Tropical Ecology (2019) 60:552–565
https://doi.org/10.1007/s42965-020-00053-1

International Society for Tropical Ecology

RESEARCH ARTICLE

# Monitoring changes in land use and distribution of mangroves in the southeastern part of the Mekong River Delta, Vietnam

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Received: 30 December 2018 / Revised: 12 October 2019 / Accepted: 4 December 2019 / Published online: 3 March 2020



## Abstract

Mangroves are one of the most valuable and productive coastal ecosystems. Previous studies show a severe loss of mangroves around the world over the last several decades due to natural and anthropogenic activities. Mangroves located in the southeastern part of the Mekong River Delta (MRD) are also affected by these activities. Shrimp farming is considered as one of the main drivers causing the rapid loss and degradation of mangroves. The goal of this study is to assess the spatiotemporal changes in land use and distribution of mangroves in the Soc Trang and Bac Lieu provinces of the southeastern part of the MRD. Multi-temporal Landsat data were used for land use and land cover (LULC) classification using the maximum-likelihood classification algorithm. The changes in mangrove forest areas were monitored using medium spatial resolution (Landsat-5 Thematic Mapper and Landsat-8 Operational Land Imager) satellite imageries from 1988 to 2018. In the study area, there were seven major LULC types namely, dense mangroves, sparse mangroves, aquaculture farms, arable land with crop cover, arable land without crop cover, settlements, and water bodies. The overall accuracies of the LULC maps in 1988, 1998, 2008, and 2018 were 81.2%, 83.3%, 78.3%, and 81.9%, respectively. This study reveals that dense and sparse mangrove forests have decreased by 90% from 5495 hectares (ha) to 515 ha and by 55% from 14,105 to 6289 ha, respectively from 1988 to 2018. On the other hand, the aquaculture farm has increased at the rate of 5024 ha/year for a period of 30 years. This rapid growth of aquaculture farming activities caused the rapid loss and degradation of mangroves in the MRD. Quantitative information about mangrove change obtained by this study is considered to be useful for future coastal management and relevant policies in the MRD.


**Keywords** Aquaculture · Landsat · Mangrove forests

## Introduction

Mangrove forests are generally referred to as tidal wetland ecosystems found in the intertidal zones between marine and terrestrial ecosystems (Saenger et al. 1983). Mangrove forests are restricted to the tropics and subtropics and considered highly productive ecosystems that provide various ecosystem services as well as climate change mitigation and adaptation (CCMA) options (Duncan et al. 2016). They serve as an enormous carbon sink, and at the same time provide climate and disturbance regulation services (Wylie et al. 2016). Besides, mangroves also play an important role in stabilizing the shoreline, preventing coastal erosion and well recognized in reducing the risks of tsunamis or storms (Danielsen et al. 2005; Vo et al. 2013; Blankespoor et al. 2014; Spalding et al. 2014; Van Coppenolle et al. 2018). Moreover, they also provide food, clean water, and other useful materials for local people (Phan et al. 2015). In addition,

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s42965-020-00053-1) contains supplementary material, which is available to authorized users.

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mangroves provide various benefits, which include aquatic resources, entertainment, ecotourism, biofiltration and so on (Locatelli et al. 2014; UNEP 2014).

The total mangrove area accounts for 0.7% of the total tropical forests in the world (Donato et al. 2011). In the Southeast Asian region, the area of mangrove forests cover was 37,019 $km^2$ and 35,694 $km^2$ in 2000 and 2012, respectively (Hamilton and Casey 2016). The largest extension of mangrove forests in 2010 was found in Asia with 42% of mangrove cover, followed by Africa with 20% (Long and Giri 2011). In Vietnam, the area of mangroves was estimated to be about 400,000 ha in the 1960s. The area declined dramatically to 73,000 ha in 1990 due to the use of herbicides during the Indo-China War, and the expansion of agriculture and aquaculture areas (FAO 2016). In Vietnam, the total mangrove area accounted for 270,000 ha in 2015 (FAO 2016).

In the Vietnamese part of the Mekong River Delta (MRD), mangrove forest ecosystems are recognized as one of the most productive and biologically complex ecosystems. These mangrove forest ecosystems have been mostly distributed along with the MRD's coastal provinces, including Tra Vinh, Ben Tre, Long An, Kien Giang, Ca Mau, and especially Soc Trang and Bac Lieu (Cosslett and Cosslett 2014). In recent decades, mangrove forest ecosystems have played vital roles not only in the biogeochemical cycle but also in providing a livelihood to the local people by aquaculture and fishing. Previous studies suggested that mangrove forests used to cover the the delta by more than 250,000 ha (Hong and San 1993; Thu and Populus 2007). The Indo-China War, forest fires, collection of fuelwood, and other human activities have resulted in the reduction of mangrove forests (Feller et al. 2017), thus increasing the potential risks of flooding and land subsidence (Bakker 2017; Truong and Do 2018). Especially, since the early 2000s, mangrove forests have been cleared for shrimp farming in many areas (Hong and San 1993; Hong 1995; Van Hao 1999). In addition, climate change has caused the sea level rise leading to saline water intrusion, which also causes a change in land use and mangrove distribution (Nguyen 2016; Dasgupta et al. 2017; Tran et al. 2019).

Among many factors that have affected the mangroves of the MRD, the most important factor contributing to mangrove destruction is the aquaculture activities (Thu and Populus 2007). Previous studies have demonstrated a complex relationship between mangroves and shrimp farming. Shrimp farming in the MRD has resulted in thousands of hectares of mangrove forests being converted to shrimp ponds. The pattern of land use and land cover (LULC) in the MRD has been changing significantly over the decades, consequently affecting both the economic growth and environmental sustainability in the region. There are a large number of previous studies that have been conducted, focusing on mangrove restoration and development in recent decades (Kaly and Jones 1998; Ellison 2000; Nguyen et al. 2016a, b; Lee et al. 2019). However, these studies have reported that mangrove restoration was a complex issue without sound and evidence-based restoration policies (Lee et al. 2019). Therefore, geospatial data-based information can play a significant role in providing evidence-based information about changes in mangrove forest areas and various drivers such as the expansion of aquaculture and its impacts on mangrove health. This analysis can help in understanding and identifying the complex relationship between mangrove status and aquaculture farming activities (Thu and Populus 2007).

The LULC classification is an integral part of extracting thematic information about various classes from the satellite data. It is useful for land resource management and planning. Multi-temporal LULC data are valuable sources of information to know the trajectory of various land use and cover types and change pattern. Monitoring the changes in LULC based on remote sensing was conducted in previous studies with the aim to monitor the cropping pattern (Nguyen et al. 2016a, b; Minh et al. 2019), as well as detecting the distribution of mangroves and urban areas at the local and global scales (Singh et al. 2010; Avtar et al. 2014; Vo et al. 2013; Avtar et al. 2017). The applications of geospatial data to study mangrove cover changes have been successfully demonstrated through previous studies (e.g. Singh et al. 2004; Muttitanon and Tripathi 2005; Giri et al. 2007; Lee and Yeh 2009; Vo et al. 2015; Avtar et al. 2018). Moreover, many studies have indicated that remote sensing has advantages over the traditional field-based investigation in the monitoring of mangrove forests because of the synoptic view and large area of coverage (Singh et al. 2010; Kuenzer et al. 2011; Avtar et al. 2017; Pham et al. 2019). The use of multi-spatiotemporal geospatial data can provide useful information about mangrove forests globally. Pham et al. (2019) have reviewed the role of multispectral, Synthetic Aperture Radar (SAR), as well as hyperspectral data for estimating various biophysical parameters of mangroves. Their study summarized the most commonly used methodologies globally for estimating the biophysical parameters of mangroves. Among these methodologies, the pixel-based classification methods are considered the most commonly used in mangrove classification (Tong et al. 2004; Binh et al. 2005; Thu and Populus 2007; Kamal and Phinn 2011; Avtar et al. 2017). Supervised classification algorithms were effectively used for mangrove classification using traditional satellite data (Conchedda et al. 2008; Giri et al. 2011; Kuenzer et al. 2011).

Although there are many studies on the impacts of shrimp farming on mangrove change, most of them focused on limited provinces of MRD, such as Kien Giang, Ca Mau, Tra Vinh, and Ben Tre (Thu and Populus 2007; Van Cuong et al. 2015; Vo et al. 2015; Nguyen and Parnell 2019). In

Soc Trang and Bac Lieu provinces, the sea dyke system has been built to protect the residential area for the purpose of economic development in the area. At present, coastal erosion along with deforestation for aquaculture has not been adequately controlled. Therefore, local authorities have a plan to protect the mangroves and rehabilitate the mangroves outside the sea dyke, which is considered essential. In addition, local authorities have co-operated with villagers to co-manage mangrove forests inside sea dykes through the benefits of mangrove-shrimp farming (DARD 2017).

Therefore, due to the limited comprehensive data on temporal changes in the mangrove ecosystems of Soc Trang and Bac Lieu provinces, this study provides a comprehensive assessment of long-term changes in mangroves distribution and its relationship with aquaculture activities. This study investigates the potential application of Landsat data using the maximum-likelihood classification (MLC) algorithm to monitor land cover changes and mangroves distribution in the Soc Trang and Bac Lieu provinces from 1988 to 2018. Change detection methods were also used to have better visualization and understanding of changing trends of mangrove forests. This study can support the local government in the decision-making process for land use planning and management practices in the future such as mangrove plantation plans for sea dyke's protection, policies of mangroves development along with aquaculture.

## Materials and methods

### Study area

In the study, two coastal provinces in the southeastern region of the MRD, namely Soc Trang (Lat. 9°12′N–9°56′N, Long. 105°33′E–106°23′E) and Bac Lieu (Lat. 9°00′–9°38′9″N, Long. 105°14′15″–105°51′54″E) were selected (Fig. 1). The total coastline is about 128 km in length, of which Soc Trang and Bac Lieu provinces cover 72 km and 56 km, respectively (DARD 2017). In terms of climatic features, Soc Trang and Bac Lieu provinces are located in the tropical climate zone with high monthly mean atmospheric temperature (Evers and Benedikter 2009; Ha et al. 2018; Huu 2011). These provinces have two distinct seasons, i.e. wet season (from May to November) and dry season (from December to April). The average annual rainfall in Soc Trang and Bac Lieu varies from 2000 to 2300 mm (DARD 2017). Noticeably, in the dry season, rainfall accounts for only 10% of the total annual rainfall, with almost no rain (often triggering droughts) in January through March, while the rainy season

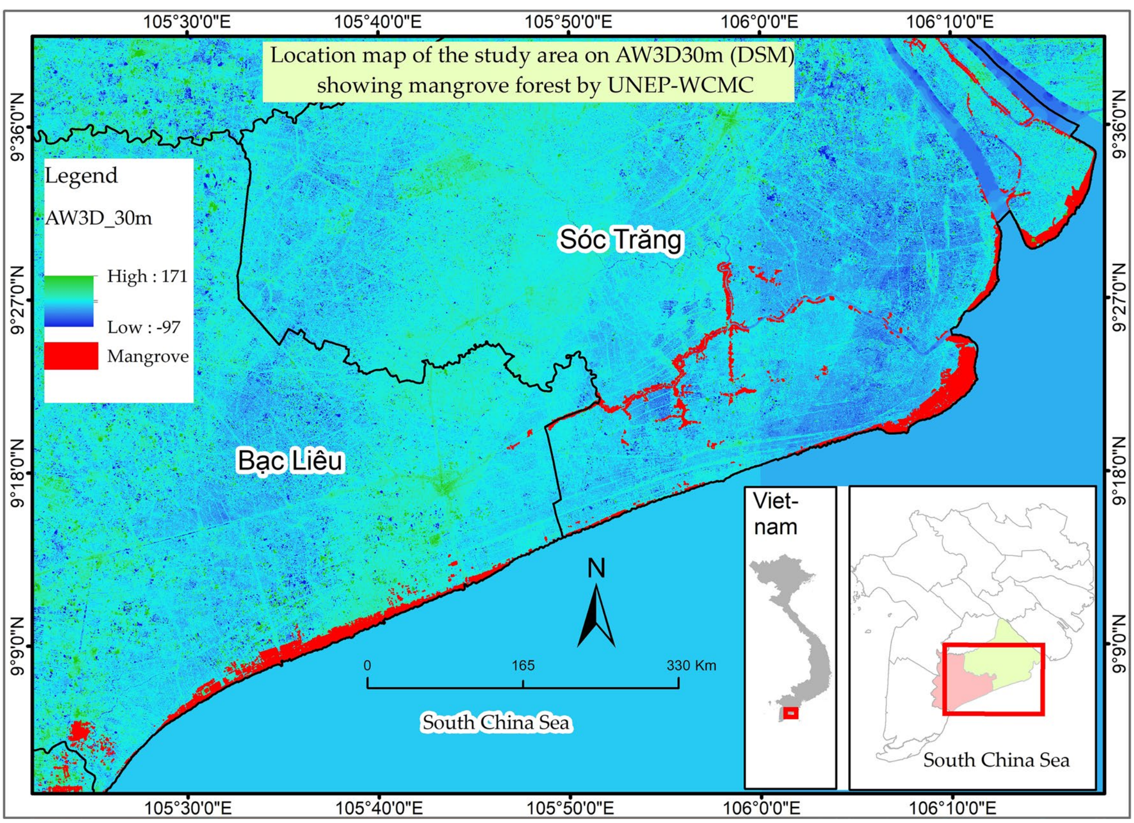



**Fig. 1** The location of Soc Trang and Bac Lieu provinces in the MRD, Vietnam, and distribution of field survey points

has continuous rain occasionally that can last for 3–5 days causing serious flooding (DARD 2017). The annual mean atmospheric temperature is 26 °C, with a maximum temperature of 30 °C in April and May and a minimum temperature of 20 °C in December and January. The average annual sunshine hours are 2500–2600 (DARD 2017).

According to the Department of Agriculture and Rural Development (DARD), the average humidity during the dry season is around 80% (DARD 2017). Historical data from the Meteorological Department (MD) shows that the increase in average humidity in Soc Trang and Bac Lieu provinces is up to 85% during the wet season (DARD 2017). Noticeably, although Soc Trang and Bac Lieu provinces are warm coastal provinces, they are less affected by storms, and tropical cyclones. However, they are under strong impacts of the semi-diurnal system of the East Sea tides and a part of the diurnal system of the West Sea. The monthly average water level of high and low tides in Soc Trang and Bac Lieu provinces varies between − 1.9 and 1.9 m (DARD 2017). Climate change in recent years is expected to increase the risk in the study area, due to flooding from the Mekong River as well as droughts and seawater intrusion (Toan 2014; Hak et al. 2016).

## Field data

In this study, two field surveys were conducted from June 1 to July 30, 2017 and from March 15 to April 15, 2018, to collect ground truth data necessary for LULC classification and validation of results. In the field surveys, 170 and 125 field sites were randomly selected in the Soc Trang and Bac Lieu provinces, respectively. Global Positioning System (GPS) device (Gamin 60x) was used to mark the locations of various LULC types. The GPS photos were also collected for various LULC types. The geo-tagged photos are highly effective in improving the accuracy of the LULC classification (Oba et al. 2014). These photos have clearly shown the difference in the vegetation vigor and density of mangrove forests in the Soc Trang and Bac Lieu provinces. Figure 2 shows the distribution of the ground truth data collected during the field survey. Figure S1 shows dense mangrove forests defined as the area in which the average mangrove density is more than 5000 trees per ha (The People's Committee of Bac Lieu Province 2017). The mangroves are mainly located along the national sea dyke systems (Fig. S1a, b). A part of the mangroves located outside the sea dyke systems was affected by high waves and was gradually swept into the sea water (Fig. S1c).

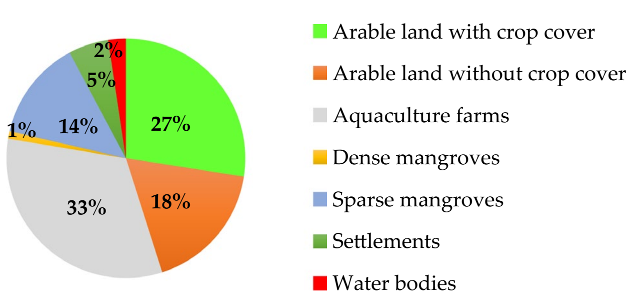



**Fig. 2** Distribution of ground truth data collected in Soc Trang and Bac Lieu provinces

In Fig. S2, the sparse mangrove forests are shown with an average mangrove density of less than or equal to 5000 trees per ha (The People's Committee of Bac Lieu Province 2017). At some field sites, the mangrove forests' density and age were directly observed according to information by DARD (2017). In addition, the total percent of mangroves cover in each aquaculture farm associated with aquaculture production were also investigated. This information and data were used as training samples for the MLC of Landsat data and validation. Each training site was delineated on the images using polygons that cover multiple pixels in the homogeneous areas. The ground data were collected based on the homogeneity of the area/class to cover the representative sample of Landsat data. The status of mangrove forests and aquaculture farming areas were also recorded as pieces of evidence for the validation of results. Besides ground truth data, high spatial resolution images on Google Earth (GE) and administrative land use maps at the provincial-level (Bac Lieu and Soc Trang) were used for validation of the classification results.

Xu et al. (2017) demonstrated the importance of field photographs in identifying the various LULC types and landscapes in the study area. Figures S1, S2, S3, S4, and S5 show a number of geo-tagged photographs with the density of mangrove forests, aquaculture farms, as well as arable land with and without crop cover. The selection of ground truth data was based on the number of classes for LULC classification. Figures S3, S4, and S5 show the aquaculture area, arable land with crop cover, and arable land without crop cover, respectively.

## Satellite data

In this study, Landsat-5 TM and Landsat 8 OLI data of 1988, 1998, 2008, and 2018 were downloaded from the United States Geological Survey (USGS) server (https://earthexplorer.usgs.gov/) for land cover classification. The Landsat data with less than 10% of cloud cover were selected from Landsat archived. Table 1 summarizes the detailed information of the satellite data that was used in this study in every 10-years period. Landsat data were only collected in the dry season to eliminate not only the effects of clouds and shadows, but also the change in surface reflectance in different seasons.

**Table 1** Detailed information of satellite data collected from the USGS server

| Satellite | Sensor | Path/row | Spatial resolution (m) | Date of acquisition |
|---|---|---|---|---|
| Landsat 5 | TM | 125/53<br>125/54 | 30 | 30 January 1988 |
| Landsat 5 | TM | 125/53<br>125/54 | 30 | 30 January 1998 |
| Landsat 5 | TM | 125/53<br>125/54 | 30 | 9 March 2008 |
| Landsat 8 | OLI | 125/53<br>125/54 | 30 | 5 March 2018 |

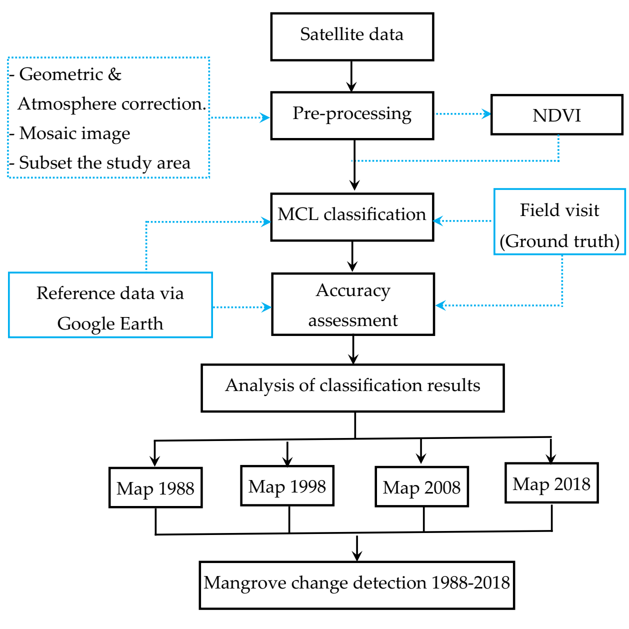



**Fig. 3** Flowchart of the methodology of the study

## Landsat data processing

Figure 3 shows the methodology adopted in this study. Information about various objects on the earth's surface was generated from the Landsat data using reflectance information in the form of digital number (DN) (Avtar et al. 2014). Visual image interpretation techniques were also used to visualize the quality of data as well as various land cover types. Different forms of distortion or shift were noticed and considered during the visual interpretation process. Therefore, the geometric rectification, including image-to-image registration was applied. The image enhancement and histogram matching techniques were also used to enhance the quality of the image (Tokola et al. 2001; Moreira and Valeriano 2014; Sari and Rosalina 2016). In the study, the Normalized Difference Vegetation Index (NDVI) was also generated to monitor the spectral reflectance properties of vegetation. The NDVI was calculated as expressed in Eq. (1):

$$\text{NDVI} = (\text{NIR}-\text{Red})/(\text{NIR}+\text{Red}) \quad (1)$$

where NIR is the reflectance at the near infra-red band, and Red is the reflectance at the red band.

NDVI has been widely used to identify various vegetation types (Rouse Jr et al. 1974; Ruiz-Luna et al. 2010; Avtar et al. 2011; Alatorre et al. 2016; Mohajane et al. 2018). The dense and sparse mangrove forests, agriculture areas, and aquaculture areas can be differentiated using NDVI values. Therefore, we further used NDVI in MLC classification.

## Image classification

There are various classification algorithms for LULC classification. Among these algorithms, the MLC is widely used due to its successful applications (Townshend 1992; Hall et al. 1995; Lillesand et al. 2015; Dan 2017). The MLC is a parametric classification algorithm that assumes a classed signature in a normal distribution (Gaussian statistical distribution) and statistically calculates the probability that a particular pixel belongs to a particular class (Ramsey III and Jensen 1996). Each pixel is assigned to the class that has the highest probability (Hall et al. 1995; Dan 2017). The ArcGIS 10.4 and ENVI 5.2 software were used for classification and change detection. It was also a useful tool to determine the relationship between the LULC class and spectral reflectance. Each LULC map was classified into seven classes, namely, dense mangroves, sparse mangroves, aquaculture farms, arable land with crop cover, arable land without crop

**Table 2** Land-cover classified in this study

| Land-cover class | Description |
|---|---|
| Water bodies | Rivers, canals |
| Aquaculture farms | Shrimp farms |
| Settlements | Residence, commercial, industrial, transportation |
| Arable land without crop cover | No vegetation covered |
| Arable land with crop cover | Rice fields, fruit gardens |
| Sparse mangroves | Mangrove coverage of less than 50% |
| Dense mangroves | Mangrove coverage of more than 50% |

cover, settlements, and water bodies (Table 2). The selection of classes for classification was based on the fieldwork and other existing maps.

### Accuracy assessment

In this study, LULC maps were generated using Landsat data and MLC algorithm. An accuracy assessment of classified maps was done using the confusion matrix. The ground truth data collected during field surveys and Google Earth (GE) images were used for accuracy assessment of classified maps (Congalton 1991; Islam et al. 2019). The sampling points were randomly collected during the field surveys. These points were converted to GE images to see the coverage and distribution in different land cover categories. These points were compared with locations on the GE images to cross-validate their locations' accuracy. In the process of LULC classification, the maps of mangrove classification were compared with the available mangrove maps from official mapping sources to avoid misclassification between mangroves and other crops. The overall accuracy and kappa coefficients were also calculated to evaluate the agreement between reference and prediction data (Congalton 1991; Liu et al. 2008; Long and Giri 2011).

## Results

### Land use and land cover maps

The spatiotemporal pattern of various LULC classes for 1988, 1998, 2008, and 2018 Landsat data using MLC classifier are shown in Fig. 4. The agricultural area was mostly located in the upper region of the study area. The mangrove forests were commonly distributed in the coastal regions, while most of the aquaculture farms were located between agricultural lands and mangrove forests.

The temporal changes in the LULC classes from 1988 to 2018 were illustrated in Fig. 5. The arable land with crop cover was the most dominant land cover type, amounting to 463,376 ha (80.9%) of the total area in 1988. The areas of dense and sparse mangrove forests were only 5495 ha (1.0%) and 14,105 ha (2.5%), respectively, in 1988. The aquaculture area covered 9673 ha (1.7%) in 1988. Noticeably, the aquaculture farms have significantly increased, reaching 160,393 ha (28.0%) in 2018. The opposite trend was seen in the total area of arable land with and without crop cover. The total area of agricultural land gradually decreased over the 30 years from 526,221 ha in 1988 to 387,102 ha in 2018. In terms of the settlement area, this area had increased from 95 ha in 1988 to 2660 ha in 2018. The areas under water

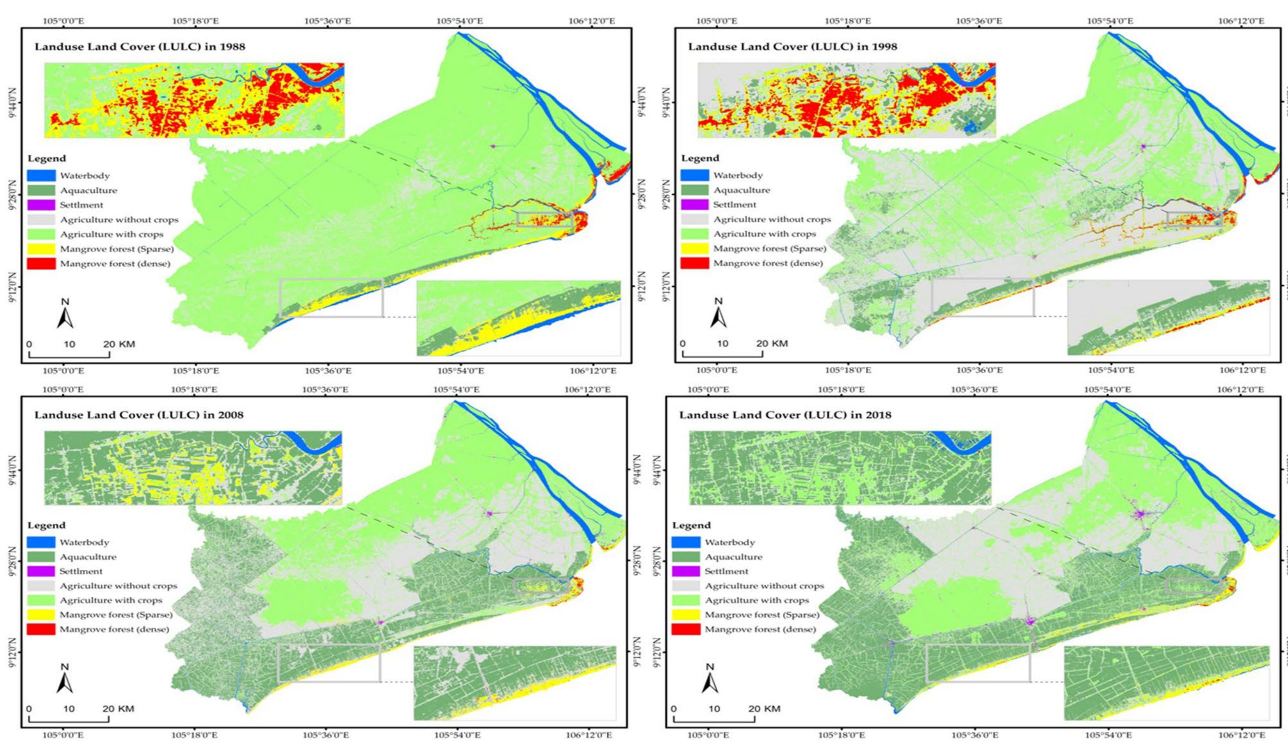
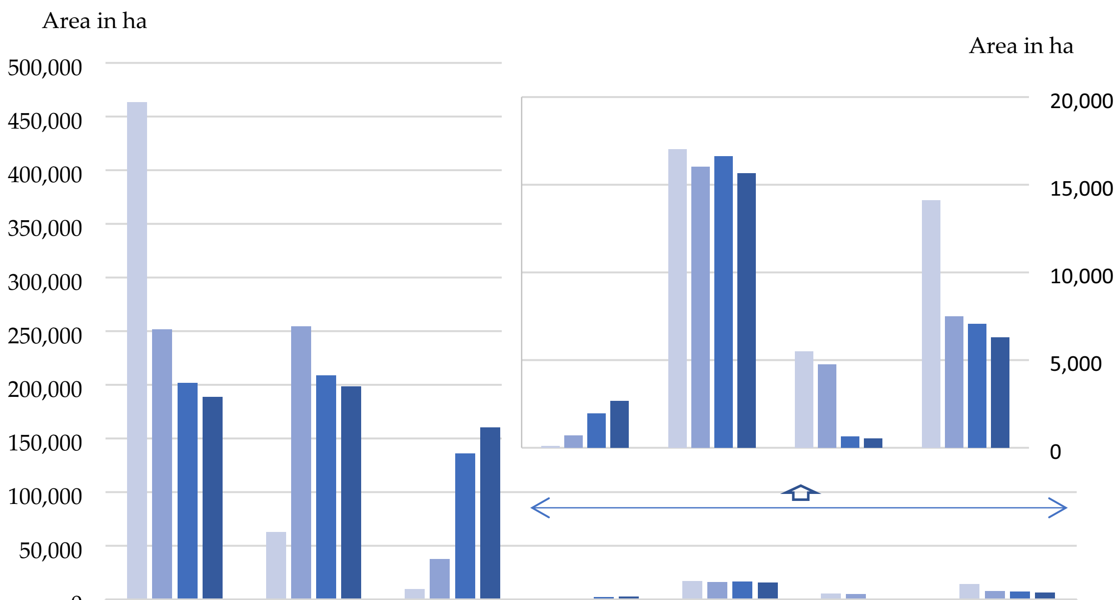



**Fig. 4** The LULC classification maps of Soc Trang and Bac Lieu provinces of the years 1988, 1998, 2008, and 2018, based on MLC of Landsat 5 TM (1988, 1998 and 2008) and Landsat 8 OLI (2018) images




| | Arable land with crop cover | Arable land without crop cover | Aquaculture farms | Settlements | Water bodies | Dense mangroves | Sparse mangroves |
|---|---|---|---|---|---|---|---|
| 1988 | 463,376 | 62,844 | 9,673 | 95 | 17,017 | 5,495 | 14,105 |
| 1998 | 251,616 | 254,474 | 37,567 | 692 | 16,013 | 4,740 | 7,503 |
| 2008 | 201,704 | 208,580 | 136,051 | 1,943 | 16,610 | 644 | 7,074 |
| 2018 | 188,776 | 198,326 | 160,393 | 2,660 | 15,646 | 515 | 6,289 |

**Fig. 5** Changing pattern of LULC classes in the study area from 1988 to 2018

bodies showed a slight decrease, from 17,017 ha in 1988 to 15,646 ha in 2018, but the change may be affected by seasonal variations in water coverage in the study area.

The results showed that mangrove forests were extensively distributed in the coastal regions of Soc Trang and Bac Lieu provinces and along the rivers interlinked with sea water. The decrease in the areas of dense and sparse mangroves from 1988 to 2008 was faster than that from 2008 to 2018. The annual rates of change in dense mangrove forests were 243 ha/year and 13 ha/year from 1988 to 2008 and 2008 to 2018, respectively. The annual change rates of sparse mangroves were 352 ha/year and 79 ha/year from 1988 to 2008 and 2008 to 2018, respectively. The study reveals that the annual deforestation rate of sparse mangroves was more than that of dense mangroves. Mangrove deforestation in the study area was caused by various drivers in the MRD. Indeed, previous studies pointed out that these drivers include shrimp farming (De Graaf and Xuan 1998; Johnston et al. 2000; Ha et al. 2014), the Indo-China war, and human activities such as cutting down trees for fuelwood or agricultural area expansion (Hong and San 1993; Orchard et al. 2016). This low rate was mainly due to the mangrove conservation projects and programmes in the MRD in recent years. One thing to note is that the annual rate of change in the aquaculture farms from 1988 to 2018 (5024 ha/year) was higher than that in previous periods. As mentioned earlier, the expansion of aquaculture farms was mainly occurred in between mangroves and agricultural areas, implying prominent land-use change from mangroves to agricultural areas (Fig. 4).

Generally, the results of the LULC classification show the decline in the mangrove forest area, while the calculated NDVI value indicates the degradation of the mangroves quality. Therefore, the NDVI-based analysis can be used to monitor mangrove density as reported by previous studies (Adi and Sari 2016; Sari and Rosalina 2016). Figure 6 shows the temporal variation in the mean NDVI of dense and sparse mangrove forests. The mean NDVI values of dense mangroves were always higher than that of sparse mangroves. As can be seen from the figure, the mean NVDI values of dense mangroves show a decreasing trend. This trend shows that together with the dense mangrove forest area, the quality of dense mangrove forests has also declined during the 1988 to 2018. In the case of sparse mangroves, the mean NVDI values have increased from 1988 to 1998, then have decreased gradually from 1998 to 2018.

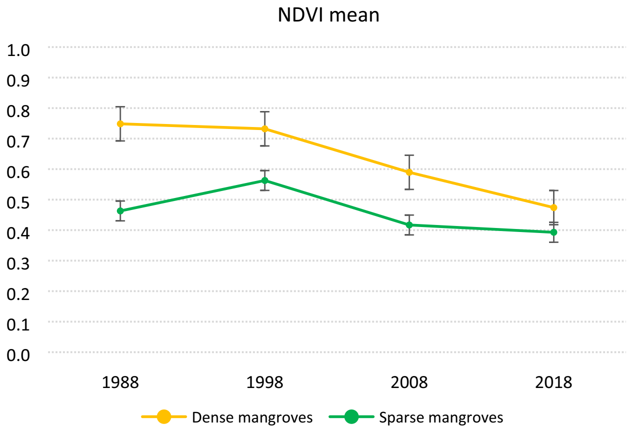



**Fig. 6** The NDVI mean values of dense and sparse mangroves in the years 1988, 1998, 2008, and 2018

## Accuracy assessment

In terms of the validation of classified images, 420 sampling points were randomly created. The accuracy assessment results are shown in "Supplementary Material 1" of LULC maps of 1988, 1998, 2008, and 2018. Table 3 illustrates the overall accuracy of LULC maps and kappa coefficient based on a confusion matrix. The overall accuracy of LULC maps for the year 1988, 1998, 2008, and 2018 were 81.2%, 83.3%, 78.3%, and 81.9%, respectively, and the kappa coefficient were 0.78, 0.81, 0.75, and 0.79, respectively.

## Change detection

Table 4 shows clear changes in LULC area in every 10-year period between 1988 and 2018. This study reveals that mangrove forests have decreased by 12,796 ha from 1988 to 2018 in the Soc Trang and Bac Lieu provinces. In the first 10-year period (1988–1998), the area of sparse mangroves had rapidly decreased by 6602 ha and continued to decline by 7816 ha during the last 30 years. The decrease was mainly due to the expansion of aquaculture farms in the coastal regions of the MRD.

The magnitude of change in different LULC classes from 1988 to 2018 is shown in Table 5. It is clearly seen that the aquaculture farms have increased, amounting to approximately 152,839 ha during the last 30 years. The LULC classes of arable land with crop cover, arable land without

**Table 3** The accuracy assessment of the land cover maps from 1988 to 2018

| Class | 1988 | | 1998 | | 2008 | | 2018 | |
|---|---|---|---|---|---|---|---|---|
| | PA (%) | UA (%) | PA (%) | UA (%) | PA (%) | UA (%) | PA (%) | UA (%) |
| C1 | 95.0 | 86.4 | 98.3 | 98.3 | 91.7 | 96.5 | 80.0 | 90.6 |
| C2 | 75.0 | 80.4 | 78.3 | 78.3 | 71.7 | 82.7 | 76.7 | 82.1 |
| C3 | 81.7 | 79.0 | 80.0 | 98.0 | 71.7 | 81.1 | 85.0 | 81.0 |
| C4 | 78.3 | 72.3 | 81.7 | 60.5 | 75.0 | 57.7 | 85.0 | 75.0 |
| C5 | 78.3 | 79.7 | 75.0 | 83.3 | 76.7 | 62.2 | 83.3 | 73.5 |
| C6 | 75.0 | 86.5 | 78.3 | 92.2 | 76.7 | 76.7 | 80.0 | 84.2 |
| C7 | 85.0 | 85.0 | 91.7 | 84.6 | 66.7 | 87.0 | 83.3 | 90.9 |
| Overall accuracy (%) | 81.2 | | 83.3 | | 78.3 | | 81.9 | |
| Overall kappa coefficient | 0.78 | | 0.81 | | 0.75 | | 0.79 | |

*PA* producer's accuracy, *UA* user's accuracy; *C1* water bodies, *C2* aquaculture farms, *C3* settlements, *C4* arable land without crop cover, *C5* arable land with crop cover, *C6* sparse mangroves, *C7* dense mangroves

**Table 4** The changes in LULC area in every 10-year period between 1988 and 2018

| Land cover | 1988–1998 | | 1998–2008 | | 2008–2018 | | 1988–2018 | |
|---|---|---|---|---|---|---|---|---|
| | ha | % | ha | % | ha | % | ha | % |
| C1 | − 1004 | − 0.18 | 597 | 0.10 | − 964 | − 0.17 | − 1371 | − 0.24 |
| C2 | 27,894 | 4.87 | 98,484 | 17.20 | 24,342 | 4.25 | 150,720 | 26.32 |
| C3 | 597 | 0.10 | 1251 | 0.22 | 717 | 0.13 | 2565 | 0.45 |
| C4 | 191,630 | 33.47 | − 45,894 | − 8.01 | − 10,254 | − 1.79 | 135,482 | 23.66 |
| C5 | − 211,760 | − 36.98 | − 49,912 | − 8.72 | − 12,928 | − 2.26 | − 274,600 | − 47.96 |
| C6 | − 6602 | − 1.15 | − 429 | − 0.07 | − 785 | − 0.14 | − 7816 | − 1.36 |
| C7 | − 755 | − 0.13 | − 4096 | − 0.72 | − 129 | − 0.02 | − 4980 | − 0.87 |

*C1* water bodies, *C2* aquaculture farms, *C3* settlements, *C4* arable land without crop cover, *C5* arable land with crop cover, *C6* sparse mangroves, *C7* dense mangroves crop cover, sparse mangroves, and dense mangroves converted into aquaculture farms by 27.1%, 29.1%, 45.7%, and 35.4%, respectively. One thing to note is that the settlements and water bodies accounted for the lowest percentages of the total LULC categories. The total unchanged areas of these two classes represented 80% and 78% during the last 30 years, respectively.

Figure 7 shows the geospatial distribution of LULC changed and unchanged areas from 1988 to 2018. During the period 1988–2018, the total area of regional land-use change accounted for 62.9%, while the total unchanged area was 37.1%. The annual rate of change was 11,998 ha/year. The results show that the major LULC change was due to the expansion of aquaculture farms. The aquaculture farms accounted for approximately 160,406 ha and increased from 1.7% in 1988 to 28.0 % in 2018. During that period, dense and sparse mangroves were converted into aquaculture farms by 35.4% and 45.7%, respectively. Besides, arable land with crop cover was converted into aquaculture farms areas by 27.1% (Table 5). Mangrove areas in the Soc Trang and Bac Lieu provinces have been continuously decreasing over the years. In 2018, the total mangrove forest area in these two provinces was 6804 ha. More than 90% of dense mangrove areas and 55% of sparse mangrove areas had reduced during the study period of 30 years. It can be indicated that settlements continued to increase, while both arable land with crop cover and mangrove forests decreased. In fact, mangrove forests were converted into not only aquaculture farms but also agricultural areas.

## Discussion

### Spatio-temporal changes of mangrove forests

The multi-temporal LULC maps show the changing trends of the LULC classes in a simplified way (Fig. 4). These maps illustrate the changing pattern of various LULC classes. For instance, the aquaculture farming areas were mainly expanded in between the agriculture areas and mangrove forests, as mangrove forests serve as nurseries and food-supplies for marine and brackish water animals, and therefore, have high potentials to function as aquaculture farming areas as well once converted. The mangroves also absorb wastes generated by shrimp farming (Gautier et al. 2001; Wösten et al. 2003). The key findings of the study show that the areas of agriculture, dense and sparse mangroves, and water bodies in Soc Trang and Bac Lieu provinces have decreasing trends of LULC change, while the areas of aquaculture farms and settlements show increasing trends. Findings from this study are similar to those from previous studies (Tong et al. 2004; Binh et al. 2008). The previous studies have reported that a large number of mangrove and agricultural lands in the MRD have been converted into aquaculture farms during the last decades. Consequently, it is clear that the rapid increase in the aquaculture farms in the MRD have negative impacts on mangroves. One of the recent studies (Truong and Do 2018) also reported a decrease in the mangrove forests in the MRD.

**Table 5** The post-classification change detection matrix indicating the direction of change between 1988 and 2018

| LULC classes changes | From | | | | | | |
|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| To (ha) | | | | | | | |
| C1 | 13,103.73* | 53.37 | 10.89 | 75.69 | 1986.39 | 77.49 | 29.25 |
| C2 | 396.99 | 7964.50* | – | 13,899.60 | 137,993.94 | 6560.19 | 1952.46 |
| C3 | 74.34 | 36.72 | 60.03* | 91.89 | 1811.52 | 14.13 | 6.39 |
| C4 | 624.24 | 1125.18 | 14.85 | 21,499.83* | 162,931.14 | 3135.42 | 599.22 |
| C5 | 675.27 | 403.29 | – | 15,447.15 | 168,181.38* | 2868.48 | 1817.82 |
| C6 | 1849.32 | 421.83 | – | 200.97 | 1590.39 | 1654.20* | 918.28 |
| C7 | 166.95 | 13.32 | – | 2.88 | 7.83 | 61.83 | 190.53* |
| To (%) | | | | | | | |
| C1 | 77.58* | 0.53 | 12.70 | 0.15 | 0.42 | 0.54 | 0.53 |
| C2 | 2.35 | 79.50* | – | 27.14 | 29.08 | 45.65 | 35.41 |
| C3 | 0.44 | 0.37 | 69.99* | 0.18 | 0.38 | 0.10 | 0.12 |
| C4 | 3.70 | 11.23 | 17.31 | 41.98* | 34.34 | 21.82 | 10.87 |
| C5 | 4.00 | 4.03 | – | 30.16 | 35.44* | 19.96 | 32.97 |
| C6 | 10.95 | 4.21 | – | 0.39 | 0.34 | 11.51* | 16.65 |
| C7 | 0.99 | 0.13 | – | 0.01 | – | 0.43 | 3.46* |

*C1* water bodies, *C2* aquaculture farms, *C3* settlements, *C4* arable land without crop cover, *C5* arable land with crop cover, *C6* sparse mangroves, *C7* dense mangroves

Asterisks (*) show unchanged areas (the areas that were not converted to any other classes)

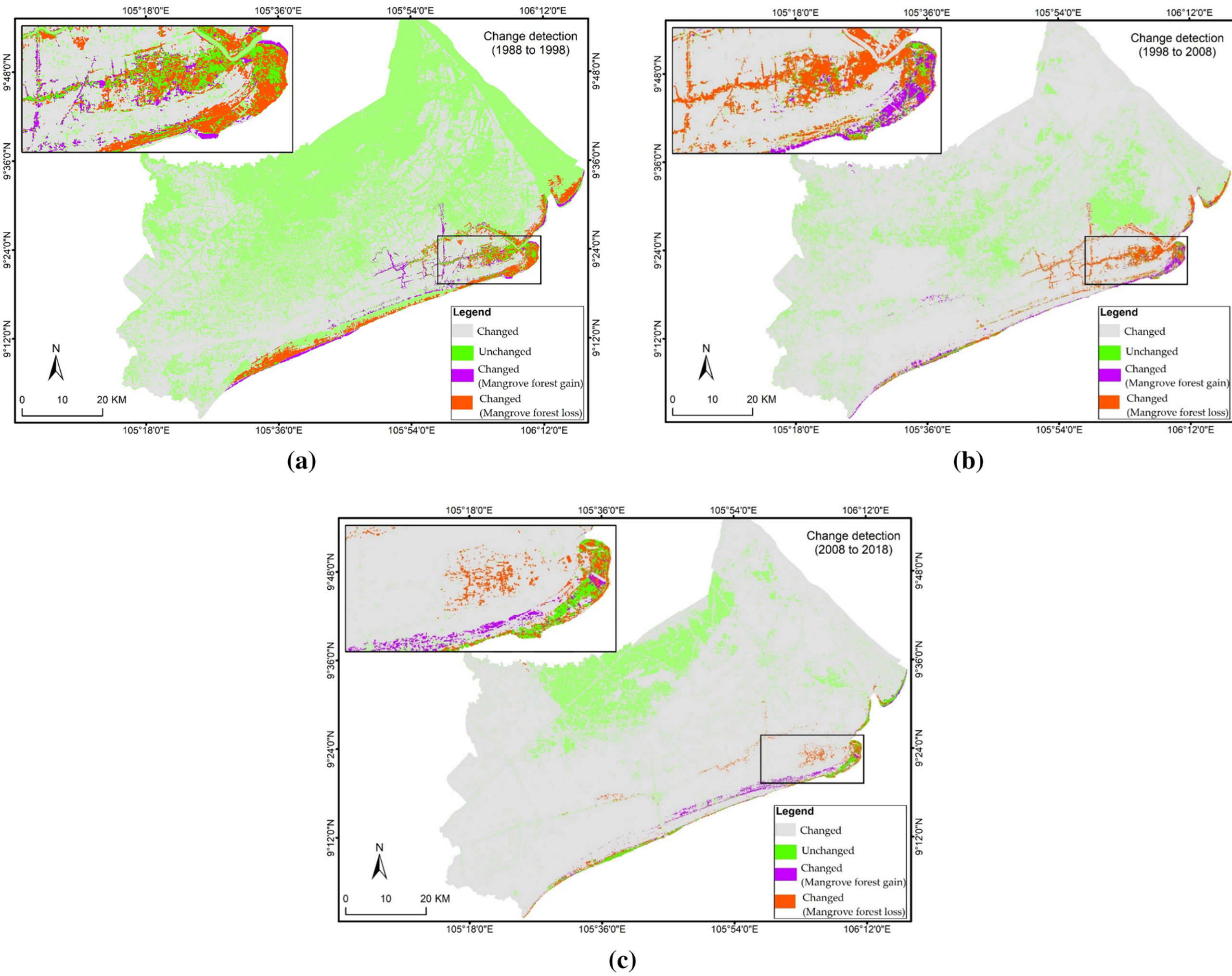



**Fig. 7** Change detection of mangrove forests **a** from 1988 to 1998, **b** from 1998 to 2008, and **c** from 2008 to 2018

The aquaculture area in the study site has increased rapidly from 1988 to 2018. It is believed that aquaculture has brought more economic benefits than maintaining and conserving mangrove forests (Vo et al. 2013). From 2008 to 2018, both dense and sparse mangrove forests only slightly decreased, which was due to a number of national and international mangrove forest conservation projects and programs. Mangroves, mainly *S. caseolaris*, were planted in the mudflats along the coastal lines in the MRD, especially in Cu Lao Dung district, Soc Trang province (DARD 2017). The mangrove replantation in the MRD usually occurred after the sediment deposition in the shallow seabed. In Bac Lieu province, however, the replantation as well as conservation of mangrove forests have been limited in recent years due to the serious erosion in the coastal lines.

Based on the analysis of NDVI, it is clear that the quality of mangroves (especially density of mangroves) has also changed. A series of results of field observation data, Landsat data and NDVI-based analysis suggest that dense mangroves have been damaged severely compared to sparse mangroves between 1988 and 2018. The NDVI-based analysis shows that there was a fluctuation in the density of sparse mangroves during the study period. It shows an increasing pattern for the period 1988–1998 and a decreasing pattern for the period 1998–2018. Noticeably, the decreasing pattern for the period 1998–2018 was mainly due to a number of mangrove forest management policies in the regional master plan that was approved by the Prime Minister in the 1996–1999 and 2000–2006 periods (FAO 2016). Under these policies, an households or organization can convert up to 40% of mangroves area to other uses such as housing and aquaculture (mainly shrimp farms—i.e. shrimp farmers in protection and production mangrove forests must maintain at least 60% mangrove canopy cover) (Decision 186/2006/QD-TTg). According to this plan, the mangrove areas in the MRD, including Soc Trang and Bac Lieu provinces, were divided into three zones such as full protection zone, buffer zone, and economic zone. In these zones, 60% of the land area was used for mangrove forest development, and the rest (40%) was used for aquaculture (mainly shrimp farming), agriculture, and other utilizations (Minh et al. 2001).

Together with other Asian countries such as India and Thailand, the mangrove forest areas in the MRD have a decreasing trend in recent decades as a result of the economic benefits (Liu et al. 2008). The recovery of the mangrove forests as well as ecosystem protection in the MRD are major challenges for the Vietnamese government. However, recovery and conservation of the mangrove forests are crucial not only for the ecosystem protection in Soc Trang and Bac Lieu provinces but also for sustainable development in the MRD. Therefore, the application of advanced techniques for the assessment of LULC change is very essential for better mangrove forest management. In this study, the use of moderate resolution (30 m) Landsat data has enabled the monitoring of spatio-temporal changes in mangroves in the study area because of low-cost or free data, long temporal coverage, and wider spatial coverage of Landsat data (Vo et al. 2013; Aziz et al. 2015; Giri et al. 2015; Ottinger et al. 2016). However, these data still have limitations of clouds and shadows which can affect the accuracy of classification (Avtar et al. 2014, 2017). Therefore, the use of high-resolution satellite data along with in situ information can improve the accuracy of classification. Use of SAR data can help to overcome the limitation of clouds and shadows (Vo et al. 2013; Nguyen et al. 2016a, b; Avtar et al. 2018; Minh et al. 2019) and can also provide more information about biophysical parameters of mangroves, such as biomass, density and height. For example, (e.g. Avtar et al. 2014, 2017) had successfully applied SAR satellite images to detect forest area and biomass. Pham et al. (2018) have applied SAR data to observe the mangrove forest changes in the MRD. Thus, such applications could be widely used in the MRD in the future. SAR data were not used in this study because of the unavailability of historical SAR data. In the future, we can study about the role of distance from the coastal areas in mangroves degradation and impacts of socio-economic factors on change in mangroves areas.

### Driving factors of mangrove degradation

Mangrove forest dynamics are undergoing constant changes due to both natural and anthropogenic forces. The decrease in mangrove areas was mainly due to an expansion of aquaculture farms. Besides aquaculture farms, mangrove areas have been lost due to fuelwood collection and cutting of mangrove trees for house construction materials (Thu and Populus 2007). Moreover, the rapid urbanization along the coastal regions had been noticed through the field surveys in the study area. Baumgartner et al. (2016) found that the degradation of mangroves in the MRD was also caused by the short-term mangrove exploitation for immediate economic benefits by local communities rather than long-term sustainable use of mangroves. Local farmers have individually expanded their aquaculture land without land-use planning. Besides, there are small new segments of the mangroves that were planted along the coast, especially in the mudflats area outside the sea dyke systems (Albers and Schmitt 2015; Joffre et al. 2018).

Recently, the Vietnamese government has allowed local people to join mangrove protection along with aquaculture farming activities under a model of "land use allocation for forestry production purposes". For example, DARD (2017) showed that the Nha Mat district of Bac Lieu province was one of the regions that allowed local farmers to join the above model. In this model, the local people can use 30% of the mangrove area for their aquaculture production for a 5-years period (Truong and Do 2018). However, a large number of local people had gradually cut down the roots of mangroves. As a result, these mangroves become weak or dead. The information collected from local people through two field surveys revealed that the mangrove forest coverage has affected the aquaculture production. In fact, local authorities allow households who have contracted co-management of mangrove forest to convert up to 40% of mangrove area where aquaculture is combined. This was consistent with Truong and Do (2018) that revealed that if mangroves coverage is more than 60% then it had a negative impacts on shrimp productivity. Therefore, the use of accurate mangrove coverage area maps can be helpful for local stakeholders including policy makers. The results of this study may assist in the decision-making process for conserving mangroves, preventing environmental degradation, and improving the ecosystem management and planning in Bac Lieu and Soc Trang provinces in the MRD.

## Conclusions

Mangrove forests are important to human beings as they provide various ecosystem services to support human livelihood activities. Detecting changes in the mangrove forest areas, especially in the coastal regions, is essential for ecosystem conservation as well as coastline protection. In this study, Landsat data were used to evaluate the LULC changes caused by development activities and policies over the 30 years. Results show a significant disappearance of the mangroves over the study period. Remote sensing-based analysis could identify low- and high-density mangrove forests based on the spectral signature. Besides, the NDVI data could also show the changes in the density and health condition of mangrove forests. This study has revealed that the expansion of aquaculture farms has been one of the major factors leading to the considerable decrease in the areas as well as the quality (density and health condition) of dense and sparse mangroves. Nevertheless, mangroves plantation activities did not compensate sufficiently for the loss of mangrove area caused by aquaculture expansion. Therefore, there is an urgent need for mangrove research and management policies and strategies, as well as plans for the sustainable development of mangroves in the MRD.

**Acknowledgements** Authors would like to thank USGS for providing Landsat data and Can Tho University for providing support during field-work. We would also like to thank JICA-JICE for their continuous support and Hokkaido University for providing facilities. This study was also supported by the "Integrated Research Program for Advancing Climate Models (TOUGOU program)" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The authors are also thankful to Stanley Anak Suab, Huynh Vuong Thu Minh, Mustafizur Rahman, Drs. La Ode Muhammad Yasir Haya and Amit Kumar Batar for suggestions and encouragement to draft the manuscript. The authors also would like to thank five students in Can Tho University for helping in the fieldwork.

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