



# Application of remote sensing and GIS for detection of long-term mangrove shoreline changes in Mui Ca Mau, Vietnam

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Received: 11 October 2013 – Published in Biogeosciences Discuss.: 20 December 2013

Revised: 22 May 2014 – Accepted: 22 May 2014 – Published: 21 July 2014

**Abstract.** Mui Ca Mau at the southern tip of Vietnam supports a large area of mangroves and has a high value for biodiversity and scenic beauty. This area is affected by erosion along the East Sea and accretion along the Gulf of Thailand, leading to the loss of huge stretches of mangroves along the East Sea and, in some cases, loss of environmental and ecosystem services provided by mangroves. In this study, we used remotely sensed aerial (1953), Landsat (1979, 1988 and 2000) and SPOT (1992, 1995, 2004, 2008, 2009 and 2011) images and the Digital Shoreline Analysis System (DSAS) to quantify the rate of mangrove shoreline change for a 58 yr period. There were 1129 transects sampled at 100 m intervals along the mangrove shoreline and two statistical methods, namely end point rate (EPR) and linear regression rate (LRR), were used to calculate the rate of change of mangrove shorelines and distance from 1953 to 2011. The study confirms that erosion and accretion, respectively, are significant at the East Sea and Gulf of Thailand sides of Mui Ca Mau. The East Sea side had a mean erosion LRR of 33.24 m yr<sup>-1</sup>. The accretion trend at the Gulf of Thailand side had an average rate of 40.65 m yr<sup>-1</sup>. The results are important in predicting changes of coastal ecosystem boundaries and enable advanced planning for specific sections of coastline, to minimize or neutralize losses, to inform provincial rehabilitation efforts and reduce threats to coastal development and human safety.

## 1 Introduction

Mangrove ecosystems occur in the transitional zone between marine and terrestrial environments. Mangrove morphology and sedimentation are good indicators of interactions between relative sea level changes, coastal processes and sediment supply (Souza Filho et al., 2006; Gilman et al., 2007; McIvor et al., 2013). As emphasized by Souza Filho et al. (2006), a mangrove shoreline is one of the best geo-indicators in global coastal change research.

Remote sensing and geographical information system (GIS) techniques have been used widely to assess changes in coastal shorelines (Chen and Rau, 1998; Ghosh et al., 2001; Lin et al., 2001; Van der Wal et al., 2002; Ali, 2003; Vanderstraete et al., 2006; Genz et al., 2007; Maiti and Bhattacharya, 2009; Sesli et al., 2009; Rebelo et al., 2009; Kuleli, 2010; Kuleli et al., 2011; and Hai-Hoa et al., 2013) and the boundaries of mangrove forests and other habitats over time (Woodroffe, 1995; Solomon et al., 1997; El-Raey et al., 1999; Wilton and Saintilan, 2000; Saintilan and Wilton, 2001; Cohen and Lara, 2003; Dahdouh-Guebas et al., 2004; Fromard et al., 2004; Souza Filho et al., 2006; Gilman et al., 2007; Satyanarayana et al., 2011; Giri et al., 2011; Heumann, 2011; and Nfotabong-Atheull et al., 2013). The Digital Shoreline Analysis System (DSAS) is an extension to ArcMap and was introduced to automatically or manually generate measurements of transects and metadata based on user-specified parameters, calculating rates of shoreline

**Table 1.** History of universal DSAS application.

No.	Purpose of DSAS application	Country	Period	References
1	Estimating rates of change of mangrove seaward edges and landward margins in Douala Estuary	Cameroon	1975–2007	Ellison and Zouh (2012)
2	Calculating shoreline change rates in Accra	Ghana	1904–2002	Appeaning Addo et al. (2008)
3	Finding out the change rate of shoreline along the coast of Bhitarkanika Wildlife Sanctuary, Orissa	India	1973–2009	Chand and Acharya (2010)
4	Analysing shoreline changes along the coast between Kanyakumari and Tuticorin	India	1999–2009	Sheik and Chandrasekar (2011)
5	Analysing shoreline change of Vedaranyam coast, Tamil Nadu	India	1930–2005	Natesan et al. (2013)
6	Consistently estimating the spatio-temporal dynamics of erosion and accretion of the Sundarbans coastline	India and Bangladesh	1973–2010	Rahman et al. (2011)
7	Detecting the shorelines of the Sele Plain coastline between the towns of Salerno and Agropoli and defining its change	Italy	1870–2009	Alberico et al. (2011)
8	Quantitatively analysing shoreline changes on the Mediterranean coast in Turkey	Turkey	1972–2002	Kuleli (2010)
9	Detecting shoreline change on coastal Ramsar wetlands of Turkey	Turkey	1972–2009	Kuleli et al. (2011)
10	Quantifying shoreline changes along the Sefton Coast	UK	1955–2005	Esteves et al. (2009)
11	Mapping shoreline change in Puerto Rico	USA	36 yr	Thieler and Danforth (1994)
12	Analysing historical shoreline changes and associated coastal land loss along the US Gulf of Mexico	USA	1800s–2002	Morton et al. (2004)
13	Analysing shoreline changes and associated coastal land loss along the US southeast Atlantic coast	USA	1800s–2000	Morton and Miller (2005)
14	Analysing historical shoreline change and associated coastal land loss along sandy shorelines of the California coast	USA	1800s–2002	Hapke et al. (2006)
15	Analysing shoreline change at Mad Island Marsh Preserve, Matagorda County, Texas	USA	1995–2005	Mangham and Williams (2007)
16	Rates and trends of coastal change in California	USA	1800s–2001	Hapke et al. (2009)
17	Estimating historical coastal cliff retreat along the California coast	USA	1920–2002	Hapke and Reid (2007)
18	Analysing estuarine shoreline change: a case study of Cedar Island, North Carolina	USA	1958–1998	Lisa et al. (2010)
19	Analysing historical shoreline change along the New England and mid-Atlantic coasts	USA	1800s–2000s	Hapke et al. (2010)
20	Determining shoreline change along sheltered coastlines in Neuse River estuary	USA	1958–1998	Cowart et al. (2011)
21	Calculating shoreline change in Phan Thiet coastal area	Vietnam	1973–2002	Thao et al. (2008)
22	Examining the rates of change in width and the associated changes in adjacent shoreline land use on Kien Giang coast, Vietnam	Vietnam	2003–2009	Hai-Hoa et al. (2013)

changes and to provide other statistical information (Thieler et al., 2009). It utilizes the Avenue code to develop transects and rates, and the Avenue programming environment to automate and customize the user interface (Morton et al., 2004). The DSAS has been used widely to calculate the rate of shoreline changes (Table 1).

By 2012, Ca Mau Province had about 69 000 ha of mangroves accounting for about 49.6 % of the whole country (139 046 ha) (MARD, 2013; Ca Mau Portal, 2014). Natural and anthropogenic factors in the mangroves around Mui Ca Mau have caused erosion along the East Sea coast and accretion along the Gulf of Thailand shoreline. As stated by the MAB Vietnam (2008), these changes have led to the loss of huge stretches of mangroves along East Sea resulting in the decrease and, in some cases, loss of mangrove environmental and ecosystem services. The effects include loss of spawning grounds for aquatic species and the loss of the wave buffering and sheltering effect of mangroves, threatening residential areas and infrastructure behind the mangrove (MAB Vietnam, 2008). In addition, by the end of the 21st century, average sea level in the study area is projected to rise 59–75 cm and 62–82 cm along the East Sea and the Gulf of Thailand, respectively (MONRE, 2012). However the change in the mangrove shoreline due to accretion and erosion at Mui Ca Mau has not been quantified but merely observed. Key weaknesses in previous attempts at government mangrove rehabilitation

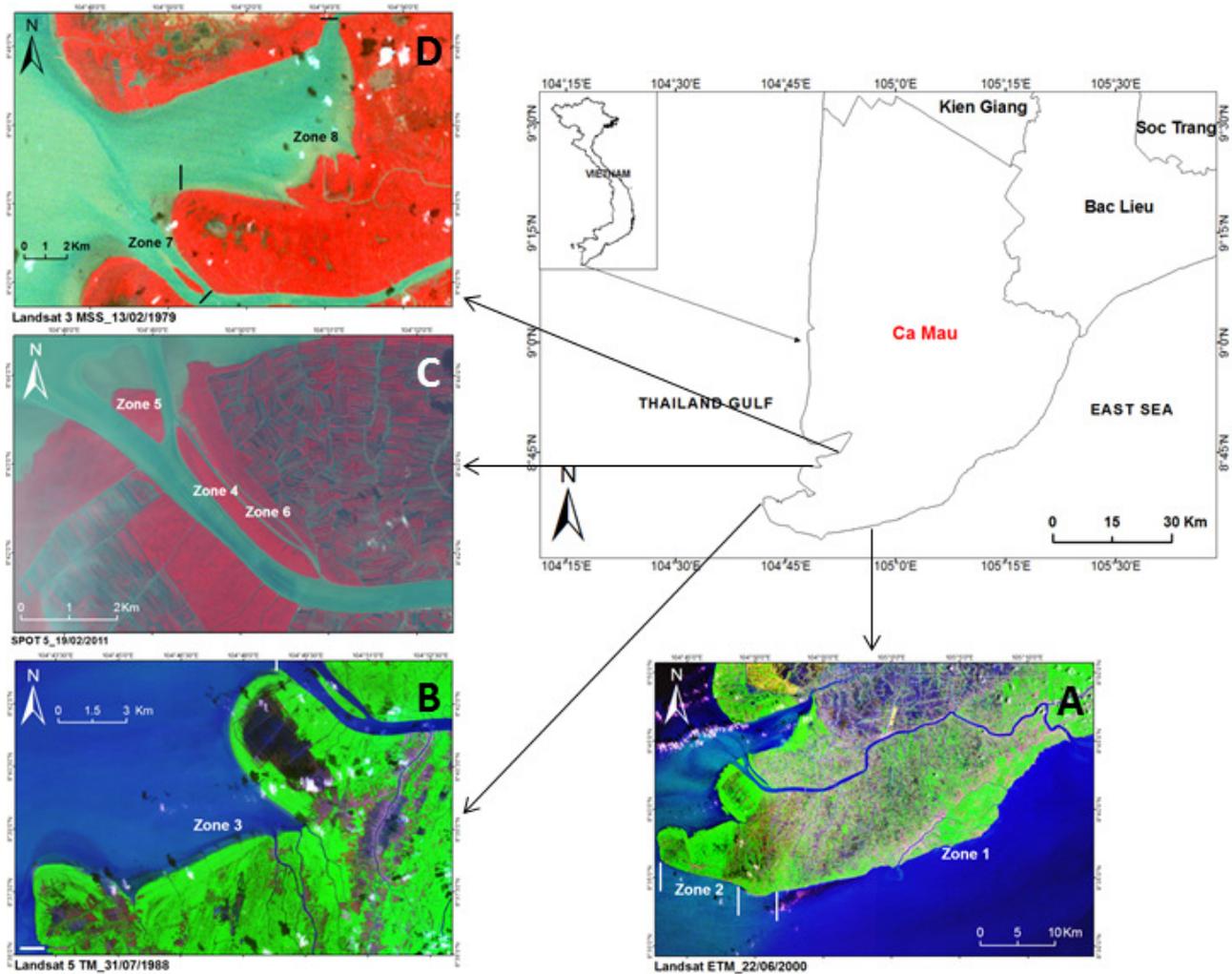
have been uniform application of homogeneous monoculture plantations with little consideration for maintenance needs or coastal dynamics, which dictate suitability of mangrove rehabilitation at any given site (IUCN, 2012). It is, therefore, very important to detect quantitatively the changes of mangrove shoreline. This will be used effectively to predict the changes of coastal ecosystem boundaries and enable advanced planning for specific sections of coastline, to minimize or neutralize losses, to inform provincial rehabilitation efforts and reduce threats to coastal development and human safety (Dahdouh-Guebas, 2002; Gilman et al., 2007; IUCN, 2012).

In this research, we quantify the rate of mangrove shoreline change around Mui Ca Mau with remotely sensed images of aerial photographs, Landsat and SPOT data for a 58 yr period and applying DSAS.

## 2 Materials and methods

### 2.1 Study area

The study area is located at the southernmost point of Ca Mau Province between latitude 8°32′–8°49′ N and longitude 104°40′–105°19′ E (Fig. 1). It covers entirely Ngoc Hien District and partly Nam Can District of Ca Mau Province. We chose this area because it is a lowland deltaic plain (0–3 m



**Figure 1.** Map of the study area. It is divided into eight zones that depend on coastal characteristics and availability of remotely sensed data. (A) zones 1 and 2; (B) zone 3; (C) zones 4, 5 and 6; and (D) zones 7 and 8.

above mean sea level) and strongly divided by a system of natural rivers and a dense network of canals (Hong and San, 1993). The water flow regime in the area is under the influence of both the East Sea and the Gulf of Thailand with the eastern flow the stronger. The whole area is characterized by a soft muddy soil and influenced by semidiurnal tides originating from the East Sea (tidal amplitude 2–3 m) and by the diurnal tides from the Gulf of Thailand (tidal amplitude 0.5–0.8 m) (Hong and San, 1993). More importantly, Ca Mau supports the most substantial area of mangroves (Hong and San, 1993), and it is a natural mangrove ecosystem with a high conservation value for its biodiversity and scenic beauty (MAB Vietnam, 2008). There are 27 true mangrove species in Ca Mau, with *Avicennia alba* Blume, *Avicennia marina* (Forssk.) Vierh., *Avicennia officinalis* L., *Rhizophora apiculata* Bl., *Bruguiera parviflora* Wight & Arnold ex Griffith, *Ceriops zippeliana* Blume and *Nypa fruticans* (Thunb.) Wurmb. amongst the major species (Hung and Tan, 1999;

Massó i Alemán et al., 2010). But natural and anthropogenic factors in the mangroves around Mui Ca Mau have caused erosion along the East Sea and accretion along the Gulf of Thailand.

Our study area extended from Bo De river mouth on the east coast to Bay Hap Estuary on the west coast of Mui Ca Mau. Based on coastal characteristics (erosion and accretion) and availability of remotely sensed data, this area was divided into eight zones for the purpose of the study (Fig. 1 and Table 2).

## 2.2 Data sources and geo-referencing

Aerial photographs from 1953 and remotely sensed image data of Landsat (1979, 1988, and 2000) and SPOT (1992, 1995, 2004, 2008 and 2009, and 2011) images were used to analyse the change rate of mangrove shorelines over 58 yr (specifications of remotely sensed data used in this study are

**Table 2.** Eight zones in the study area divided basing on coastal characteristics and availability of remotely sensed data.

Zone	Length (km)	Direction	Description position	Accretion/erosion	Time series
1	49.0	Northeast	From Bo De river mouth to O Ro river mouth	High erosion	1953, 1979, 1988, 1992, 1995, 2000, 2004, 2008, 2011
2	11.1	Southeast	From Vam Xoay to Rach Tau river mouth	Erosion	1953, 1979, 1988, 1992, 1995, 2000, 2004, 2009, 2011
3	22.0	Southwest	From Hai Thien canal to Cua Lon Estuary	Accretion	1953, 1979, 1988, 1992, 1995, 2000, 2004, 2009, 2011
4	7.5	West	Con Trong island, formed in 1960s, at Cua Lon Estuary	Accretion	1979, 1988, 1992, 1995, 2000, 2004, 2009, 2011
5	1.7	West	Con Ngoai island, formed in 1980s, at Cua Lon Estuary	Accretion	1992, 1995, 2000, 2004, 2009, 2011
6	4.5	West	Con Moi island, newly formed in 2000s, at Cua Lon Estuary	Accretion and erosion	2009, 2011
7	6.3	West	On right bank of Cua Lon river	Accretion	1953, 1979, 1988, 1992, 1995, 2000, 2004, 2009, 2011
8	11.8	Northwest	From Cua Lon to Bay Hap estuaries	Accretion	1979, 1988, 1992, 2000, 2004, 2011

**Table 3.** Specifications of image data.

No.	Name	Path/row	Acquisition date	Resolution (m)	Study area
1	Aerial photos		1 Jan 1953	20	1,2,3,7
2	Landsat 3 MSS	135/054	13 Feb 1979	79	1,2,3,4,7,8
3	Landsat 5 TM	125 and 126/054	31 Jul 1988	30	1,2,3,4,7,8
4	Landsat ETM	125 and 126/054	22 Jun 2000	30	1,2,3,4,5,7,8
5	SPOT 2	273/332	3 Jan 1992	20	1,2,3,4,5,7,8
	SPOT 2	273/333	3 Jan 1992	20	
	SPOT 2	274/333	3 Jan 1992	20	
6	SPOT 2	273/333	12 Dec 1995	20	1,2,3,4,5,7
	SPOT 2	274/333	12 Dec 1995	20	
7	SPOT 5	273/332	7 Jan 2004	10	1,2,3,4,5,7,8
	SPOT 5	273/333	7 Jan 2004	10	
	SPOT 5	274/333	7 Jan 2004	10	
8	SPOT 4	274/333	8 Sep 2008	10	1
9	SPOT 2	273/333	19 Jan 2009	20	2,3,4,5,6,7
10	SPOT 5	273/332	19 Feb 2011	10	1,2,3,4,5,6,7,8
	SPOT 5	273/333	19 Feb 2011	10	
	SPOT 5	274/333	19 Feb 2011	10	

given in Table 3). The Landsat images were freely downloaded from the US Geological Survey (USGS) at level 1T which has been processed to standard terrain correction. Other images were purchased by the Laboratory of Plant Biology and Nature Management, Vrije Universiteit Brussel and the Institute of Meteorology, Hydrology and Environment. The SPOT images were processed at the level of orthorectified using ground control points and a digital elevation model. All these data were geo-referenced to the UTM

WGS-1984 Zone 48N projection and coordinate system with further geometric correction using ENVI.

### 2.3 Mangrove shoreline digitization and detection

The mangrove forest edge was used as the shoreline indicator to derive historical rates of mangrove shoreline change in the study area. For the eroding east side, mangrove trees occur as far seaward as there is soil to remain stable, with no mudflats

beyond them. For the accreting west side, the first occurrence of a closed mangrove canopy was used as a border. Long intertidal mudflats extend beyond the mangrove vegetation in these areas, but they are not yet suitable for mangrove propagules to establish as the water depth over time is still too high. Using the closed canopy mangrove forests as border of the land area is an acceptable solution to distinguish the mudflats from the land area, although single mangrove individuals and young plants colonizing the newest areas are excluded from the analysis. ArcGIS was used to manually digitize the mangrove shoreline position in 1953.

Normalized Difference Vegetation Index (NDVI) is one of the most successful and widely used ways to simply and quickly identify vegetated areas by detecting living green plant canopies in multispectral remote sensing data (Seto and Fragkias, 2007; Vo et al., 2013). In this study, NDVI was used to distinguish vegetated areas from other surface types, especially for the purpose of this study between water or land and mangrove. In order to improve the accuracy of mangrove shoreline detection, the clustering threshold technique of Otsu (1979) was used. This detects an optimum threshold by minimizing weighted sum of within-class variances of the foreground and background pixels and gives satisfactory results when the numbers of pixels in each class are close to each other. The Otsu method remains one of the most cited threshold methods (Sezgin and Sankur, 2004; Kuleli, 2010; Kuleli et al., 2011). The border pixels between segmented vegetation/water or land regions can be delineated as mangrove shorelines. These are delineated using binary images produced from a threshold-based segmentation algorithm. As a result, images were divided into two major segments: mangrove and water or land. After this process, the boundaries of the classified regions were vectorized by using the raster to vector conversion application of ENVI. Next, the conversion accuracy was evaluated by overlaying the extracted mangrove shorelines with the original Landsat and SPOT images.

## 2.4 Mangrove shoreline rate calculation

Calculating mangrove shoreline movement and changes were formalized into DSAS version 4.2, an extension to ArcMap developed by the USGS. DSAS computes rate-of-change statistics from multiple historic shoreline positions residing in a GIS (Thieler et al., 2009). DSAS generates transects that are cast perpendicular to the baseline at a user-specified spacing alongshore. The intersections of transects and the mangrove shorelines along this baseline are then used to calculate the rate-of-change statistics. In this study, a total of 1129 transects were regularly placed at a spacing of 100 m by applying DSAS software. To assess the spatial and temporal movement trend of mangrove shoreline positions, a hypothetical baseline was constructed offshore and parallel to the general orientation of the mangrove shoreline. The generated

transects together with the extracted mangrove shorelines are graphically shown in Figs. 2–5.

In order to calculate erosion/accretion rates, many statistical methods have been applied, such as end point rate (EPR), average of rates (AOR), minimum description length (MDL), jackknifing (JK), linear regression rate (LRR), reweighted least squares (RLS), weighted least squares (WLS), reweighted weighted least squares (RWLS), least absolute deviation (LAD), and weighted least absolute deviation (WLAD) (Dolan et al., 1991; Thieler et al., 1995; Crowell et al., 1997; Coyne et al., 1999; Honeycutt et al., 2001; Genz et al., 2007; Kuleli, 2010; Kuleli et al., 2011; Sheik and Chandrasekar, 2011). The two most frequently cited methods are EPR and LRR. In this study, two comparative statistical methods of EPR and LRR were used to calculate the change in rates of mangrove shorelines in Mui Ca Mau. The EPR is simply the rate determined by the changes in position between the oldest and most recent shorelines in a given data set. As it only considers the earliest and the latest shoreline positions, it was suitable for the short-term mangrove shoreline change analysis of zone 6 (Con Moi) with only two mangrove shorelines of 2009 and 2011 available. The LRR is the result of estimating the average rate of change using a number of shoreline positions over time, with the change statistic of fitting a least-squared regression line to all shoreline points for each transect. The linear regression rate is the slope of the line. Therefore, LRR was used to analyse the long-term mangrove shoreline change (from 1953 to 2011) of the other study zones. In this study, data uncertainty was  $\pm 5$  m, and confidence interval was 90 % determined as a weighted linear rate parameter.

## 2.5 Ground truth and social survey

Field ground truth was carried out in 2006, 2007, 2010 and 2011. A total of 150 GPS points collected in the field with attribute information on location of the seaward edge of the mangroves and households in and around the mangroves area. These points were imported to ArcGIS for analysis.

Social surveys in households close to the mangrove area were conducted using interviews. The target group was the population with experience of the region. In 1980s, there was unauthorized influx of people from other provinces migrated to Ngoc Hien District (Hong and San, 1993). Therefore, the people with ages ranging from 45 to 65 yr old were chosen for the interviews. The major objectives regarded changes they had observed in the mangrove area over time. Collected information is used in the discussion.

## 3 Results

Table 4 summarizes rates of mangrove shoreline change as averages of the erosion or accretion values on generated transects in each zone, along with maximum and minimum

**Table 4.** Change rate of mangrove shoreline in eight zones of the study area. For zone 6, there are only two mangrove shorelines of 2009 and 2011, no linear regression statistic was run, and hence end point rate is used. For the rest, mangrove shoreline change was derived from linear regression rates.

Items	Zones									
	1	2	3	4 A	4 B	5	6 A	6 B	7	8
Number of transects	489	108	219	72	2	16	22	22	62	117
Transect length (m)	5500	1050	1100 2000 5600 3700 2700	300 170	1900	500	90	90	1900 3700	1800 4500 2000
Mean of mangrove shoreline change (m yr <sup>-1</sup> )	-38.31 ±14.26	-10.28 ±2.64	+44.74 ±24.36	+1.31 ±1.46	+48.69 ±3.01	+7.38 ±7.61	+9.59 ±6.99	-5.80 ±3.69	+23.00 ±11.26	+65.00 ±46.61
Maximum of mangrove shoreline change (m yr <sup>-1</sup> )	-71.54	-13.73	95.67	5.52	50.82	20.07	20.38	0.94	47.03	133.41
Minimum mangrove shoreline change (m yr <sup>-1</sup> )	-12.61	-2.54	1.14	0	46.56	0.25	1.16	-11.17	6.40	0.62

values. Positive EPR and LRR values represent mangrove shoreline movement towards the sea (accretion rate), and negative values indicate movement inland (erosion rate). Mangrove shoreline changes emphasize erosion along the East Sea and accretion along the Gulf of Thailand, as observed previously. It is also clear that the islands in the Cua Lon Estuary were recently formed.

Along the East Sea, mangrove shoreline of zone 1 is located between Bo De and O Ro river mouths. Over 49 km, there were 489 transects used to intersect the base line and nine mangrove shorelines of 1953, 1979, 1988, 1992, 1995, 2000, 2004, 2008 and 2011 (Table 2 and Fig. 2). The rate of change varied from  $-12.61 \text{ m yr}^{-1}$  to  $-71.54 \text{ m yr}^{-1}$  with a mean rate of  $-38.31 \pm 14.26 \text{ m yr}^{-1}$  (Table 4). The maximum erosion rate was near to Bo De river mouth,  $-71.54 \text{ m yr}^{-1}$  (Fig. 2).

The mangrove shoreline of zone 2, from Vam Xoay to Rach Tau river mouth, recorded dominant erosion. Similar to zone 1, nine mangrove shorelines were observed in zone 2, but mangrove shoreline 2008 was replaced by the one in 2009 (Fig. 3). Along the 11.2 km, 111 transects were generated (Table 4 and Fig. 3). Over the period 1953–2011, the change rate of the shorelines ranged from  $-2.54 \text{ m yr}^{-1}$  to  $-13.73 \text{ m yr}^{-1}$ , with an average of  $-10.28 \pm 2.64 \text{ m yr}^{-1}$  (Table 4).

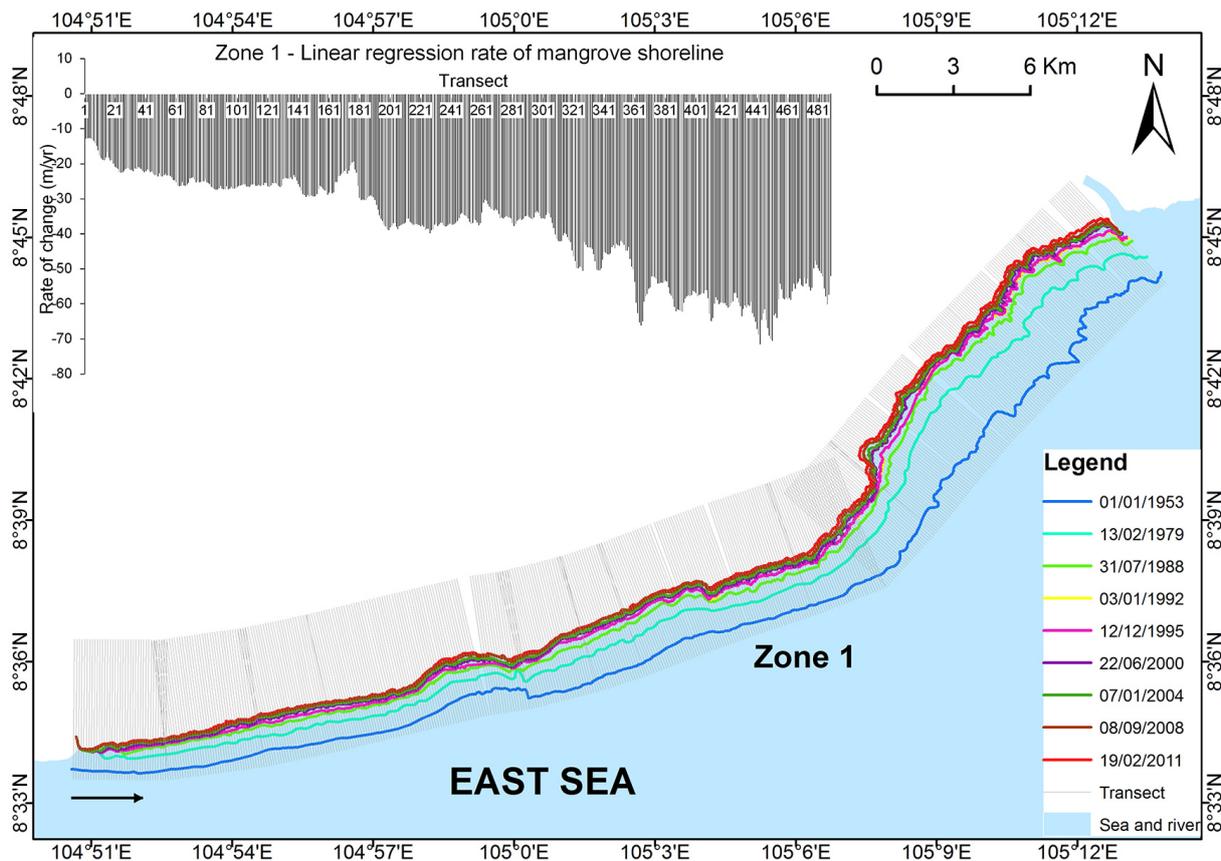
On the other hand, mangrove accretion is significant along the Gulf of Thailand. A time series of nine mangrove shorelines was extracted. Along the 22 km of mangrove shoreline of zone 3 from Ca Mau tip (Hai Thien canal) to Cua Lon Estuary, the rate of accretion averaged over 219 transects was  $44.74 \pm 24.36 \text{ m yr}^{-1}$ . Maximum accretion rate in this

zone was  $95.67 \text{ m yr}^{-1}$  at transect between Nam Khoi and Ba Mang canals (Table 4 and Fig. 3).

Further, in the Cua Lon Estuary, three newly formed islands of Con Trong (zone 4), Con Ngoai (zone 5) and Con Moi (zone 6) continue to be accreted (Fig. 4). Con Trong Island (zone 4) was formed during the 1960s and is located in the middle of the estuary. Hence, there was no mangrove shoreline in 1953 to be observed (Fig. 4). A total of 74 transects were extracted in zone 4 (Table 4 and Fig. 4). Maximum accretion rate was observed at the northeastern tip of the island. Hence, zone 4 was divided into two subzones 4A and 4B. During 1979–2011, 72 transects of subzone 4A were evidenced average accretion rate of  $1.31 \pm 1.46 \text{ m yr}^{-1}$  that was much lower than the two transects of subzone 4B ( $48.69 \pm 3.01 \text{ m yr}^{-1}$ ) (Table 4).

Located further offshore, Con Ngoai (zone 5) was formed during the 1980s. Hence, mangrove shorelines of 1953, 1979 and 1988 are not available. It is clearly seen that this island is expanding at the northeastern tip. For 16 transects there, the average accretion rate was  $7.38 \pm 7.61 \text{ m yr}^{-1}$  over the period 1992–2011 (Table 4 and Fig. 4). For the other parts of the island, the mangrove shoreline was stable, and no change was observed (Fig. 4).

Con Moi (zone 6) is a newly formed island during the 2000s, and only two mangrove shorelines are available (2009 and 2011) for comparison (Fig. 4). The EPR was applied and showed accretion dominated the eastern bank of the island (subzone 6A), whereas erosion dominated the western bank (subzone 6B) (Table 4 and Fig. 4). Over the 22 transects of subzone 6A, the mean accretion rate was  $9.59 \pm 6.99 \text{ m yr}^{-1}$ . The mean erosion rate was  $-5.80 \pm 3.69 \text{ m yr}^{-1}$  for the 22 transects of subzone 6B.



**Figure 2.** Mangrove shoreline changes in zone 1 which is located between Bo De and O Ro river mouths, along the East Sea. DSAS software generated 489 transects. The arrow shows the direction of transects from 1 to 489 which have a linear regression rate illustrated in the graph at the top left corner.

Located on the western bank of the Cua Lon River, zone 7 is also a sediment receiver. Over the period 1953–2011, nine mangrove shorelines were reported. There were 62 transects generated in zone 7 (Fig. 5). Change rate of mangrove shorelines ranged from  $6.40 \text{ m yr}^{-1}$  to  $47.03 \text{ m yr}^{-1}$  with mean accretion rate of  $23.00 \pm 11.26 \text{ m yr}^{-1}$  (Table 4).

Next to zone 7, six mangrove shorelines of 1979, 1988, 1992, 2000, 2004, and 2011 were remained in zone 8. Over 11.8 km of zone 8, 117 transects were recorded (Fig. 5). The mean accretion rate was  $65.00 \pm 46.61 \text{ m yr}^{-1}$  (Table 4).

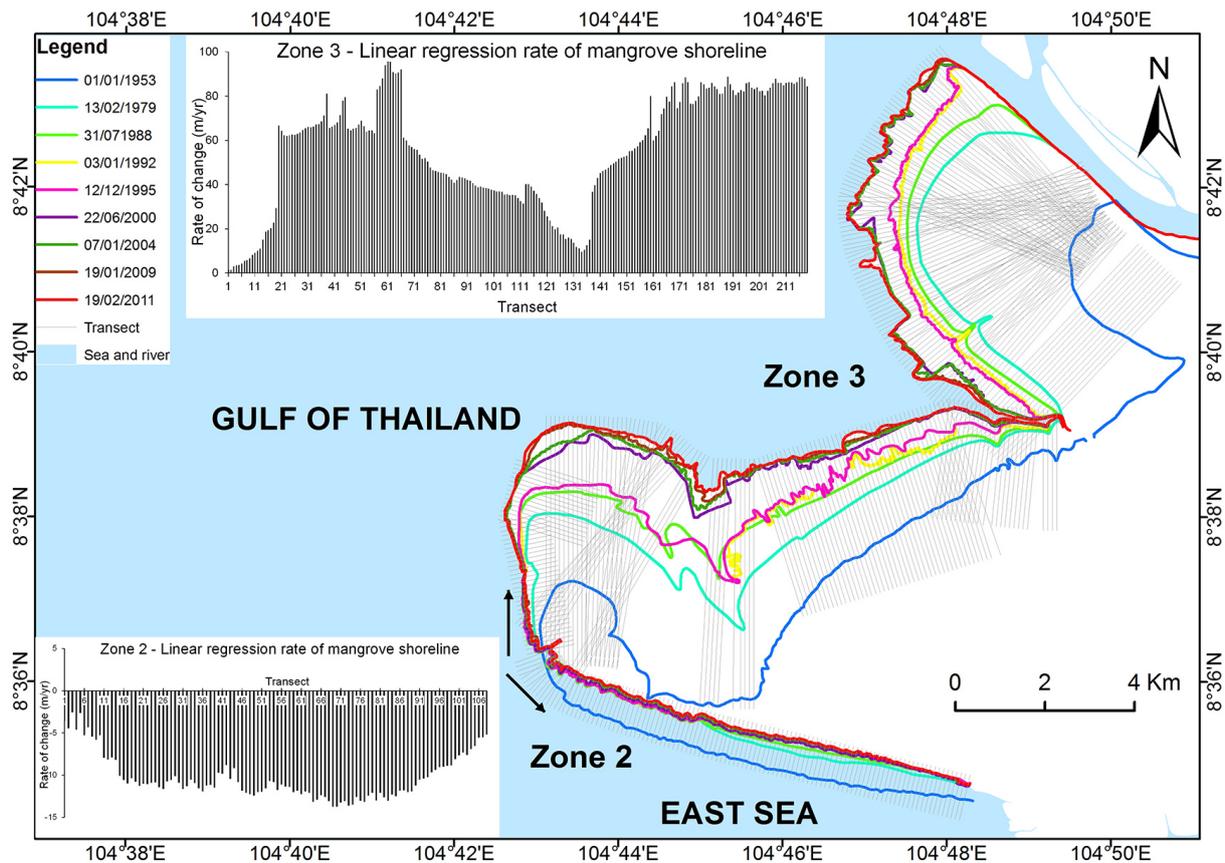
## 4 Discussion

### 4.1 Erosion along the East Sea

Analysis from a time series of mangrove shoreline along the East Sea shows average erosion rate varying from  $10.28 \text{ m yr}^{-1}$  (zone 2) to  $38.31 \text{ m yr}^{-1}$  (zone 1) (Table 4). In comparison to studies at other sites, these are much higher. In the Douala Estuary, Cameroon, results showed the seaward edge of mangroves had over two thirds of the shoreline experiencing dieback, at a rate of up to  $3 \text{ m yr}^{-1}$  over

the period 1975–2007 (Ellison and Zouh, 2012). Gilman et al. (2007) observed mean landward migration of American Samoa mangroves over 4 decades was from  $6.39 \text{ cm yr}^{-1}$  to  $3.27 \text{ m yr}^{-1}$ . Recently, Hai-Hoa et al. (2013) found the width of fringe mangroves had been significantly reduced on Kien Giang coast, Vietnam, with average rates of width reduction from  $3 \text{ m yr}^{-1}$  to  $7 \text{ m yr}^{-1}$  over the period 2003–2009. The causes of the changes have been proposed to be reduction in sediment supply and mangrove overexploitation (Ellison and Zouh, 2012), shrimp farm expansion (Hai-Hoa et al., 2013) and climate change, especially sea level rise (Gilman et al., 2007).

Because of the specific history of the study area, it is very difficult to compare the mangroves in the study area to mangrove systems elsewhere (Koedam et al. 2007). This constitutes an added value to performing this research. Indeed, it is clear that the coast of Mui Ca Mau is strongly dynamic. Mangrove loss on the eastern side is arising primarily because of natural changes in the coastal system and the impact of the northeast monsoon, plus as a consequence of human activities such as herbicide application during the Vietnam War, deforestation, and the reduction of sediment supply from the



**Figure 3.** Mangrove shoreline change in zones 2 and 3. Zone 2 is located on the East Sea coast and zone 3 on the Gulf of Thailand. DSAS software generated 108 and 219 transects for zones 2 and 3, respectively. The arrow shows the direction of transects from 1 to 108 for zone 2 and from 1 to 219 for zone 3.

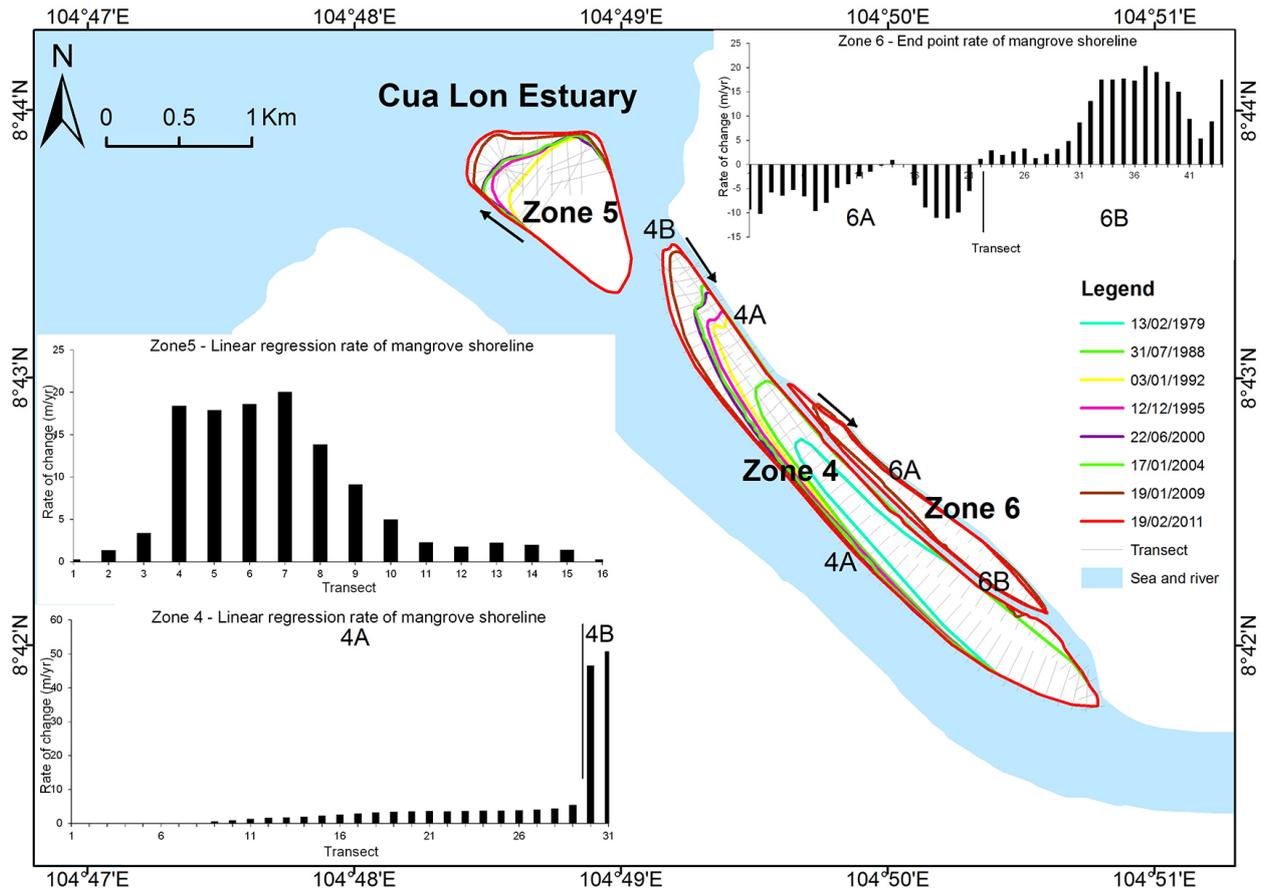
Mekong mouths by the rapidly increasing number of dams on the Mekong system.

During the Vietnam War (1961–1971), herbicides were sprayed by the United States forces for military purposes at a rate more than an order of magnitude greater than for similar domestic weed control (Stellman et al., 2003). Mui Ca Mau was one of the two heavily sprayed regions in the south of Vietnam (Hong and San, 1993). Ross (1975) reported from 1966 to 1970 the tip of Ca Mau received 1027 kg of Agent Orange from 55 missions and 285 kg of Agent White. As a result, 52 % of dense mangroves at the tip of Ca Mau were destroyed (Hong and San, 1993). In the study area, bare waste land area increased about 10 times from 2003 ha in 1953 to 21 964 ha in 1975 (Van et al., 2014), with a similarity to the flight paths of spray missions delivering Agent Orange and Agent White during the war (Stellman et al., 2003). After this time, forests in the affected areas have consisted mainly of secondary growth, much of it scrubby, and plantations (FAO, 2007).

In Mui Ca Mau, *Rhizophora* sp. has value for timber and poles, firewood and charcoal (Hong and San, 1993). After the war, there was rapid population growth in the

study area, which resulted in increased demands on the mature forests remaining in Ca Mau. Exploitation was indiscriminate despite regulation of the utilization of mangrove forests. From 1975 to 1983, there were 207 798.4 m<sup>3</sup> of timber, 686 961.6 m<sup>3</sup> of firewood, and 23 030.19 tons of charcoal exploited from the mangrove forests of the former Minh Hai Province (Ca Mau and Bac Lieu provinces) (Hong and San, 1993). In addition, conversion to brackish water aquaculture is a major agent of mangrove change in Vietnam (Giesen et al., 2006). Extensive expansion of aquaculture in the 1980s and 1990s resulted in the loss of about two thirds of Vietnam's mangroves by 2000 (Hashimoto, 2001). At the initial stage, extensive tidal areas in Ca Mau were converted for agriculture. Although initially yields were high, crops eventually failed. The reclaimed land was rapidly converted to aquaculture (Hong and San, 1993; Binh et al., 2005). In 1980s, most of forestry aquaculture enterprises in Ca Mau cleared mangrove forest for the expansion of shrimp farming area, and this led to the further deterioration of mangrove forests (Hong and San, 1993).

Upstream hydrological engineering (hydroelectric dams and irrigation canals) contributes an additional layer of



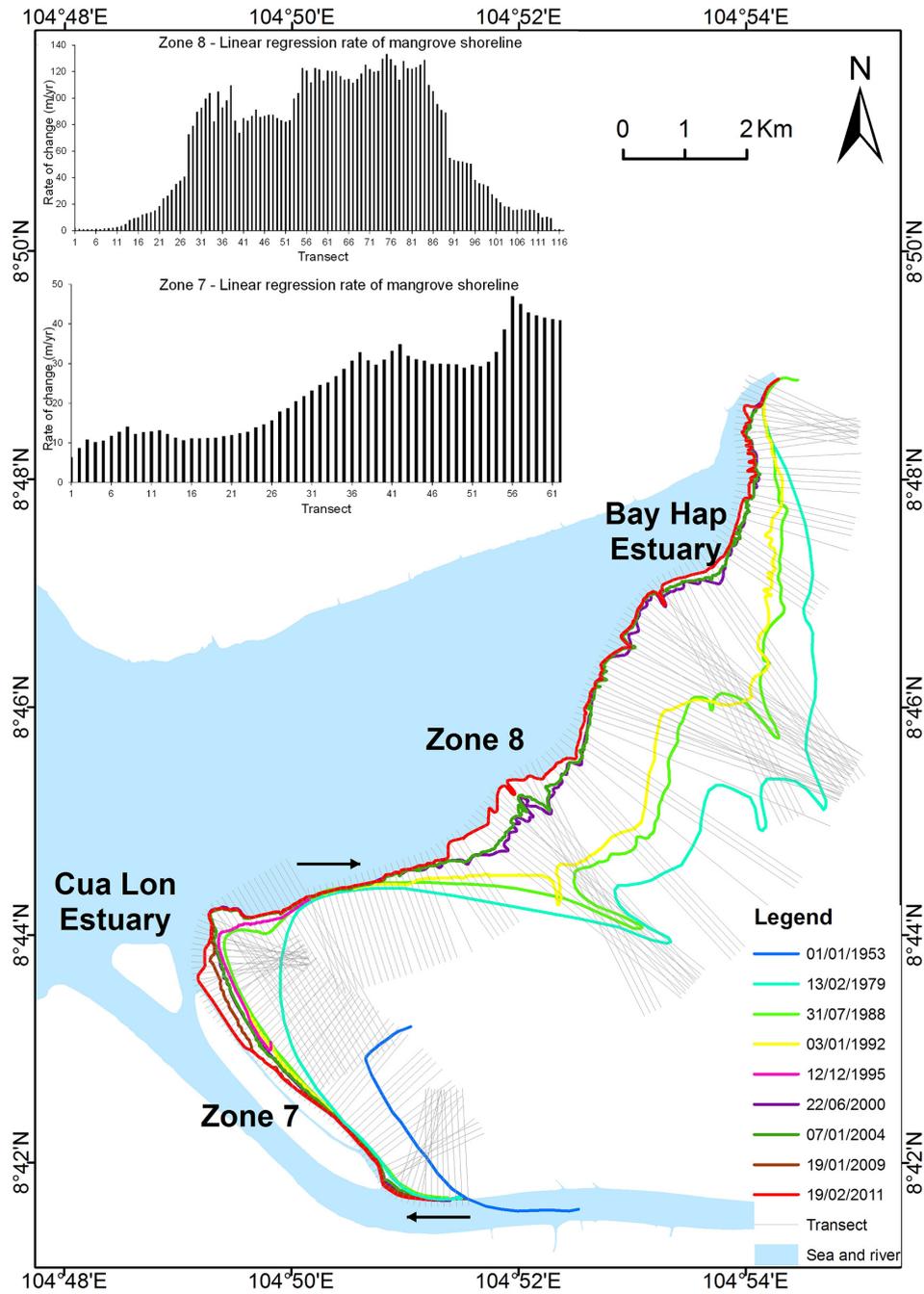
**Figure 4.** Mangrove shoreline change in zone 4 (Con Trong), zone 5 (Con Ngoai) and zone 6 (Con Moi) in the Cua Lon Estuary. These are new islands were formed in the 1960s, 1980s, and 2000s, respectively. Therefore, 8, 5 and only 2 mangrove shorelines were generated for zone 4, zone 5 and zone 6, respectively. DSAS software generated 74, 16 and 44 transects for zone 4, zone 5 and zone 6, respectively. Zone 4 and zone 6 each is divided into two dynamic regions, A and B. The arrows show the direction of transects from 1 to 74 for zone 4, from 1 to 16 for zone 5 and from 1 to 44 for zone 6.

complexity by modifying local coastal dynamics, which can impact mangrove ecosystem permanence by altering rates of erosion or accretion (Hashimoto, 2001). Dam construction on rivers has been reported to reduce (Ellison and Zouh, 2012) or to increase (Dahdouh-Guebas et al., 2005; Koedam and Dahdouh-Guebas, 2008) the volume of water and riverine sediment supply to the sea and coastal mangroves in the affected and adjacent river basins resulting in altered mangrove extent and/or quality. The Mekong River is likely to already have lower sediment loads due to damming of the main stream and tributaries, and this will be exacerbated in the future with more dam construction. Longshore drift from the Mekong River mouths is southwards towards Mui Ca Mau. As compared with the pre-dam period, monthly suspended sediment concentration decreased about 20–30 % at the Vietnamese stations of Tan Chau, My Thuan and Can Tho (Lu and Siew, 2006), but the impact particularly on the erosion of the eastern coast is unpredictable.

**4.2 Accretion along the Gulf of Thailand**

The strong longshore drift associated with the wave action eroding the East Sea shoreline transfers sediment to the Gulf of Thailand (MAB Vietnam, 2014). A huge amount of sediment in the East Sea is transported to the Gulf of Thailand by the Cua Lon River, then accumulates at the Cua Lon Estuary at an average rate of 70–80 mg L<sup>-1</sup> (November–April) and 30 mg L (May–October). It is estimated Cua Lon River transfers about 1 030 000 tons yr<sup>-1</sup> of sediment from the East Sea to the Gulf of Thailand (MAB Vietnam, 2014). As a consequence, this study shows accretion is dominant along the Gulf of Thailand (Table 4, Figs. 3–5). Especially, the three islands of Con Trong (zone 4), Con Ngoai (zone 5) and Con Moi (zone 6) were newly formed in the 1960s, 1980s, and 2000s, respectively.

Figure 6 clearly shows Con Trong (zone 4) is continuing to advance seaward to meet Con Ngoai (zone 5) at the northeastern tip and Con Moi (zone 6) on the western bank. Geographically, sediment from the Cua Lon River and from



**Figure 5.** Mangrove shoreline change in zones 7 and 8. Mangrove shoreline 1953 is not observed in zone 8. DSAS software generated 62 and 117 transects for zone 7 and zone 8, respectively. The arrows show the direction of transects from 1 to 62 for zone 7 and from 1 to 117 for zone 8.

the East Sea (transported by rivers, canals and shore drift) is interpreted as the main sediment source (MAB Vietnam, 2014). Mangroves on these three newly formed islands have been growing naturally.

### 4.3 Implication for mangrove management and conservation

Sediment accretion and erosion evidently influences the ability of propagules to disperse and establish, which therefore influences the spatio-temporal changes in mangroves (Clarke et al., 2001; Sousa et al., 2007). Most of propagules were

found to disperse over a short distance up to tens of metres (McGuinness, 1997; Breiffuss et al., 2003; Sousa et al., 2007; De Ryck et al., 2012). However, some propagules dispersed over extensive ranges, even more than 50 km (Clarke, 1993). In all cases, microtopography and sediment dynamics of the site colonized will determine to a great extent whether or not propagules will establish and survive their earliest stages as a growing tree. Excessive erosion will prevent the propagules from establishing or stabilizing in the soil, whereas excessive accretion might cover and suffocate the seedlings. In addition, propagule buoyancy, period of obligate dispersal, anchoring time, tides, currents, wind and even dyke removal are primary factors determining dispersal and establishment of mangroves (Clarke, 1993; McGuinness, 1997; Di Nitto et al., 2013; Van der Stocken et al., 2013). After stranding and establishment, other factors become important in determining survival including predation, interspecific competition, flooding regime, and soil physico-chemical characteristics (Clarke et al., 2001; Delgado et al., 2001; Cannicci et al., 2008; Krauss et al., 2008). As stated by Duke et al. (1998), if (an adult specimen of) a species is present, the environment must be suitable for it, but the opposite does not apply. The shoreline of Mui Ca Mau is characterized by river alluvium and is a “soft shoreline” where the mangrove forest plays a vital important role in the erosion and accretion process of the coast (MAB Vietnam, 2008). The results show the mangrove shoreline is changing dynamically with erosion and accretion dominating along the East Sea and Gulf of Thailand, respectively.

Along the East Sea coastline, it was observed that some sections of the Ho Chi Minh road (Prime Minister, 2007, 2012) are being built about 1 km inland from the mangrove shoreline. If erosion persists along the East Sea, mangroves at some parts will be lost resulting in loss of their wave buffering and sheltering effect. This will threaten residential areas and infrastructure behind the mangrove, such as the Ho Chi Minh road. Similar situations are reported from Suriname, where dynamic mud banks shifting along the shore lead to mangrove destruction and eventually to road destruction (S. Naipal, personal communication, 2010). Therefore, adaptation measures combining “soft” and “hard” solutions focusing on wave reduction, facilitating accretion, and mangrove reforestation are needed. This is not only for the purpose of existing coastal protection but also long-term coastal engineering to take advantage of alluvium from the rivers in the Mekong Delta to advance the shoreline to the sea. In order to achieve success in these combined measures, the following recommendations should be considered by mangrove managers in the study area. Firstly, measures for accretion combining mangrove reforestation should be implemented seaward progressively. Secondly, infrastructure for wave reduction should be considered in short-term, simple and locally used material terms. For mangrove growth, these measures should aim to ensure the accretion rate is not too fast with too small-grained alluvium only. Thirdly, advanced

techniques for mangrove reforestation and protection should be considered.

Along the Gulf of Thailand, the mangrove shoreline of zone 3, from Rach Tau to the Cua Lon Estuary, is considered an important spawning ground for valuable aquatic species. There are about 8 billion breeding shrimps generated per year in Mui Ca Mau (MAB Vietnam, 2008). From interviews, it is noted that local people usually use rakes to illegally collect breeding aquatic organisms (fish, shrimp, clam, etc.) for livelihood. In the field, we observed fingerprints of peanut worms digging in the mangrove floor. These techniques threaten the aerial root system and propagules of pioneer mangrove species, especially *Avicennia* spp. In addition, Ha and van Dijk (2013) stated that overexploitation is unavoidable in nearshore waters because of the limitation of alternative sources of income. Therefore, the issue of overcapacity in aquaculture and capture fisheries needs to be addressed, and national policy is required to move a significant proportion of coastal livelihoods to non-marine livelihood alternatives (IUCN, 2012). In addition, public awareness should be raised. Mangroves on the three newly formed islands of Con Trong (zone 4), Con Ngoai (zone 5) and Con Moi (zone 6) have been growing naturally. These can potentially be open laboratories for scientific activities on mangrove ecosystems and should be strictly protected.

However, the capacity to implement any measure is not yet present. The staff of the Mui Ca Mau National Park lacks the numbers for functional operation. In order to be able to enlarge the mangrove protection zone and to maintain the present status of the forest, more staff is needed. It could be that volunteering co-workers will step forward after awareness has risen, but still encouragement by higher authorities is necessary (Van Dam, 2010).

Furthermore, there is a need for solutions concerning the lack of interaction between the different agencies responsible for the protection of certain aspects of mangrove management. Policies, laws and regulations governing mangroves in Vietnam are incoherent, incomplete and inconsistent. Consequently, attempts to manage mangrove ecosystems are frustrated by policy, legislative and regulatory complexity, confusion, contradiction and conflict. A root cause is that administrative responsibility for mangroves and the coastal area is shared among multiple government institutions within two ministries: the Ministry of Natural Resources and Environment, which is responsible for coastal planning, land allocation, biodiversity conservation, aquatic ecosystem management and protection, and climate change; and the Ministry of Agriculture and Rural Development, which is responsible for the management of forests, terrestrial and marine protected areas, capture fisheries, aquaculture, sea dykes, storm and flood control (IUCN, 2012). Even at a local scale there is a poor communication between the monitoring, managing and exploiting authorities. The contact of these groups with provincial authorities is hardly present (Van Dam, 2010). We agree with Ha et al. (2014) stating that forest management

in Ca Mau has become more decentralized on paper; however decentralization of management cannot be implemented because of both vertical (from central to local) and horizontal (among local) linkages. At the local level, the following measures should be considered by the public servants and officials: (i) allocation of mangroves and forestland to households for long-term use; (ii) management rights between contractors and sub-contractors; (iii) better dissemination of benefit sharing; (iv) allocating forests to different organizations; and (v) enhancement of monitoring and control mechanisms against lobbying or corruption (Ha et al., 2014).

## 5 Conclusions

The study on mangrove shoreline changes in Mui Ca Mau between 1953 and 2011 confirms that erosion and accretion, respectively, are significant along the East Sea and the Gulf of Thailand. Along 60 km of mangrove shoreline at the East Sea side, the mean LRR of erosion was found to be  $33.24 \text{ m yr}^{-1}$ . The accretion trend at the Gulf of Thailand side had an average rate of  $40.65 \text{ m yr}^{-1}$ .

The combination of remote sensing and GIS techniques is a helpful tool to detect mangrove shoreline movement changes over time in response to both natural and anthropogenic forces. The method should be good for application in other Mekong Delta areas where there has been erosion or where the situation is complex. Understanding the nature of changes, either natural or human, is a basic knowledge to facilitate suitable planning, management, and regulation of coastal wetland.

The results obtained from the study will aid scientists in predicting areas most at risk of erosion and/or progress of accretion in the future. Furthermore, it will facilitate the managers and decision makers to propose adaptation measures as well as to incorporate wetland management plans into plans and strategies at both provincial and national levels. Especially, it will contribute to a provincial, effective coastal zone management plan to respond to climate change and sea level rise in Ca Mau.

*Acknowledgements.* This study was supported by the Vlaamse Interuniversitaire Raad (VLIR) and the Mangrove Ecosystem Research Centre, Hanoi National University of Education in cooperation with Belgian Science Policy Office (BelSPO) and the Vietnamese Ministry of Science and Technology (MOST) project. We are thankful to colleagues of the Laboratory of Plant Biology and Nature Management, Vrije Universiteit Brussel, Belgium and the Center for HydroMet and Environment Consultancy, Institute of Meteorology, Hydrology and Environment, Vietnam for giving us facilities to carry out this study. The authors would like to thank Le Minh Loc (Ca Mau Forestry Department, Vietnam) and Nick Wilson (Forest Science Institute of South Vietnam) for their scientific comments. Further thank is given to Mui Ca Mau National Park for all logistics support in the field.

Edited by: B. Satyanarayana

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