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Managing mangroves and coastal land cover in the Mekong Delta

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ABSTRACT

Mangroves play an important role in sustaining a healthy coastal environment, providing a natural habitat to various species, a stable shoreline and forestry products. However, the extent of mangroves developed along the tidal coast of the Mekong delta in southern Vietnam has faced and still faces the impact from both natural and anthropogenic drivers. Since the area of mangroves in the coastal Mekong delta is not well documented, this study aims to quantitatively document the evolution of the mangrove area over the past 48 years, i.e. between 1973 and 2020. Satellite Landsat images, along with a classification method comprising Iso Cluster and Maximum Likelihood algorithms, have been used for mapping land cover types including mangroves, aquaculture, soils, plants and water surfaces along the coastal districts of the Mekong delta. The study shows that remote sensing and GIS techniques can be applied to obtain mapping of the land cover, as well as detect and analyse spatial and temporal changes caused by e.g. coastal erosion or aquaculture expansion. The findings reveal that the total mangrove area of an estimated 185,800 ha in 1973 decreased significantly to 102,160 ha in 2020. Approximately 2150 ha/yr of the total mangrove loss over 1973–2020 was due to invasion by aquaculture, while roughly 430 ha/yr was lost due to coastal erosion. A slight increase in mangrove area occurred since 2010 as a result of the implementation of a series of projects to protect against coastal erosion and to restore mangroves by the Vietnamese government and international non-governmental and governmental organizations, although the success rates of mangrove restoration are relatively low. The survival of mangrove forests in the Mekong delta is related to the main pressure drivers: pollution, land use conversion, insufficient sediment sources, coastal erosion and coastal mangrove squeeze. Therefore, an integrated mangroves and shrimp farming model is one of the most appropriate approaches to achieve a beneficial balance between both aquaculture and mangroves.

1. Introduction

Mangroves are extremely prolific ecosystems providing numerous goods and services both to the coastal environment and its residents (Kathiresan, 2012). Mangrove forests are home to a large variety of fish, crab, shrimp and mollusc species (Lee et al., 2014). The fisheries form an essential source of food for numerous coastal communities worldwide. Moreover, mangrove woods or forests, being resistant to decomposition and insects, provide extremely suitable construction material. Furthermore, the dense root systems of mangroves trap sediments, which help stabilizing the coastline and prevent erosion from waves and storms (Marshall, 1994; Suzuki et al., 2011). Several countries are discovering the potential for ecotourism of the diverse mangrove forest ecosystems. However, the global mangrove forest coverage declined by 3.6 million ha, equivalent to about 20% of the total area in the period of 1980–2005 (Spalding et al., 2010). If no drastic action to reduce mangrove forest degradation is implemented, mangrove ecosystems would be wiped out globally in the near future (Duke et al., 2007).

Mangrove forests in the Mekong Delta covered more than an estimated area of 410,000 ha in 1943 (Sam et al., 2005). The dominant mangrove species in the coastal Mekong delta include Avicennia sp., Rhizophora sp., Bruguier asp. and Sonneratia sp. (Duke et al., 2010). War, forest fires, collection of wood for fuel and timber, coastal erosion, as well as other human activities have resulted in the reduction of the mangrove forest coverage in the Mekong Delta. The use of herbicides by the USA in the Vietnam War between 1962 and 1971 devastated approximately 105,000 ha, comprising 36% of the extent of total mangroves in South Vietnam (NAS, 1974). After the change from a centralized economy to a household based economy in 1980s, agriculture developed remarkably fast, converting the country from poverty into a rice exporting country, nevertheless leading to mangrove degradation as a result of rice farming practices and, later, aquaculture

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expansion. Especially since the end of the 1990's, in many areas the mangrove forests have been cleared for shrimp farming (Hao, 1999). Aquaculture area in the lower Mekong delta of Vietnam increased 4.3%/yr from 546,800 ha to 769,000 ha in the period of 2001–2010 (http://xttm.agroviet.gov.vn/Site/vi-vn/76/tapchi/69/108/7832/Default.aspx, MARD). Population pressure and economic development have led to an increasing need for land use of agricultural and aquaculture production in the recent years being one of the main drivers for the change of mangroves area. A few studies on mangroves change was only implemented in some local areas (Veettil and Quang, 2018; Bullock et al., 2017), but accurate and timely information on the spatial – temporal dynamics of these changes in the whole coastal region of Mekong delta has not been investigated.

Understanding the situation of mangrove forests by monitoring and assessing mangrove dynamics is important to allow for a better management and conservation of mangrove systems (Wang et al., 2004). Observation of the temporal change of mangrove areas is really a challenge when based on ground surveys. A more efficient method for the mapping of coastal habitats in recent years is remote sensing (Kirui et al., 2012). Remote sensing is a powerful tool for monitoring the spatial and temporal progress of mangrove forests; it is cost-effective, time-efficient and able to access remote and unreachable regions (Kuenzer et al., 2011). The obtained information of mangrove dynamics is shown to be valuable for the sustainable management of tropical coastal ecosystems (Satyanarayana et al., 2011). Furthermore, remote sensing and GIS assist in the continuous monitoring of forests and detecting changes that can be integrated into existing databases. The results are valuable for the planning of mangrove management to improve their significant contribution towards natural resources, ecotourism and local livelihoods (Koedam et al., 2007).

IKONOS, QuickBird, SPOT, WorldView, Kompsat satellite images have been widely applied for mapping the mangrove extent because of the availability of a high resolution up to 0.25 m (Gandhi and Sarkar, 2016; Wu and Chen, 2016; Wilson et al., 2019). However, the cost to realize commercial satellite images for continuous monitoring long term mangrove change on a large spatial scale is expensive. In recent years, free downloadable MODerate Imaging Spectroradiometer (MODIS) data are widely used in diverse fields of study, including mangrove extent detection as well (Ogilvie et al., 2015; Rahimi et al., 2015). Nevertheless, because of the low spatial resolution ranging from 250 to 500 m, it is at a disadvantage compared to free downloadable satellite images as Landsat. As a product provided by the U.S. Geological Survey (USGS) and NASA, Landsat stands for the longest uninterrupted collection of spatial moderate-resolution land remote sensing data in the world. Images collected over four decades offer a helpful resource for global study and management of agriculture, geology, forestry, land cover, emergency reaction and disaster assistance (http://landsat.usgs.gov). Data from multispectral satellite sensors as Landsat MSS, TM, ETM + or OLI, are useful sources sufficient to allow an effective refinement between mangrove and nearby non-mangrove regions (Haito et al., 2003; Nguyen et al., 2013; Hu et al., 2018). Multi-band spectral data as typically red and near-infrared (NIR) wavelengths have been used to identify the mangroves based on spectral reflectance, whereas remotely sensed spectral difference measurements, such as the Normalized Difference Vegetation Index (NDVI) have been associated to biophysical characteristics, such as chlorophyll index and biomass (Green et al., 1997). Although the remote sensing technique has been broadly applied for assessing the health of different types of ecosystems, detailed environmental assessments of wetlands in the coastal area of South Vietnam are still scarce.

In the lower Mekong River Delta, a few studies have applied remote sensing and GIS to detect changes of mangrove cover (NAS, 1974; Binh et al., 2005; Koedam et al., 2007; Lam-Dao et al., 2011; Nguyen et al., 2013), but these concern only local studies (Nguyen et al., 2013). Besides the influence of two main drivers, aquaculture and agriculture, coastal erosion has not yet been identified as a cause of a reduction in mangrove extent in previous studies.

Therefore, the objectives of this study are twofold. Firstly, it will show an overview of the dynamics of the mangrove ecosystem in the Mekong delta from 1973 to 2020 on a spatial and temporal scale. Secondly, it aims to contribute to a better understanding of mangrove loss associated with diverse drivers of land use change as the causes of mangrove reduction vary from region to region. As such it plays an important role in detecting and quantifying the nature and timing of changes associated with anthropogenic impacts. The results are necessary to assist in providing clear goals for local conservation, economic activities and coastal protection management in particular and the development of regional action plans in general.

2. Materials and methods

2.1. Study area

The study area is the Mekong deltaic coast which has a length of about 600 km and is located between 8°32′-10°22′ N latitude and 104°26′-106°47′ E longitude. The study focuses on those districts along the Mekong deltaic coast in Vietnam (Fig. 3) that are facing significant threats to mangroves due to the effects of rapid conversion into human land use, coastline treatment, coastal squeeze, salt water intrusion and pollution.

2.2. Data and methods

2.2.1. Satellite images data

Various types of remote sensing satellite data have been used for the mapping and monitoring of mangroves at local, regional and global scales. Freely available Landsat scale (30 m) satellite data are found to be suitable for a large-scale area as the Mekong delta.

Multi-temporal remote sensing data of the Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM+) and Landsat Operational Land Imager (OLI) from 1973, 1979, 1990, 1995, 2000, 2005, 2010 and 2020 are achieved from U.S. Geological Survey (http://earthexplorer.usgs.gov) in this study (Fig. 1). Due to a coastline length of 600 km, five adjacent Landsat paths/rows (path 124, 125, 126 and row 53, 54) are needed to cover the entire Mekong deltaic coast.

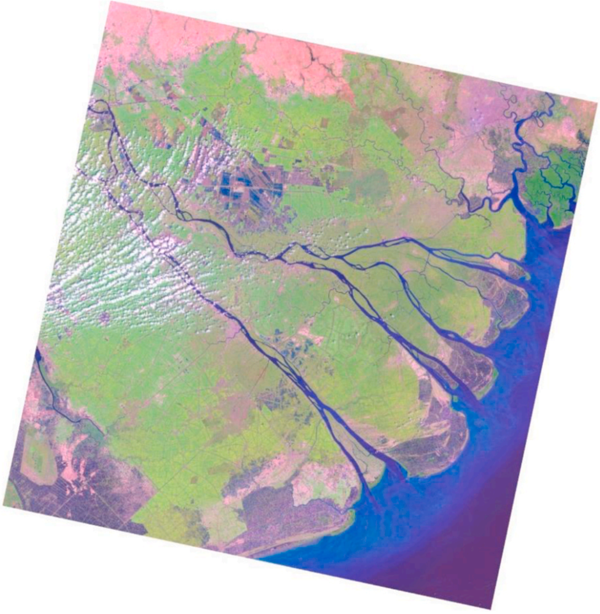


Fig. 1. Typical Landsat image in study area (https://earthexplorer.usgs.gov/).

2.2.2. *Pre-processing*

The use of multi-temporal satellite data at a regional scale faces a number of challenges: geometric correction errors, noise arising from atmospheric effects and changing solar zenith angles (Homer et al., 2004). Such errors are likely to introduce noise into land use classification and change detection analyses. Hence pre-processing is necessary to remove or minimize such errors.

Pre-processing steps for this study included Top Of Atmosphere (TOA) reflectance conversion and atmospheric correction. Each image was normalized for solar irradiance by converting digital number values to the TOA reflectance. This conversion algorithm is “physically based, automated, and does not introduce significant errors to the data” (Huang and Townshend, 2003). This process substantially removes variations among the images including sensor differences, the earth-sun distance and the solar zenith angle. All images were converted to TOA reflectance values, as proposed by Chander and Markham (2003), so that a standardized measure could be obtained for a comparison among images. Besides, the images were corrected for atmospheric interference caused by haze, dust, smoke using the dark-object subtraction method (Chavez, 1996). The Dark Object Subtraction (DOS) model was applied to data that were converted to the reflectance values at earth surface. The DOS model is widely used and is considered as one of the best methods for atmospheric correction in change detection studies. DOS is a simple empirical atmospheric correction method for satellite imagery which assumes that reflectance from dark objects includes a substantial component of atmospheric scattering. DOS searches each band for the darkest pixel value. The scattering is removed by subtracting this value from every pixel in the band. The DOS model, which is an image-based procedure, does not require field measurements and it is simple and easy to apply (Chavez, 1996).

2.2.3. *Image classification*

Satellite data were geo-referenced to coordinate the system of UTM WGS 84 with a Root Mean Square Error (RMSE) of less than half a pixel (<15 m). This study used the combined unsupervised and supervised classification approach which has employed in many fields including the remote sensing (Thomas et al., 2003; Lo and Choi, 2004; Mohammady et al., 2015; Bernabe and Plaza 2010) (Table 1). Five land cover classes consisting of mangrove, aquaculture, soil, plant and water were mapped in the study area (Fig. 4). Post-classification editing ‘recoding’ was performed to remove obvious errors. Finally, post-classification change analysis was performed (Giri et al., 2007).

The purpose of remote sensing for land cover monitoring is established as a response to the reflection of land cover categories to radiation in the visible and reflected infrared radiation of the electromagnetic spectrum. The reflectance of most land cover types from visible radiation is moderately low, however near infrared radiation is mostly reflected from all land cover types except water. The Normalized Difference Vegetation Index (NDVI) method was also used to estimate the density cover of mangroves as well as to differentiate the vegetation and non-vegetation parts. The NDVI data layer was estimated as (Red - NIR)/(Red + NIR), where Red and NIR are the reflection in the red and near-infrared bands of the MSS, TM, ETM, OLI images, respectively. The function of NIR and Red wavelengths can also be effectively used to monitor the vegetation status and condition of a mangrove ecosystem (Gillies et al., 1997). Besides, the ratio of a short wave infrared band and green band (Normalized Canopy Index - NCI) is often used to get information on different vegetation types more clearly, especially between forests and croplands (Vescovo and Gianelle, 2008). Therefore, this study combines the NDVI band and the NCI band to create 30 classes by the Iso cluster unsupervised classification methodology, which uses a modified iterative optimization clustering procedure (Richards, 1986). The methodology creates a signature file containing the multivariate statistics for a subset of the cells for the identified clusters. The resultant calculations identify which cell location belongs to which cluster, the mean value for the cluster and the variance-co-variance matrix. This information is essential in the clustering and classification of the remaining un-sampled cells.

Table 1
Steps for classification and change detection analysis of land cover types.

Process Step	Process Name	Description
1	Download and Extract Images	USGS EROS DATA CENTER
2	Atmospheric correction	Sun and radiometric correction
3	Normalized Difference Vegetation Index (NDVI)	Red and Near Infrared Bands
4	Normalized Canopy Index (NCI)	Green band and Short wave infrared band
5	Developing approach for land cover creation by combining NDVI and NCI	Unsupervised classification by iso cluster algorithm to create 30 classes
6	Classifying 5 classes: aquaculture, mangrove, plant, bare soil, water.	Supervised classification from 30 classes to 5 classes by maximum likelihood algorithm
7	Change detection analysis	Characteristic difference of pixel change between images from two dates

Consecutively, supervised classification by a maximum likelihood algorithm is used to reclassify the types into the five classes: aquaculture, mangroves, plants (rice crop, fruit trees, shrub, soils (bare soil, urban, vegetable field with very low canopy cover, salt field) and water. Supervised classification is a pixel-based process, where pixels of known classes are used for classifying unknown classes. The field data supported the selection of a representative training data set for a maximum likelihood algorithm and an accuracy assessment of the classification. Maximum likelihood classification is known as one of the most effective methods in categorizing land use cover using moderate spatial resolution satellite remote sensing data (Green et al., 1998; Held et al., 2003). This method allocates each pixel to one of the different classes based on the highest probability according to the means and variances of the class signatures. The software was used to plot all the types of the results and data analysis in the Arcmap project (ArcGIS 10.5 version).

2.2.4. *Accuracy assessment of classification and land cover detection analysis*

The accuracy assessment was implemented to determine how effective the classification process is, based on field data (Fig. 2 and Fig. 3) and other relevant information, including historical aerial photos, orthophotos, Google Earth imagery and regional technical papers. A precision assessment was implemented using the Kappa coefficient approach to evaluate the accuracy of the classification results. The Kappa coefficient is calculated from the error matrix which compares the value achieved by the classification process of the remote sensing technique and the actual value (Congalton, 1991). The Kappa function indicated how well the classification process is executed as compared to allocated values. A sampling with 100 pixels produced for the study area was applied to assess classification accuracy. Comparing these two values from field data and classified maps completed the error matrix table. The overall classification accuracy as well as user and producer accuracies for individual classes based on the reference data was achieved.

By the application of the change detection technique, land cover can be observed at different times. For change detection, satellite images should be attained by the same sensor and with the same resolution (Lillesand et al., 2004). Satellite devices offer cyclical images of surface coverage and help to obtain multi-temporal data sets for different use. Several measures for land cover change detection, including algebra based change detection approach (Ke et al., 2018; Ferraris et al., 2018), transform based change detection (Sadeghi et al., 2016; Massarelli 2018), classification based change detection (Radhika and Varadarajan 2018; Alonso et al., 2016), neural network and fuzzy based approach (Su et al., 2017; Zhang et al., 2017b; Tian and Gong 2018) can be implemented.

Fig. 2. Ground survey of (a) plant types, (b) mangrove types, (c) aquaculture types and (d) soil types in 2015.

In this study, a change detection technique for each land cover class was used as post-classification comparison. This approach identifies changes in land cover type comparing the classified images pixel by pixel. Assigning any value to each class can produce a complete matrix of changes. Finally, the cross-tabulation technique by a simple mathematical function for images of t_1 and t_2 is employed to visualise the changes in each land cover class. Further, the accuracy of this approach depends on the accuracy of the initial classifications.

3. Results

3.1. Mangroves and land cover mapping

The mangroves and land cover mapping rule sets developed in this study were successfully implemented on the entire Landsat images collection of MSS, TM, ETM+, OLI imagery, producing consistent image maps. Combined unsupervised and supervised classifications on Landsat MSS, TM, ETM+ and OLI 2011 indicated 5 land cover classes in agreement with the ground-truth observations. The efficacy of satellite images in providing informative data from the mangrove area during the 48-year period is an advantage, as it monitors a vast area over a short time interval. Spatial and spectral information given by the satellite images enable classification of land use cover using pixel-by-pixel changes in every image with more than 80% of accuracy. The image classification for mangroves in 2015 indicated an accuracy assessment of 87% with Kappa statistics of 0.84 (Table 2). Therefore, it is assumed that classifications have been performed adequately for the purposes of assessing temporal change in mangrove extent and other land cover types.

Distribution of mangroves from the classification from 1973 to 2020 is depicted in Fig. 5. Mangroves have grown in several coastal areas, such as Ben Tre, Tra Vinh, Soc Trang, Ca Mau, especially in areas where sedimentation has occurred. The total mangrove area in 1973 was estimated at 185,800 ha and had decreased significantly to 113,440 ha in 1990 to 92,560 ha in 2000. In the following periods, the extent of the mangroves is quite stable only slightly decreasing to 89,650 ha in 2010 and increasing again to 102,160 ha in 2020 (Table 3).

Fisheries have been very successful in the Mekong delta, which has resulted in a significant contribution to the development of Vietnam's economic development in recent years. Aquaculture, the farming of fish,

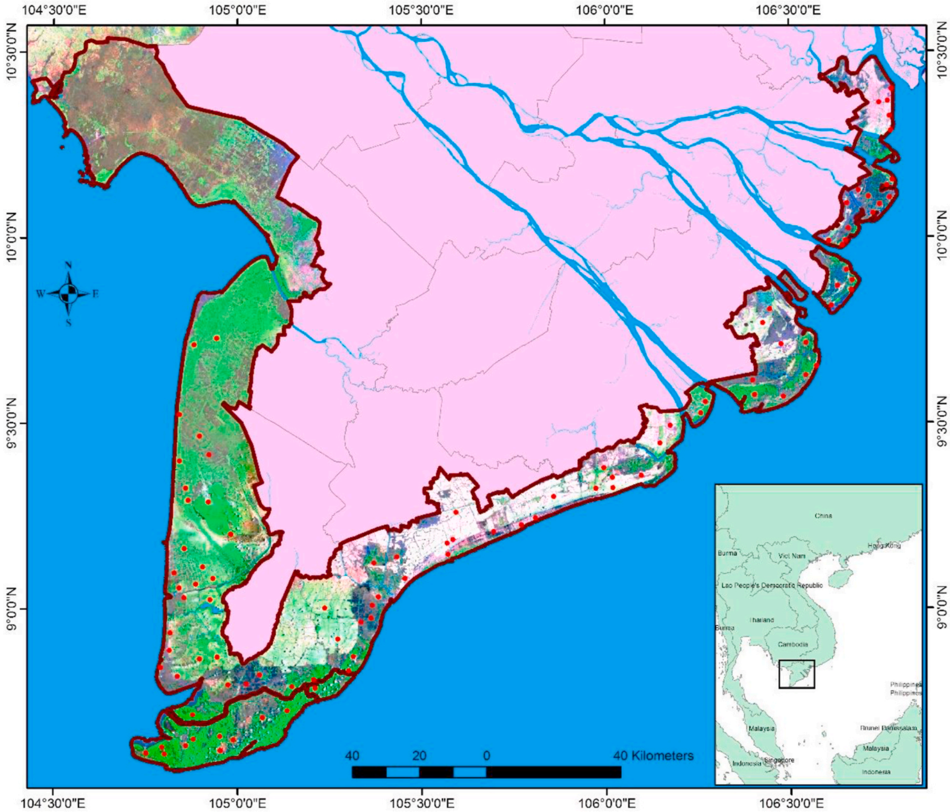


Fig. 3. Collected sites for accuracy assessment in red color along the coastal Mekong delta. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

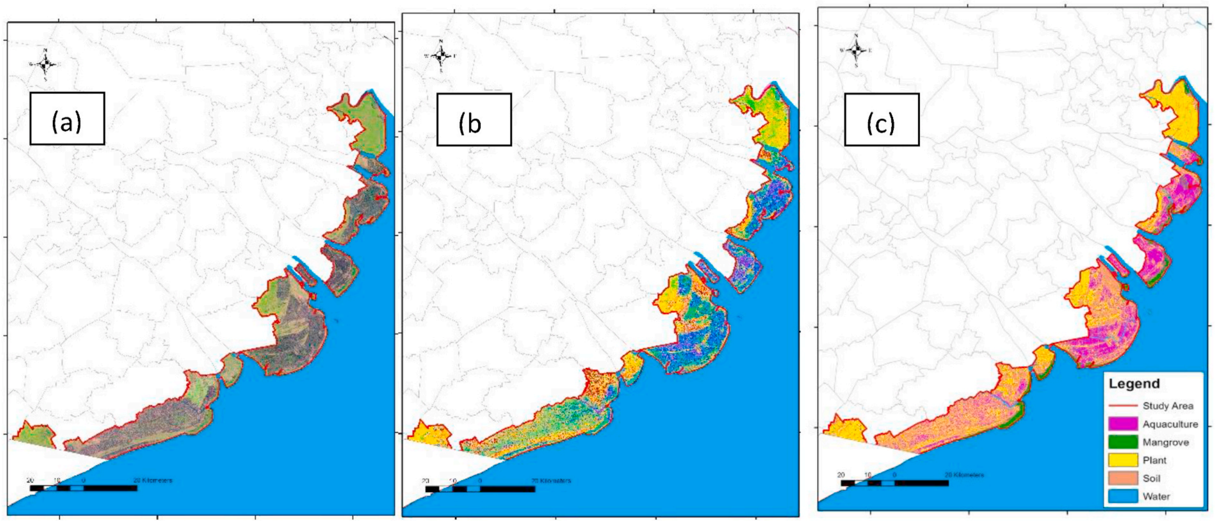


Fig. 4. The satellite image (a), the image of 30 classes (b) and the final image of five classes (c), respectively.

crustaceans, molluscs, aquatic plants, algae and other organisms, covered a minor area of about 700 ha in 1973. A growth in the aquaculture extent took place in 1990, increasing from 51,370 ha to 264,010 ha in 2010 with an average annual increase of over 10,000 ha. The annual increase of the aquaculture area in the period from 2010 to 2020 is a half compared to period between 2000 and 2010 with an area of nearly 321,560 ha in 2020; Camau province occupying over a half of the aquaculture area in this region (Table 3).

Both plant and soil areas showed a steady decline for the period 1973 to 2020 in the study area. In four land cover categories, plant were the dominant cover in the study area; however, it diminished steadily during the entire study period, similar to mangrove and soil categories. Table 3 shows that plant fields started to drop gradually from 643,940 ha in 1973 to 477,160 ha in 2020. Compared with other periods, the result indicates a quite significant decrease of plant area of nearly 9000 ha/yr in the period between 2000 and 2010 (Table 4). Meanwhile, there was an increase of soil area from 1973 to 1990 by 1660 ha/yr, however the soil area also began to decline from 186,570 ha in 1990 to 89,640 ha in 2020.

Table 3 shows the percentage of each land cover type in the period of

Table 2
The accuracy assessment for classification of land cover mapping in 2015.

Species	Mangrove	Aquaculture	Plant	Soil	Water	Total	User Accuracy
Mangrove	16	1	0	1	0	18	0.89
Aquaculture	1	23	1	0	1	26	0.88
Plant	0	2	20	1	0	23	0.87
Soil	0	1	1	15	1	18	0.83
Water	1	0	1	0	13	15	0.87
Total	18	27	23	17	15	100	
Producer accuracy	0.89	0.85	0.87	0.88	0.87		
Overall accuracy	0.87						
Kappa coefficient	0.84						

1973–2020. The plant, mangrove and soil areas, indicating a decreasing trend between 1973 and 2020, correspond to the revolution of the aquaculture area. There was only an extremely small aquaculture area in 1973, which then increased gradually to nearly 33% of the total land cover area in 2020. The plant area occupied more or less 65% in 1973, however this area dropped to only 50% of the entire study area. The soil area is quite steady in size; there is only a slight decline of occupied area rate from 16% to 14% for the total coastal study area in the whole period from 1973 to 2020. Similarly, the extent of mangroves in 1973 of nearly 19% of the total land cover area decreased to 9% in 2010, however it started to increase to above 10% for the whole study area in 2020.

3.2. Distribution of mangrove and aquaculture extent at coastal province level

Land cover area between 1973 and 2020 in Fig. 5 and Table 5 clearly showed that the extent of mangroves has decreased inversely proportional to the rise of aquaculture area taking place in most coastal districts, except in the coastal area of Baclieu province. The aquaculture area in the entire study area, particularly the aquaculture area in the three coastal provinces Camau, Kiengiang and Baclieu, increased remarkably compared to other provinces. Especially, the coastal Camau province with an aquaculture area occupying 164,030 ha covers nearly 51% of the total aquaculture extent. The percentage of mangrove area among the districts of the coastal provinces is quite stable, indicating that the decrease rate of the extent of mangroves distributed rather consistently. Not only the largest aquaculture extent in the total study area, the coastal area of Camau province is likewise the place where the mangrove extent has occupied most territory compared to the remaining areas with roughly 67% of the total mangrove extent. Inversely, there are three coastal provinces, Kiengiang, Baclieu, Tiengiang, where the percentage proportional to the total mangrove area is lower than only 5%.

3.3. Change detection analysis of mangrove and aquaculture extents

Mapping changes of land cover categories is necessary to determine and understand the reasons causing these changes, especially the ecosystem that includes mangroves. The results from the change detection maps (Fig. 6 and Fig. 7) indicate that most mangrove changes that occurred along the coastal area, are caused by the expansion of shrimp farming, in addition to agricultural activities and coastal erosion.

The unchanged aquaculture extent (Fig. 7) increased dramatically from 30 ha/yr in the period of 1973–1990 to 46,520 ha/yr in the period of 2010–2020. This information clearly shows that shrimp famers not only continue to use the current aquaculture area, but also expand it considerably to absorb other land categories. The Vietnamese government has encouraged shrimp farming for export since the early 1980s and it became a wide-spread economic activity. From 1980 until the late 1990s, there was rapid expansion in shrimp aquaculture throughout most of the coastal Mekong Delta, driven by opening up its economy, high profit, and government promotion (Hong and San, 1993; Hashimoto, 2001). In addition, shrimp farming was promoted by international organizations, such as the World Bank and the Asian Development Bank, as a means to reduce poverty and create employment and income (Binh et al., 2005). The extent of land cover including plant and soil types changed to aquaculture from 550 ha/yr in the period of 1973 and 1990 to 10,570 ha/yr in the period of 2010 and 2020, especially at a peak rate of 16,220 ha/yr in the short period of 2000–2010. Fig. 8 determined that in the beginning of the 1990s, a remarkable change to aquaculture area in the coastal land cover occurred in at first the three provinces of Camau, Baclieu and Soctrang. Then, the aquaculture extension spread rapidly to the coastal zones of Travinh, Bentre and the southern part of Kiengiang province. Meanwhile, the change of aquaculture to other land cover types is largely within the approximately range of 4000 ha/yr and 6000 ha/yr. The reason for the change is the result of several causes. A failing wastewater management from shrimp farming leads to a relatively frequent loss of aquaculture areas after the success of aquaculture in some previous years (Le and Munekage, 2004; Shimizu et al., 2013). A part of this land became bare; farmers change to shrimp-rice or shrimp-forest field farming or just let the land turn bare.

Major causes of mangrove forest loss include conversion to agriculture, urban development and shrimp ponds. Similar to some other countries, in Vietnam a conflict exists between the conservation of mangroves and the development of shrimp farming (Dahdouh-Guebas, 2002). The loss of mangroves in the study area by the expansion of aquaculture ranges between 1500 ha/yr and 2700 ha/yr. In general, there is a slight decreasing trend of mangroves converted to aquaculture from 2440 ha/yr in the period of 1990–1973 to 1490 ha/yr in the period of 2010–2020. This is the result of a law introduced in 1991 by the Vietnamese government to protect forests (Hong, 2000). Not only due to the expansion of aquaculture, the analysis of satellite images shows that the other reasons causing the reduction of mangrove area was due to conversion to plant, soil extent and erosion. The yearly loss of mangroves by coastal erosion and conversion to other land covers varied from 3150 ha/yr to 4360 ha/yr. In 1990s the Vietnamese government considerably enhanced irrigation system to develop rice fields in the Mekong delta (Kotera et al., 2013; Tuong et al., 2003; Veettil and Quang, 2018). The irrigation constructions, supported and implemented by the government, brought about the de-acidification and de-salination of brackish and salt water to be converted into fresh water to develop rice fields and fruit tree areas.

Nowadays, Vietnam is one of the biggest rice exporters in the world and nearly 90% of the Vietnamese exported rice is from the Mekong delta (Ricepedia, n.d.; Toang, 2017). The result from the significant conversion from mangrove to agriculture during 1973 and 2020 (Fig. 7). Coastal erosion occurred early in Camau and then spread to other coastal provinces, including Travinh and Bentre. Besides the conversion of mangroves to other types of land cover, some types of land cover also change to mangrove type. Fig. 7 indicates an obvious gradual changing growth of other types of land cover to mangroves from 1700 ha/yr in period of 1973–1990 to 5550 ha/yr in the period of 2010–2020. Mangrove areas have expanded from original mudflats by sedimentation, which occurred in Camau, Soctrang, Travinh and Bentre. The further rise of mangrove area in recent years relates to reforestation related decisions, including instant actions for the protection and

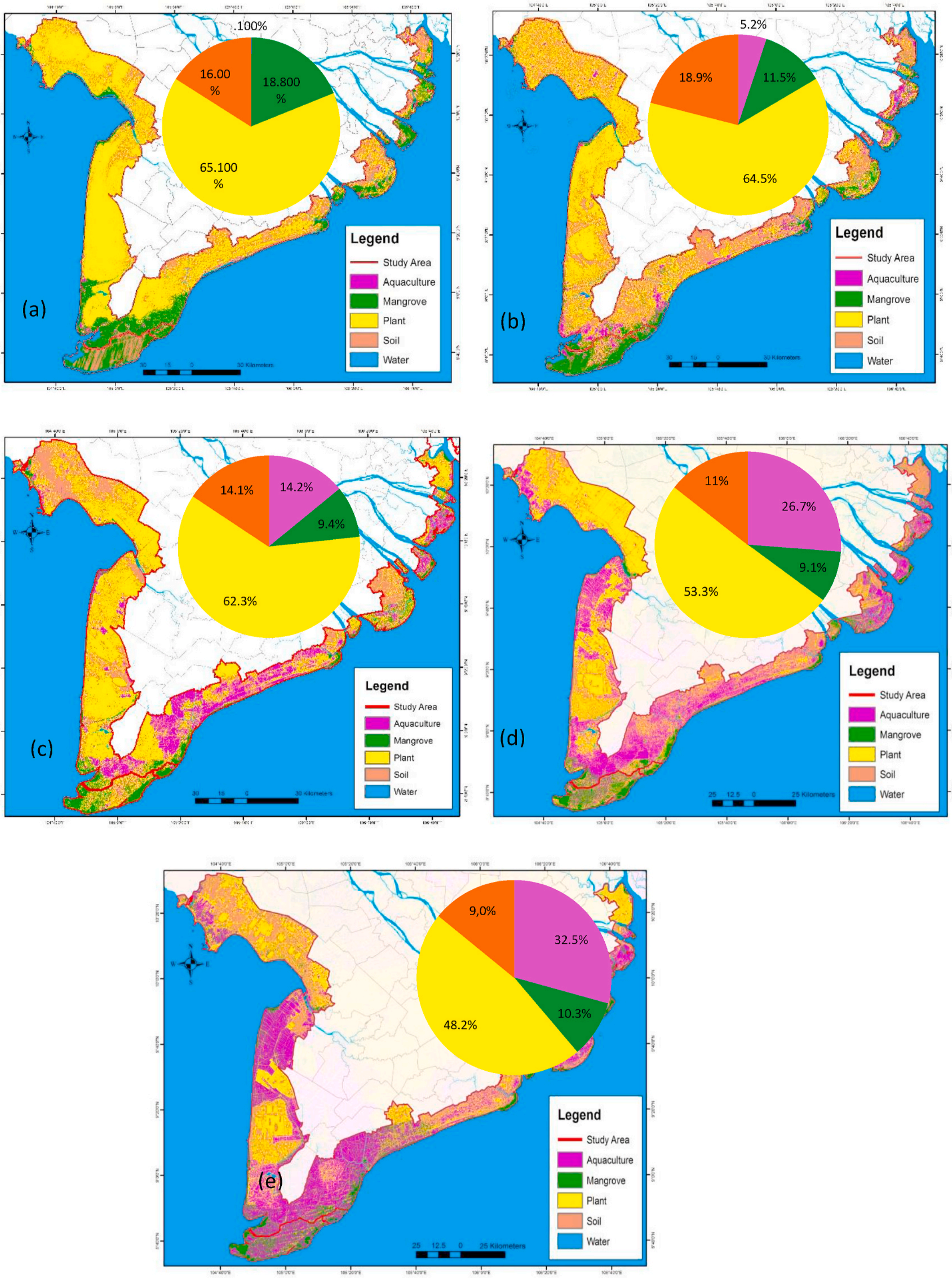


Fig. 5. Classification results of land cover categories in the coastal Mekong delta in (a) 1973, (b) 1990, (c) 2000, (d) 2010, (e) 2020.

Table 3
The four different land cover categories in the coastal Mekong delta between 1973 and 2020.

TYPE	1973		1990		2000		2010		2020	
	ha	%	ha	%	ha	%	ha	%	ha	%
Aquaculture	700	0.1	51370	5.2	141060	14.2	264010	26.7	321560	32.5
Mangrove	185800	18.8	113440	11.5	92560	9.4	89650	9.1	102160	10.3
Plant	643940	65.1	638320	64.5	617220	62.3	527900	53.3	477160	48.2
Soil	158400	16.0	186570	18.9	139100	14.1	108670	11.0	89640	9.0

Table 4
Annual change of land cover types in periods.

TYPE	ANNUAL CHANGE OF LAND COVER AREAS in PERIODS (ha/yr)			
	1990–1973	2000–1990	2010–2000	2020–2010
Aquaculture	2980	8970	12300	5760
Mangrove	−4260	−2090	−290	1250
Plant	−330	−2110	−8930	−5070
Soil	1660	−4750	−3040	−1900

improvement of forest areas (Decision 286/QD-TTG) following a plan to create 5 million ha of forests along the country (Decision 661/QD-TTG) (Binh et al., 2005). International organizations, as GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), Australian Aid, have also implemented projects to boost the mangrove extent in several coastal provinces, such as Soctrang, Baclieu and Kiengiang. Therefore, leading to the first accretion of mangrove area being higher than the loss of mangrove area in the period 2010–2020. During the total study period of 1973–2020, the average yearly loss of mangrove by changing to other land cover types, including plants, soils, aquaculture and erosion, is 5870 ha/yr. While the change from other land cover types to mangrove is approximately 3590 ha/yr before 2010 (less than the loss of mangrove more or less 6280 ha/yr in the same time), this phenomenon is reversed in the period of 2010–2020 with 5580 ha/yr in terms of other land cover types to mangroves, compared with 4640 ha/yr due to mangroves to the remaining land cover types.

4. Discussion

4.1. Main pressures to the survival of mangroves

Mangroves which are usually scattered along the intertidal zone of low energy tropical coastlines are highly productive ecosystems that (Kathiresan and Bingham, 2001). Mangroves play important roles in the ecosystem, especially in terms of ecological, environmental, biological, medical and economical values (Ellison et al., 2020). However, mangroves in the Mekong Delta still face survival threats such as land use conversion, pollution, insufficient nutrient sediment, coastal erosion, coastal mangrove squeeze.

4.1.1. Conversion to aquaculture and other land cover types

In the mangrove regions of Asian countries, such as Thailand, Indonesia, Philippines and Vietnam, a significant change to brackish water aquaculture is taking place (Giesen et al., 2006). Approximately 50%–65% of mangroves have been lost to shrimp farm conversion since 1975 in Thailand (Barbier, 2003) and in the Philippines about half of the 279,000 ha of mangroves lost in the years from 1951 to 1988 were to develop aquaculture (Primavera, 2000). With the encouragement and support of the Vietnamese government and international organizations, such as the World Bank and the Asia Development Bank, shrimp farming areas spread along the coastal zone of the Mekong delta. The Vietnamese Prime Minister issued the National Decree 773-TTg in 1994, stipulating that open coastal areas and water bodies could be used for aquaculture (Nguyen et al., 2013). However, it led to problems of rapid deforestation as local authorities were incapable to control the expanding aquaculture (Fig. 9). Although government had indicated a priority from bare soil, low productivity rice crops or fruit tree areas to shrimp farming, local people still destroyed the mangroves for aquaculture to gain income. In this study, the loss of approximately 2150 ha/yr of mangrove through 1973–2020 was largely due to the conversion to aquaculture. This study is consistent with numerous studies in terms of the severe impact of the conversion to aquaculture on the mangrove vegetation (Wolanski et al., 2000; Valiela et al., 2001). Besides, the widespread of aquaculture system can alter the system dynamics, interrupting the continuity of natural events, such as local dispersion and migration of flora and fauna species, and modifying the local hydrology, leading to a weakening of mangrove health. This study shows that mangroves were not only converted to aquaculture but also changed to other land cover types, such as built-up land, salt fields, agriculture extent and bare soil, as a consequence of deforestation for firewood. This study revealed that the cause of the loss of mangrove forests is primarily the conversion to other land covers excluding aquaculture, such as mentioned above, with an annual rate of 3710 ha/yr, which is higher compared with area conversion of mangroves to aquaculture.

4.1.2. Pollution

a) Herbicides from chemical warfare

The forests under study experienced significant damage during the Vietnam War from the application of herbicides and defoliants by the U. S. Air Force. As part of the war strategy (1962–1972) large tracts of forest, including mangrove forest in the southern provinces of Vietnam, were defoliated by the use of herbicides in order to reveal military shelters and food supplies (Stellman et al., 2003). NAS (1974) estimated that 104,939 ha or 36% of the area of mangrove in southern Vietnam was subjected to one or more chemical attacks. Heavy defoliation not only devastated the vegetation, but also affected heterotrophs changing the whole ecosystem (Hong and San, 1993). The profound impact of the attacks in the Mui Ca Mau province is detected by the large increase in bare wasteland in 1975 compared to 1953. The pattern of impact has a similarity to the flight paths of spray missions (NAS, 1974; Stellman

Table 5
Aquaculture and mangrove extent at coastal provincial level between 1973 and 2015.

PROVINCE	TYPE	1973		1990		2000		2010		2020	
		ha	%	ha	%	ha	%	ha	%	ha	%
Kiengiang	**Aquaculture**	30	4.3	6060	11.8	11580	8.2	39630	15.0	44610	13.9
	Mangrove	11000	5.9	8310	7.3	5490	5.9	4650	5.2	4920	4.8
Camau	**Aquaculture**	230	32.9	15070	29.3	53270	37.8	119040	45.1	164030	51.0
	Mangrove	129660	69.8	67570	59.6	56020	60.5	54460	60.7	68110	66.7
Baclieu	**Aquaculture**	100	14.3	2820	5.5	33850	24.0	40080	15.2	40140	12.5
	Mangrove	1700	0.9	2470	2.2	2840	3.1	2890	3.2	3890	3.8
Soctrang	**Aquaculture**	70	10.0	5910	11.5	11800	8.4	15270	5.8	18650	5.8
	Mangrove	8750	4.7	8810	7.8	5690	6.1	6550	7.3	7010	6.9
Travinh	**Aquaculture**	60	8.6	6820	13.3	13250	9.4	26270	10.0	28380	8.8
	Mangrove	15250	8.2	12970	11.4	10750	11.6	9810	10.9	10030	9.8
Bentre	**Aquaculture**	100	14.3	8700	16.9	13070	9.3	17780	6.7	20210	6.3
	Mangrove	12170	6.6	9020	8.0	8410	9.1	8360	9.3	6820	6.7
Tiengiang	**Aquaculture**	110	15.7	5990	11.7	4240	3.0	5940	2.2	5540	1.7
	Mangrove	7270	3.9	4290	3.8	3360	3.6	2930	3.3	1380	1.4
Total	**Aquaculture**	700	100	51370	100	141060	100	264010	100	321560	100
	Mangrove	185800	100	113440	100	92560	100	89650	100	102160	100

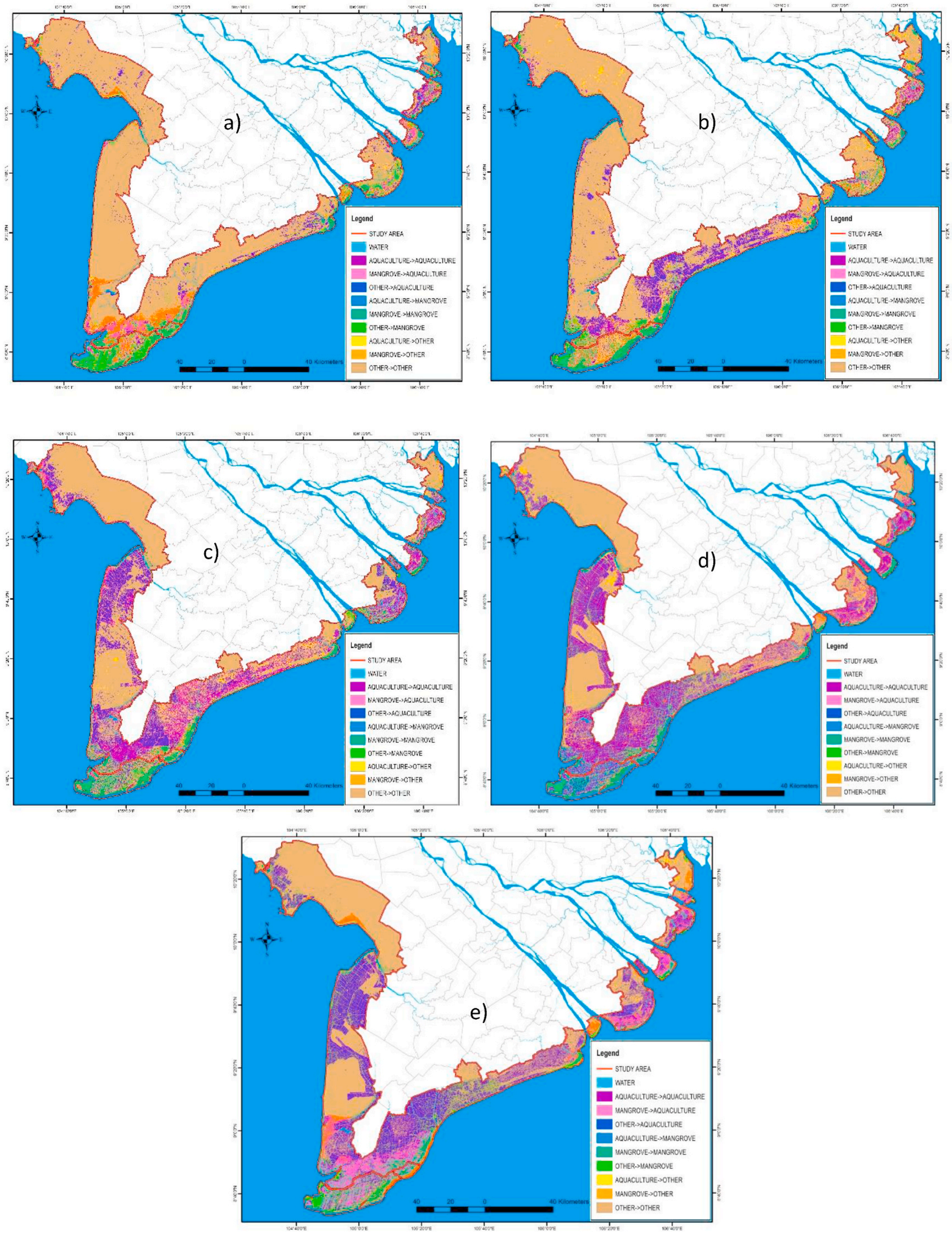
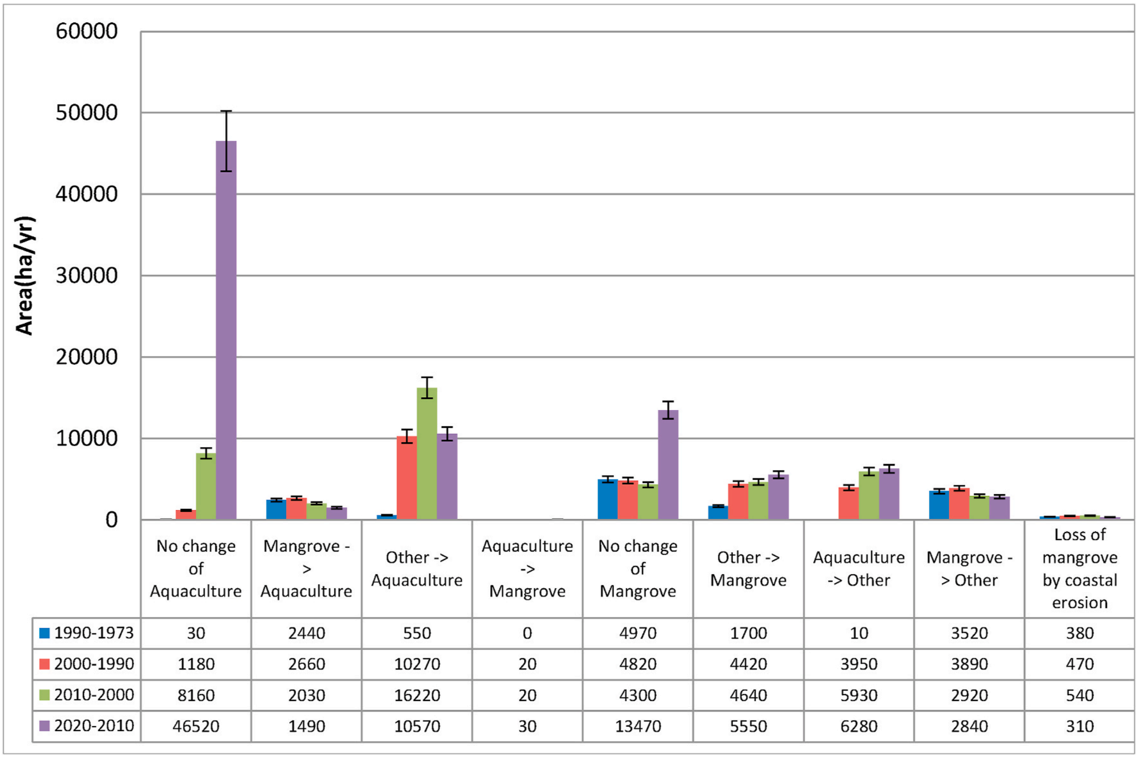


Fig. 6. Conversion dynamics of mangrove and aquaculture in period of 1973–1990 (a), period of 1990–2000 (b), period of 2000–2010 (c), period of 2010–2020 (d) and period of 1973–2020 (e). 'Other' means land cover of non-determined plants and soils types.

et al., 2003). A large difference of mangrove growth between the affected and non-effected mangrove forest by chemical warfare was noticeable (T.T. Van et al., 2015). However, this factor only affected the mangrove expansion in first study phase of 1973–1990, and almost no longer impacted the development of mangroves in the Mekong delta in later years.

b) The waste of aquaculture

Corresponding to many other Southeast Asian countries (Huitric et al., 2002) mangrove deforestation in Vietnam has become a serious issue, with at least 220,000 ha of mangrove forest removed over the last 50 years (Tuan et al., 2003). Whereas agriculture, salt pan development and the wartime use of chemicals were previously the most important threats to mangroves, for the last decade the greatest threat has been the shrimp aquaculture. Disease outbreaks and acidification of soils have led to crop failure rates as high as 70–80% in some areas of Vietnam, and subsequently the abandonment of ponds and further expansion of shrimp cultivation to new coastal areas (Lebel et al., 2002). To reduce the risk of crop failure, Vietnamese farmers use a relatively large amount



	No change of Aquaculture	Mangrove -> Aquaculture	Other -> Aquaculture	Aquaculture -> Mangrove	No change of Mangrove	Other -> Mangrove	Aquaculture -> Other	Mangrove -> Other	Loss of mangrove by coastal erosion
🟦 1990-1973	30	2440	550	0	4970	1700	10	3520	380
🟥 2000-1990	1180	2660	10270	20	4820	4420	3950	3890	470
🟩 2010-2000	8160	2030	16220	20	4300	4640	5930	2920	540
🟪 2020-2010	46520	1490	10570	30	13470	5550	6280	2840	310

Fig. 7. Annual mangrove and aquaculture dynamics in the coastal Mekong Delta.

of food, pesticides and antibiotics in shrimp farming (Lan, 2013). Several concerns have been raised about the use of toxic compounds, including their persistence in aquatic environments, the possibility of residues in non-cultured seafood, the toxicity to non-target (off farm) species, the possible effects on sediment bio-geo-chemistry and, finally, the possible effects on the health of farm workers. As other studies have noted (Mang et al., 2008), shrimp farming in Vietnam may also lead to serious water pollution with wastewaters containing high Biological Oxygen Demand (BOD), and high Nitrogen (N) and Phosphorus (P) concentrations from food residues, often released directly into canals and rivers, causing oxygen depletion and eutrophication. Several studies have also indicated that intensive shrimp farming in particular has the largest share in the overall environmental impact of all shrimp production systems. The water pollution per hectare of shrimp farming from the farming process are 1373 kg BOD, 4077 kg COD, 6201 kg TSS, 159 kg of total nitrogen and 20 kg of total phosphorus, 26 kg of Ammonia-Nitrogen (N–NH3), respectively. Hence, with aquaculture areas in the coastal study area of nearly 300,000 ha, enormous amounts of harmful substances are estimated to have been released via discharge channels into the coastal zone. The above numbers do not include solid waste from aquaculture, which is discharged directly into the river or discharge canal; therefore the estimated pollution loads into the water body could even be higher.

4.1.3. Change of sediment-nutrient source

Changes in sediment regimes in coastal regions can have harmful effects on adjacent estuaries and coastal habitats, including mangroves which are sensitive to the change of the environment due to natural and anthropogenic impact. If a decrease of sediment occurs, it can lead to degradation of an ecosystem by starving it of the elements needed to sustain production, since often a variety of minerals, nutrients and organic matter is attached to the sediments. A substantial fraction of the fine particle material and the associated nutrients originate from land are responsible for the continuous accretion of sediment, allowing sustained progression of the mangrove (Duarte et al., 1998). The change of sediment load is a consequence of the construction and operation of the Chinese cascade dams in the upper part of the Mekong main stream in China, called the Lancang River (Fu and He, 2008). Analyses of discharge and sediment flux at various gauging stations on the Lower Mekong River have indicated a disruption in water discharge, water fluctuations and sediment transport downstream of the first Chinese dam among the 8 cascades (i.e. the Manwan Dam), after its reservoir was taken into use in 1992. Measurements of suspended sediment concentration data at Tanchau permanent stations showed that there is a marked difference among the periods 1988–1996, 1997–2007 and 2008–2012 (Phan et al., 2017) (Fig. 10). Suspended sediment concentrations declined significantly from 126 mg/l in the period of 1988–1996 to an average 98 mg/l in the period of 1997–2007. Although there is the slight rise of suspended sediment concentration at 104 mg/l in the next period of 2008–2012, the declining trend of suspended sediment concentration is completely obvious in lower Mekong River Delta (Phan et al., 2017).

Several studies clearly document that the growth of *Rhizophora apiculata* seedlings, living at the edge of progressing mangrove forests, is directly correlated to the nutrient and silt contents within the sediments of mangrove sites (Duarte, C. et al., 1998; Tanner et al., 1998, Feller, 1995). Seedlings growing over nutrient-poor, coarse sediments had very low growth rates to the point that their canopy only gained a couple of new leaves per year, while the highly branched canopy of seedlings growing over nutrient-rich, silty sediments gained a new leaf every other day. Experiments with fertilization suggest that the growth of mangrove trees is constrained by insufficient nutrient supplies (Onuf et al., 1977; Boto and Wellington 1983). The mangrove forests in the sheltered boggy hydro environments facilitate the deposition of fine sediments normally enriched with nutrients, metals and minerals. The concentration level of nutrients in the mangrove sediments is largely influenced by the microbial activities. For seedlings growing in the outermost fringes of mangroves, however, variable exposure may markedly change the balance between export and import of silt and nutrients, resulting in highly variable nutrient and silt contents in the sediment (Asp et al., 2018). It is, therefore, not a surprise that the growth of newly established seedlings in the mangrove progression zone is variable and strongly controlled by

Fig. 8. (a) Existing coastal protection structures, (b) Groynes systems in Camau, (c) Mangrove restoration project in Baclieu.

local differences in sediment nutrient content. Hence, sediment load from large river plays important role in the development of mangrove area.

4.1.4. Coastal erosion

Erosion was also observed as a factor contributing to the loss of mangroves at specific locations. Most of the mangrove species are influenced by hydrodynamics, including waves and currents, and its survival becomes a high risk under extreme weather conditions. In spite of the role of mangroves to shield coastlines against hazards as wave action and coastal erosion (Tomlinson, 1994; Cuc et al., 2013), mangroves are exposed to erosion caused by natural as well as anthropogenic intervention including wave, wind, longshore currents, insufficient sediment supply and relative sea level rise (Prasetya, 2006).

At the present, the Mekong deltaic coast is facing a coastal erosion length of nearly 340 km of approximately 630 km total coastline extent as shown in Fig. 11 (Phan et al., 2017). Similar to other regions, the coastal erosion in the Mekong delta is caused by sediment transport gradients based on wave and tidal currents, deficiency of river sediments and relative sea level rise (Marchesiello et al., 2019). A remarkable finding of this study, which has not yet been analysed in previous studies, is that the effect of coastal erosion for the loss of mangrove is quantified for each period. There is a gradual rise/increase of annual loss of mangrove area by coastal erosion from 380 ha/yr to 540 ha/yr during 1973–2010, especially in coastal Camau province. Nevertheless, the rate of mangrove loss started to decline to 320 ha/yr as a result of the deployment of series measurements from the Vietnamese government and by several international organizations to control coastal erosion, especially in the coastal provinces of Soctrang, Baclieu, Camau and Kiengiang (Thai et al., 2021). In addition to hard structures introduced to fix the coastline in Tiengiang, Travinh, Baclieu and Camau provinces, in recent years local people have planted mangroves as soft structures to stabilise the shoreline. However, because of the absence of sediment supply, the planting of mangrove seedlings as well as the stabilization of the shoreline in several local regions is only moderately successful (Besset et al., 2019). Natural nourishment by trapping sediment or artificially supplying sediment from other sedimentation regions should be considered as a one of the measures appropriate to resolve such

Fig. 9. Aquaculture expansion in adjacent mangrove forest.

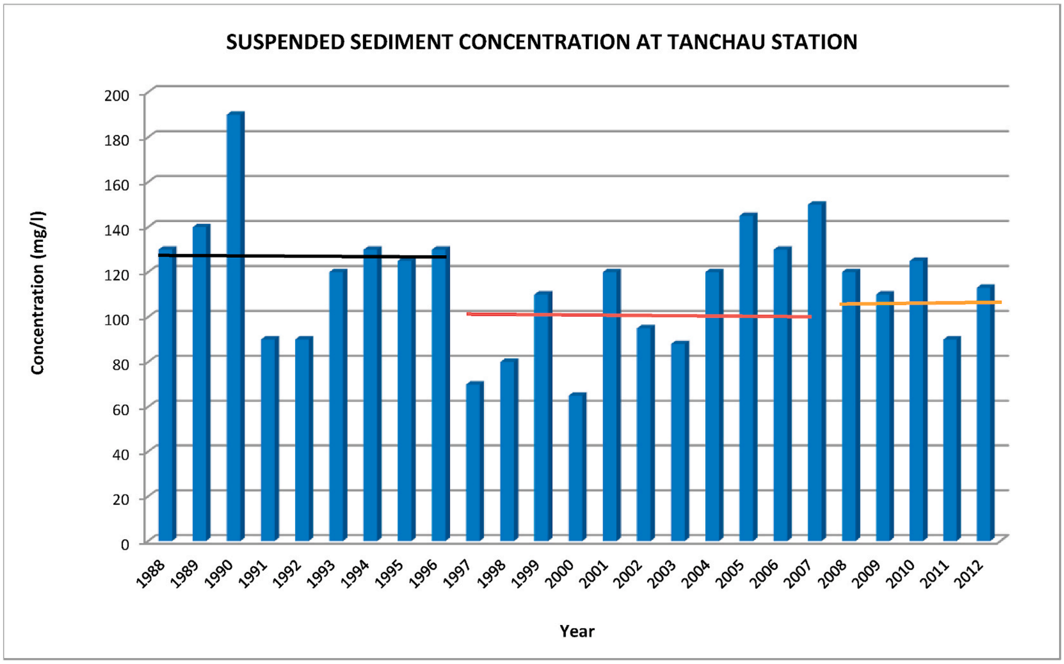


Fig. 10. Suspended sediment concentration at Tanchau station (Phan., 2017).

Fig. 11. Coastal erosion to mangrove forest in Camau (a) and Tiengiang (b).

problems. The close relationship between the loss of the total area and the loss of the mangrove area in the dominant mangrove area along the coastal Mekong delta, caused by coastal erosion from 1973 to 2015, indicates a correlation value up to 99% (Fig. 12).

4.1.5. Coastal Mangrove squeeze

An important risk for marine life is loss of habitat due to coastal land claim, erosion and sea level rise. Coastal land claim often involves building to protect the land from erosion and/or flooding and conversion of mangrove to land cover categories (Fig. 13). Coastal erosion and sea level rise push mangroves landward, meaning that the mangrove habitat is squeezed into a narrowing zone when it faces the coastal land claim and, as a consequence, coastal mangrove squeeze takes place (Doody., 2004, 2013). Torio and Chimura (2014) developed a Coastal Squeeze Index to evaluate the potential of a coastal marshes squeeze and to classify the threatening pressures of various wetlands in the United States and Canada. At present, the coastal Mekong delta is facing coastal mangrove squeeze by infra-gravity waves and a sea dikes system with a critical width of 140 m to maintain a healthy mangrove forest (Phan et al., 2015).

4.2. Sustainable coastal land cover development

4.2.1. Improving the technique of planting mangroves

Vietnam has implemented an effort of mangrove restoration in the beginning of 1990s. The Vietnam government kick off a considerable mangrove replantation program with area of 52,000 ha under Decision No. 327 in 1992. Next, the Five Million Hectares Reforestation Project was carried out under Decision No. 661/ND-TTg in 1998. 48,096 ha of mangroves were restored under the National Target Program, the Forest Protection and Development Plan within from 2011 to 2020 (Hai et al., 2020). Although there was an occurrence of rising mangrove extent in the coastal Mekong delta from 2010, the success rate of mangrove restoration is quite low similar to the cases of other countries. In Bangladesh, 120,000 ha of mangroves have been planted since 1966 (Saenger and Siddiqi, 1993), however this work failed completely (Lewis et al., 2005). More than 44,000 ha of mangroves have been planted in Philippines and the survival rate is likewise low at 10–20% (Primavera and Esteban 2008). In Vietnam, there have been several attempts to restore mangroves in erosion-prone areas, but the success rate of mangrove planting in depositional areas was less than 50% (Duke

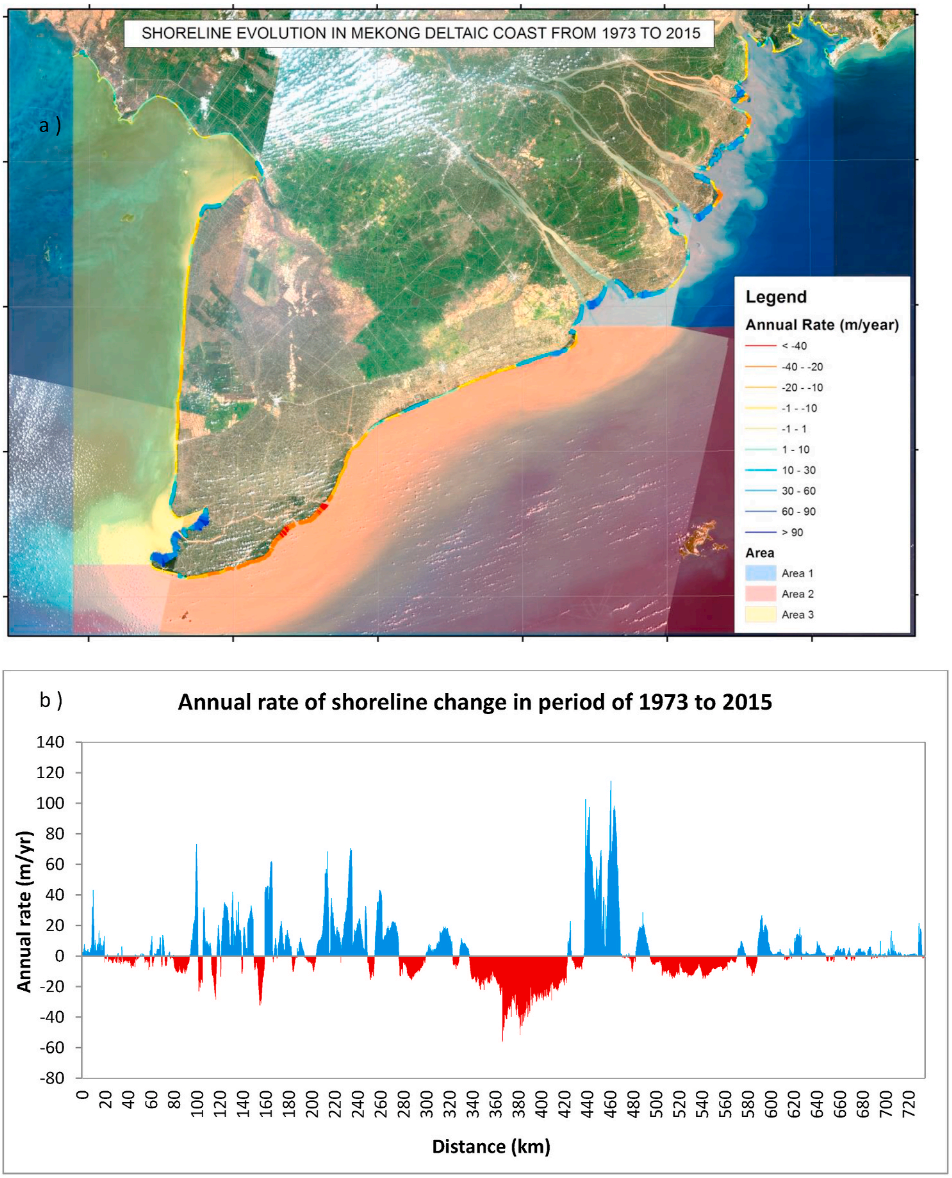


Fig. 12. (a) Shoreline evolution, (b) annual shoreline change rate and (c) area change rate along Mekong deltaic coast (Phan et al., 2017), (d) annual area loss of coastal erosion and mangroves due to by coastal erosion in Mekong deltaic coast in the period of 1973–2015.

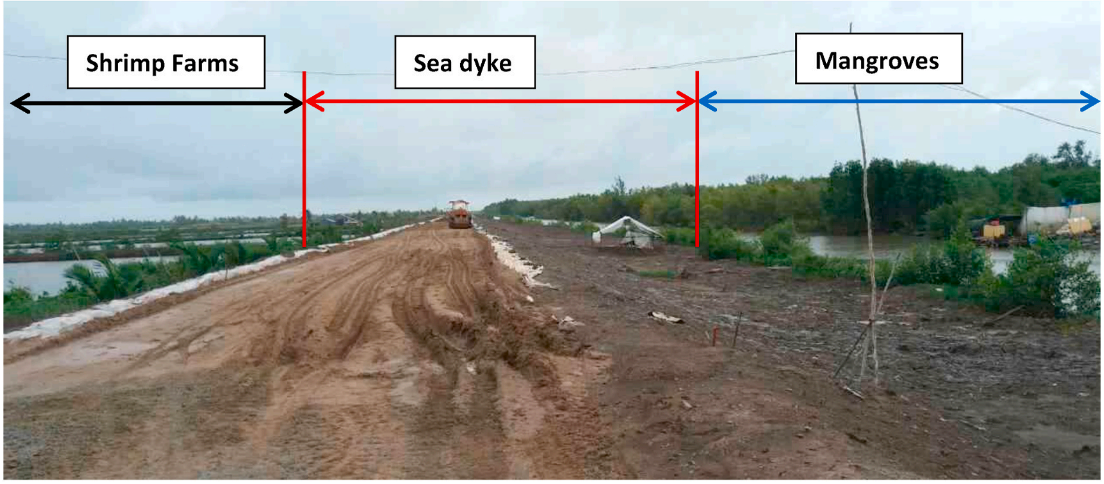


Fig. 13. Sea dyke, shrimp farm and mangrove system in coastal area of Camau province.

et al., 2010; Hong and San, 1993; Chu., 2015) (Fig. 14). There is very high survival rate from 70 to 90% in the first 3-month from projects of the mangrove rehabilitation, however, survival rates in the long-term only remain from 30 to 50%. There are cases that mangrove failed completely, e.g. a mangrove restoration project in Binh Dinh province (Hai et al., 2020) (see Fig. 15).

Primavera and Esteban (2008) attribute poor survival of mangrove stands mainly to two factors: inappropriate species and sites. With respect to the experiences in the Philippines, the favoured, but unsuitable, Rhizophora are planted in sandy substrates of exposed coastlines instead of the natural colonizers, Avicennia and Sonneratia. More significantly, planting sites are generally in the lower intertidal to subtidal zones where mangroves do not thrive, rather than in the optimal middle to upper intertidal levels. Mangrove planting on lower intertidal mudflats is to be discouraged or, at least, to be reconsidered (Samson and Rollon 2008). The single most important factor in designing a successful mangrove restoration project is determining the normal hydrology (depth, duration and frequency of tidal flooding) of existing natural mangrove plant communities in the area where restoration is executed (Lewis et al., 2005).

A thorough planning is an essential key to reduce the risk of failures in mangrove restoration. Analysing the reason of mangrove loss as well as infertile natural rehabilitation needs to be considered a priority before implementing mangrove restoration with the correct seedlings. Too little attention has been paid to the coastal dynamics of wave action and sediment transport, as well as implementing consistent species; the weak points in the mangrove restoration of Vietnam (IUCN, 2012). Besides, the dense oysters clinging to the seedlings and the rudimentary methods to catch crab, goby, clams by local people also affect mangrove growth. Therefore, the need to seriously study the characteristic of mangrove types, soil as well as hydrodynamics in the coastal area in the Mekong delta is an obvious and urgent matter.

4.2.2. Reconciliation of coastal protection and aquaculture

Mangroves act as a natural wall against storms, sea level rise and erosion, and have a high potential to accumulate carbon. In addition, the mangrove ecosystems produce a natural habitat for many aquatic and terrene species, as well as provide a home of livelihood for coastal communities. For that reason, it is beneficial to include mangroves in the coastal protection policy (Truong et al., 2021). Nevertheless, along the coastal Mekong Delta, mangrove forests have been disappearing at alarming rates from 185,800 ha in 1973 to only 102,160 ha in 2020 as detailed in the analyses of the previous section. One of the reasons is that the development of the aquaculture sector generates high values on the world market. Fisheries have been very successful in the Mekong delta, which has resulted in a significant contribution to not only the higher income for local people but also Vietnam's economic development in recent years. Along coastal districts, aquaculture covered only a few hectares in 1973, however it has exploded to roughly 300,000 ha in 2015 and the aquaculture invaded mangroves area averaged over 2000 ha/yr within 43 years. Therefore, an approach to attain the benefit of both aquaculture and mangroves without destroying each other has been receiving attention in recent years. Based on an evaluation framework of the costs and benefits, Silke (2016) indicated that the best coastal protection strategy is a combination with alternative use of the foreshore, for example the reconciliation of extensive aquaculture and

Fig. 14. The failure of mangrove restoration in Baclieu province.

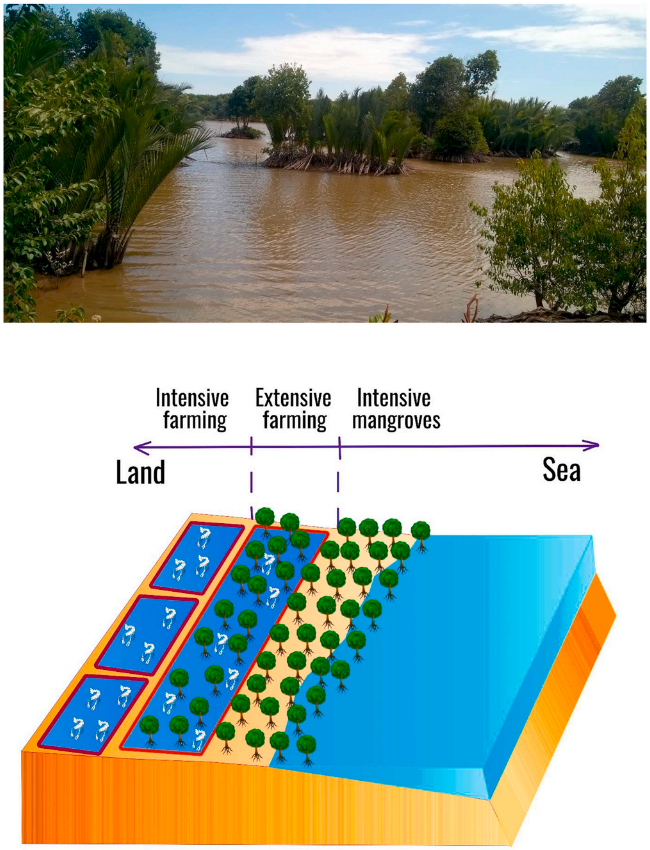


Fig. 15. An example of extensive farming in the coastal Mekong delta (above) and the transitional reconciliation model of mangroves and aquaculture in the coastal Mekong delta (below).

mangroves. Furthermore, the recent success in the coastal Mekong delta of the integrated coastal management programme is a program for mangrove restoration based on sustainable mangrove-shrimp farming and simultaneous reducing emission of SNV, the Netherlands Development Organization, and the International Union for Conservation of Nature and Natural Resources. The advantage of this integrated mangrove-shrimp farming is that mangroves raise biodiversity of plankton, improve water quality as well as reduce the risk for diseases of aquatic species. Thus, not only shrimp productivity is improved but also the risk of high fluctuation of shrimp profits can be reduced due to diversification into other aquatic yields. Integrated shrimp-mangrove farming systems along coastal Mekong Delta provide a reasonable basis for organic production as they are already built on ideas of bio-diversity and social sustainability.

5. Conclusion

This work provides a detailed picture of long-term mangroves and other land cover types dynamics in the coastal area of the Mekong delta in Vietnam. The results reveal that there is a significant decline amounting to half the mangrove extent over the past 48 years, from 185,800 ha in 1973 to 102,160 ha in 2020. However, the mangrove extent, dropping to a minimum during 43 years at 89,650 ha in 2010, started to give an optimistic signal of an increase in the period of 2010–2020 after the implementation of coastal erosion limitation and mangrove restoration projects. Meanwhile, the outbreak of aquaculture area took place, initially with only a few hectares in 1973, rising to 321,560 ha in 2020 due to the economic benefits of this farming type. It is one of the main reasons leading to the serious decline of the mangrove area in the Mekong delta, specifically aquaculture invading mangroves approximately 2150 ha/yr in the recent 48 years. For the first time, this study quantifies the loss of mangrove areas in the Mekong delta due to coastal erosion, viz. an average loss of over 400 ha/yr.

The results from these findings demonstrate that Landsat images are capable to evaluate the dynamics of mangrove and other land cover categories in the spatial and temporal scale. The study stresses the advantage and importance of the application of satellite imagery to analyse the extent of anthropogenic activities and their impact on the land covers over several decades. Hence, this technique is one of the suitable tools for monitoring, analysing as well as managing the mangroves.

The study highlights the main threatening drivers to the survival of the mangrove in the Mekong delta, including pollution, land use conversion, insufficient nutrient-enriched sediment, coastal erosion and coastal mangrove squeeze. In order to cope with the previous drivers causing vast and extensive mangrove degradation, an Integrated Coastal Management Programme is an appropriate approach for the various challenges occurring in the Mekong Delta. Proper mangrove restoration techniques as well as the reconciliation of coastal protection and aquaculture should be considered in efforts to achieve the benefit and to balance between the economy of aquaculture and the environment of mangroves. This approach can be one of the solutions that contribute to the sustainable management of mangroves, not only in the coastal Mekong delta but also in other similar areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alonso, M.J., Martínez, D.M., Sagrado, J., Águila, I.M., Batlles, F.J., 2016. The application of Bayesian network classifiers to cloud classification in satellite images. Renew. Energy 97, 155–161. https://doi.org/10.1016/j.renene.2016.05.066.

Asp, N.E., Gomes, V.J.C., Schettini, C.A.F., Souza-Filho, P.W.M., Siegle, E., Ogston, A.S., Nittrouer, C.A., Queiroz, M.C., 2018. Sediment dynamics of a tropical tide-dominated estuary: Turbidity maximum, mangroves and the role of the Amazon River sediment load Estuarine. Coastal and Shelf Science 214, 10–24.

Barbier, E.B., 2003. Habitat-fishery linkages and mangrove loss in Thailand. Contemp. Econ. Pol. 21 (1), 59–77.

Bernabe, Sergio, Plaza, Antonio, 2010. A new system to perform unsupervised and supervised classification of satellite images from Google maps. In: Proceedings Volume 7810, Satellite Data Compression, Communications, and Processing VI, p. 781010. https://doi.org/10.1117/12.863243.

Besset, M., Gratiot, N., Anthony, E.J., Bouchette, F., Goichot, M., Marchesiello, P., 2019. Mangroves and shoreline erosion in the Mekong River delta, Viet Nam. Estuar. Coast Shelf Sci. 226 art. no. 106263.

Binh, T.N.K.D., Vromant, N., Hung, N.T., Hens, L., Boon, E.K., 2005. Land cover changes between 1968 and 2003 in Cai Nuoc, Ca Mau peninsula, Vietnam. Environ. Dev. Sustain. 7, 519–536.

Boto, K., Wellington, J., 1983. Phosphorus and nitrogen nutritional status of a Northern Australian mangrove forest. Mar. Ecol. Prog. Ser. 11, 63–69.

Bullock, E.L., Fagherazzi, S., Nardin, W., Vo-Luong, P., Nguyen, P., Woodcock, C.E., 2017. Temporal patterns in species zonation in a mangrove forest in the Mekong Delta, Vietnam, using a time series of Landsat imagery. Continent. Shelf Res. 147, 144–154.

Chander, G., Markham, B., 2003. Revised landsat 5 TM radiometric Calibration procedures and postcalibration dynamic ranges. IEEE Trans. Geosci. Rem. Sens. 41, 11.

Chavez, P.S., 1996. Image-based atmospheric correction—revised and improved. Photogramm. Eng. Rem. Sens. 62, 1025–1036.

Chu, V.C., Brown, S., Huynh, H.T., Hockings, M., 2015. Using Melaleuca fences as soft coastal engineering for mangrove restoration in Kien Giang. Vietnam. Ecological Engineering 81, 256–265.

Congalton, R.G., 1991. A review of assessing the accuracy of classifications of remotely sensed data. Rentote Sensing of Environment 37, 35–46.

Cuc, N.T.K., Suzuki, T., Steveninck, E.D.R., Hai, H., 2013. Modelling the impacts of mangrove vegetation structure on wave dissipation in ben Tre province, Vietnam, under different climate change scenarios. J. Coast Res. 31, 340–347. https://doi.org/10.2112/JCOASTRES-D-12-00271.1.

Dahdouh-Guebas, F., 2002. The use of remote sensing and GIS in the sustainable management of tropical coastal ecosystems. Environ. Dev. Sustain. 4, 93–112.

Doody, J.P., 2004. Coastal squeeze e an historical perspective. J. Coast Conserv. 10, 129–138.

Doody, J.P., 2013. Coastal squeeze and managed realignment in southeast England, does it tell us anything about the future? Ocean Coast Manag. 79, 34–41.

Duarte, C., Geertz-Hansen, O., Thampanya, U., Terrados, J., Fortes, M., Kamp-Nielsen, L., Boromthanarath, S., 1998. Relationship between sediment conditions and mangrove Rhizophora apiculata seedling growth and nutrient status. Mar. Ecol. Prog. Ser. 175, 277–283. Retrieved January 15, 2020, from. www.jstor.org/stable/24831860.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I., Dahdouh-Guebas, F., 2007. A world without mangroves? Science 317, 41–42.

Duke, N.C., Wilson, N., Mackenzie, J., Hai Hoa, N., 2010. Report on Assessing Mangrove Forests. Shorelines Conditions and Feasibility of REDD for Kien Giang Province, Vietnam, p. 137.

Ellison, A.M., Felson, A.J., Friess, D.A., 2020. Mangrove rehabilitation and restoration as experimental adaptive management. Front. Mar. Sci. 7, 327. https://doi.org/10.3389/fmars.2020.00327.

Feller, I.C., 1995. Effects of nutrient enrichment on growth and herbivory of dwarf red mangrove (Rhizophora mangle). Ecol. Monogr. 65, 477–505.

Ferraris, V., Dobigeon, N., Wei, Q., Chabert, M., 2018. Detecting changes between optical images of different spatial and spectral resolutions: a fusion-based approach. IEEE Trans. Geosci. Rem. Sens. 56, 1566–1578.

Fu, K.D., He, D.M., 2008. Sedimentation in the manwan reservoir in the upper Mekong and its downstream impacts. Quat. Int. 186 (1), 91–99. https://doi.org/10.1016/j.quaint.2007.09.041.

Gandhi, S.M., Sarkar, B.C., 2016. Essentials of Mineral Exploration and Evaluation. Elsevier, 9780128053324.

Giesen, W., Wulffraat, S., Zieren, M., Scholten, L., 2006. Mangrove Guidebook for Southeast Asia. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, p. 769.

Gillies, R.R., Carlson, T.N., Cui, J., Kustas, W.P., Humes, K.S., 1997. A verification of the triangle method for obtaining surface soil water content and energy fluxes from remote measurements of the Normalized Difference Vegetation Index (NDVI) and surface radiant temperature. Int. J. Rem. Sens. 18, 3145–3166.

Giri, C., Zhu, Z., Tieszen, L., Singh, A., Gillette, S., Kelmelis, J., 2007. Mangrove forest distributions and dynamics (1975-2005) of the tsunami-affected region of Asiay. J. Biogeogr. 35, 519–528.

Green, E.P., Mumby, P.J., Edwards, A.J., Clark, C.D., Ellis, A.C., 1997. Estimating leaf area index of mangroves from satellite data. Aquat. Bot. 58, 11–19.

Green, E.R., Mumby, P.J., Edwards, A.J., Clark, C.D., Ellis, A.C., 1998. The assessment of mangrove areas using high-resolution multispeciral airborne imagery. J. Coast Res. 14, 433–443.

Hai, N.T., Dell, B., Phuong, V.T., Harper, R.J., 2020. Towards a more robust approach for the restoration of mangroves in Vietnam. Annals of Forest Science, Springer Nature/EDP Science 77 (1), 18.

Haito, H., Bellan, M.F., Al-Habshi, A., Aizpuru, M., Blasco, F., 2003. Mangrove research and coastal ecosystem studies with SPOT-4 HRVIR and TERRA ASTER in the Arabian Gulf. Int. J. Rem. Sens. 24, 4073–4092.

Hao, N.V., 1999. Shrimp health research in Vietnam, including current and planned activities. In: Proceedings of the Workshop on towards Sustainable Shrimp Culture in Thailand and the Region. Hat Yai, Songkhla, Thailand, pp. 94–97, 28 Oct-1 Nov 1996.

Hashimoto, T.R., 2001. Environmental Issues and Recent Infrastructure Development in the Mekong Delta: Review, Analysis and Recommendations with Particular Reference to Large-Scale Water Control Projects and the Development of Coastal Areas. University of Sydney, Australia, p. 70. Working Paper No. 4.

Held, A., Tichehurst, C., Lymburner, L., Williams, N., 2003. High resolution mapping of tropical mangrove ecosystems using hyper-spectral and radar remote sensing. Int. J. Rem. Sens. 24, 2739–2759.

Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 national land cover database for the United States. Photogramm. Eng. Rem. Sens. 70, 829–840.

Hong, P.N., 2000. Effects of mangrove restoration and conservation on the biodiversity and environment in Can Gio district. In: Mangrove Management and Conservation Workshop, pp. 111–137. Okinawa, Japan, 2004.

Hong, P.N., San, H.T., 1993. Mangrove of Vietnam. IUCN, Bangkok, Thailand, p. 173p.

Hu, L., Li, Wenyu, Xu, B., 2018. Monitoring mangrove forest change in China from 1990 to 2015 using Landsat-derived spectral-temporal variability metrics. Int. J. Appl. Earth Obs. Geoinf. 73, 88–98.

Huang, C., Townshend, J., 2003. Astepwise regression tree for nonlinear approximation: applications to estimating subpixel land cover. Int. J. Rem. Sens. 24, 75–90.

Huitric, M., Folke, C., Kautsky, N., 2002. Analysing development and government policies of the shrimp farming industry in Thailand in relation to mangrove ecosystems. Ecol. Econ. 40, 441–445.

IUCN (International Union for Conservation of Nature), 2012. Viet Nam national strategy and action plan (2011-2013). Mangroves for the Future 32. Gland, Switzerland.

Kathiresan, K., 2012. Importance of mangrove system. Int. J. Mar. Sci. 2 (10), 70–89.

Kathiresan, K., Bingham, B.L., 2001. Biology of mangroves and mangrove ecosystems. Adv. Mar. Biol. 40, 81–251.

Ke, L., Lin, Y., Zeng, Z., Zhang, L., Meng, L., 2018. Adaptive change detection with significance test. IEEE Access 6, 27442–27450. https://doi.org/10.1109/ACCESS.2018.2807380.

Kirui, K.B., Kairo, J.G., Bosire, J., Viergever, K.M., Rudra, S., Huxham, M., Briers, R.A., 2012. Mapping of Mangrove forest land cover change along the Kenya coastline using Landsat imagery. Ocean Coast Manag.

Koedam, N., Dahdouh-Guebas, F., Monbaliu, D., Merken, R., Ruyck, J. De, Minh, V.Q., 2007. Improvement of Shrimp Production Sustainability and Shrimp Safety in Vietnam. Vrije Universiteit Brussel, Brussels, Belgium, p. 88 (BelSPO Project Report).

Kotera, A., Nguyen, K.D., Sakamoto, T., Lizumi, T., Yakozawa, M., 2013. Amodelingapproachforassessingricecroppingcycleaffectedbyflooding, salinityintrusion,andmonsoonrainsintheMekongDelta. Vietnam.PaddyWaterEnviron 12, 343–354. https://doi.org/10.1007/s10333-013-0386-y.

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T.V., Dech, S., 2011. Remote sensing of mangrove ecosystem: a review. Rem. Sens. 3, 878–928.

Lam-Dao, N., Pham-Bach, V., Nguyen-Thanh, M., Pham-Thi, M.T., Hoang-Phi, P., 2011. Change detection of land use and riverbank in Mekong delta, Vietnam using time series remotely sensed data. J. Resour. Ecol. 2 (4), 370–374.

Lan, N.T., 2013. Social and ecological challenges of market-oriented shrimp farming in Vietnam. SpringerPlus 2, 675. https://doi.org/10.1186/2193-1801-2-675. Published 2013 Dec 17.

Le, T.X., Munekage, Y., 2004. Residues of selected antibiotics in water and mud from shrimp ponds in mangrove areas in Viet Nam. Mar. Pollut. Bull. 49, 922–929. https://doi.org/10.1016/j.marpolbul.2004.06.016, 2004.

Lebel, L., Tri, N.H., Saengnoree, A., Pasong, S., Buatama, U., Thoa, L.K., 2002. Industrial transformation and shrimp aquaculture in Thailand and Vietnam: pathways to ecological. social, and economic sustainability. AMBIO A J. Hum. Environ. 31, 311–323.

Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., Record, S., 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. Global Ecol. Biogeogr. 23 (7), 726–743.

Lewis, R.R., Hodgson, A.B., Mauseth, G.S., 2005. Project facilitates the natural reseeding of mangrove forests (Florida). Ecol. Restor. 23, 276–277.

Lillesand, T.M., Keifer, R.W., Chipman, J.W., 2004. Remote Sensing and Image Interpretation, fifth ed. Wiley, New York.

Lo, C.P., Choi, J., 2004. A hybrid approach to urban land use/cover mapping using Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images. Int. J. Rem. Sens. 25, 2687–2700.

Mang, T.L., Tran, L.T.H., Dan, N.P., 2008. Water quality assessment and propose sollutions for improvement of industrial shrimp pond in Kien Luong, Kien Giang province, Vietnam. In: Workshop on "Technical and Management Approaches to Control Wastes from Aquaculture and Seafood Processing Industries". An Giang province, Vietnam.

Marchesiello, P., Nguyen, N.M., Gratiot, N., Loisel, H., Anthony, E.J., Dinh, C.S., Nguyen, T., Almar, R., Kestenare, E., 2019. Erosion of the coastal Mekong delta: assessing natural against man induced processes. Continent. Shelf Res. 181, 72–89.

Marshall, N., 1994. Mangrove conservation in relation to overall environmental consideration. Hydrobiologia 285, 303–309.

Massarelli, C., 2018. Fast detection of significantly transformed areas due to illegal waste burial with a procedure applicable to landsat images. Int. J. Rem. Sens. 39, 754–769. https://doi.org/10.1080/01431161. 2017.1390272.

Mohammady, M., Moradi, H.R., Zeinivand, H., Temme, A.J.A.M., 2015. A comparison of supervised, unsupervised and synthetic land use classification methods in the north of Iran. Int. J. Environ. Sci. Technol. 12 (5), 1515–1526. https://doi.org/10.1007/s13762-014-0728-3.

NAS National Academy of Sciences, 1974. The Effects of Herbicides in South Vietnam, Part a - Summary and Conclusions. National Academy of Sciences, Washington.

Nguyen, H.H., McAlpine, C., Pullar, D., Johansen, K., Duke, N.C., 2013. The relationship of spatial – temporal changes in fringe mangrove extent and adjacent land use: case study of Kien Giang coast, Vietnam. Ocean Coast Manag. 76, 12–22.

Ogilvie, A., Belaud, G., Delenne, C., Bailly, J.S., Bader, J.C., Oleksiak, A., Martin, D., 2015. Decadal monitoring of the Niger Inner Delta flood dynamics using MODIS optical data. J. Hydrol. 523, 368–383.

Onuf, C.P., Teal, J.M., Valiela, I., 1977. Interactions of nutrients, plant growth and herbivory in a mangrove ecosystem. Ecology 58, 514–526.

Phan, H., Reniers, A., Ye, T., Stive, M., 2017. Response in the Mekong deltaic coast to its changing sediment sources and sinks. Denmark. In: Aagaard, T., Deigaard, R., Fuhrman, D. (Eds.), Proceedings of Coastal Dynamics 2017: Helsingør, pp. 311–322 [Paper No. 225].

Phan Khanh, Linh, Van Thiel De Vries, J.S.M., Stive, M.J.F., 2015. Coastal mangrove squeeze in the Mekong delta. J. Coast Res. 31 (2), 233–243.

Prasetya, G.S., 2006. The Role of Coastal Forest and Trees in Combating Coastal Erosion. FOA.

Primavera, J.H., 2000. Development and conservation of Philippine mangroves: institutional issues. Ecol. Econ. 35 (1), 91–106.

Primavera, J.H., Esteban, J.M.A., 2008. A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. Wetl. Ecol. Manag. 16, 345, 2008.

Radhika, K., Varadarajan, S., 2018. A neural network based classification of satellite images for change detection applications. Cogent Eng 5, 1–9.

Rahimi, S., Gholami Sefidkouhi, M.A., Raeini-Sarjaz, M., Valipour, M., 2015. Estimation of actual evapotranspiration by using MODIS images (a case study: Tajan catchment). Archives Agron. Soil Sci. 61 (5), 1–15.

Ricepedia. Vietnam basic statistics. Available from. http://ricepedia.org/vietnam.

Richards, J.A., 1986. Remote Sensing Digital Image Analysis: an Introduction. Springer–Verlag, Berlin.

Sadeghi, V., Farnood Ahmadi, F., Ebadi, H., 2016. Design and implementation of an expert system for updating thematic maps using satellite imagery (case study: changes of Lake Urmia). Arabian J. Geosci. 9, 1–17. https://doi.org/10.1007/s12517-015-2301-x.

Saenger, P., Siddiqi, N.A., 1993. Land from the seas: the mangrove afforestation program of Bangladesh. Ocean Coast Manag. 20, 23–39.

Sam, D.D., Binh, N.N., Que, N.D., Phuong, V.T., 2005. Overview of Vietnam Mangrove Forest. agriculture publisher House, Ha Noi, Vietnam (in Vietnamese).

Samson, M.S., Rollon, R.N., 2008. Growth performance of mangroves at the enhancement sites: need to revisit forest management strategies. Ambio 37 (4), 234–240.

Satyanarayana, B., Mohamad, K.A., Idris, I.F., Husain, M.L., Dahdouh-Guebas, F., 2011. Assessment of mangrove vegetation based on remote sensing and ground-truth measurements at Tumpat, Kelantan delta, East Coast of Peninsular Malaysia. Int. J. Rem. Sens. 32 (6), 1635–1650.

Shimizu, A., Takada, H., Koike, T., Takeshita, A., Saha, M., Rinawati, N., 2013. Ubiquitous occurrence of sulfonamides in tropical Asian waters. Sci. Total Environ. 452 (453), 108–115. https://doi.org/10.1016/j.scitotenv.2013.02.027.

Silke, Tas, 2016. Coastal Protection in the Mekong Delta. Master thesis published by TU Delft. uuid:2f82f861-73e2-4bb3-8332-e51e917e64cd.

Spalding, M., Kainuma, M., Collins, L., 2010. World Atlas of Mangroves. Earthscan, UK and USA, p. 319.

Stellman, J.M., Stellman, S.D., Christian, R., Weber, T., Tomasallo, C., 2003. The extent and patterns of usage of agent Orange and other herbicides in Vietnam. Nature 422, 681–687.

Su, L., Gong, M., Zhang, P., Zhang, M., Liu, J., Yang, H., 2017. Deep learning and mapping based ternary change detection for information unbalanced images. Pattern Recogn. 2–42.

Suzuki, T., Zijkema, M., Burger, B., Meijer, M., Narayan, S., 2011. Wave dissipation by vegetation with layer schematization in SWAN. Coast Eng. 59 (1), 64–71.

Tanner, E.V.J., Vitousek, P.M., Cuevas, E., 1998. Experimental investigation of nutrient limitation of forest growth on wet tropical mountains. Ecology 79, 10–22.

Thai, T.L., Nguyen, T.P., Scott, S., Tang, V.T., 2021. Protected mangrove forests and aquaculture development for livelihoods. Ocean Coast Manag. 205 https://doi.org/10.1016/j.ocecoaman.2021.105553.

Thomas, N., Hendrix, C., Congalton, R.G., 2003. A comparison of urban mapping methods using high-resolution digital imagery. Photogramm. Eng. Rem. Sens. 69, 963–972.

Tian, D., Gong, M., 2018. A novel edge-weight based fuzzy clustering method for change detection in SAR images. Inf. Sci. 467, 415–430. https://doi.org/10.1016/j.ins.2018.08.015.

Toang, Y.D., 2017. Rice intensive cropping and balanced cropping in the Mekong Delta, Vietnam — economic and ecological considerations. Ecol. Econ. 132, 205–2012. https://doi.org/10.1016/j.ecolecon.2016.10.013.

Tomlinson, P.B., 1994. The Botany of Mangroves. Cambridge University Press, Cambridge.

Torio, Dante D., Chimura, Gail L., 2014. Assessing coastal squeeze of tidal wetlands. J. Coast Res. 29 (5), 1049–1061.

Truong, D.T., Vo, Q.T., Pham, K.N., 2021. Does the devolution of forest management help conserve mangrove in the Mekong Delta of Viet Nam? Land Use Pol. 106 https://doi.org/10.1016/j.landusepol.2021.105440.

Tuan, L.X., Yukihiro, M., Tho, N.H., Dao, P.T.A., 2003. Environmental management in mangrove areas. Environmental Informatics Archives 1, 38–52.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Barr, J., Ben, D.C., 2003. Impactofseawaterintrusioncontrolontheenvironment, landuseandhouseholdincomesinacoastalarea. Paddy Water Environ. 1, 65–73. https://doi.org/10.1007/s10333-003-0015-2.

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51 (10), 807–815.

Van, T.T., Wilson, N., Tung, H.T., Quistoudt, K., Minh, V.Q., Tuan, L.X., Dahdouh-Geubas, F., Keodam, N., 2015. Changes in mangrove vegetation area and character in a war and land use change affected region of Vietnam (Mui Ca Mau) over six decades. Acta Oecol. 63, 71–81.

Veettil, B.K., Quang, N.X., 2018. Environmental changes near Mekong Delta in Vietnam using remote sensing. Rendiconti Lincei. Sci. Fis. Nat. 29, 639–647. https://doi.org/10.1007/s12210-018-0695-6.

Vescovo, L., Gianelle, D., 2008. Using the MIR bands in vegetation indices for the estimation of grassland biophysical parameters from satellite remote sensing in the Alps region of Trentino (Italy). Adv. Space Res. 41, 1764–1772, 2008.

Wang, L., Sousa, W., Gong, P., 2004. Integration of object-based and pixed-based classification for mapping mangroves with Ikonos imagery. Int. J. Rem. Sens. 25, 5655–5668.

Wilson, K.L., Skinner, M.A., Lotze, H.K., 2019. Eelgrass (Zostera marina) and benthic habitat mapping in Atlantic Canada using high-resolution SPOT 6/7 satellite imagery. Estuar. Coast Shelf Sci. 226.

Wolanski, E., Spagnol, S., Thomas, S., Moore, K., Alongi, M.D., Trott, L., Davidson, A., 2000. Modelling and visualizing the fate of shrimp pond effluent in a mangrove-fringed tidal creek. Estuar. Coast Shelf Sci. 50, 85–97.

Wu, S.T., Chen, Y.S., 2016. Examining eco-environmental changes at major recreational sites in Kenting National Park in Taiwan by integrating SPOT satellite images and NDVI. Tourism Manag. 57, 23–36.

Zhang, X., Xiao, P., Feng, X., Yuan, M., 2017. Separate segmentation of multi-temporal high-resolution remote sensing images for object based change detection in urban area. Remote Sens. Environ. 201, 243–255. https://doi.org/10.1016/j.rse.2017.09.022.