gio experience can be applied in other countries worldwide. Information from our published findings (Hayashi *et al*., 2006; Miyagi *et al*., 2004) and two Master theses (Hayashi, 2005; Saitoh, 2008) along with some new results are presented.

2. Overview of the Study Area

Can Gio is located ~50 km southeast of HCMC (Figure 1). Of its total area of 72,000 ha and land cover of 40,000 ha, mangroves cover 32,000 ha (HCMC People's Committee, 2012). The whole area is situated within a deltaic confluence of the rivers of Saigon, Dong Nai and Vam Co with smaller rivers such as Nha Be, Dong Tranh and Nga Bay forming a network of waterways.

In Can Gio mangroves, rivers and tidal water channels form a single drainage system (Miyagi, 1995). At the mouth of Dong Tranh River, tidal channels flow into the main channel through a beach ridge in the south, forming a broad tidal flat, which is now designated the Can Gio Forest Park. Figure 2 is an aerial photo of Can Gio at high tide. The topography of Can Gio can be classified into the following five types based on the tidal level: unflooded upland (2–10 m above sea level), multi-year cycle flooded lowland (1.5–2.0 m), monthly cycle flooded lowland (0.5–1.0 m), daily cycle flooded lowland (0.3–0.5 m), and lower tide accretion area (less than 0.3 m).

Inundation frequencies at different ground levels were determined based on a tidal chart of the nearby Vung Tau port (Figure 3). Mangroves grow in the upper half of the tidal zone and in Can Gio, they grow within the range of 0–2 m ground level.

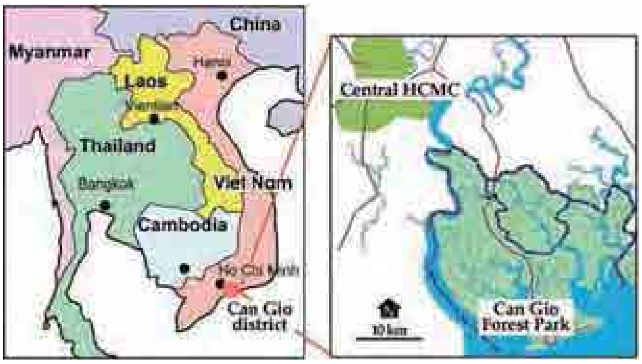


Figure 1 Location of study site

Figure 2 Can Gio district during high tide (photo by Miyagi, taken in December 2006)

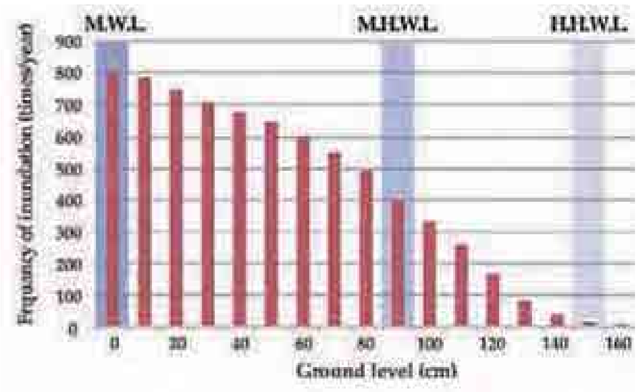


Figure 3 Inundation frequencies by ground level (based on a tidal chart of Vung Tau port).
M.W.L.: mean water level, M.H.W.L.: mean highest water level, H.H.W.L: highest high water level.

During the Viet Nam War from 1964 to 1970, mangrove forests in Can Gio were largely destroyed due to spraying of defoliants by the US military. However, some mangroves such as *Avicennia* spp. *Ceriops* spp. and *Excoecaria agallocha* survived at relatively higher ground level. Where the mangroves used to grow, palm (*Phoenix paludosa*), fern (*Acrostichum aureum*), and climber (*Derris trifoliata*) took their place.

After the Viet Nam War, a large-scale reforestation program was implemented by the HCMC Forestry Department since 1978. The restoration of mangrove ecosystems was evaluated highly and the area was designated as a UNESCO-MAB Mangrove Biosphere Reserve in January 2000.

3. Change in Mangrove Forest Distribution

3.1 Mangrove forest prior to defoliation

The oldest information obtained was a map (1:100,000) produced from a survey conducted by the Indochina Governor-General Geography Station in 1926 (map: Cap St. Jacques) and place names were added in Japanese by the Japanese Army General Staff in 1940 (Figure 4).

According to the 1926 map, there was a ferry service in Nha Be, which suggested that there was frequent traffic between Saigon (now HCMC) and Can Gio mangrove forests.

Although villages such as An Thoi Dong, Can Gio, Long Thanh and Tan Thauh dotted the landscape, there was no excavation of waterways except for opposite of Nha Be sub-district. Mangrove forests were kept pristine and no road construction was observed within the 30 km between Nha Be and Can Gio. From these observations, it is possible that the entire area was forested with mangroves at that time. There was a lighthouse and beacon at the mouth of Nha Be River. A river route connecting Cho Lon and Saigon harbors played an important role in the transportation of people and goods.

In 1928, the French Colonial Geography Station revised the 1926 map at 1 km mesh (1:100,000) with cities such as Saigon and Cho Lon shown. In 1954, 1:50,000 topographic maps were produced using aerial photographs for the first time. There was not much difference in the road network and the entire area of Can Gio was covered with mangrove forests.

Pictographic maps produced from aerial photographs taken by the U. S. military in 1965 at the time of Viet Nam War reflected a fairly accurate status of the topography and mangrove forests in Can Gio (Figure 5). We scanned the map and the forests were extracted using the Adobe Photoshop software. Forest polygons were then generated using the auto polygon function of the ArcGIS software. The forest area during the onset of the Viet Nam War was estimated to be ~39,500 ha.

From the 1965 pictographic map of Thanh An, fine tidal channels draining the mangrove forests were evident (Figure 6). At the distal end of tidal channels, the barren areas of 50−200 m width and 100−300 m depth indicated logging activities by the local people with logs transported out of the forest in boats using the tidal channels.

Figure 4 A map of Can Gio district produced in 1926 (1:100,000).
A: An Thoi Dong, C: Can Gio, L: Long Thanh,
N: Nha Be, T: Tan Thauh.

3.2 Mangrove forest after defoliation

Immediately after the aerial spraying of defoliants by the US military during the Viet Nam War, mangrove forests in Can Gio were devastated (Figure 7).

Landsat TM imagery taken in 1972 (Figure 8) shows areas deforested by defoliation and the total forest area was reduced to 18,600 ha or ~50% of the original area. Based on interviews, small-scale replanting activities were carried out by the local people in Can Gio towards the end of the war (Figure 9).

To better understand the changes in mangrove distribution after the war, Landsat and/or ASTER imageries taken in 1972, 1974, 1989, 1994 and 2002 were analyzed. Areas with and without mangrove vegetation was estimated using the auto polygon function of the ArcGIS software. The mangrove polygons from the different years were categorized as

Figure 5 A pictographic map produced in 1965 by geometric correction of aerial photos taken by the US military. Thanh An is depicted in yellow.

Figure 7 Can Gio immediately after the defoliation spray. Denuded land with tidal water channels (top) and a completely deforested site with dead tree stumps of *Ceriops* spp. (bottom, photo by C.P. Weatherspoon).

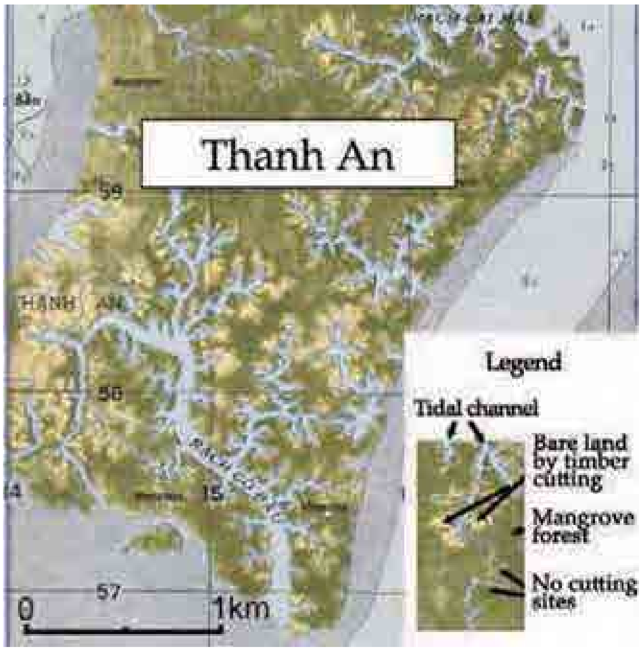


Figure 6 A 1965 pictographic map of Thanh An

Figure 8 Landsat TM image of forested and deforested areas of Can Gio in 1972

forest loss (Figure 10 left) and gain (Figure 10 right) over time.

Deforestation of Can Gio due to defoliation is shown in white (Figure 10 left). The loss of forest that continued after the war is shown in blue (1974–1989), pink (1989–1994), orange (1994–2002) and yellow (2002–2005). After the war, massive reforestation activities led to forest gain (Figure 10 right). Forested areas, mainly in the central part of Can Gio, are shown in dark green (1974–1989) and light green (1989–1994). Later, the forest was extended into the peripheral areas from 1994–2002 (orange) and from 2002–2005 (yellow). Based on these two maps, we can speculate that, after the war, with the effort of the large-scale reforestation activities conducted especially within the devastated areas, the mangrove forest area increased. However, the mangrove forest near HCMC (shown in blue) was intensively logged from 1974–1989 to provide fuel wood (Figure 10 left).

We also used polygons to depict the forest area based on ALOS imagery taken in 2011 (Figure 11). No mangroves were apparent in the communes of Bihn

Figure 9 Mangrove reforestation activities by the local people in Can Gio soon after the Viet Nam War (left) and a 1-year-old plantation (right, photo by V.N. Nam)

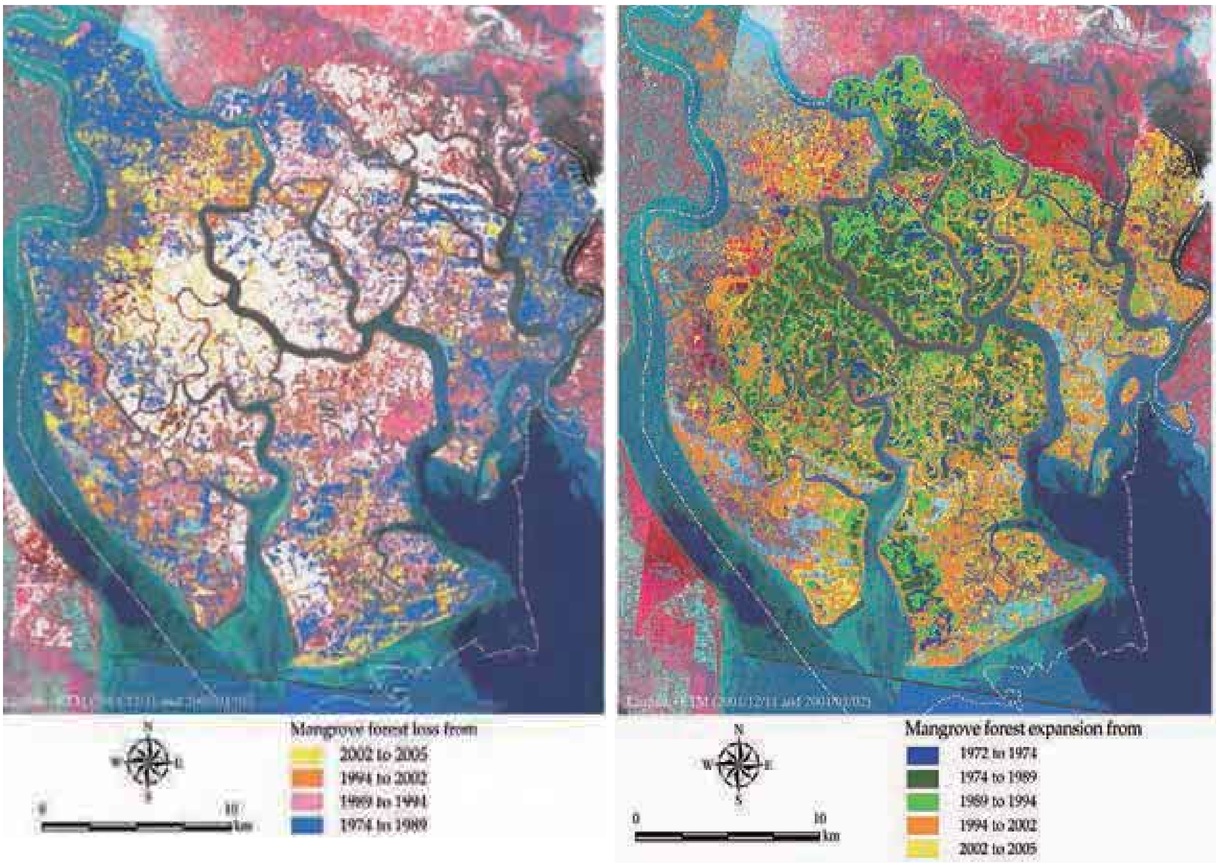


Figure 10 Mangrove loss (left) and gain (right) in Can Gio over time (Hayashi *et al*., 2006)

Khanh in the north, An Thoi Dong and Ly Nhon in the west, and Can Thanh in the south. These areas, which have been used for various purposes, form the transition zone of Can Gio MBR.

The overall change of Can Gio mangrove forest area from 1966–2005 is shown in Figure 12. With mangrove reforestation implemented in the 1970s, the total planted mangrove area reached ~18,000 ha by 1994. Since reforestation efforts slowed down after 1990, the increase of mangrove area may be attributed to natural regeneration of the existing forest.

Figure 11 Mangrove forest distribution in Can Gio based on 2011 ALOS imagery

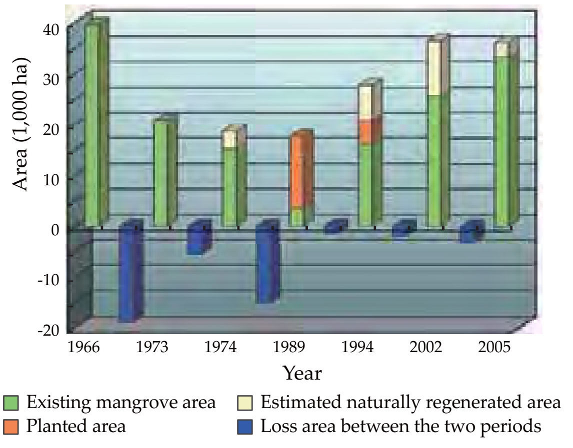


Figure 12 Mangrove forest area change from 1966–2005 (Saitoh, 2008)

3.3 The role of natural regeneration

To verify the reason for the increase of mangrove area in Can Gio after 1990, a field survey was conducted in five areas to assess the role of natural regeneration (Figure 13).

As shown in Figures 14A-1 and 14B-1, large mangrove areas were destroyed in Area 3 and Area 4 in Figure 13 by spraying of defoliants during the Viet Nam War (pink). Although the rate of forest loss was reduced after the war, it continued from 1974–1989 (blue), from 1994–2002 (orange) and from 2002–2005 (yellow). The original mangrove forests are shown in green.

Figure 13 Study areas for Can Gio mangrove forest change (Saitoh, 2008)

As shown in Figures 14A-2 and 14B-2, reforestation of mainly *Rhizophora apiculata* was carried out from 1974–1989 (dark green). From 1989–1994, the mangrove forest was extended to the peripheral areas (light green). As the deposition of sediments from the rivers progressed, mangrove forest expanded along the riverbanks from 1994–2002 (orange) and from 2002–2005 (yellow).

Cross-section data of species composition and topography of Areas 4 and 6 in 2008 are shown in Figures 15A and 15B, respectively. From the composite results of the Area 4 (Figure 15A), we confirmed that *R. apiculata* was planted in 1981 within a degraded mangrove site where *Nypa fruticans*, *Ceriops decandra* and *Avicennia officinalis* used to grow. Then as sedimentation progressed towards the water channels, seedlings of *A. officinalis* (from the surroundings) and of *R. apiculata* (from the plantations) established through natural regeneration, expanding the total area. The same tendency was observed in Area 6 (Figure 15B) where *R. apiculata* was planted in 1981 within a degraded site *A. officinalis* and *A. alba* used to grow. As the planted trees grew, they served as mother trees producing natural regenerated seedlings and expanding the area.

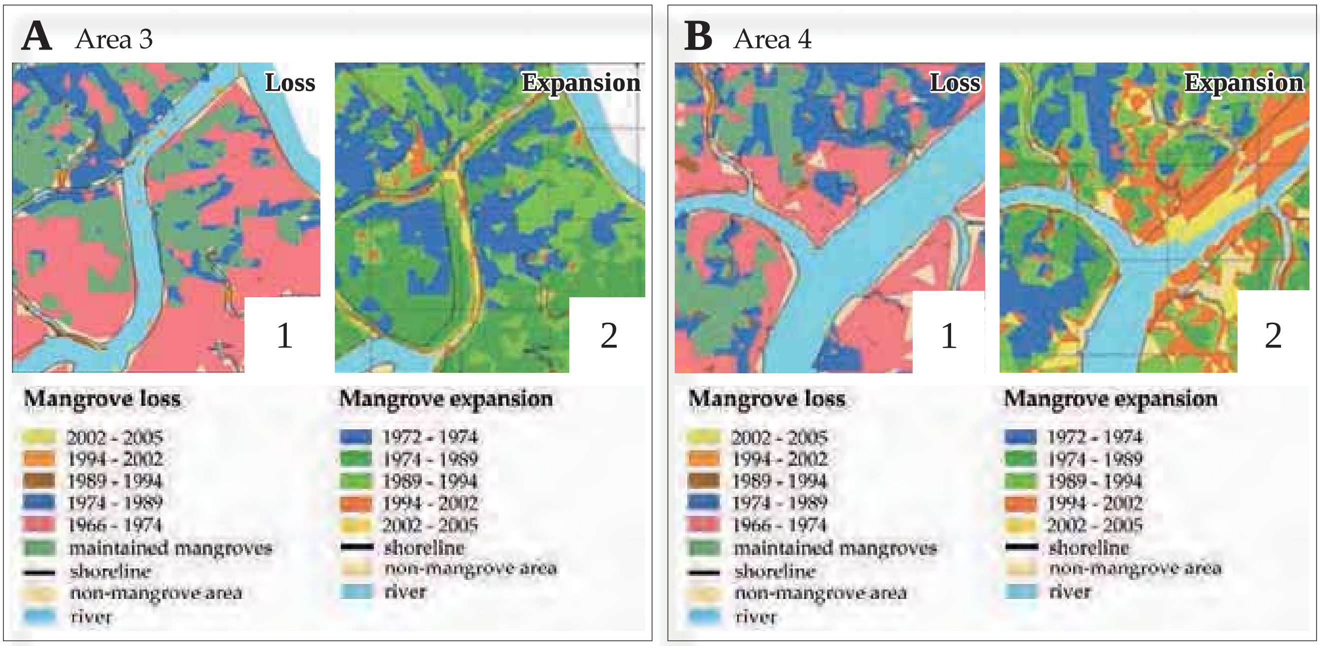


Figure 14 Mangrove loss (1) and gain (2) in Area 3 (A) and Area 4 (B) over time (Saitoh, 2008)

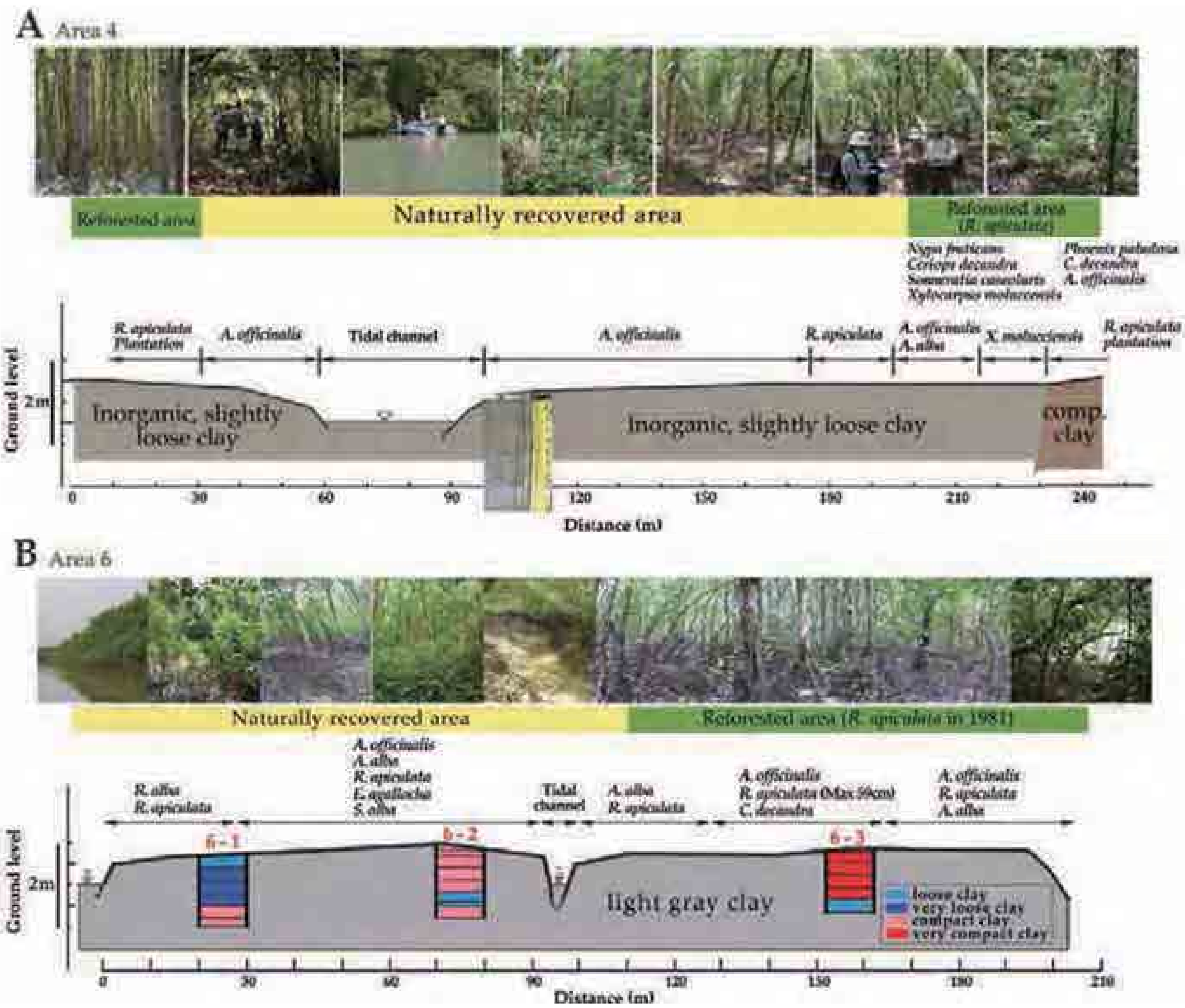


Figure 15 Cross-section data of topography and species distribution in Area 4 (A) and Area 6 (B) in 2008 (Saitoh, 2008)

From these results, we speculate that the root system of the planted trees slows down water flow of the rivers, resulting in accumulation of sediment in the forest. These environmental conditions created habitats suitable for the establishment of *R. apiculata* and other mangrove species such as *A. alba*, *A. officinalis* and *C. decandra* to establish through natural regeneration, leading to expansion of the forest.

To summarize, reforestation is important especially when the land is destroyed but once the plantations established, they are capable of expanding through natural regeneration. Understanding the mechanisms of such natural regeneration will be valuable for mangrove reforestation activities being carried out in many countries.

4. Forest Structure Analysis

To understand the transition process or the development of Can Gio mangrove forests after the spraying of defoliants, we established two study sites, one in the Forest Park and another at the Mangrove Ecosystem Education Training (MEET) Center, to investigate their forest structures in detail.

4.1 Mangrove forest in the Forest Park

The Forest Park, located in Compartment 17 in the southern part of Can Gio, is formed on tidal flats (3 km wide and over 10 km long) along the east bank of Dong Tranh River (Figure 16). According to a vegetation map produced in 1957 by V. N. Nam and others, *A. alba* and *S. alba* used to be the dominant species with *R. apiculata*, *Ceriops* spp. and *Phoenix paludosa* occupying the more landward sites.

The Forest Park was deforested by defoliation during the Viet Nam War and after the war, an intensive reforestation of mainly *R. apiculata* was undertaken from 1978 (Hong, 1996). After 1983, *R. mucronata* and *C. tagal* were also planted. By 1987, *R. apiculata* dominated the forest at the center on higher ground level while a natural forest of *A. alba* rapidly developed along rivers on low ground level (Miyagi

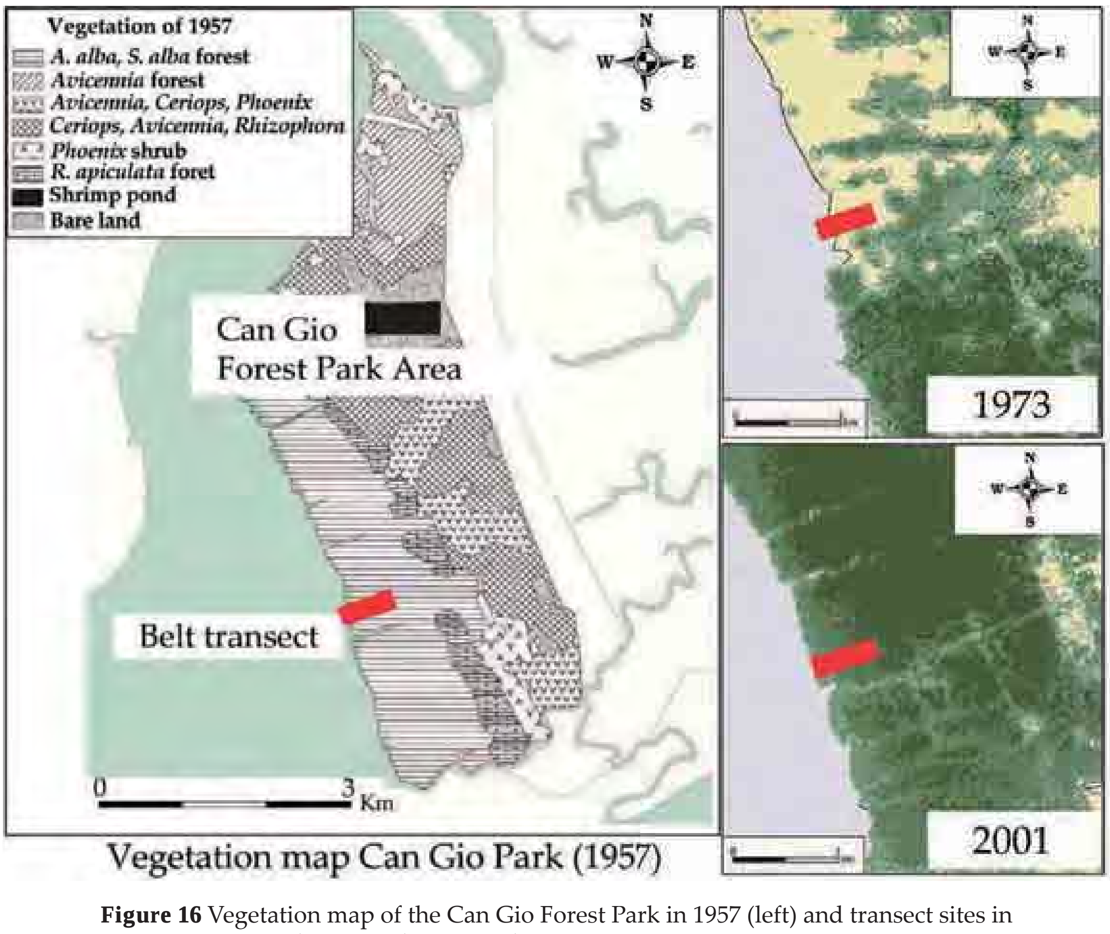


Figure 16 Vegetation map of the Can Gio Forest Park in 1957 (left) and transect sites in 1973 and 2001 (right) (Hayashi *et al.*, 2006)

et al., 2003). The cross-section data of topography and species distribution of the park in 1993 is shown in Figure 17.

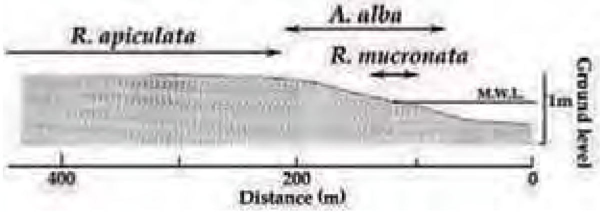


Figure 17 Cross-section data of topography and mangrove species distribution of Can Gio Forest Park in 1993 (Miyagi, 1995). (See abbreviation in Figure 3).

In 2003, a belt transect (2 x 500 m) was set up landward from the bank of Dong Tranh River (Figure 16). Within the transect, the relationship between the distribution of species (taller than 1.5 m) and the ground level is shown in Figure 18. Ground level from 0–50 m was low. Except for tidal channels at 150 m and 420 m, the ground level was 0.3–0.6 m (mean water level), lower than the mean high water level of 0.91 m. With the transect, the following seven species were found, namely, *A. alba*, *A. marina*, *A. officinalis*, *Bruguiera parviflora*, *C. decandra*, *R. apiculata*, *R. mucronata* and *S. alba*.

From -30–50 m, *A. alba* was dominant. From 50–130 m and from 200–450 m, the forest was of the *A. officinalis* and *R. apiculata* mixed type. *R. apiculata* was dominant from 130–200 m and from 450–490 m. Shrubs of *C. decandra* grew along the channel from 330–390 m.

To further understand the forest condition of the transect, a 10 x 30 m quadrat was set from -30–0 m where *A. alba* was dominant (Figure 19a). In addition, we established another 10 x 30 m quadrat from 274–304 m where the forest was of the *A. officinalis* and *R. apiculata* mixed type (Figure 19b) and a 10 x 20 m quadrat from 465–485 m where *R. apiculata* was dominant (Figure 19c).

Within each quadrat, all trees including seedlings and saplings were enumerated, measured and identified. All trees were mapped. The data were presented as species distribution (A), species density by tree height (B) and seedling density (C).

Figure 19a depicts a study area with ground level 0.21–0.39 m above mean water level (m.w.l.). Forest composition and tree density was: *A. alba* 1700 trees/ha (78%), *R. apiculata* 233 trees/ha (11%), *R. mucronata* 200 trees/ha (9%) and *A. officinalis* 33 trees/ha (2%). The upper layer was almost 100 % occupied by *A. alba* as well as the middle layer and many *A. alba* seedlings

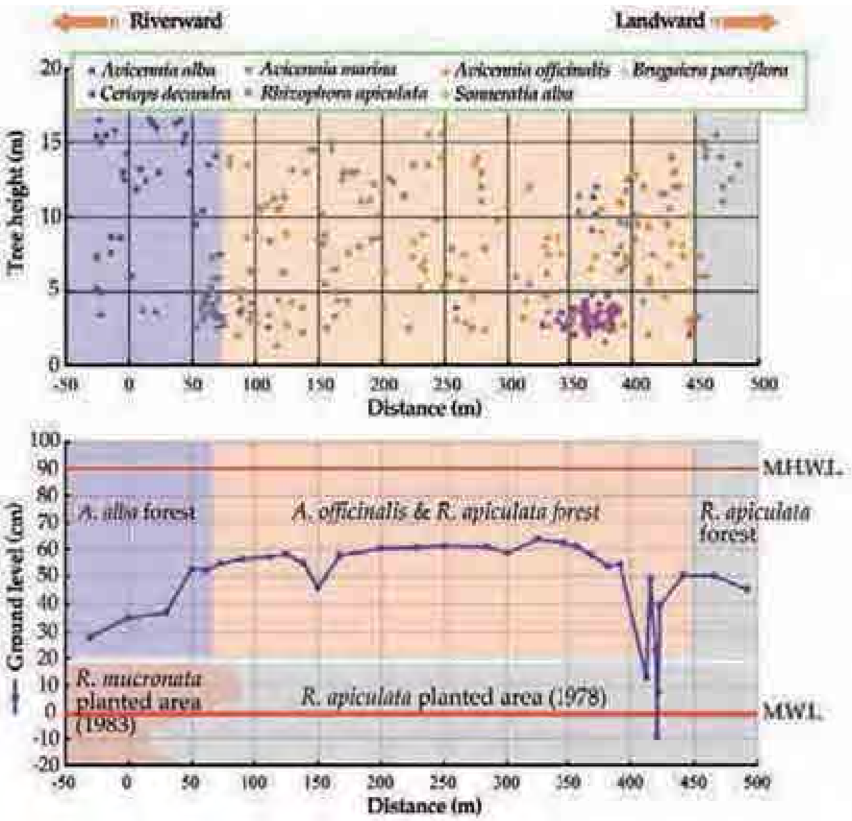
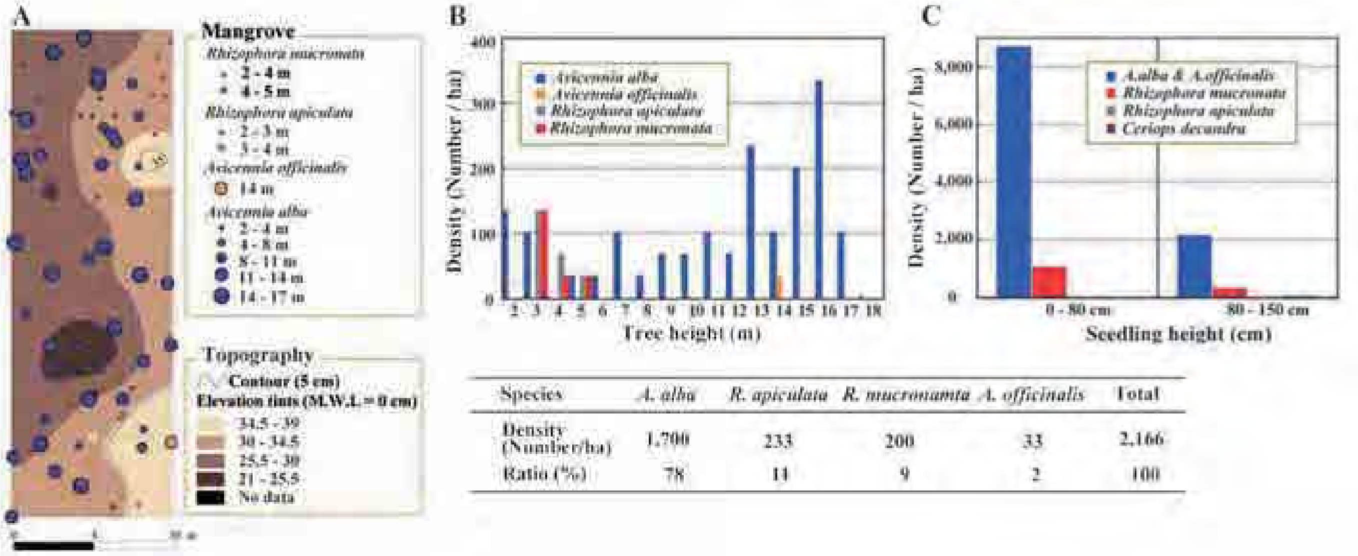
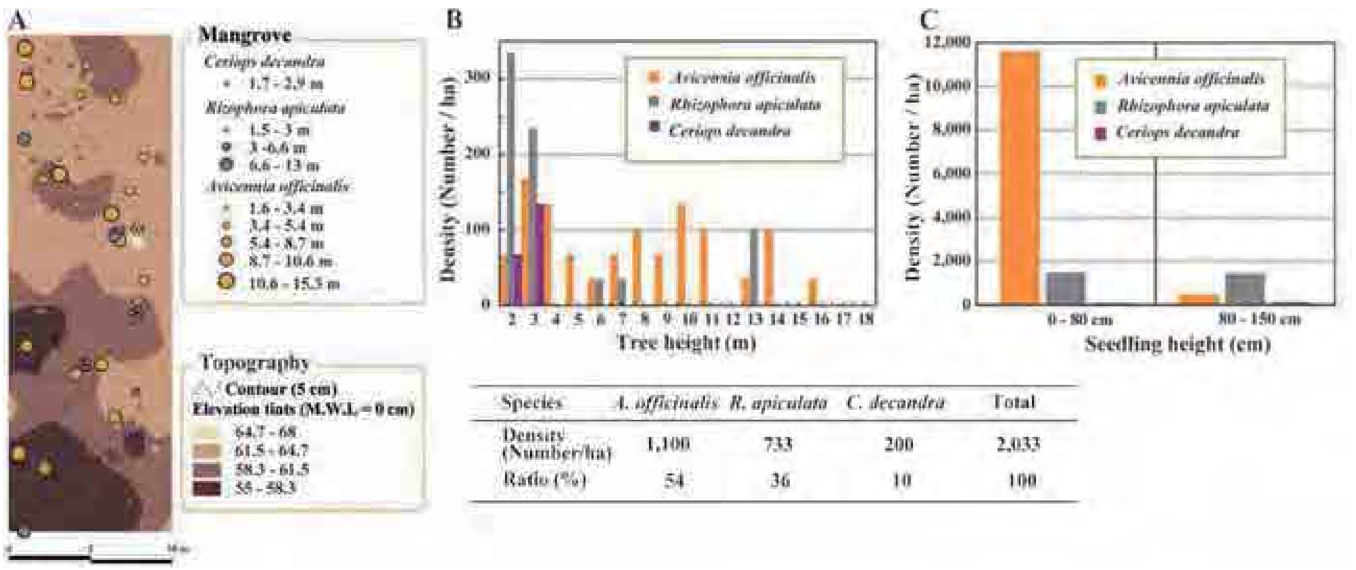


Figure 18 Distribution of species (over 1.5 m height) (top) and cross-section data of ground level (bottom) in the belt transect of the Can Gio Forest Park (Hayashi *et al*., 2006). (See abbreviations in Figure 3).



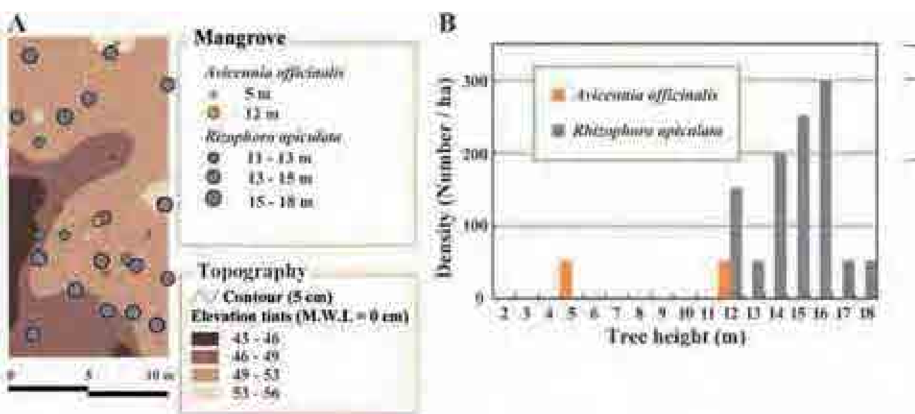
Species	A. alba	R. apiculata	R. mucronamta	A. officinalis	Total
Density (Number/ha)	1,700	233	200	33	2,166
Ratio (%)	78	11	9	2	100

Figure 19a Detailed structure of *A. alba* dominant forest (Hayashi *et al*., 2006).
Species distribution within the quadrat (A), densities by tree height (B) and seedling height (C).



Species	A. officinalis	R. apiculata	C. decandra	Total
Density (Number/ha)	1,100	733	200	2,033
Ratio (%)	54	36	10	100

Figure 19b Detailed structure of *A. officinalis* and *R. apiculata* mixed forest (Hayashi *et al*., 2006).
Species distribution within the quadrat (A), densities by tree height (B) and seedling height (C).



Species	R. apiculata	A. officinalis	Total
Density (Number/ha)	1,050	100	1,150
Ratio (%)	91	9	100

Figure 19c Detailed structure of *R. apiculata* dominant forest (Hayashi *et al*., 2006).
Species distribution within the quadrat (A) and densities by tree height (B).

were identified at the forest floor. The distribution of *A. alba* continued along the river in this quadrat. Planted in 1983, *R. mucronata* did not establish, perhaps due to inadequate ground level for the species (Miyagi *et al.*, 2004).

The ground level of the study site described in Figure 19b was 0.55–0.68 m above m.w.l. Barren after the defoliation, the site was planted with *R. apiculata* and later with *C. decandra*. Forest composition and tree density was: *A. officinalis* 1100 trees/ha (54%), *R. apiculata* 733 trees/ha (36%) and *C. decandra* 200 trees/ha (10%). The upper canopy layer was dominated by *A. officinalis*, and natural regeneration was observed at the shrub layer, indicating that although *R. apiculata* was originally planted, the site conditions were more suitable for *A. officinalis*.

The ground level of the study area shown in Figure 19c was 0.43-0.56 m above m.w.l. and the area was planted with *R. apiculata* in 1978. Forest composition and tree density was: *R. apiculata* 1,050 trees/ha (91%) and *A. officinalis* 100 trees/ha (9%). The planted *R. apiculata* became well established with tree heights of ~10 m in the middle layer with good natural regeneration of seedlings on the forest floor.

As shown in Figure 20, the sediment condition was surveyed along the transect. From 0–70 m, the surface soil (20 cm depth) consisted of soft loose gray clay. Further inland, the surface soil contained relatively hard gray or brown mottled iron, which generally occurs when soil in bare land is oxidized. From these results, we could speculate that erosion and deposition had repeatedly happened from 0–70 m in which *A. alba* dominated. Beyond 70 m, soil deposition was evident as the surface soil (50 cm depth) was blackish brown, indicating the presence of organic matter.

Based on these studies, we hypothesized the following processes for the establishment of mangrove forest in Can Gio Forest Park:

- From the aspects of phytosociology, topography, sedimentation characteristics and sea-level change, the mangroves before defoliation was a typical deltaic formation seen in Southeast Asia.
- Due to spraying of defoliants, mangrove forests in Can Gio were destroyed with serious soil erosion and land desiccation. In some parts, gray or brown mottled iron was present in the sediments, which generally occurs when soils in barren land become oxidized.
- Since 1978, reforestation was undertaken with *R. apiculata* as a major species. The mangrove area has gradually expanded through natural regeneration and the formation of mud flats along riverbanks encourages the rapid colonization and establishment of *A. alba*.

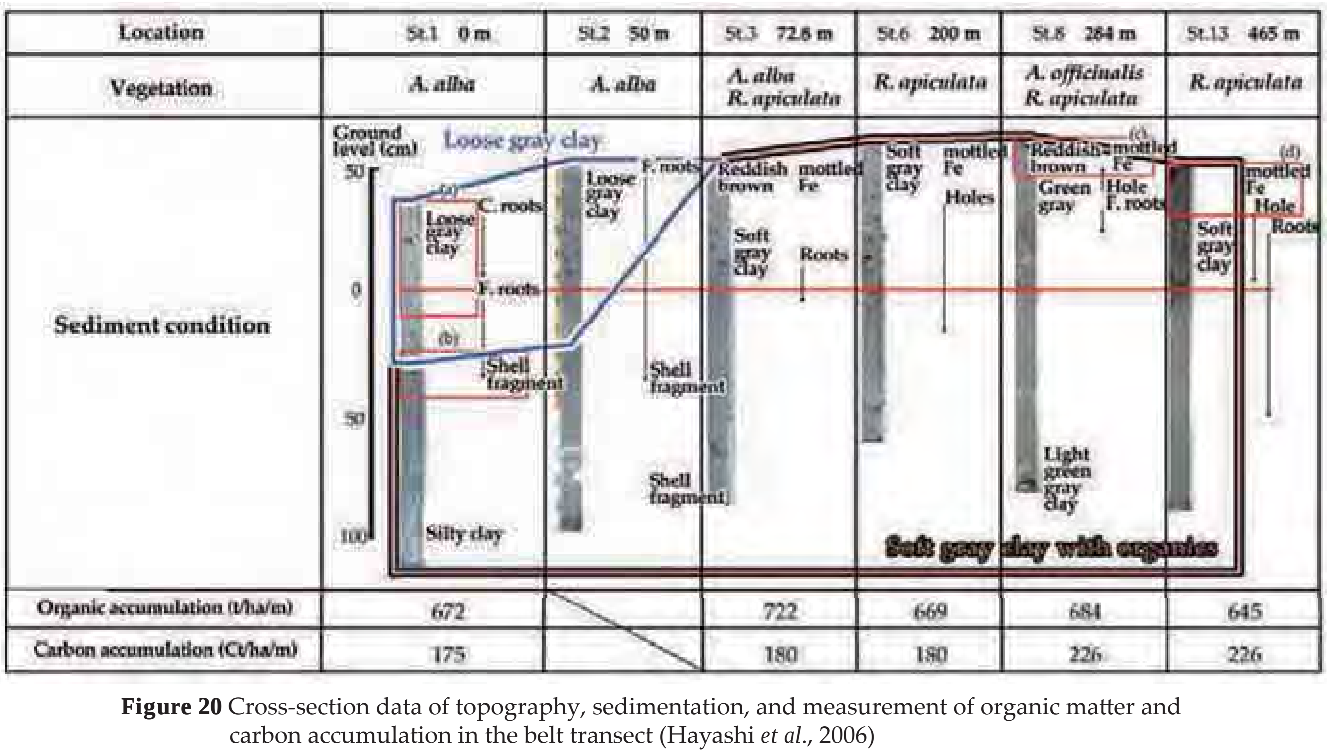


Figure 20 Cross-section data of topography, sedimentation, and measurement of organic matter and carbon accumulation in the belt transect (Hayashi *et al.*, 2006)

4.2 Mangrove forest at the MEET Center

The MEET Center is located in Compartment 10, bordering the Core Zone of Can Gio MBR (Figure 21).

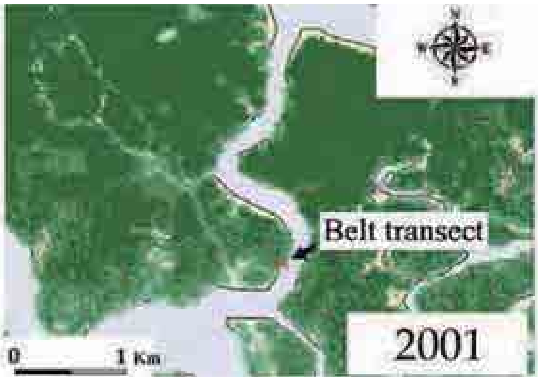


Figure 21 Study site at the MEET Center showing the location of the belt transect (Hayashi *et al.*, 2006)

Field surveys were conducted in August 2003, August 2004 and March 2005. A 180-m long belt transect was set up landward from the river (Figure 21). The transect was 20 m wide from 0–80 m and 10 m wide from 80–180 m. The overall ground level of the study site was higher than average sea level and some areas with mud lobster mounds were higher than highest high water level. A small tidal channel flowed through part of the transect.

Soil core samples were collected from four locations, namely, MEET-1, -2, -3 and -4 at ground levels of 0.68, 0.85, 1.31 and 1.41 m above m.w.l., respectively (Figure 22). Surface soils of MEET-1 and -2 were loose clay, indicating recent sediments accumulated within the past 10 years. The soil of MEET-3 was rich in organic matter and carbon content was 1.5–2 times higher than that of MEET-1. At MEET-4, within a *Phoenix paludosa* forest, the soil was very compacted clay and the uppermost surface had a strong reddish color.

Mangrove species distribution in the transect was surveyed (Figure 23 top). Mangrove trees were mapped within a 20 m wide transect from 0–80 m site and within a 10-m wide transect from 80–180 m. The distribution of each species was further plotted by ground level (Figure 23 inset). The results showed that each species has a ground level range suitable for growth. For example, *Lumnitzera racemosa* and *P. paludosa* grow at the highest ground level (140–150 cm above m.w.l.), *R. apiculata* and *C. decandra* grow at the next highest ground level (120–130 cm above m.w.l.), with *A. officinalis* next below (80–90 cm above m.w.l.), and *A. alba* at the lowest ground level (20–50 cm above m.w.l.).

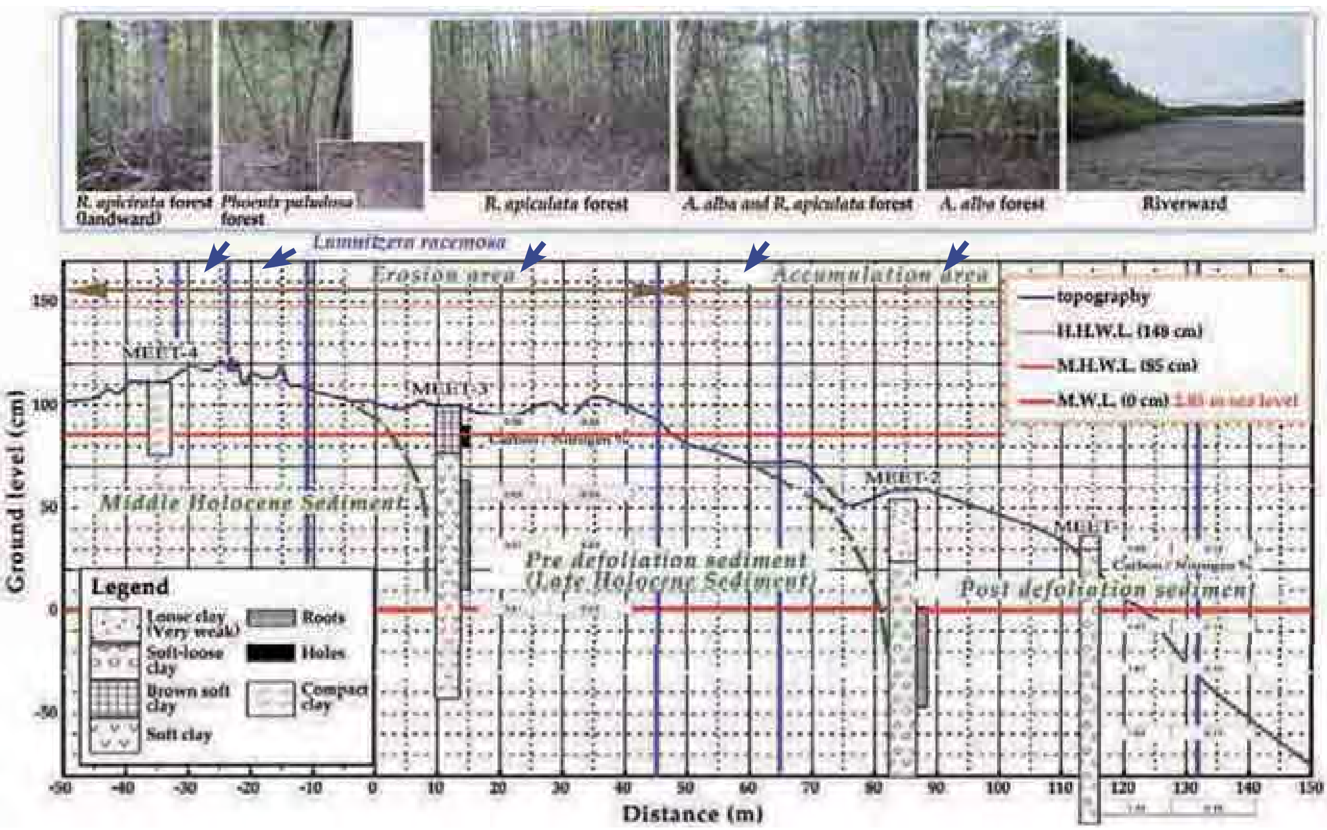


Figure 22 Geological and geomorphological cross-section data and forest landscape in the belt transect of the MEET Center (Hayashi *et al.*, 2006). (See abbreviations in Figure 3).

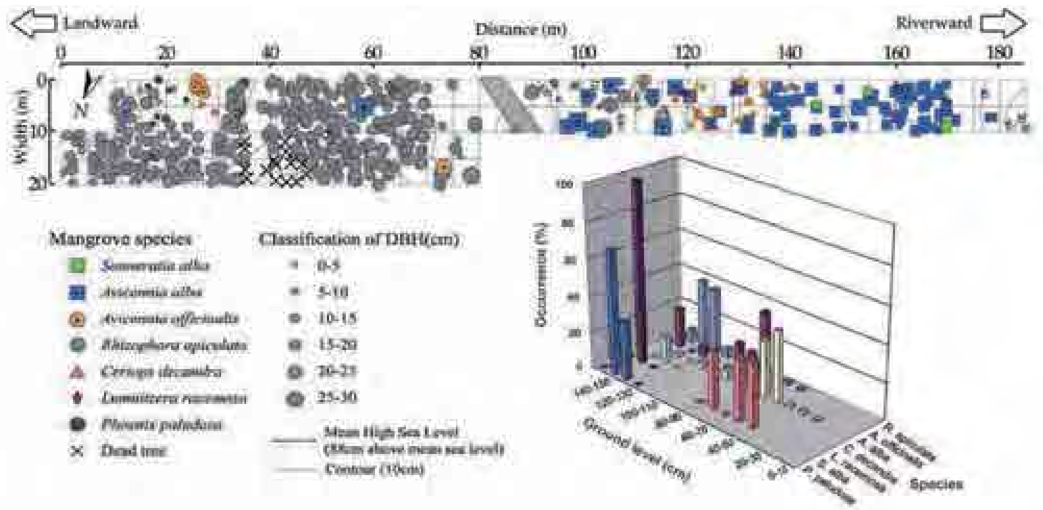


Figure 23 Mangrove species distribution along the belt transect at the MEET Center (top) and percent of total tree for species at a given ground level range (inset) (Hayashi *et al*., 2006)

4.3 Resurvey of the MEET Center

In 2012−2013 (some 10 years later), the belt transect in the MEET Center was resurveyed (Figures 24 and 25). Unfortunately, the majority of the labels and tags were lost and therefore the resurvey was conducted based the position of remaining tags. The *R. apiculata* forest became a dense forest with a fully developed canopy (Figure 24 top) and some gaps caused by lightning were observed (Figure 24 bottom).

Although not identical, the resurvey conducted in 2012−2013 was proximate enough to make predictions of forest structure changes over the course of 10 years. The crown coverage (%) and topographic data of 2003 (ground level (cm)) were plotted with landscape photographs shown (Figure 26). Except for the lightening gap (Figures 26-2 and -3), the canopy was mostly closed but the *A. alba* dominant forest near the river had more light compared to the *R. apiculata* dominant forest.

To understand the relationship between micro-topography and forest distribution, a 5-m wide belt transect was set up (Figure 27). The forest edge at the river was 80 m from the promenade (gray) in 2003 but it was extended to 100 m, indicating that the mangrove forest had accreted by 20 m in 10 years. The new forest beside the river was mostly *A. alba*.

Figure 24 The *R. apiculata* forest in 2012−2013 (top right), looking up the forest canopy (top left), a lightening gap (bottom left) and the forest floor with natural regeneration (bottom right)

Figure 25 The 2012–2013 MEET Center field survey during high tide. Distribution of *A. alba* extended riverward (left), a *R. apiculata* forest near the promnade (middle) and an *Avicennia* forest damaged by a typhoon in 2006 (right).

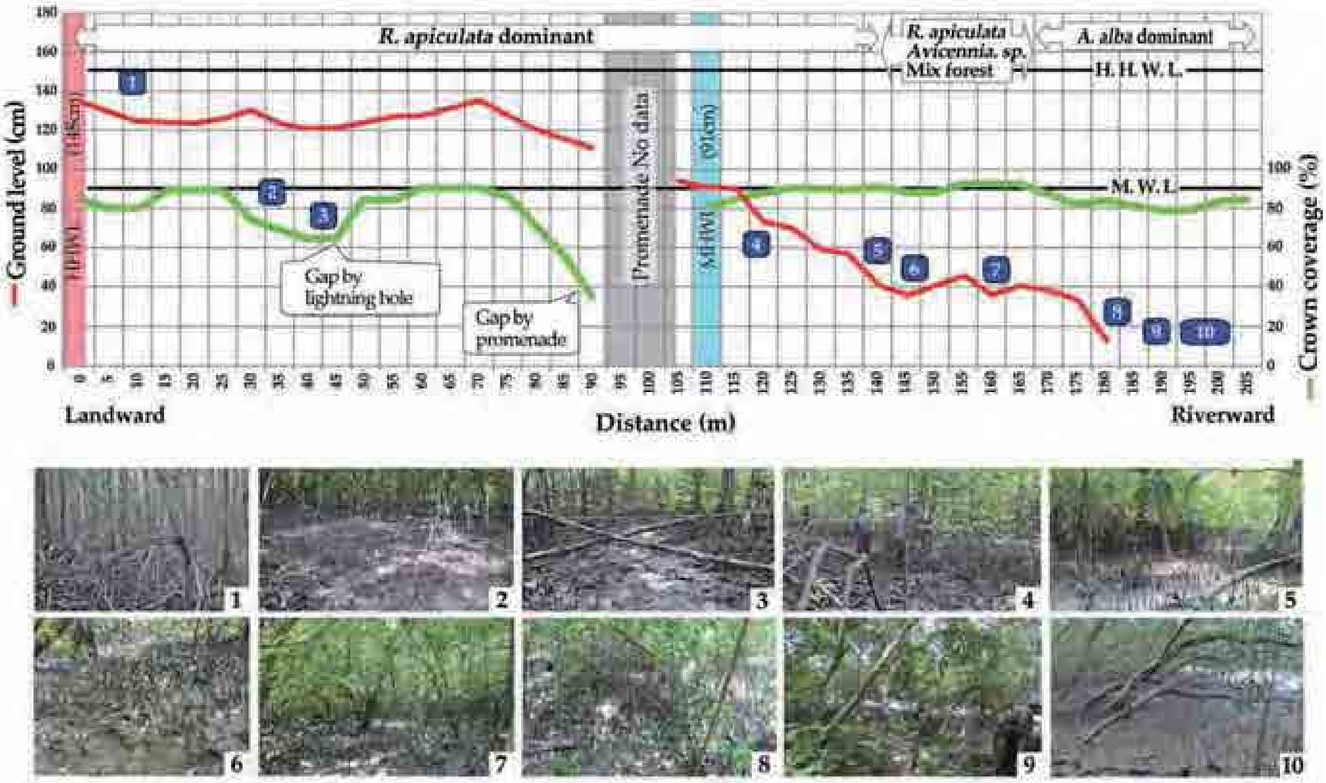


Figure 26 Plot of crown coverage (%) and topographic data of 2003 (ground level (cm)), with landscape photographs. (See abbreviations in Figure 3).

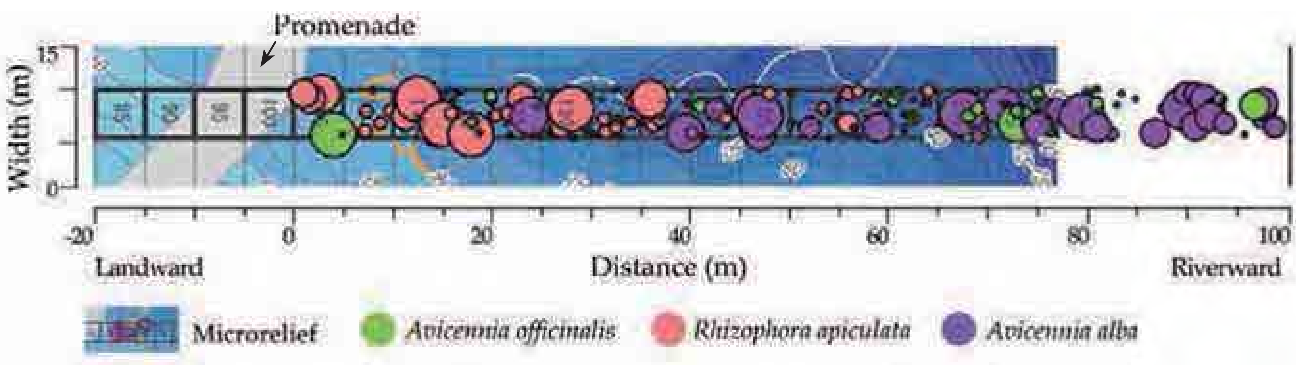


Figure 27 Mangrove distribution map along the transect at the MEET Center

To further investigate the age constituent in the study area, the transect was divided into 5 m segments and the tree age was categorized as follows: seedling (less than 40 cm in height), sapling (0.4–1.5 m in height), and mature tree (over 1.5 m in height) (Figure 28).

Along the transect, *R. apiculata* seedlings were abundant at both the river and landward sides, saplings occurred from 40–60 m and from 135–160 m, and mature trees were found up to 185 m. Saplings of *A. alba* and *A. officinalis* occurred at 50 m and from 200–205 m. Mature trees of *A. alba* grew at lower ground levels at 200–205 m near the river side whereas *A. officinalis* grew at higher ground level from 150–205 m. Saplings of *C. decandra* were observed from 0–30 m.

The results showed that *A. officinalis* and *A. alba* colonized the mud flats of riverbanks at lower ground level, extending their distribution where *R. apiculata* does not grow.

5. Importance of Canopy Formation

Many rivers flow through the mangroves of Can Gio depositing fine particle soils. This led us to hypothesize that unimpeded raindrops can have a substantial impact on the erosion of these fine fluvial soils. To assess the role of canopy cover in reducing surface soil erosion, we set up rain gauges and sediment traps inside a *R. apiculata* forest and inside a lighting gap at the MEET Center in 2012–2013 (Figure 29).

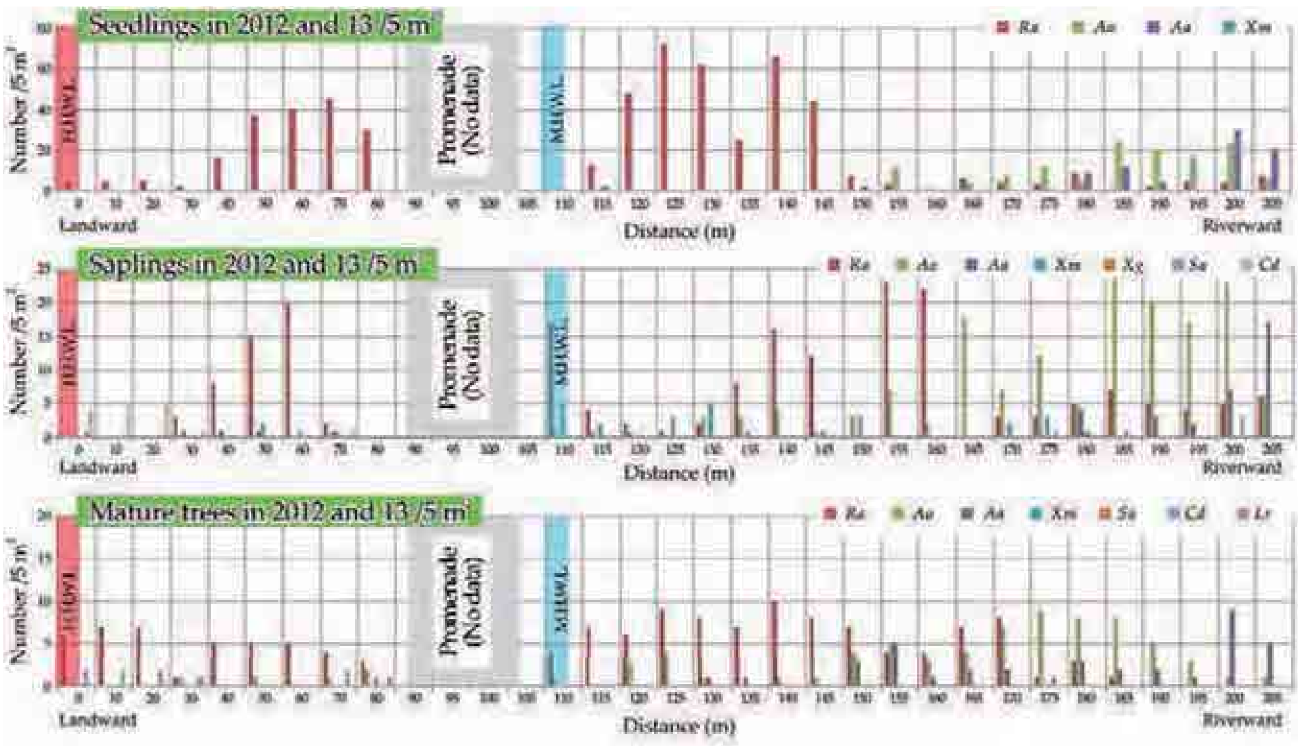


Figure 28 Numbers of seedlings, saplings and mature trees within 25 m² (5 x 5 m) segments of the transect in 2012–2013 Ra: *R. apiculata*, Ao: *A. officinalis*, Aa: *A. alba*, Xm: *X moluccensis*, Xg: *X. granatum*, Sa: *S. alba*, Cd: *C. decandra*, Lr: *L. racemosa* (See other abbreviations in Figure 3).

Figure 29 Set up of stemflow trap (left), throughfall trap (middle) and gross precipitation trap (right) at the MEET Center (Saitoh, 2008)

The result of rainfall events is shown in Table 1. During the 11 rainfall events recorded, the minimum and maximum rainfall per hour was 0.5 mm and 36 mm, respectively.

Table 1 Selected rainfall events at the MEET Centre measured in 2012–2013 (Saitoh, 2008)

Rain fall event	Date	Starting time	Duration (min)	Precipitation (mm)	Intensitiy (mm/h)
1	9/18	4:03	59	11.2	11.4
2	9/20	2:07	48	15.0	14.3
3	8/ 5	14:48	4	2.4	36.0
4	8/ 5	19:31	18	4.8	16.0
5	8/ 8	17:55	554	5.0	0.5
6	8/ 9	10:59	230	1.8	0.5
7	8/ 9	15:50	140	10.6	4.5
8	8/10	5:55	54	14.2	15.8
9	8/10	6:50	115	2.0	1.0
10	8/10	15:45	11	5.8	31.6
11	8/10	19:10	14	0.6	2.6

The relationship between rainfall intensity and sediment accumulation was plotted (Figure 30). During a heavy rain of 8 mm/15 min, sediment movement was hardly discernable under the forest canopy, but resulted in sediment movement of 300 g/m^2 in the exposed lightning gap. When there is rainfall, the soft soil of the mangrove floor can be easily eroded where there is no canopy cover. Therefore, it is important to reconstruct the mangrove canopy as soon as possible applying appropriate reforestation techniques. Based on these observations, one can imagine the amount of sediment erosion following defoliation of Can Gio mangrove forests during the Viet Nam War must have been immeasurable.

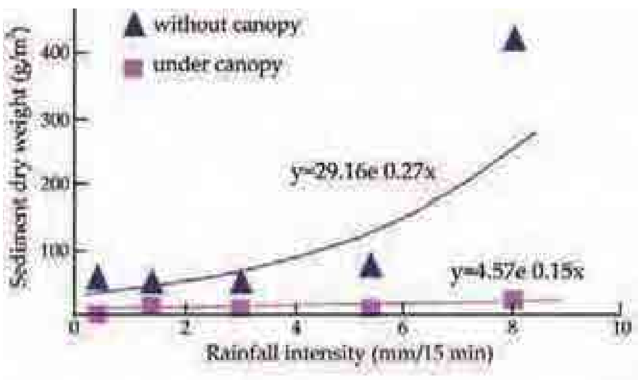


Figure 30 The relationship between rainfall intensity and sediment accumulation in the sediment trap (Saitoh, 2008)

6. Conclusion and Recommendations

Mangrove forests of Can Gio were severely damaged by spraying of defoliants during the Viet Nam War. However, through extensive reforestation efforts undertaken by the HCMC Forestry Department and participation of the local people, the mangrove forests were restored and designated a UNESCO Biosphere Reserve in January 2000.

Chosen as the primary species for reforestation, *R. apiculata* grew well when planted in sites with proper topography. When a *Rhizophora* forest was established, sedimentation was promoted in the surrounding areas, particularly along riverbanks. These accreting banks facilitated the colonization of *A. alba* and *A. officinalis*, which gradually led to a mangrove forest ecosystem that is more diversified and richer in species (Figure 31).

Further investigation of the colonization of *A. alba* and *A. officinalis* revealed that each species has a suitable ground level and soil condition for growth. For plantations of *R. apiculata*, only areas with suitable ground level and soil condition would expand by natural regeneration. When planning a reforestation or afforestation program, we need to consider the proper environmental conditions (i.e. topography) suited for respective planted species.

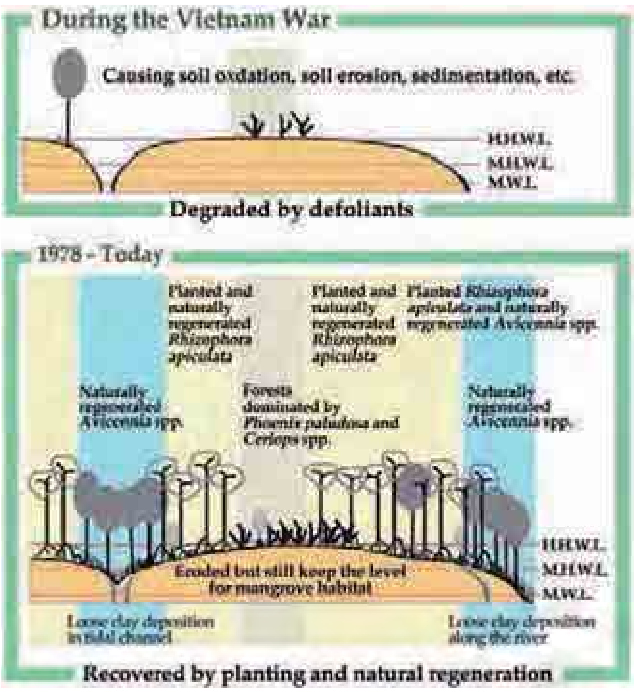


Figure 31 Illustration of mangrove forest transition in Can Gio from forest degradation by defoliants during the Viet Nam War (top) and recovery by planting and natural regeneration (bottom) (modified from Saitoh, 2008). (See abbreviations in Figure 3).

In many countries, reforestation activities are implemented where mangrove forests have been lost. In many cases, *Rhizophora* is chosen due to the ease of propagule collection and planting techniques. Even so, one should identify the proper ground level and soil conditions for each *Rhizophora* species. One should also consider planting other mangrove species. The establishment of a mangrove forest with mixed species is recommended over a monoculture *Rhizophora* plantation.

It is also recommended that degraded mangrove sites be rehabilitated as soon as possible. During the rainy season, surface soil erosion would be severe in sites with no vegetation. During the dry season, soil oxidation would become a problem and render these sites unsuitable for mangrove rehabilitation.

Damaged by spraying of defoliants during the Viet Nam War, the Can Gio mangrove forests have been successfully restored through massive reforestation efforts. There is much to be learned from the dynamics of the recovery processes. We hope that the lessons from the Can Gio mangroves will guide mangrove rehabilitation activities around the world. We sincerely extend our tribute to those people who were involved in Can Gio mangrove reforestation.

Acknowledgments

We are grateful to Dr. HT Chan, Prof. Mike Cohen and Prof. Shigeyuki Baba for editing and rewriting, and Ms. Mio Kezuka, Ms. Ryoko Miyagawa, Ms. Eriko Tamaki and Ms. Nozomi Oshiro for redrawing figures and layout setting.

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Erosion and Accretion in Can Gio Mangroves (1953 to 2010)

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1. Introduction

Mangrove shores are stable, accreting or eroding (Chan & Baba, 2009). An accreting mangrove shore typically has a low crop of vegetation colonising newly formed mud flats. A stable shore shows minimal shoreline fluctuations. An eroding shore is characterised by the general lowering of the near-shore profile, formation of retreating scarps, collapsing of mangrove trees and deposition of sand cheniers. Globally, retreating coastlines exceed advancing coastlines (Bird, 1985). There is evidence that coastal erosion is an escalating environmental threat of global concern. Factors influencing coastal erosion are natural or human-induced. Climate change and sea level rise are major factors causing coastal erosion.

In Can Gio Mangrove Biosphere Reserve (MBR), erosion and accretion are actively on-going natural processes along the shorelines. A study on sediment transport in the Dong Tranh estuary indicated that mangroves play a role in trapping sediments (Cang *et al.*, 2008). Information on the extent of erosion and accretion would provide useful baseline data for authorities and stakeholders in planning and implementing mitigating measures. In this study, erosion and accretion in 10 selected sites were monitored from 1953–2010.

2. Study Sites

Ten sites, located in proximity to five communes with strong erosion and accretion, were selected for study (Figure 1). They were An Thoi Dong (Site 1), Ly Nhon (Sites 2 and 3), Long Hoa (Sites 4, 5 and 6), Can Thanh (Sites 7 and 8), and Thanh An (Sites 9 and 10) of Can Gio MBR (Dung & Thai, 1997).

3. Methods of Study

Erosion and accretion from 1953–2010 in 10 selected sites of Can Gio MBR were monitored using GIS tools, maps and satellite images. The sources of maps and satellite images were as follows:

1. Map of Vietnam National Geographic in 1953, scale 1:100,000
2. Pictomap 1965 by the U.S. Army, scale 1:25,000
3. Landsat – 1/MSS, 01/01/1973, resolution 80 x 80 m
4. Landsat – 4/TM, 06/03/1989, resolution 30 x 30 m
5. JERS – 1/OPS, 16/01/1997, resolution 18 x 18 m
6. Quickbird, 19/01/2010, resolution 0.6 x 0.6 m

Using UTM coordinates (Datum WGS 84), the 10 study sites were digitised by MapInfo tool to calculate and compare their extent of erosion and accretion based on five periods of 1953–1965, 1965–1973, 1973–1989, 1989–1997 and 1997–2010 (Figure 2).

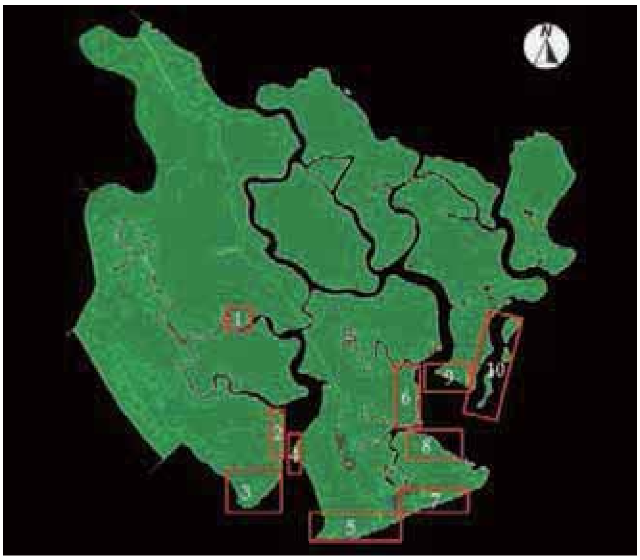

Figure 1 Location of the 10 study sites

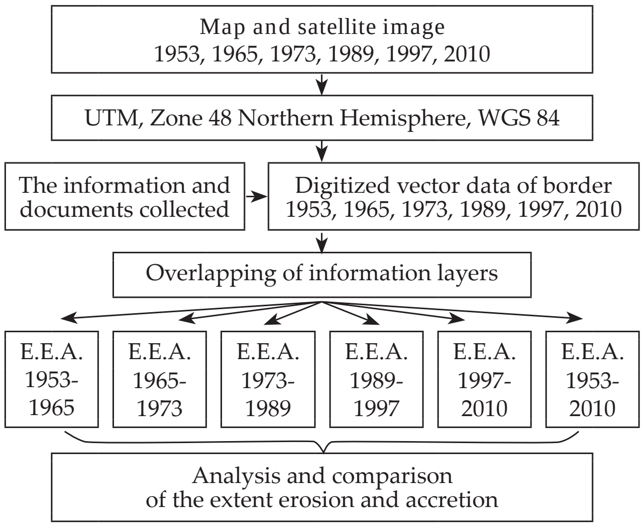

Figure 2 The diagram of study
E.E.A.: Extent of erosion and accretion

4. Results and Discussion

4.1 Site 1 (An Thoi Dong)

Site 1 is located in Compartment 10 along the banks of a tributary of Dong Tranh River. In 1953, Con Ba was an island separated from Zone 1 in the site. From 1989, the island merged with Zone 1 through accretion. Both Zone 1 and Con Ba showed some accretion for the five periods, particularly from 1997–2010 (Table 1). Accretion ranged from 1.2–8.5 ha for Zone 1 and from 1.8−6.5 ha for Con Ba. No erosion was observed from 1997 for Zone 1 and from 1989 for Con Ba. Overall, with a net gain of ~40 ha or 0.7 ha/yr from 1953–2010, the shoreline in Site 1 can be considered as stable. In accreting areas, natural regeneration of *Avicennia alba* is evident (Figure 3).

4.2 Site 2 (Ly Nhon)

Site 2 is located in Compartment 20 on the bank of Dong Tranh River. Between 1953 and 1965, Site 2 had the strongest deposition of 122 ha or 10.2 ha/yr, accounting for 49% of the total accretion (Table 2). Since then, it experienced gradual accretion ranging from 26.0−48.4 ha from 1965–2010 except between 1973 and 1989, which had erosion of 46.9 ha. Overall, the site had a net gain of ~194 ha or 3.4 ha/yr from 1953−2010. Accretion is most likely due to alluvium brought down by Dong Tranh River. Accreting shores with newly established seedlings can be observed (Figure 4).

4.3 Site 3 (Ly Nhon)

Site 3 is located in Compartment 20 at the estuary of Dong Tranh River, which drains into the East Sea. From 1953−1965 and 1973−1989, there was severe erosion which led to a loss of 609 ha (51 ha/yr) and 166 ha (10.4 ha/yr), respectively (Table 3). Even with accretion from 1965−1973 (136 ha), 1989−1997 (38.6 ha) and 1997–2010 (69.7 ha), Site 3 experienced a net loss of ~585 ha from 1953–2010. Due to its seaward location, Site 3 is vulnerable to the vagaries of the East Sea, which are accompanied by strong waves, coastal storms and occasional typhoons. Mud flats where mangroves previously existed are evident during the low tide (Figure 5).

4.4 Site 4 (Long Hoa)

Site 4 is located in Compartment 17 near the estuary of Dong Tranh River. There was erosion of 29.6 ha between 1973 and 1989, which was compensated by

Table 1 Erosion and accretion (ha) in Site 1

Site 1	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Zone 1					
Erosion	−0.2	−0.1	−0.9	−0.3	
Accretion	+3.5	+7.6	+4.5	+1.2	+8.5
Con Ba					
Erosion	−0.1	−0.1	−0.1		
Accretion	+1.8	+1.9	+1.9	+5.7	+6.5
Net	+5.0	+9.3	+5.4	+6.6	+15.0

Net gain of ~41 ha from 1953−2010

Table 2 Erosion and accretion (ha) in Site 2

Site 2	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−3.8		−46.9		
Accretion	+122.0	+48.4		+48.1	+26.0
Net	+118.2	+48.4	−46.9	+48.1	+26.0

Net gain of ~194 ha from 1953−2010

Figure 3 Natural regeneration of *Avicennia alba* in accretion area

Figure 4 Accreting shoreline with newly established seedlings

progressive accretion from 1953–1973 (32.3–47.0 ha) and from 1989–2010 (14.2–19.7 ha) (Table 4). Being upstream of the estuary of Dong Tranh and partly sheltered by Cape Mui, the site has a mildly accreting shoreline with a net gain of ~82 ha or 1.4 ha/yr from 1953–2010. Site 4 can be categorised as stable with low crops of *A. alba* trees (Figure 6).

4.5 Site 5 (Long Hoa)

Site 5 is located at Cape Mui of Dong Tranh estuary, which borders the East Sea. As such, it is most susceptible to strong waves, coastal storms and typhoons. Severe erosion which led to a loss of 1,787 ha or 148 ha/yr occurred between 1953 and 1965 (Table 5). From 1973–1989, there was a further loss of another 92.7 ha or 5.8 ha/yr. Although there was some mild accretion from 1953–2010, the net loss of ~1,730 ha or 30.4 ha/yr was substantial. The shoreline of Site 5, with only remnant mangroves left and with extensive deposition of sand cheniers, can be categorised as severely eroding. Local government authorities have constructed concrete groins and rock dykes to arrest the erosion (Figure 7) and to protect the livelihood of the coastal communities of Long Hoa living nearby.

4.6 Site 6 (Long Hoa)

Site 6 is located in Compartment 18 at the estuary of Nga Bay River. The site lost 137 ha or 11.4 ha/yr from 1953–1965 and 51.6 ha or 4.0 ha/yr from 1997–2010 (Table 6). Although there was some mild accretion ranging from 0.7–16.9 ha between 1965 and 2010, the site had a net loss of ~220 ha from 1953–2010. Site 6 can be categorised as eroding (Figure 8).

4.7 Site 7 (Can Thanh)

Site 7 is located in Can Thanh at the seaward side of the East Sea. Significant erosion which led to a loss of 1,543 ha or 129 ha/yr occurred from 1953–1965 (Table 7). Since then, there was a balance between erosion and accretion. Overall, Site 7 suffered a net loss of ~1,470 ha from 1953–2010. It is severely eroding, and local government authorities have constructed concrete groins and rock dykes (Figure 9) to protect the shore and to slow down the erosion by trapping sand sediments.

4.8 Site 8 (Can Thanh)

Site 8 is located in Compartment 22 at the estuary of Nga Bay River. Like other sites, severe erosion occurred from 1953–1965 which led to a loss of 161 ha or 13.5 ha/yr (Table 8). From then on, there was erosion during the remaining four periods from 1965–2010, ranging from 0.8–46.3 ha. No accretion was observed from 1989–2010. Site 8, which had a net loss of ~232 ha or 4.1 ha/yr from 1953–2010, can be categorised as eroding. Ships navigating the area may contribute to the erosion (Figure 10).

4.9 Site 9 (Thanh An)

Site 9 is located in Compartment 19 at the estuary of Nga Bay River. The area experienced minimal erosion

Table 3 Erosion and accretion (ha) in Site 3

Site 3	1953 –1965	1965 –1973	1973 –1989	1989 –1997	1997 –2010
Erosion	−609	−8.1	−166	−24.4	−21.7
Accretion		+136.0		+38.6	+69.7
Net	−609	+127.9	−166	+14.2	+48.0

Net loss of ~585 ha from 1953–2010

Table 4 Erosion and accretion (ha) in Site 4

Site 4	1953 –1965	1965 –1973	1973 –1989	1989 –1997	1997 –2010
Erosion	−1.7		−29.6	−0.1	
Accretion	+32.3	+47.0		+19.7	+14.2
Net	+30.6	+47.0	−29.6	+19.6	+14.2

Net gain of ~82 ha from 1953–2010

Figure 5 Mud flat where mangroves previously existed

Figure 6 Mud flat with a low crop of *Avicennia alba* trees

and accretion from 1953–2010 (Table 9). Island 2 (3.5 ha) was formed in 1965. Overall, with a net loss of only 17 ha, Site 9 can be categorised as stable although some bank erosion is evident (Figure 11).

4.10 Site 10 (Thanh An)

Site 10 are the four islands of Thanh An at the Gulf of Ganh Rai. Like most other sites, severe erosion occurred from 1953−1965 which led to a loss of 703 ha or 58.6 ha/yr (Table 10). From 1965−2010, erosion and accretion occurred concurrently. Overall, the islands had a net loss of ~874 ha from 1953−2010. Site 10 can be categorised as eroding. Rock dykes and groins have been constructed to control coastal erosion (Figure 12).

Table 5 Erosion and accretion (ha) in Site 5

Site 5	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−1,787.0	−2.7	−92.7	−17.7	−4.6
Accretion	+4.2	+110.0	+3.5	+24.8	+33.4
Net	−1,782.8	+107.3	−89.2	+7.1	+28.8

Net loss of ~1,730 ha from 1953–2010

Table 6 Erosion and accretion (ha) in Site 6

Site 6	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−137	−2.0	−25.2	−23.5	−51.6
Accretion		+16.9	+1.0	+1.1	+0.7
Net	−137	+14.9	−24.2	−22.4	−50.9

Net loss of ~220 ha from 1953−2010

Figure 7 Concrete groins and rock dykes constructed to arrest coastal erosion

Figure 8 Erosion with collapsing banks

Table 7 Erosion and accretion (ha) in Site 7

Site 7	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−1,543	−0.8	−37.6	−7.8	−0.1
Accretion		+49.2	+4.7	+2.2	+62.9
Net	−1,543	+48.8	−32.9	−5.6	+62.8

Net loss of ~1,470 ha from 1953–2010

Table 8 Erosion and accretion (ha) in Site 8

Site 8	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−161	−0.8	−13.9	−46.3	−24.4
Accretion		+13.9	+0.7		
Net	−161	+13.1	−13.2	−46.3	−24.4

Net loss of ~232 ha from 1953−2010

Figure 9 Rock dyke installed at the foreshore for erosion control

Figure 10 Erosion caused by waves from ships and boats

Table 9 Erosion and accretion (ha) in Site 9

Site 9	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−7.1	−9.0	−0.5		−0.4
Accretion					
Net	−7.1	−9.0	−0.5		−0.4

Net loss of 17 ha from 1953−2010

Table 10 Erosion and accretion (ha) in Site 10

Site 10	1953 −1965	1965 −1973	1973 −1989	1989 −1997	1997 −2010
Erosion	−703	−32.0	−93.7	−81.5	−29.7
Accretion		+35.7	+2.4	+5.5	+22.4
Net	−703	+3.7	−91.3	−76.0	−7.3

Net loss of ~874 ha from 1953−2010

Figure 11 Eroding bank with tree roots exposed

Figure 12 Rock dyke and groin constructed for erosion control

5. Conclusion

From this study, it is possible to classify the 10 sites in Can Gio as riverine (Site 1), estuarine (Sites 2, 3, 4, 6, 8, 9 and 10), and seaward (Sites 5 and 7). Of these sites, only one site is accreting (Site 2), three sites are stable (Sites 1, 4 and 9), four sites are eroding (Sites 3, 6, 8 and 10), and two sites are severely eroding (Sites 5 and 7). It is evident that the two seaward sites are severely eroding and require protective measures. Overall, the total extent of erosion (5,126 ha or 89.9 ha/yr) far exceeded that of accretion (316 ha or 5.5 ha/yr) from 1953−2010. With climate change and sea level rise, coastal storms and typhoons will become more powerful and destructive. The problem of coastal erosion at Can Gio will inevitably be further aggravated.

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Monitoring Riverbank Erosion in Can Gio Mangroves

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1. Introduction

Four major rivers and their tributaries traverse the Can Gio mangroves before draining into the East Sea. They are Soai Rap, Dong Tranh, Nga Bay and Thi Vai (Figure 1). Together they cover an area of 22,160 ha or ~20% of the Can Gio district. These large rivers together with small ones such as Long Tau are the main shipping lanes, enabling cargo tankers and ships of up to 20,000 tonnes carrying capacity to enter into the port of Ho Chi Minh City (HCMC) (Luong, 2011).

The Steering Committee for Flood and Storms (SCFS) of HCMC has identified 36 areas with high risk of erosion (SCFS, 2010). They included the districts of Binh Thanh, Nha Be and Can Gio. In Can Gio district, vulnerable areas are the riverbanks of Nha Be, Nga Bay, Long Tau and Soai Rap. Passing tankers and ships create water disturbance in the form of primary and secondary waves (also known as wash). These waves would scour the riverbanks causing erosion in the form of bank collapse and toppling of mangrove trees.

In addition to riverbank erosion, coastal areas bordering the East Sea are subjected to severe coastal erosion. With climate change such as sea-level rise and extreme weather conditions such as coastal storms and typhoons, the problem of coastal erosion would be further aggravated.

Erosion in Can Gio mangroves is more extensive than accretion. The problem of riverbank and coastal erosion needs to be addressed as it leads to loss of land and human property. This study on the monitoring of riverbank erosion in Can Gio is aimed at providing information on the severity of erosion along the banks of selected rivers, which will be made available to decision makers, planners and resource managers.

2. Materials and Methods

Satellite imageries and maps from previous years of Can Gio were collected for data analysis. The rivers studied were Dua, Nga Bay, Long Tau and Tac Roi (Figure 1). In the field, bamboo stakes were piled into the ground as markers to monitor the rate of bank erosion along the banks of studied rivers. The distance between stakes was 100 m along the riverbank and at each location, two stakes were piled (Figure 2). The first stake was 2 m and the second stake was 20 m from the riverbank. The total length of the four studied rivers was 78 km with 780 numbered stakes. Using GPS to determine coordinates, the positions of the stakes along the riverbanks were recorded. Monitoring was done annually with missing stakes replaced and their positions recorded.

Figure 1 Major rivers of Can Gio mangroves and rivers where riverbank erosion was monitored

Estuaries of major rivers
(a: Soai Rap, b: Dong Tranh, c: Nga Bay and d: Thi Vai)

Study sites
(1: Dua, 2: Nga Bay, 3: Long Tau and 4: Tac Roi)

Along the eroding riverbanks, 10 x 10 m plots were set up in four different habitat types. They were mixed natural forests, *Rhizophora* plantations, *Nypa* forests and bare land. In each habitat type, three plots were established, and enumerations and measurements were made every three months for two years.

The data were processed using GPS to determine the coordinates of the plots and stakes, which were transferred onto digital maps *via* MapSource Version 5.7 program and MapInfo 7.5.

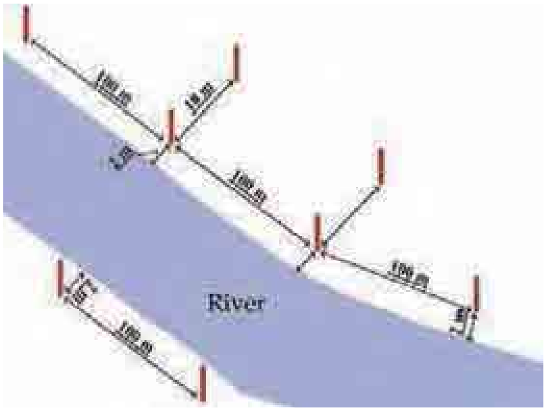

Figure 2 Positions of bamboo stakes piled along the riverbank to monitor erosion

The following procedures described by Minh *et al.* (2002) and Hirose *et al.* (2004) were used to interpret satellite images of mangrove vegetation. Satellite images of Landsat MSS 1972 (http://glcf.umiacs.umd.edu) and Spot Image 2006 (http://imar.usf.edu) were interpreted using the ENVI 4.0 program (Figure 3). Using the MapInfo program, the coordinates of rivers and plots in the studied sites were digitized. The average rate of erosion between two periods was calculated using the following formulae:

Average rate of erosion (E) = Wr/(time interval from 1972–2006)

Wr = (SR2 – SR1)/(Lr x 2)

Wr: average width eroded away on both sides of the river
SR1: area of the river in 1972
SR2: area of the river in 2006
Lr: length of river

3. Results and Discussion

A total of 780 bamboo stakes were piled along the riverbanks in 17 locations (including two communes of An Hua and An Phouc) of 12 forest compartments

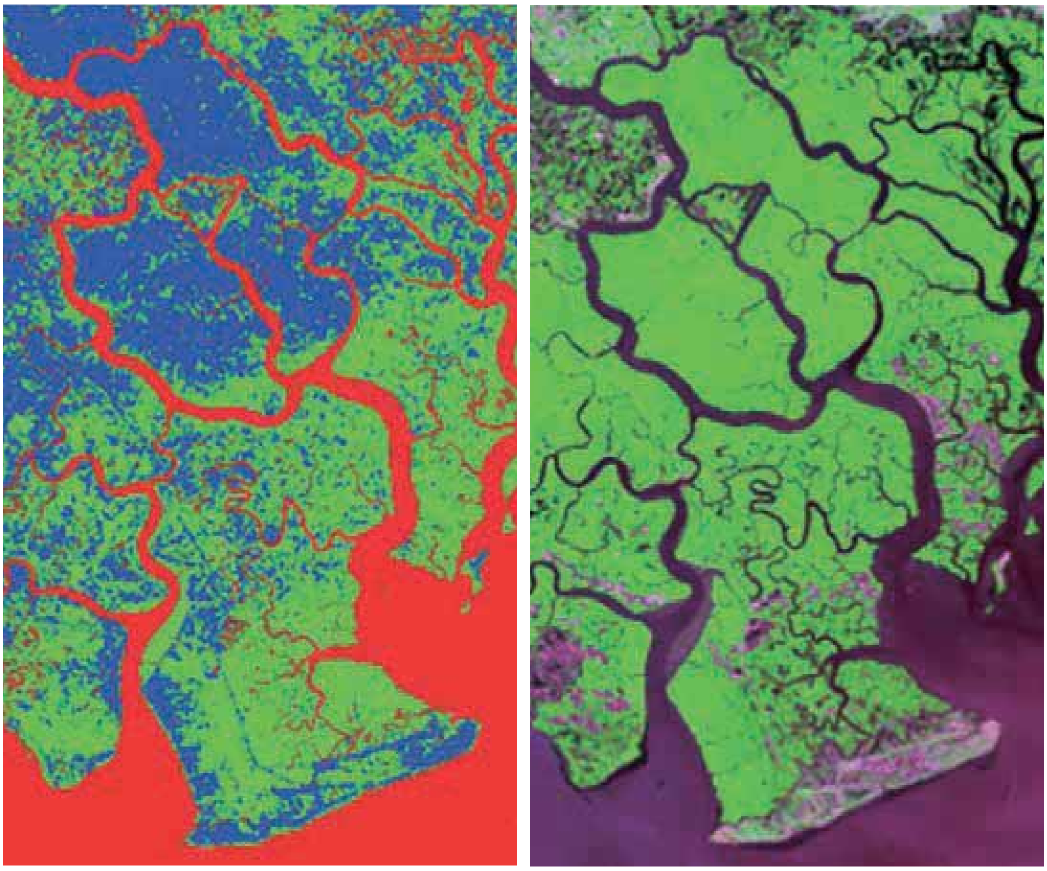

Figure 3 Landsat MSS 1972 (left) and Spot Image 2006 (right) analysed using the ENVI 4.0 program

(Table 1). Long Tau and Nga Bay rivers had the most number of stakes as they are two major waterways used by cargo tankers and ships to reach the port of HCMC (Figure 4). Dua and Tac Roi rivers are smaller rivers used mainly by passenger speedboats commuting between Vung Tau and HCMC.

Table 1 Number and location of bamboo stakes along the studied riverbanks

Forest Compartment	Rivers				Total
	Dua	Long Tau	Nga Bay	Tac Roi	
3	62		4		66
7			44		44
11		11			11
12		41			41
13		8	85		93
18			38		38
19			55		55
24		63			63
10a		36			36
4a		75			75
4b	24				24
5a		18			18
5b		29			29
6a		41			41
6b	39	49			88
An Hoa				35	35
An Phuoc				23	23
Total	125	371	226	58	780

Figure 4 Cargo ships (top) and passenger speedboat (bottom) using the Can Gio rivers

Results showed that Long Tau (1.73 ± 0.47 m/yr) and Nga Bay (1.87 ± 0.40 m/yr) experienced higher rates of erosion than Dua (1.43 ± 0.36 m/yr) and Tac Roi (1.44 ± 0.36 m/yr). However, the differences in erosion rates were not significantly different at 95% confidence level between rivers (Table 2). This implied that larger rivers used by tankers and ships had comparable erosion rates as smaller rivers used by boats. Within rivers, the differences in values were also insignificant. The only exception was in Nga Bay where the erosion rate of FC7 (2.32 ± 0.27 m/yr) was significantly greater than FC3 (1.51 ± 0.26 m/yr).

Table 2 Erosion rates of riverbanks

Location	Rate of erosion (m/yr)			
	Dua	Long Tau	Nga Bay	Tac Roi
FC3	1.42 ± 0.35		1.51 ± 0.26	
FC7			2.32 ± 0.37	
FC11		2.16 ± 0.51		
FC12		1.88 ± 0.42		
FC13		2.01 ± 0.40	1.72 ± 0.28	
FC18			1.73 ± 0.32	
FC19			2.06 ± 0.37	
FC24		1.84 ± 0.42		
FC10a		1.95 ± 0.38		
FC4a		1.44 ± 0.37		
FC4b	1.35 ± 0.26			
FC5a		1.88 ± 0.31		
FC5b		1.58 ± 0.57		
FC6a		1.58 ± 0.48		
FC6b	1.52 ± 0.42	1.73 ± 0.44		
An Hoa				1.36 ± 0.33
An Phuoc				1.53 ± 0.39
Erosion	1.43 ± 0.36[a]	1.73 ± 0.47[a]	1.87 ± 0.40[a]	1.44 ± 0.36[a]

FC: forest compartment, Same letters in superscript indicate non-significant difference at 95% confidence level

Data showed that the erosion rates of plots with forests were less severe than plots located on bare land (Table 3). Examples of erosion of riverbanks with and without vegetation are shown in Figure 5.

The data on erosion rates obtained from the bamboo stakes from December 1970 to November 2009 were compared between habitat types (plantations, natural forests and bare land), and between the rainy season of May to November and the dry season of December to April (Table 4).

Between habitat types, the rate of erosion was 1.6 m/yr for plantations and natural forests compared to 1.8 m/yr for bare land. This finding was consistent with the results obtained from the vegetation plots.

Between seasons, the erosion rate during the rainy season (1.00 ± 0.02 m/yr) was significantly higher

Figure 5 Erosion of riverbanks without vegetation (top) and with vegetation (bottom)

Table 3 Erosion rates of plots in different habitats

Plot	Habitat type	Dominant vegetation	N/ha	$D_{1.3}$ (cm)	H_{total} (m)	Erosion (m/yr)
B1	Bare	Grasses				1.3
B2	land					2.6
B3						1.7
NP1	*Nypa*	*Nypa*				1.7
NP2	forest					1.3
NP3						1.3
MF1	Man-made	*Rhizophora*	3,300	6.0	5.5	1.2
MF2	forest		2,100	7.0	7.5	1.3
MF3			2,500	14.0	13.0	1.8
NF1	Natural	*Avicennia*	1,900	0.3	1.0	2.2
NF2	forest	*Ceriops*	6,000	3.5	5.5	1.6
NF3		*Avicennia*	2,500	6.2	13.0	1.8

B: Bare land, NP: *Nypa* palm, MF: Man-made forest and NF: Natural forest

than during the dry erosion (0.71 ± 0.02 m/yr) at the 95% confidence level. The greater rate of erosion during the rainy season may be attributed to rainfall which loosens the soil particles making them more vulnerable to erosion by waves. A comparison was also made between both banks of the rivers (Table 5). Overall, there was no significant difference between the right bank (1.69 ± 0.38 m/yr) and the left bank (1.60 ± 0.36 m/yr).

Table 4 Level of erosion in the forest types

Habitat type	Dec 07 - Apr 08	May 08 - Nov 08	Dec 08 - Apr 09	May 09 - Nov 09	Erosion (m/yr)
I. Plantations					
- *R. apiculata*	0.3	1.3	0.8	1.0	1.7
- *Eucalyptus*	0.3	0.7	0.4	1.0	1.2
- *R. mucronata*	0.1	1.5	0.9	0.8	1.7
- *Acacia*	0.0	1.7	0.7	1.2	1.8
II. Natural forests					
- *Rhizophora*	0.4	1.4	0.8	1.3	2.0
- *Sonneratia*	0.2	1.0	0.7	0.7	1.3
- Shrub	0.1	1.5	0.7	1.3	1.8
- *Phoenix*	0.0	0.9	0.3	1.4	1.3
- *Ceriops*	0.3	1.2	0.9	1.1	1.7
- *Avicennia*	0.2	0.7	0.8	0.7	1.2
- *Excoecaria*	0.4	1.0	0.7	1.3	1.7
- *Nypa*	0.1	1.2	0.6	1.3	1.6
- Mixed forest	0.2	1.3	0.7	1.2	1.7
III. Bare land					
- *Rhizophora*	0.3	0.5	0.7	1.4	1.5
- *Avicennia*	0.2	0.9	1.3	1.2	1.8
- *Xylocarpus*	0.0	1.2	0.6	0.7	1.3
- *Nypa*	0.2	1.5	0.8	1.1	1.7
- *Eucalyptus*	0.3	1.9	0.2	2.4	2.4
- *Phoenix*	0.2	0.5	0.0	1.4	1.1
- Mixed	0.4	1.2	0.7	1.3	1.8

Table 5 Erosion on the right and left banks of the rivers

River	Right bank		Left bank	
	Location	Erosion(m/yr)	Location	Erosion(m/yr)
Dua	3	1.42 ± 0.35	4b	1.35 ± 0.27
			6b	1.52 ± 0.44
Long Tau	4a	1.44 ± 0.37	10a	1.95 ± 0.38
	6a	1.58 ± 0.48	5a	1.88 ± 0.31
	24	1.85 ± 0.42	5b	1.58 ± 0.57
			11	2.16 ± 0.51
			12	1.89 ± 0.42
Nga Bay	7	2.32 ± 0.37	13	1.74 ± 0.30
	19	2.06 ± 0.37	18	1.73 ± 0.32
Tac Roi	An Phuoc	1.53 ± 0.39	An Hoa	1.36 ± 0.33
Average		1.69 ± 0.38[a]		1.60 ± 0.36[a]

Same letters in superscript indicate non-significant difference at 95% confidence level

4. Conclusion

The average erosion of the four rivers studied was 1.7 m/yr. This would imply that Can Gio mangrove forests are losing ~133,500 m^2/yr of land to erosion. The presence of trees along the rivers has a positive effect in limiting riverbank erosion as forested areas tend to erode at lower rates than bare soils. There is greater erosion during the rainy season than during the dry season. The effects of waves generated by cargo tankers and ships, and passenger boats warrant further investigations.

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Monitoring Natural Regeneration in a Dead *Rhizophora apiculata* Site in Can Gio Mangroves

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1. Introduction

After the war (1965–1969), which almost destroyed all mangrove forests in Can Gio, a massive mangrove reforestation program was undertaken by the HCMC Forestry Department. Some 20,000 ha were planted with *Rhizophora apiculata*. Most of the forests are now more than 20 years of age, with the oldest forest being 35 years old. In recent years, some patches of dead trees such as those in Compartment 20 were observed. The compartment forms part of the buffer zone of the Can Gio Mangrove Biosphere Reserve.

A dead site (29 ha) in Compartment 20 was selected for study (Figure 1). The density, species composition and rate of natural regeneration were monitored annually from 2007–2009. Measurements were made on soil and water salinity and pH, topography and tidal range. The objectives of the study were to understand the processes of natural succession and the rate of recovery, and to propose silvicultural treatment to promote natural regeneration.

2. Materials and Methods

In 2007, nine study plots (25 x 20 m each) were established in the dead site with another three control plots (10 x 10 m each) in the adjacent forest planted in 1994 (Figure 2). The layout of the plots is shown in Figure 3. The total plot area in the dead site was 0.45 ha or 5% of the total area of 9.0 ha.

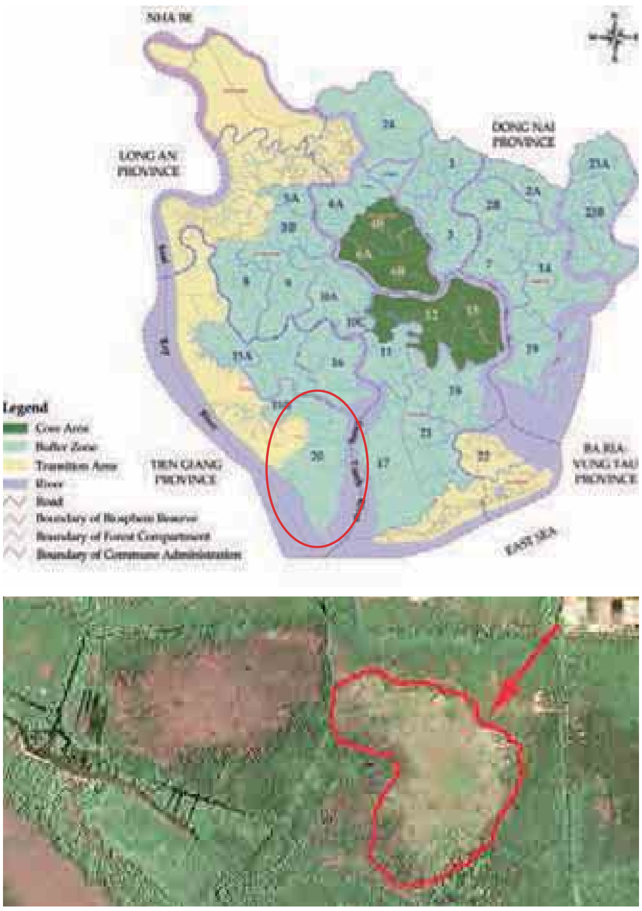

Figure 1 Location of the dead site (arrow) in Compartment 20 (circle) of Can Gio

Figure 2 The dead site (top) and adjacent forest (bottom)

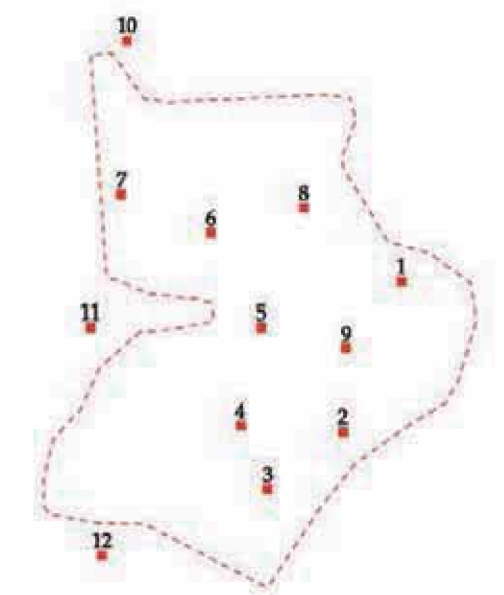

Figure 3 Location of the study and control plots

The study plots were cleared of all dead trees. Natural regenerating species were identified, enumerated, and their diameter at the base and top height measured. Trees in the control plots were tagged, identified, enumerated, and their diameter at the base (D_{base}) and at breast height of 1.3 m ($D_{1.3}$) and their top height (H_{top}) measured.

Environmental parameters monitored included topography, inundation, and soil and water salinity and pH (Figure 4). Data collected were processed and analysed using Excel and Statgraphics 5.1.

Figure 4 Sampling soil (left) and measuring water pH (right)

3. Results and Discussion

The topography of the study site had a slight depression in the central portion. A cross section diagram showed that the lowest elevation at 221 m was 1 m above sea level (asl) (Figure 5). The surrounding forest area was 3.7 m asl and inundated only during monthly spring tides. Due to this topographic feature,

Figure 5 Cross-sectional topography of the study site

the central portion of the study site was permanently submerged during high tide especially in the rainy season (Figure 6). The root systems of mangrove vegetation were submerged at an average of 5.4 cm depth and the water surface was covered with a layer of algae. Due to poor drainage, permanent pools of stagnant water were formed even during the low tide. This caused trees to die of suffocation with their root systems under prolonged water submergence. Mass mortality of trees occurred as standing dead stems.

Figure 6 Permanent water-logging (top) and a layer of algae covered the water surface (bottom)

Soil samples showed low salinity of 3–5 ppt and pH of 6–7. Water samples had salinity of 10–20 ppt and alkaline pH of 8.5–9.5. Highest water salinity of 20 ppt was recorded during the dry season.

In 2007, a vegetation survey of the study plots showed poor natural regeneration ranging from 5–29 seedlings (Table 1). Plots with the most number of seedlings were dominated by single species. Plot 2 with 29 seedlings and Plot 5 with 22 seedlings comprised solely of *Lumnitzera racemosa* and *Ceriops tagal*, respectively. *Avicennia marina* was the main species in Plot 7. Overall, *L. racemosa* (60 seedlings) was the most common species, followed by *C. tagal* (32 seedlings) and *A. marina* (31 seedlings). Only six seedlings of *Excoecaria agallocha* were recorded in Plots 3 and 4. Photographs of these four species are shown in Figure 7.

Table 1 Vegetation survey of the study plots in 2007

Plot number	Number of individuals				Total
	Am	*Lr*	*Ct*	*Ea*	
1	5	1	3	0	9
2	0	29	0	0	29
3	0	0	0	5	5
4	0	6	0	1	7
5	0	0	22	0	22
6	0	17	1	0	18
7	18	6	0	0	24
8	8	0	1	0	9
9	0	1	5	0	6
Total	31	60	32	6	129

Am: *Avicennia marina*, *Lr*: *Lumnitzera racemosa*, *Ct*: *Ceriops tagal* and *Ea*: *Excoecaria agaloocha*

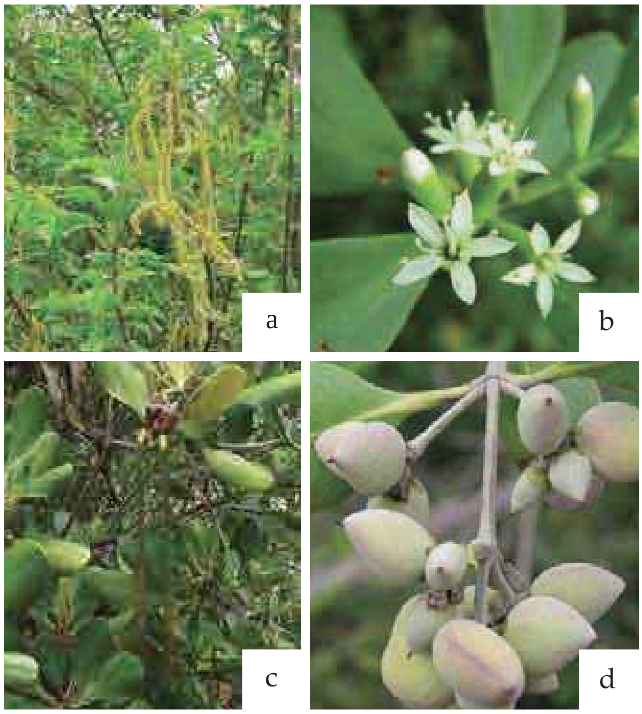

Figure 7 Flowers of *Excoecaria agallocha* (a), flowers of *Lumnitzera racemosa* (b), propagules of *Ceriops tagal* (c) and propagules of *Avicennia marina* (d)

In comparison, a survey of the control plots in the adjacent forest showed numbers ranging from 70 trees (Plot 11) to 110 trees (Plots 10 and 12), indicating densities of 7,000 and 11,000 trees/ha (Table 2). The average dbh and top height ranged from 5.2–8.7 cm and 5.3–15 m, respectively. Based on diameter and height growth of the original seedlings in the study plots, *L. racemosa* and *A. marina* are the two best performing species (Table 3). In 2009, their D_{base} and H_{top} were 3.48 cm and 0.81 m for *L. racemosa*, and 3.78 cm and 1.29 m for *A. marina*, respectively. Their survival rates were 87% and 94% after two years of growth, compared to *C. tagal* (41%) and *E. agallocha* (17%).

Recruitment of new seedlings was enumerated in the study plots (Table 4). Plots 1, 7 and 8 showed very good recruitment of *A. marina* exceeding 10,000 seedlings since 2008 (Figure 8). This could be due to its prolific fruiting, and its small and buoyant propagules, which can be easily dispersed by the tide. The remaining plots had comparatively poor recruitment ranging from three seedlings in Plot 3 to 116 seedlings in Plot 4. Seedlings of *A. marina* were represented in all plots while *L. racemosa* was found in all plots except Plots 3 and 8. Few seedlings of *C. tagal* and *E. agallocha* represented in five and two plots, respectively, had high mortality rates.

Table 2 Vegetation survey of the *Rhizophora apiculata* control plots in 2007

Plot number	N	$D_{1.3}$ (cm)	H_{top} (m)
10	110	5.2	5.3
11	70	8.7	15.0
12	110	5.2	6.1

N: number of individuals, $D_{1.3}$: diameter at breast height of 1.3 m and H_{top}: top height

Table 3 Survival rate, and diameter and height growth of original seedlings in the study plots

Species*	2007			2008			2009		
	D_{base}	H_{top}	N	D_{base}	H_{top}	N	D_{base}	H_{top}	N**
Lr	1.43	0.38	60	2.16	0.63	57	3.48	0.81	52
Am	0.98	0.55	31	2.70	0.81	29	3.78	1.29	29
Ct	1.30	0.41	32	1.25	0.47	15	1.73	0.54	13
Ea	1.29	0.22	6	1.72	0.27	6	1.45	0.70	1

* *Lr*: *Lumnitzera racemosa*, *Am*: *Avicennia marina*, *Ct*: *Ceriops tagal* and *Ea*: *Excoecaria agaloocha*
** D_{base}: diameter at the base (cm), H_{top}: top height (m) and N: number of individuals

Figure 8 A study plot with good seedling recruitment of *Avicennia marina*

Table 4 Number of new seedlings in the study plots

Plot number	Species	Number of new seedlings		
		2007	2008	2009
1	*L. racemosa*	3	8	15
	C. tagal	3	7	0
	A. marina	5	> 10,000	> 10,000
2	*L. racemosa*	28	34	58
	A. marina	0	4	4
3	*E. agallocha*	5	5	2
	A. marina	0	1	1
4	*L. racemosa*	45	48	71
	E. agallocha	2	2	0
	A. marina	0	28	45
5	*L. racemosa*	2	3	15
	C. tagal	14	18	18
	A. marina	0	5	31
6	*L. racemosa*	17	21	34
	C. tagal	1	1	0
	A. marina	0	7	29
7	*L. racemosa*	4	8	7
	A. marina	18	> 10,000	> 10,000
8	*A. marina*	11	> 10,000	> 10,000
	C. tagal	51	5	2
9	*L. racemosa*	1	0	14
	C. tagal	5	0	0
	A. marina	0	7	27

L.: *Lumnitzera*, *A.*: *Avicennia*, *C.*: *Ceriops* and *E.*: *Excoecaria*

5. Conclusion

The likely cause of the death of *R. apiculata* trees in the study plots is suffocation of rooting systems caused by prolonged submergence. Because of the lower topographic elevation in the central portion compared to the surrounding forest area, drainage is poor and a permanent pool of stagnant water is formed. Water in the area has an alkaline pH and a surface layer of algae. Whether this contributes to the tree mortality remains unclear.

Seedlings of *A. marina* and *L. racemosa* in the study plots showed good growth and regeneration, and had high survival rates. They are the two species recommended for silvicultural treatment. Currently, a canal system has been constructed in the site to facilitate drainage and to promote natural regeneration. Its cost-effectiveness need to be evaluated. In terms of rehabilitation, localities with high seedling densities especially *A. marina* should be thinned by extracting seedlings and transferring them to localities with poor regeneration. Collection of propagules from the adjacent forest for planting may also be practical.

Effects of Thinning on CO_2 Absorption Capacity of *Rhizophora apiculata* Plantations in Can Gio Mangroves

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1. Introduction

Can Gio, a suburban district of Ho Chi Minh City (HCMC), was designated a Mangrove Biosphere Reserve (MBR) in 2000 (HCMC People's Committee, 2012). Of the forested area (31,773 ha), 60% are planted forests and 40% are natural forests. The Can Gio MBR comprises 24 forest compartments. *Rhizophora apiculata* is the main species planted (Nam *et al*., 2003). The mangrove plantations play an important role in providing useful products (e.g. fuel wood and construction poles), and services (e.g. coastal protection and carbon sequestration). Since 2000, thinning of trees had not carried out and some of the oldest forests are 35 years of age.

The aim of this study was to assess the effects of silvicultural thinning on the CO_2 absorption capacity of *R. apiculata* plantations in Can Gio based on different age classes and thinning intensities. Findings will provide useful information for forest managers, planners and policy makers in making sound decisions on the sustainable management and utilization of the Can Gio mangroves.

2. Materials and Methods

The study conducted in Can Gio from 2009−2011 was located at An Hoa and An Phuoc, and in forest compartments (FC) 2, 3, 6, 7, 11, 12 and 16. Four age classes of plantations were selected. They were Class IV (14−18 yr), Class III (19−23 yr), Class II (24−28 yr) and Class I (29−33 yr). For each age class, a 2 ha plot was established and divided into 4 sub-plots. Three of the sub-plots were subjected to different thinning intensities of 20% (T1), 35% (T2) and 50% (T3), and one sub-plot was retained as control. An example of a thinned sub-plot is shown in Figure 1.

In each sub-plot, all trees were enumerated, their bole diameter at 1.3 m ($D_{1.3}$) and top height (H_{top}) measured, and their yield (m^3/ha) determined. Using the allometric equation of Nam (2010), absorption of carbon dioxide (CO_2) and carbon (C) was calculated.

$$CO_2 \text{ of tree} = 0.6171*D_{1.3}^{\ 2.2896},\ CO_2 = \text{carbon}*44/12$$

Analysis of variance (ANOVA) between age classes and between treatments was conducted at 95% confidence level with $P < 0.05$.

Figure 1 Looking up from within a thinned sub-plot

3. Results and Discussion

3.1 Before Thinning

An example of a *R. apiculata* forest in Can Gio before thinning is shown in Figure 2. Trees are densely packed with small crowns.

Figure 2 *Rhizophora apiculata* trees in unthinned forests are densely packed with small crowns

a. Age class IV (14–18 yr)
At An Hoa, the average density was 5,220 trees/ha with average diameter of 7.1 cm and yield of 128 m^3/ha. CO_2 absorption was 300 t/ha at an average rate of 23.1 t/ha/yr. At An Phuoc, the average density was 6,930 trees/ha with average diameter of 5.2 cm and yield of 75.8 m^3/ha. CO_2 absorption was 202 t/ha at an average rate of 15.5 t/ha/yr. In FC 3-4, the values were 5,130 trees/ha, 6.7 cm, 107 m^3/ha, 257 t/ha and 17.2 t/ha/yr, respectively. The average values of age class IV were 5,760 trees/ha, 6.3 cm, 104 m^3/ha, 253 t/ha and 18.6 t/ha/yr.

b. Age class III (19–23 yr)
In FC 2, the average density was 4,070 trees/ha with average diameter of 9.9 cm and yield of 258 m^3/ha. CO_2 absorption was 528 t/ha at an average rate of 29.3 t/ha/yr. In FC 3-3, the average density was 5,130 trees/ha with average diameter of 6.7 cm and yield of 107 m^3/ha. CO_2 absorption was 257 t/ha at an average rate of 17.2 t/ha/yr. Values of FC 6-3 were 3,790 trees/ha, 8.5 cm, 158 m^3/ha, 341 t/ha and 19.0 t/ha/yr, respectively. The average values of age class III were 4,330 trees/ha, 8.1 cm, 174 m^3/ha, 375 t/ha and 21.8 t/ha/yr.

c. Age class II (24–28 yr)
In FC 16, the average density was 2,050 trees/ha with average diameter of 14.1 cm and yield of 302 m^3/ha. CO_2 absorption was 565 t/ha at an average rate of 22.6 t/ha/yr. In FC 3-2, the average density was 2,260 trees/ha with average diameter of 11.7 cm and yield of 207 m^3/ha. CO_2 absorption was 409 t/ha at an average rate of 15.7 t/ha/yr. Values of FC 7 were 6,900 trees/ha, 6.7 cm, 154 m^3/ha, 360 t/ha and 14.5 t/ha/yr, respectively. The average values of age class II were 3,737 trees/ha, 10.8 cm, 221 m^3/ha, 445 t/ha and 17.6 t/ha/yr.

d. Age class I (29–33 yr)
In FC 11, the average density was 1,850 trees/ha with average diameter of 12.1 cm and yield of 192 m^3/ha. CO_2 absorption was 371 t/ha at an average rate of 12.8 t/ha/yr. In FC 12, the average density was 2,120 trees/ha with average diameter of 14.6 cm and yield of 345 m^3/ha. CO_2 absorption was 640 t/ha at an average rate of 22.1 t/ha/yr. Values of FC 6-1 were 1,840 trees/ha, 15.1 cm, 324 m^3/ha, 595 t/ha and 20.5 t/ha/yr, respectively. The average values of age class I were 1,937 trees/ha, 13.9 cm, 287 m^3/ha, 535 t/ha and 18.5 t/ha/yr.

3.2 Two Years After Thinning

An example of a *R. apiculata* forest in Can Gio two years after thinning is shown in Figure 3. The positive effects of thinning are evident by trees showing healthy growth with large crowns.

Figure 3 Two years after thinning, *Rhizophora apiculata* trees are showing healthy growth with large crowns

a. Between age classes
ANOVA showed that the CO_2 absorption of age class III was highest at 39.3 t/ha/yr which is equivalent to 10.7 t/ha/yr of carbon (Table 1). Age class IV ranked second with comparable CO_2 absorption of age class III was highest at 35.3 t/ha/yr or 9.6 t/ha/yr of carbon. Values of these two age classes (III and IV) were significantly higher than those of age class II (24–28 yr) yielding 31.0 t/ha/yr of CO_2 or 8.4 t/ha/yr of carbon, and age class I (29–33 yr) yielding 30.9 t/ha/yr of CO_2 or 8.4 t/ha/yr of carbon. The result showed that silvicultural thinning operations can be applied in plantations of age class III (19–23 yr) and age class IV (14–18 yr).

Table 1 Rate of CO_2 absorption and carbon accumulation between age classes

No.	Age class	Mean increment (t/ha/yr)	
		CO_2	Carbon
1	IV (14–18 yr)	35.3	9.6[a]
2	III (19–23 yr)	39.3	10.7[a]
3	II (24–28 yr)	31.0	8.4[b]
4	I (29–33 yr)	30.9	8.4[b]

Same letters in superscript indicate non-significant difference at 95% confidence level

b. Between treatments
The rate of CO_2 absorption and carbon accumulation between thinning treatments in comparison with the control is shown in Table 2. The control had the highest carbon absorption of 42.6 t/ha/yr of CO_2 which is equivalent to 11.6 t/ha/yr of carbon. T1 (20%) yielded 35.7 t CO_2/ha/yr of CO_2 or 9.7 t/ha/yr of carbon which was comparable to that of the control.

Values of T2 (35%) which yielded 31.2 t/ha/yr of CO_2 or 8.5 t/ha/yr of carbon and T3 (50%) which yielded 27.1 t/ha/yr of CO_2 or 7.4 t/ha/yr of carbon were comparable but were significantly lower than those of the control and T1. This could be due to the greater amount of carbon removed through the more intensive thinning operations of T2 and T3.

For the purpose of the conservation of forests and the sustenance of carbon sequestration, the thinning at lower intensity (20%) is rational. This would promote faster growth of trees, and the thinning products can serve the needs of Can Gio and HCMC based on sustainable forest management.

Table 2 Rate of CO_2 absorption and carbon accumulation between treatments

No.	Treatment	Mean increment (t/ha/yr)	
		CO_2	Carbon
1	T3 (50%)	27.1	7.4^{b}
2	T2 (35%)	31.2	8.5^{b}
3	T1 (20%)	35.7	9.7^{a}
4	Control	42.6	11.6^{a}

Same letters in superscript indicate non-significant difference at 95% confidence level

4. Conclusion

From results of the study, it can be concluded that silvicultural thinning when operated in 14–18 yr and 19–23 yr *R. apiculata* plantations at an intensity of 20% is appropriate, and will not adversely affect CO_2 absorption and carbon accumulation.

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Carbon Sequestration of *Ceriops zippeliana* in Can Gio Mangroves

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1. Introduction

After the Second Indochina War, large tracts of degraded land in Can Gio, a suburban district of Ho Chi Minh City (HCMC), Viet Nam, have been reforested with mangroves (Nam *et al*., 1993). From 1978–2000, 21,100 ha of *Rhizophora apiculata*, 715 ha of *Eucalyptus* spp., 638 ha of *Ceriops* spp. and 281 ha of *Nypa fruticans* were planted. Other species planted included *Intsia bijuga*, *Thespesia populnea*, *Rhizophora mucronata*, *Avicennia alba*, *Xylocarpus granatum*, *Kandelia obovata* and *Bruguiera sexangula*.

Two species of *Ceriops* were planted. They were *Ceriops tagal* and *Ceriops zippeliana*. Formerly recognized as *Ceriops decandra*, *C. zippeliana* is native to Australia, Cambodia, Indonesia, Malaysia, Papua New Guinea, Philippines, Singapore, Thailand and Viet Nam (Duke *et al*., 2010). The species is a tree 12 m tall (Sheue *et al*., 2010). Bark is brownish with some lenticels and flaky at the base. Leaves are glossy green and oval with a rounded tip (Figure 1). Flowers are small and white. Propagules are long and pointed with fluted ridges along the length and a red collar when mature. They point upwards in all directions, unlike those of *Ceriops tagal*, which hang downwards.

Prior to 1991, these plantations provided fuel wood, poles, chip wood and other construction materials for Can Gio and HCMC. With the declaration of Can Gio mangroves as an Environmental Protection Forest in 1991 and as a Mangrove Biosphere Reserve (MBR) in 2000, there is greater focus on the environmental services of mangrove forests.

Figure 1 *Ceriops zippeliana* with oval leaves and propagules pointing in all directions

The mangrove ecosystems of Can Gio play important roles in protecting the environment of HCMC and surrounding areas. The trees provide large amounts of oxygen, absorb and store CO_2, and contribute to the reduction of greenhouse gases. The reserve is also the habitat for marine life of economic value, and is the traditional fishing grounds of local residents and fishermen. The mangroves provide protection from coastal storms and erosion. This is also an ecosystem of particular interest for development of ecotourism, environmental education and extra-curricular learning for students in HCMC and adjacent areas.

The main objective of this study was to gather scientific data and information on carbon accumulation and CO_2 absorption capacity of *C. zippeliana* plantations in Can Gio as a basis for payment of environment services, which contribute to the socio-economic development, and environmental protection of the district.

2. Materials and Methods

2.1 Study Sites

A total of 35 (10 x 10 m) plots were established in forest compartments 6, 10, 11, 12, 13, 17 and 21 of Can Gio MBR. The location of the plots is shown in Figure 2.

2.2 Field Measurements

In each plot, all trees were enumerated, and their bole diameter at 1.3 m ($D_{1.3}$) and total height (H_{total}) measured (Figure 3). To develop the allometric equations, 35 trees representing the full range of diameter classes from minimum to maximum were felled. Stems, branches and leaves were sampled to obtain their fresh weight. The felled trees were then divided into 1 m lengths to determine D_1 (first position of the tree), D_2 (second position), until D_n (n position) to calculate their volume. Wood (1 kg) and leaves (1 kg) were dried in the laboratory at 105^{o}C and 80^{o}C, respectively, to obtain their carbon content.

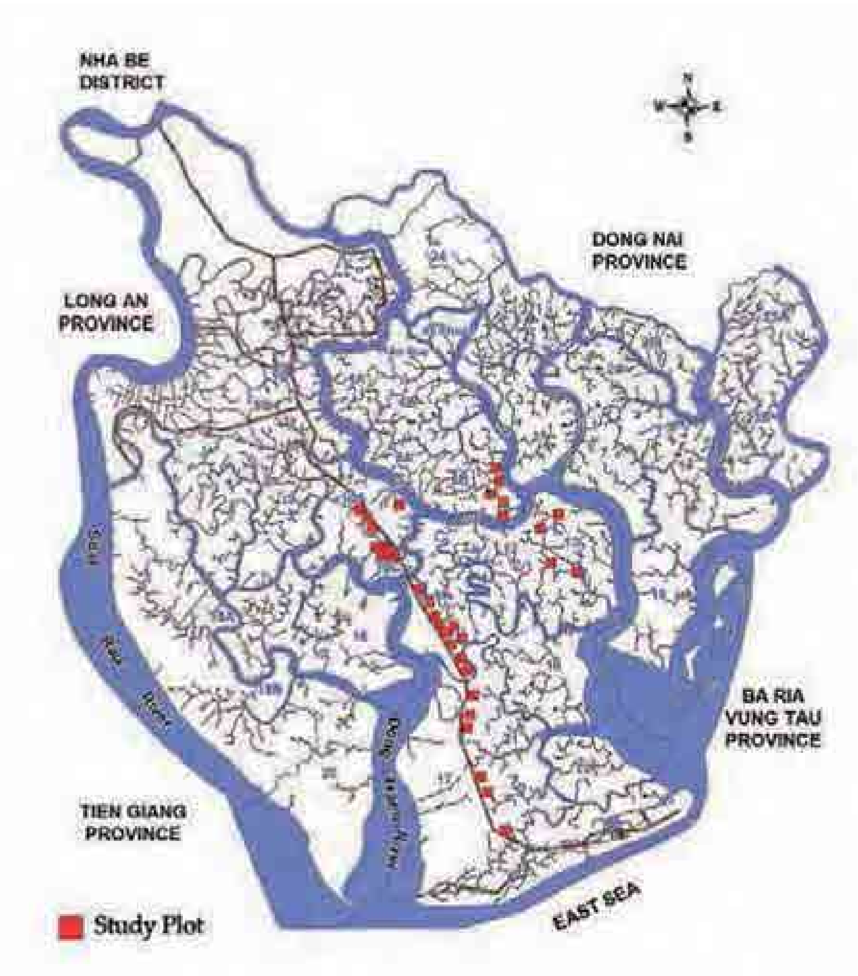

Figure 2 Location of study sites in Can Gio Mangrove Biosphere Reserve

Figure 3 Measuring total height of a felled tree (left) and sampling leaves for fresh weight (right)

2.3 Data Analysis

Carbon accumulation was calculated by multiplying the dried biomass with coefficients of 0.454 for stems, 0.480 for branches and 0.503 for leaves. From carbon accumulation, the absorption of CO_2 was calculated as CO_2 absorbed = carbon accumulation*44/12 or 1 t of carbon is equal to 3.67 t of CO_2 (Que *et al*., 2006; Duke *et al*., 2013).

3. Results and Discussions

3.1 Correlation between Fresh Biomass and $D_{1.3}$

All the equations correlating fresh biomass of different tree parts and $D_{1.3}$ (Table 1) had high correlation coefficients with R of 0.958–0.985, small standard errors (SE) of 0.185–0.297, and F-ratio values higher than those in the F-table at 95% confidence level.

3.2 Correlation between Dry Biomass and $D_{1.3}$

All the equations correlating fresh biomass of different tree parts and $D_{1.3}$ (Table 2) had R values of 0.958–0.983, small SE of 0.197–0.297, and with F-ratio values larger than those in the F table at 95%.

3.3 Correlation between Dry and Fresh Biomass

The following equation correlating dry and fresh biomass was used:

$$\ln(DW_{total}) = -0.599 + 1.018 * \ln(FW_{total})$$

$R = 0.999$; SE = 0.030

The relationship between total dry weight and the total fresh weight of trees is important. Its practical purpose is that the total fresh weight of trees measured in the field can be converted to total dry weight using the equation.

3.4 Correlation between Carbon Accumulation and $D_{1.3}$

All the equations correlating carbon accumulation in different tree parts and $D_{1.3}$ (Table 3) had *R* values of 0.957–0.982, small SE of 0.158–0.220, and with F-ratio values larger than those in the F table at 95%.

3.5 Carbon Accumulation and CO_2 Absorption

The average density of *C. zippeliana* in the plots was 13,500 ± 1,500 trees/ha with the highest density in Plot 4 with (25,700 tree/ha) and the lowest density in Plot 19 (2,600 trees/ha) (Table 4). The average $D_{1.3}$ of trees was 2.8 ± 0.2 cm with Plot 31 (4.1 cm) having the highest value and plot 24 (1.9 cm) having the lowest value. The average height of trees was 4.3 ± 0.3 m with plot 32 (5.8 m) having the tallest trees and plot 2 (2.9 m) having the shortest trees.

The amount of carbon accumulated in different tree parts was 19.2 ± 3.4 t/ha (Table 4). Ranking based on carbon accumulation was of the order: stems (10.5 ± 1.8 t/ha) > branches (4.9 ± 1.0 t/ha) > leaves (3.8 ± 0.6 t/ha).

3.6 CO_2 Absorption and Economic Value

The average CO_2 absorption capacity of *C. zippeliana* trees in Can Gio was 70.5 ± 12.3 t/ha with average density of 13,500 ± 1,500 trees/ha, average diameter of 2.8 ± 0.2 cm, and average height of 4.3 ± 0.3 m. Results showed that factors such as the diameter, height and density of trees affect the amount of carbon accumulated and consequently their CO_2 absorption capacity. With a CO_2 absorption capacity of 70.5 ± 12.3 t/ha, the value revenue from CO_2 of *C. zippeliana* forests in Can Gio MBR is worth ~USD776/ha.

Table 1 Equations of fresh biomass of different tree parts and $D_{1.3}$

Tree part	Equation of the fitted model	*R*	SE	F-ratio
Whole tree	$\ln(FW_{total}) = -0.957 + 2.366*\ln(D_{1.3})$	0.985	0.185	1038
Stems	$\ln(FW_{stem}) = -1.497 + 2.300*\ln(D_{1.3})$	0.976	0.223	673.6
Branches	$\ln(FW_{branch}) = -2.884 + 2.740*\ln(D_{1.3})$	0.971	0.297	539.2
Leaves	$\ln(FW_{leaf}) = -2.154 + 2.088*\ln(D_{1.3})$	0.958	0.273	368.4

$D_{1.3}$: bole diameter at 1.3 m height, FW: fresh weight, *R*: correlation coefficient and SE: standard error

Table 2 Equations of dry biomass of different tree parts and $D_{1.3}$

Tree part	Equation of the fitted model	*R*	SE	F-ratio
Whole tree	$\ln(DW_{total}) = -1.571 + 2.407*\ln(D_{1.3})$	0.983	0.197	938.9
Stems	$\ln(DW_{stem}) = -2.054 + 2.340*\ln(D_{1.3})$	0.971	0.253	539.9
Branches	$\ln(DW_{branch}) = -3.410 + 2.747*\ln(D_{1.3})$	0.971	0.297	540.9
Leaves	$\ln(DW_{leaf}) = -2.951 + 2.103*\ln(D_{1.3})$	0.958	0.277	364.7

$D_{1.3}$: bole diameter at 1.3 m height, DW: dry weight, *R*: correlation coefficient and SE: standard error

Table 3 Equations of carbon accumulated in different tree parts and $D_{1.3}$

Tree part	Equation of the fitted model	*R*	SE	F-ratio
Whole tree	$\ln(C_{total}) = -2.281 + 2.374*\ln(D_{1.3})$	0.982	0.158	899.6
Stem	$\ln(C_{stem}) = -2.778 + 2.290*\ln(D_{1.3})$	0.969	0.204	501.3
Branches	$\ln(C_{branch}) = -4.206 + 2.786*\ln(D_{1.3})$	0.971	0.220	536.7
Leaves	$\ln(C_{leaf}) = -3.611 + 2.086*\ln(D_{1.3})$	0.957	0.207	362.7

C: carbon, $D_{1.3}$: bole diameter at 1.3 m height, *R*: correlation coefficient and SE: standard error

Table 4 Carbon sequestration of *Ceriops zippeliana* in Can Gio

Plot number	N/ha (tree/ha)	$D_{1.3}$ (cm)	H_{total} (m)	C_{stem} (t/ha)	C_{branch} (t/ha)	C_{leaf} (t/ha)	C_{total} (t/ha)	Total CO_2 (t/ha)
1	7,800	2.1	3.7	2.9	1.1	1.2	5.2	19.1
2	8,200	2.2	2.9	3.8	1.5	1.5	6.8	25.1
3	13,100	2.3	3.2	6.0	2.4	2.4	10.8	39.5
4	25,700	2.9	5.1	19.9	8.7	7.5	36.2	133.0
5	8,400	2.0	3.4	2.8	1.0	1.1	5.0	18.3
6	12,000	2.0	3.5	4.0	1.4	1.6	6.9	25.4
7	12,200	2.1	3.6	5.1	2.1	2.0	9.2	33.7
8	13,500	3.0	4.1	13.2	6.6	4.7	24.4	89.6
9	14,500	2.8	4.1	11.4	5.1	4.3	20.8	76.2
10	9,500	3.3	4.3	12.1	6.3	4.2	22.7	83.2
11	11,500	3.2	4.3	11.8	5.5	4.3	21.6	79.2
12	13,900	2.8	4.1	10.9	4.9	4.1	19.8	72.7
13	11,600	3.0	4.2	10.4	4.9	3.8	19.2	70.3
14	9,100	3.2	4.3	9.4	4.5	3.4	17.3	63.3
15	13,400	2.5	3.9	7.8	3.2	3.0	13.9	51.1
16	18,400	2.3	3.7	8.0	3.1	3.2	14.3	52.3
17	21,000	2.9	4.2	17.0	7.6	6.3	30.9	114
18	18,900	3.1	4.2	18.0	8.4	6.6	33.0	121
19	2,600	3.8	4.7	3.9	2.0	1.4	7.3	26.7
20	12,000	2.6	3.9	8.1	3.5	3.1	14.6	53.7
21	12,100	3.1	4.3	11.0	5.0	4.1	20.1	73.8
22	18,400	2.3	3.8	9.2	3.7	3.6	16.5	60.5
23	13,400	2.3	3.7	6.1	2.4	2.4	10.9	40.0
24	15,700	1.9	3.3	4.6	1.6	1.8	8.0	29.4
25	10,500	2.5	3.8	6.2	2.7	2.4	11.3	41.4
26	10,200	3.4	5.4	12.2	6.2	4.3	22.7	83.4
27	16,600	2.8	5.1	13.0	5.8	4.9	23.7	86.8
28	13,500	3.5	5.2	15.7	7.3	5.8	28.8	106
29	10,600	3.5	5.2	12.4	5.8	4.6	22.9	83.9
30	17,900	2.6	4.3	18.6	13.6	3.9	36.1	133
31	15,000	4.1	5.7	25.3	12.7	9.1	47.0	173
32	14,400	3.0	5.8	11.9	5.1	4.5	21.5	79.0
33	15,700	2.6	4.8	10.0	4.1	3.9	18.0	66.0
34	15,500	2.9	4.9	11.8	5.1	4.5	21.4	78.4
35	15,300	3.0	5.6	13.3	5.9	5.0	24.1	88.6
Average	13,500 ± 1,500	2.8 ± 0.2	4.3 ± 0.3	10.5 ± 1.8	4.9 ± 1.0	3.8 ± 0.6	19.2 ± 3.4	70.5 ± 12.3

4. Conclusion

The average density of *C. zippeliana* forest in Can Gio was 13,500 ± 1,500 trees/ha, average $D_{1.3}$ was 2.8 ± 0.2 cm, and average height was 4.3 ± 0.3 m, the average carbon accumulation was 19.2 ± 3.4 t/ha. Carbon accumulation was highest in stems (10.5 ± 1.8 t/ha) followed by branches (4.9 ± 1.0 t/ha) and leaves (3.8 ± 0.6 t/ha). Forest structures such as the diameter, height and density of trees affect their ability to accumulate carbon and sequester CO_2. The capacity to absorb CO_2 of *C. zippeliana* forests in Can Gio is 70.5 ± 12.3 t/ha, valued at ~USD776/ha.

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Mangrove and Human Interactions: A Case Study of Can Gio Mangrove Forests and the Surroundings

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1. Introduction

Mangroves are plant communities distributed in the upper inter-tidal coastal zone of tropics and subtropics. Surrounding Ho Chi Minh City (HCMC) in southern Vietnam is the downstream basin of the Mekong, Saigon and Dong Nai rivers, and the low-lying ground spreads to the south of the city. Mangroves (~32,000 ha) occur in the Can Gio district, southeast of the city. The maximal tidal range of this area is approximately 4 m. Even where there is no forest, *Rhizophora apiculata* and *Sonneratia caseolaris* can be seen growing in ponds of the residential areas in the outskirts of the city. The palm (*Nypa fruticans*) grows gregariously along river waterways and channels used by residents.

Many mangrove areas have become secondary forests (Komiyama, 1992) that have long been used by local coastal residents. It is said that the relationship between coastal residents and mangroves is similar to that of the well-documented "Satoyama" relationship between the people and the rural environment in Japan (Miyagi *et al.*, 2003).

In recent years, large areas of mangroves have been destroyed due to conversion for aquaculture ponds, urbanization, port construction and other development. Conversely, conservation measures and planting activities are being carried out in various places. Thus mangrove forests have been subjected to human-related pressures that vary in degree and type.

As the landscape and the role of Satoyama in Japan has changed, mangroves and their natural environment could also be altered by socio-economic development, development of infrastructures, and changes in people's values and lifestyles. If so, in order to assess the human impact on mangroves, the study should cover not only areas where the mangrove forests exist but also extend to their surrounding areas where various human activities occur.

According to Ajiki and Miyagi (1992), the relationship between mangrove use and its destruction depends on human activities both inside and outside of the forests, which have direct and indirect impacts. This rare study captured the effects of socio-economic change on mangrove forests and their surrounding areas.

I hypothesize that mangroves and humans are mutually interacting at the zone of overlap that exists between marine, mangrove and terrestrial areas. Thus, a human-mangrove overlap area is set as one area (hereafter referred as the human-mangrove area) composed of organized elements. By identifying the interrelationship between the elements and their regional structure, I intend to understand the human-mangrove relationship in HCMC and its surrounding areas.

To understand the interaction between humans and mangroves, a preliminary empirical field survey was conducted around HCMC. Six villages outside of the mangrove forests were selected for study, and the use of water channels by villagers was surveyed and analyzed. The survey also focused on the Can Gio mangrove forests and their surrounding areas. In the study, the following two questions were addressed: 1) Do human activities, outside of mangrove forests, influence the mangrove environment? 2) What are suitable indicators to understand the human-mangrove connection? This paper reports the first outcome of the case study.

2. Materials and Methods

The relationship between the mangrove environment and the use of water channels was investigated in the human-mangrove overlap areas at the village level. Topographic maps (1:100,000) produced in 1967 by the US Military were used to locate water channels, main roads, villages and mangrove forests in the vicinity of HCMC and a GIS database was produced. For map production and analysis, the ESRI Japan ArcGIS 10.1 software was used. Further, 100 m buffer zones from the water channels and the main roads were created and villages were mapped by proximity analysis and classified into the following four types: i) near channel, ii) not near channel or road, iii) near channel and road, and iv) near road.

From the data obtained by the GIS analysis, based on the distance between village and water channels, and the shape of the channels, six villages (Phuoc Kieng, Hiep Phuoc, Huu Thanh, My Loc, My Hanh Nam, Cai Be) from the outside of the Can Gio mangrove forests were selected for study. The location of the six villages in relation to HCMC and Can Gio mangrove forests is shown in Figure 1.

An evaluation sheet was prepared categorizing elements related to the use of water channels as human activity and mangrove environmental characteristic such as vegetation, environment and topography. Information on the channel use in the Mekong river basin and the mangrove environment were organized based on available references (Kikuchi, 1966; Takada, 1998; Miyagi *et al.*, 2003; Haruyama, 2009).

Categories evaluated for the water channel use were drainage, irrigation, movement, transportation, production and livelihood, and for the mangrove environment use were delta, tide, and mangrove plants. A field survey was conducted to score each element. The scoring system was as follows: 2 points when the elements fit, 1 point when the conditions are not known or unclear and 0 point when the elements do not fit.

3. Results and Discussion

Figure 2 shows the structure of human-mangrove interactions and its interrelated elements. Table 1 lists the elements involved in human activities and the mangrove environment. The elements relating to human activities are not fully understood and these are tentatively listed.

The field survey score result is shown in Table 2 and the correlation diagram in Figure 3. Figure 4-9 shows the detailed maps and photos of each village. Among the six villages, mangroves were grown in three villages (Phuoc Kieng, Hiep Phuoc and Huu Thanh) located near water channels, and elements for water channel use scored high. On the other hand, villages distant from water channels (My Loc and My Hanh Nam) has lower scoring in elements of the mangrove environment and their livelihood is less dependent on mangroves. There seems to be positive correlation between water channel use and the mangrove environment, except for one village (Cai Be) that is located close to both a main road and a water channel but far away from Can Gio.

Based on the scores for the studied villages, it becomes clear that some villages located near a water channel outside the mangrove forest have an effect on the mangrove environment that can be discussed in terms of the indicator elements identified in this study. Further, the results suggest that the mangrove environment is connected to people's living via waterways in the human-mangrove overlap area.

In this on-going study, the impact of water channel use on mangroves will be extended to include villages beyond the six described here, to better understand the human-mangrove relationship.

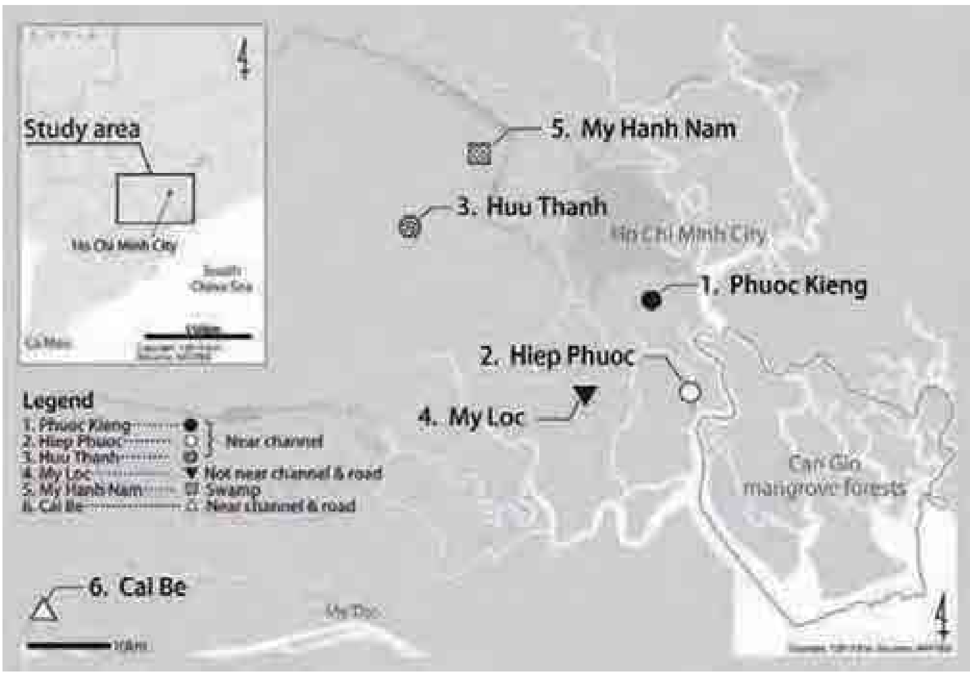

Figure 1 Location of the six villages in relation to Ho Chi Minh City and Can Gio mangrove forests

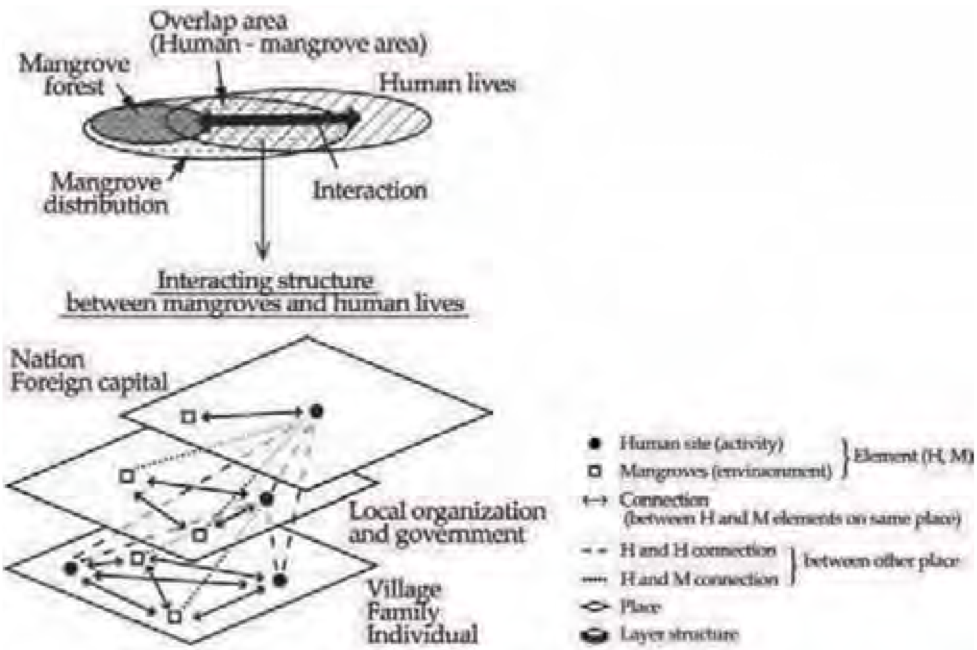

Figure 2 Elements and structure of the human-mangrove interactions (concept)

Table 1 Elements for human activities and mangrove environment

Elements for human activities		
General classification		Detailed classification
Current status	Facilities	Roads, water channel, tools Mangroves, forest, mangrove environment
	Transportation	Land transportation, water transportation, car, boat travel
	Occupation	Employment, land use, mangrove use
Background	Manpower	Culture, values and life style Technology development, infrastructure Population increase, regional development, economic development
	System	Social system, land ownership Policy, legal framework

Elements for mangrove environment		
General classification		Detailed classification
Vegetation	Mangroves (Tomlinson, 1986)	Major components Minor components Mangrove associates
	Others	Crops, rice, useful plants
Environment	Conversion	Aquaculture, agriculture, urbanisation, port, salt pan
	Tidal environment	Tidal amplitude
	Ground level	Meters above sea level
	Geomorphology (Woodroffe, 1992)	River dominated Tide dominated Inland
Topography (Miyagi et al., 1999)	Estuary and delta	Natural levee, inter-chenier wetland, distributary channel, flood plain, river
	Lagoon and beach ridge	Tidal flat (wetland), lagoon, sandbar
	Tidal flat	Tidal flat (wetland), coral reef

Table 2 Scores of human activities and mangrove environment at selected villages

No.	Village	Human activity							Mangrove environment			
		Dr	Ir	Mo	Tr	Pr	Li	Score	De	Ti	Ma	Score
1	Phuoc Kieng	x	x	○	○	Δ	x	5	○	○	○	6
2	Hiep Phuoc	x	x	○	○	○	x	6	○	○	○	6
3	Huu Thanh	○	x	Δ	○	x	Δ	6	○	Δ	Δ	4
4	My Loc	x	Δ	x	x	x	x	1	○	Δ	x	3
5	My Hanh Nam	Δ	Δ	x	x	x	x	2	○	Δ	x	3
6	Cai Be	x	Δ	○	○	x	Δ	6	○	Δ	x	3

Villages: Phuoc Kieng, Hiep Phuoc and Huu Thanh are located near channel, My Loc is located not near channel and road, My Hanh Nam is located in a swamp, and Cai Be is located near channel and road. The types of channels for Phuoc Kieng, Hiep Phuoc and Huu Thanh were straight, reticular and river distributary, respectively

Dr: Drainage, Ir: Irrigation, Mo: Movement, T: Transportation, Pr: Production, Li: Livelihood, De: Delta, Ti: Tide and Ma: Mangrove plants

Scoring system: ○ = Yes (elements fit) → 2, Δ = not clear → 1, and x = No (elements do not fit) → 0

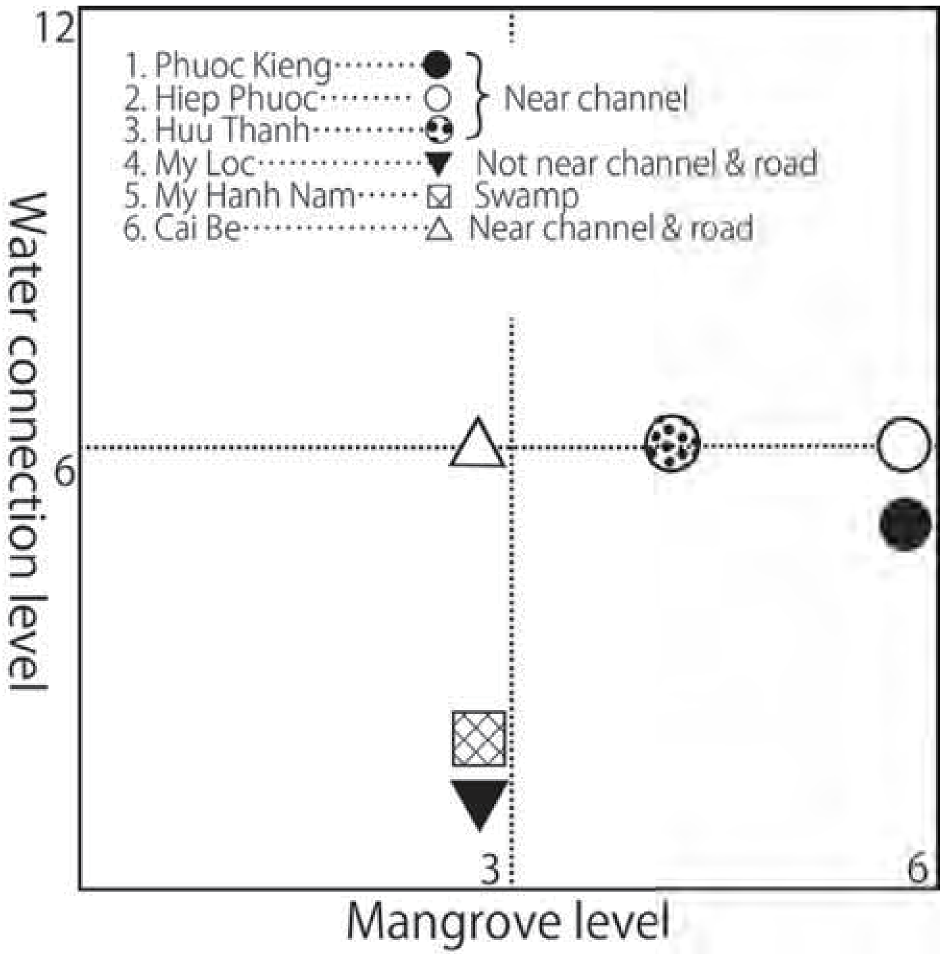

Figure 3 Relationship between the use of water channels and the mangrove environment at the six villagers

Figure 4 Illustrated map (A) of Phuoc Kieng village indicating where photos (B) were taken.
1. Bridge leading to the village (cars cannot go beyond this point), 2. boats below the road, 3. remnants of dock and 4. a village road

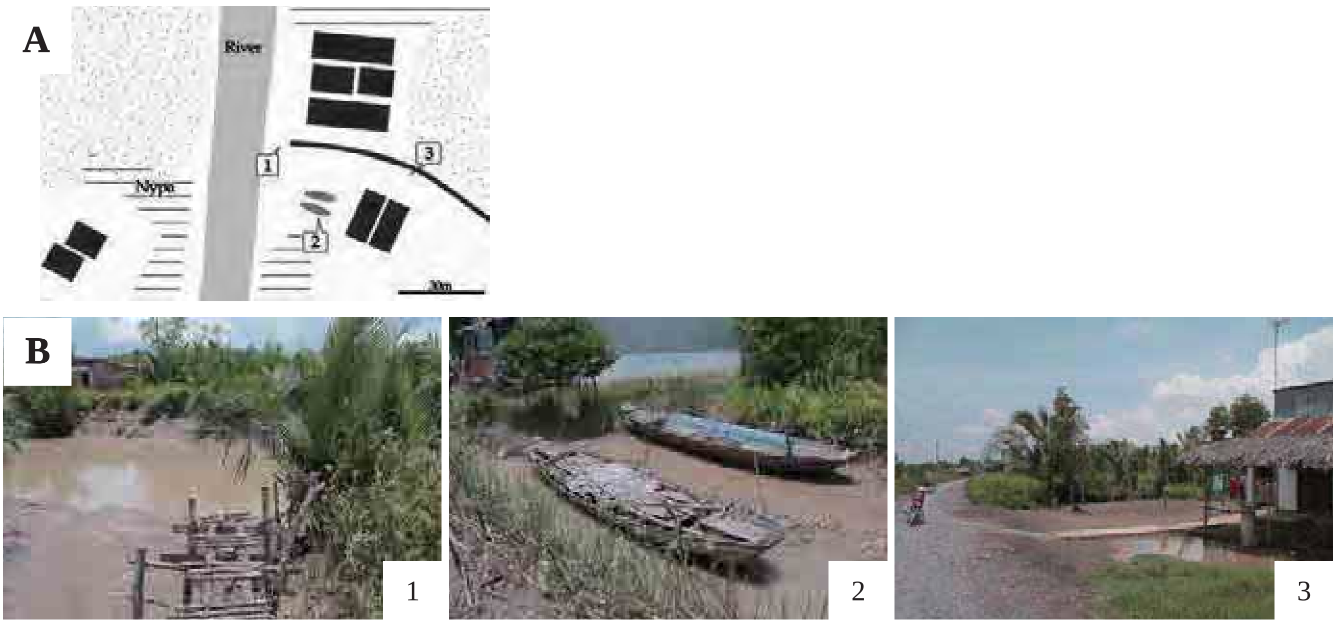

Figure 5 Illustrated map (A) of Hiep Phuoc village indicating where photos (B) were taken.
1. A boat landing extending into the channel (a house across the channel also belongs to the same district),
2. fishing boats docked near the house and 3. a gravel road near the house

Figure 6 Illustrated map (A) of Huu Thanh village indicating where photos (B) were taken.
1. A channel running through the village, 2. a concrete road next to houses, 3. a main road in the village and 4. a power boat next to a small boat

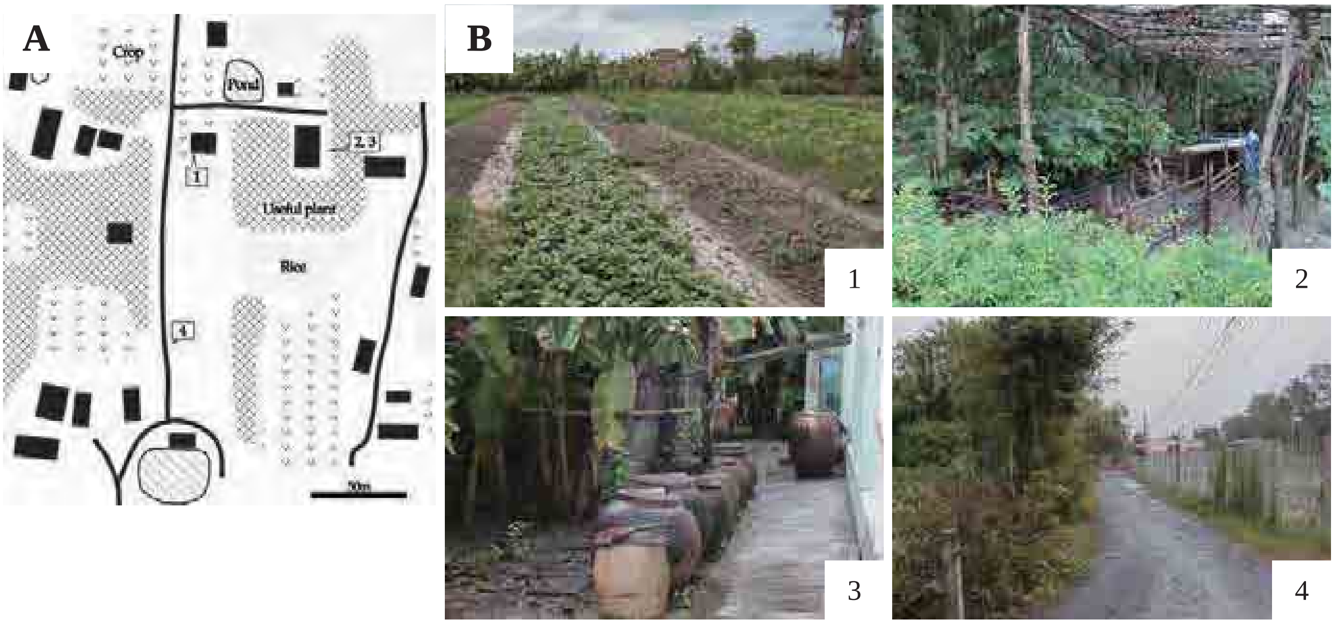

Figure 7 Illustrated map (A) of My Loc village indicating where photos (B) were taken.
1.Vegetable field in front of a house (lettuce, onion and malabar spinach are grown), 2. chickens raised in the back yard, 3. rainwater storage vessels and 4. a gravel road leading to the village

Figure 8 Illustrated map (left) of My Hanh Nam village describing where photo (right) was taken.
1. Swamp area (according to the villagers, the place used to be a marsh but was landfilled)

Figure 9 Illustrated map (A) of Cai Be village indicating where photos (B) were taken.
1. A rice storage building (left) and a road (right), 2. inside of the building, 3. loading rice into a truck (transported by boats and then brought to the market by trucks) and 4. boats behind the building delivering rice (a 30 cm wide board connects the boat to the building for rice transfer)

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