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LANDCOVER CHANGE IN MANGROVES IN THE LOWER GULF OF THAILAND: POTENTIAL LANDWARD MIGRATION DUE TO SEA LEVEL RISE

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Abstract: Mangrove forests are an intertidal habitat that dynamically responds to anthropogenic and natural disturbances. Rising sea levels due to climate change pose a critical threat to their existence. Nevertheless, knowledge about regional impacts on mangrove forests is limited. This study examined mangrove forest and land cover changes in Surat Thani Province in the lower Gulf of Thailand, using Thailand Earth Observation Satellite (THEOS) images from 2011 to 2021. Results showed changes in the Surat Thani mangrove forest area from 76.68 km^2 in 2011 to 57.03 km^2 in 2021. Mangrove forests were mainly converted to agriculture (12.91 km^2), barren vegetation (7.73 km^2), and aquaculture (1.57 km^2). Decreased mangrove forest areas occurred inland, adjacent to community/urban areas, and along the coastline. Between January 2008 and December 2021, the sea level linearly increased by 5.28 mm/year. Concurrently, mangrove forest areas along the coastline increased by 4.63 km^2 while inland growth was only 0.96 km^2. These results highlight the seaward migration of mangrove forests, with less inland migration due to urbanisation within the study area.

Keywords: Sustainability, sea level rise, mangrove forest migration, land use change.

Introduction

Mangrove forests are an essential ecosystem resource, providing carbon storage and protection against severe storms and natural hazards for hatcheries and fisheries that support the livelihood of coastal communities. Note that mangrove forests are critical in climate change mitigation but remain vulnerable ecosystems affected by wind, coastal hydrology, and geomorphology. Over the last decade, climate change has increased global warming, sea level rise, and freshwater floods, culminating in a 10% to 15% reduction in mangrove forest areas (Dang *et al*., 2022). Flooding, mean annual run-off, high water levels, and estuary flow regimes limit mangrove forest area expansion, with the main drivers for mangrove forest area loss as water inundation, soil accretion, and organic matter accumulation (Krauss *et al*., 2014; Adams & Rajkaran, 2021; Dang *et al*., 2022).

Moreover, mangrove forests have been shown to adapt to rising sea levels through vertical accretion, a process facilitated by aerial roots that trap sediment and organic matter (Rogers *et al*., 2013; Krauss *et al*., 2014). Water inundation is the main driver of mangrove forest loss in the Mekong Delta (Dang *et al*., 2022). Note that rising sea levels affect the chemical and physical properties of the plants in mangrove forests (Pumijumnong, 2014) by impacting root growth contributions (Krauss *et al*., 2014) and modifying the anatomical and morphological patterns of plant vascular systems. This includes vessel density, vessel diameter, vessel grouping, vessel length, and fibre wall thickness, depending on the reactions of specific plant species (Yanez-Espinosa & Flores, 2011).

Asia accounts for 41.9% of the global mangrove forest area, rapidly decreasing due to agricultural and aquacultural anthropogenic activities (Wards *et al*., 2016). In Thailand, mangrove forests grow along the east coast of the Gulf of Thailand and the west coast of the Andaman Sea. Mangrove forest areas in Thailand have declined from 3,200 km^2 in 1975 to 1,600 km^2 in 1996 due to area loss and pollution from urbanisation, agriculture, aquaculture, and coastal development. Surat Thani Province has the second-highest mangrove forest area in the Lower Gulf of Thailand and shows similar decline trends, with mangrove forest areas decreasing from around 118 km^2 in 1961 to 61 km^2 in 2007 (Pumijumnong, 2014).

Mangrove forest areas have been converted to agriculture, aquaculture, and coastal development, but climate change poses an important threat. Over the past 30 to 40 years, the Gulf of Thailand has recorded a 93% reduction in annual coastal sediment yield, causing flooding impacts on mangrove forests due to rising sea levels (Wards *et al*., 2016). Mangrove forests are predicted to decline in area, structural complexity, and/or functionality by 1% to 2% per year due to human impacts and climate change (Alongi, 2015).

Mangrove forests respond to climate change differently according to their geographical distribution. Hence, knowledge concerning the role of sea level rise in mangrove forest area reduction is limited and detailed local and regional studies are required to fill this research lacuna. This study investigated the response of mangrove forests to human impacts and sea level rise at the local scale by comparing land use and land cover changes from satellite imagery between 2011 and 2021. Consequently, results can offer alternative solutions for optimal management of mangrove forest coastal areas in the Gulf of Thailand.

Materials and Methods

Study Area

The study area comprised mangrove forests in Surat Thani Province, located on the east coast of Southern Thailand, covering four districts: Chaiya District (Ta Krop Subdistrict, Thung Subdistrict, Phumriang Subdistrict, and Lamet Subdistrict), Tha Chang District (Khao Than Subdistrict, Tha Chang Subdistrict, and Tha Khoei Subdistrict), Phunphin District (Li Let Subdistrict), and Mueang Surat Thani District (Bang Sai Subdistrict, Bang Chana Subdistrict, and Khlong Chanak Subdistrict) (Figure 1).

Satellite Data Processing

THEOS satellite images with 2 m spatial resolution were used to identify changes in mangrove forest distribution. The images were pre-processed, utilising atmospheric correction and enhancement of spatial resolution, and a supervised classification approach was used to identify land use categories. The classification map included 11 categories: Mangrove forest, swamp forest, beach forest, aquaculture, agriculture, urban and building, mudflat, beach, river, hill forest, and barren vegetation based on definitions described in the mangrove resource database project by classifying mangrove land use zones using high-resolution satellite images (Department of Marine and Coastal Resources and GISTDA, Thailand). Mangrove forest area changes between 2011 and 2021 were digitised using QGIS 3.24.3 and the differences were assumed to be habitat loss and gain. Thus, mangrove forest area loss resulted directly from development and human activity, not including indirect causes such as density or biomass change.

Accuracy Assessment

Field surveys were conducted to verify the GIS analysis between March and July 2022, 330 sampling points were obtained. Subsequently, the overall accuracy and kappa coefficient of the classification map were calculated.

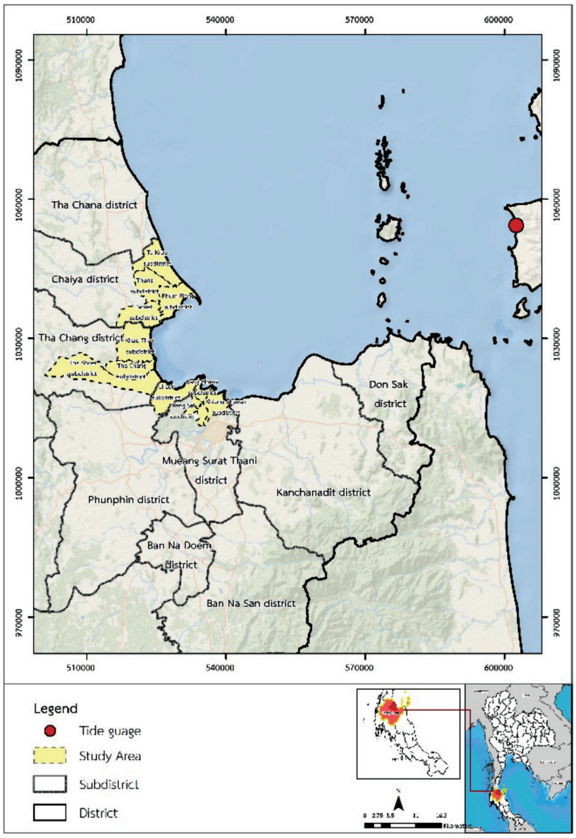


Figure 1: Map of the research area in Surat Thani Province, Gulf of Thailand

Water Level

Daily sea level data from the Koh Prab sea level tide gauge located in Surat Thani Province at 9.263056, 99.438333 (shown as a red dot in Figure 1) were collected between January 2008 and December 2021 from the Hydrographic Department, Royal Thai Navy. Missing values were imputed using the inputeTS function in the R package. Consequently, seasonal variations were removed by subtracting the monthly average and adding the overall mean sea level (Taninpong *et al*., 2021). A linear regression model was employed for trend detection analysis.

Mangrove Forest Area Prediction

The L-band Synthetic Aperture Radar (SAR) Global Mangrove Watch (1996-2022) Version 3.0 dataset from the Japan Aerospace Exploration Agency (JAXA), with an accuracy of 87.4% was used for prediction (Bunting *et al*., 2022). Data between 2015 and 2020 were used to analyse mangrove forest areas using QGIS. As presented by the equation below, a simple exponential smoothing method was used to predict mangrove forest areas with a 95% confidence level. The mangrove forest areas for the years 2021 to 2025 for both Thailand and Surat Thani Province were predicted as follows:

$$s_t = \alpha x_t + (1 - \alpha)\, s_{t-1} = s_{t-1} + \alpha(x_t - s_{t-1})$$

where α is a smoothing factor.

Results and Discussion

Mangrove Forest Cover and Drivers of Change

Land use and land cover maps of Chaiya District, Tha Chang District, Phunphin District, and Mueang Surat Thani District, Surat Thani Province were assessed using THEOS satellite maps in 2011 and 2021. In 2011, the area was mainly agricultural (228.81 km^2, 53.35%), mangrove forest (76.68 km^2, 17.88%), and aquaculture (46.92 km^2, 10.94%). In 2021, the three largest areas were agricultural (255.62 km^2, 59.60%), mangrove forest (57.03 km^2, 13.30%), and barren (42.15 km^2, 9.83%) (Table 1, Figure 1). Thus, an error matrix was used to assess the classification accuracy. The overall accuracy and kappa coefficient of the mangrove forest classification map were 93.03% and 0.93, respectively.

The LULC change map 2011/2021 provided information about converting mangrove forest areas in Surat Thani Province to other types of land use (Figure 2). Between 2011 and 2021, Surat Thani Province experienced a significant loss of mangrove forest area, totalling 19.65 km^2 or a 25.63% decline. Mangrove forests were mainly converted to agricultural areas (12.91 km^2), barren vegetation (7.73 km^2), and aquaculture (1.57 km^2) (Figure 3). Results were consistent with the main cause of the reduction in mangrove forest areas in Thailand as land use for agriculture, aquaculture, and the expansion of urban areas (Pumijumnong, 2014). From 1961 to 1993, mangrove forest areas in Thailand decreased by more than 50% due to increased agricultural land usage and expanding urban areas (Sremongkontip *et al*., 2000). In Samut Songkhram Province in the Upper Gulf of Thailand, the causes of mangrove forest area decline from 2001 to 2012 were conversion to agriculture and aquaculture and the expansion of urban communities (Upakankaew & Shrestha, n.d.).

Mangrove Migration Potential

The detailed analysis demonstrated that other land uses transformed into mangrove forests, including aquaculture areas (3.14 km^2), beaches (1.98 km^2), and barren areas (1.11 km^2) (Figure 3). Reductions in mangrove forest areas were similar in inland areas adjacent to communities and coastline areas (Figure 4). Mangrove forest areas along the coastline increased by 4.63 km^2, with changes from the water/sea and aquaculture areas. In comparison, the increase in mangrove

Table 1: Summary of LULC classes in Surat Thani Province in 2011 and 2021

Class Name	2011 (km^2)	2021 (km^2)	Land Use Change (km^2)	Percentage Change (%)	Percentage Accuracy (%)
Mangrove forest	76.68	57.03	-19.65	-25.63	95.83
Swamp forest	1.57	1.03	-0.54	-34.25	100
Beach forest	1.57	1.12	-0.46	-29.15	75.00
Hill forest	1.67	1.80	0.13	7.69	100
Aquaculture	46.92	32.10	-14.82	-31.58	98.31
Agriculture	228.81	255.62	26.81	11.71	86.09
Urban and building	22.77	24.71	1.94	8.51	98.21
Mudflat	0.44	0	-0.44	-99.50	100
Beach	0.40	0.32	-0.08	-19.18	100
River	12.54	12.99	0.45	3.58	96.88
Barren	35.47	42.15	6.68	18.82	92.50

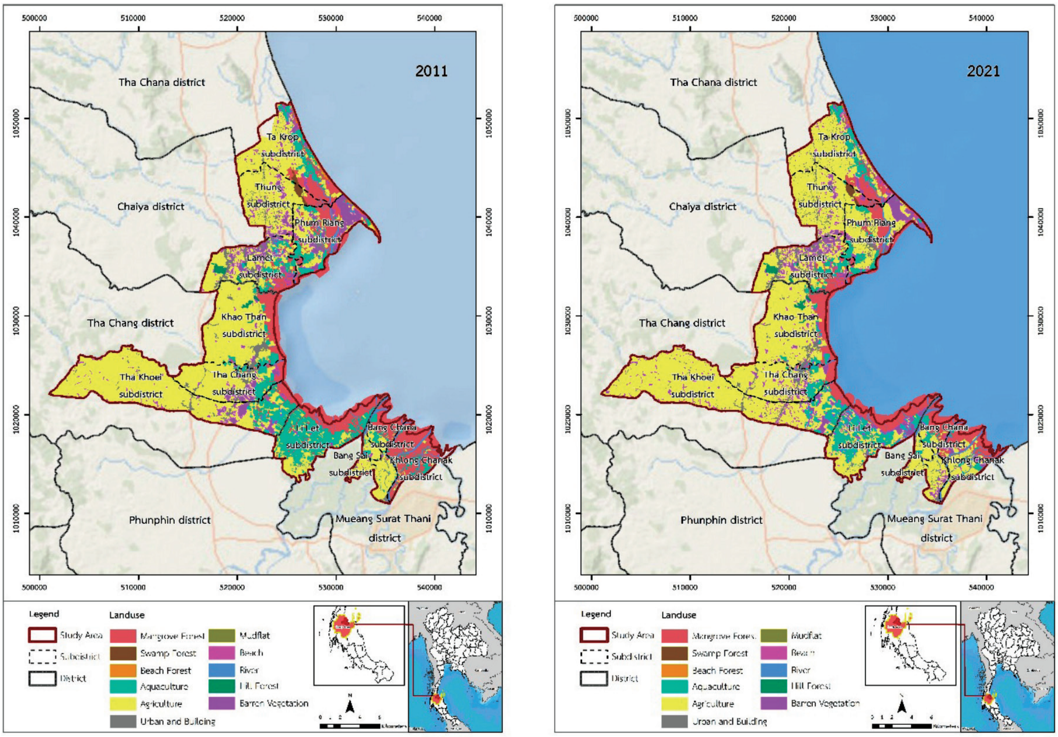
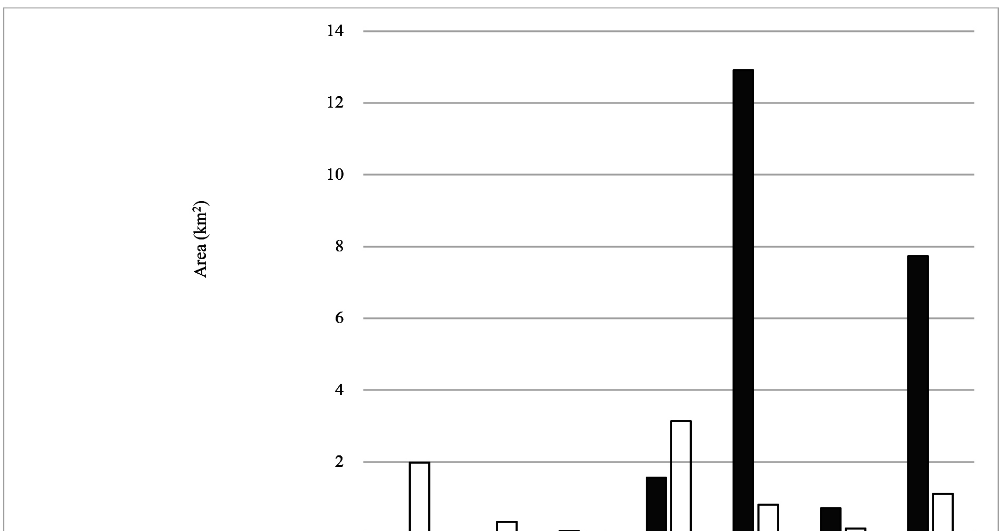


Figure 2: LULC map for 2011/2021 of Surat Thani Province (Chaiya District, Tha Chang District, Phunphin District, and Mueang Surat Thani District). (Interpretations of the colour references are listed in the figure legend)



	Beach	Swamp Forest	Beach Forest	Aqua-culture	Agri-culture	Urban and Building	Barren Vegetation
■ Mangroves tranform to other land covers	-	-	0.07	1.57	12.91	0.71	7.73
□ Other land covers transform to mangroves	1.98	0.34	0.05	3.14	0.81	0.14	1.11

Figure 3: Changes in mangrove forest areas in Surat Thani Province between 2011 and 2021

forest area in land adjacent to the community was only 0.96 km^2 (T-test, statistical difference, $p < 0.05$), indicating the ability of mangrove forests in the study area to expand in the direction of the sea. A study in Pamurbaya, Indonesia, in 2014 also recorded the expansion of mangrove forests along the coast by 2.40 km^2 within 12 years after the coastline was designated as a conservation area in 2002 (Prasita, 2015).

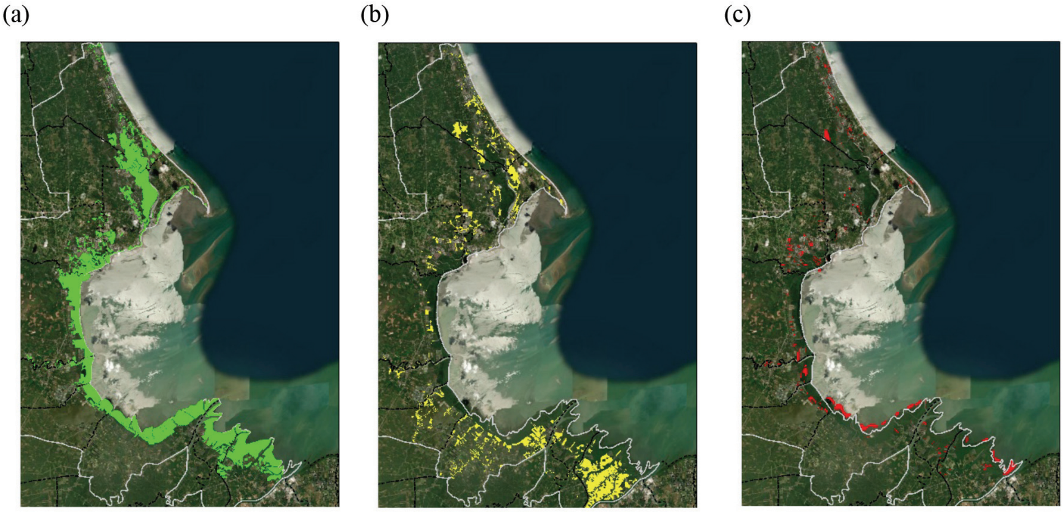


Figure 4: Increases and decreases in mangrove forest area between 2011 and 2021, (a) no change, (b) loss, and (c) gain

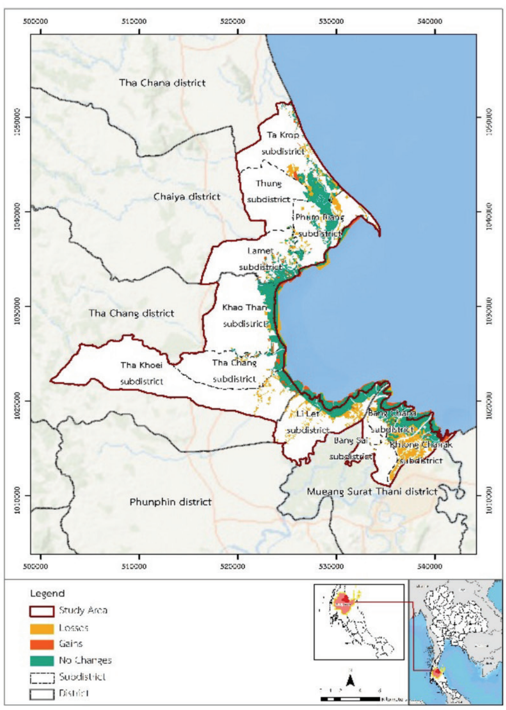


Figure 5: Mangrove forest area change detection map 2011 to 2021

Satellite image data also showed that coastal erosion impacted the reduction of mangrove forest areas in the Gulf of Thailand due to sea level rise and the amount of sediment deposited (Figure 5). The previous study using aerial photographic data from 1967, 1995, and 1999 showed the lower Gulf of Thailand as an open sea coast with no shelter from the wind and waves. Note that high coastal erosion results from wind and waves from the South China Sea (Somprathana & Chaiphan, 2004).

A study of Landsat satellite images between 1987 and 2002 found high coastal erosion at the mouth of the Chao Phraya River and the Gulf of Thailand in the southern region (Siripong, 2010). Hourly water level data collected from water measuring stations in the Lower Gulf of Thailand showed that the rise in sea level was not globally uniform (Alongi, 2015) and varied according to latitude (Vongvisessonjai, 2006). A previous study concluded that the sea level change rate in the Gulf of Thailand varied from station to station (Taninpong *et al*., 2021). In this study, the nearest tide gauge at Koh Prab was 20 km from the mangrove study site.

Between 2008 and 2021, the sea water level in Surat Thani Province increased linearly by 5.28 mm/year. The linear regression model predicted a linear increase over the next five years (Figure 6). Our data indicate the same trend as previous studies. Taninpong *et al*. (2021) recorded sea level data from 18 tide gauge stations in the Gulf of Thailand, including Surat Thani, from 1977 to 2019, with results showing a linear increase from 3.44 mm to 19.19 mm/year. Trisirisatayawong *et al*. (2011) and Sojisuporn *et al*. (2013) reported that from 1985 to 2009, sea level rise in the Gulf of Thailand increased linearly at a rate of 3 mm to 5.5 mm/year, similar to rates of sea level rise in Asia at 2.0 mm to 5.4 mm/year (Ward *et al*., 2016).

The increase in sea level at Surat Thani Province was higher than the global level. Global mean sea level rise during the 20th century was between 1.3 mm and 1.7 mm/year. However, since 1993, this has increased to between 2.8 mm and 3.6 mm/year (Wilson, 2017). A sea level rise vulnerability modelling study showed that the sea level had risen 3.2 mm/year over recent decades and is likely to increase between 0.28 m and 0.98 m by 2100.

Mangrove forests cannot expand inland and rising sea levels may cause forests to drown and disappear (Ward *et al*., 2016). Our results

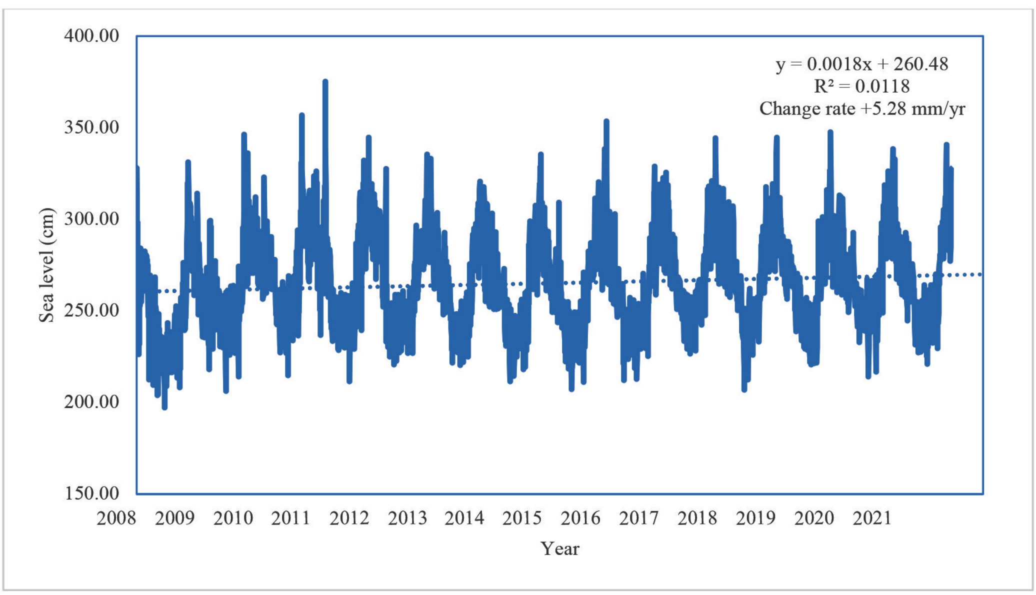


Figure 6: Sea level data from Koh Prab tide gauge, Surat Thai Province

indicated that urbanisation had hindered the inland migration of mangrove forests, leading to a decline in mangrove areas adjacent to communities and urban areas (Figure 4). Infrastructure development such as road construction and building projects can severely disrupt mangrove ecosystems, constricting their growth space and hindering their ability to expand.

Results indicated that seaward migration increased by 4.63 km^2 during the last decade. Meanwhile, mangrove forests in Surat Thani Province have demonstrated resilience to rising sea levels. Their long-term survival is threatened by projected future increases. Global studies have revealed varying responses of mangrove forests to sea level rise, influenced by sediment availability, coastal topography, and human activities. For instance, mangrove forests in Bermuda and Australia have exhibited different thresholds for sea level rise tolerance (Rogers *et al*., 2013; Wilson, 2017). Mangrove forests in Bermuda will not be impacted by seawater rising at a rate of 8 cm to 9 cm per 100 years (approximately 0.8 mm to 0.9 mm/year).

Nonetheless, they will not be able to survive if sea levels rise by 12 cm per 100 years (approximately 1.2 mm/year) (Wilson, 2017) while mangrove forests in Australia will not be affected by sea level rise of 3.65 mm/year but will not survive at rates higher than this (Rogers *et al*., 2013). Similarly, coastal landscapes in South Africa and Vietnam have experienced contrasting impacts, with some areas benefiting from increased sedimentation and others facing constraints from land use practices (Adams & Rajkaran, 2021; Dang *et al*., 2022). In South Africa (uMhlathuze, uMlalazi, Mntafufu, and Nahoon estuaries) and the east coast of Africa, increasing sea level rises have created favourable habitats for mangrove forest colonisation (Adams & Rajkaran, 2021). A study in Vietnam reported that fringe mangrove forests were limited on their landward side due to extensive aquacultural and agricultural land use (Dang *et al*., 2022).

This study forecasted future mangrove forest areas over the next five years using data from the Japan Aerospace Exploration Organisation (JAXA) between 2015 and 2020. Our results indicated that Thailand would experience a continuous increase in mangrove forest areas, with an estimated expansion of 46.63 km^2 from 2015 to 2020 (Figure 7, Table 2). Our findings align with regional and global trends, as mangrove forest loss rates have significantly decreased worldwide in recent decades (Bunting *et al*., 2022). Correspondingly, mangrove forest loss rates have significantly decreased in recent decades, falling below the original rate of 0.13% per year observed between 2010 and 2016 (Lovelock *et al*., 2022).

Previous reports concluded that mangrove forest areas in Thailand continuously increased after the cancellation of mangrove logging concessions on 19 November 1996 and Cabinet Resolution B.E. 2000, which prohibited logging in mangrove and conservation areas. However, although the area of mangrove forests in Thailand is increasing, during the same period, the area of mangrove forests in Surat Thani Province continued to decrease (Figure 8, Table 2) because of changes in land use and sea level rise (Bunting *et al*., 2022). In recent decades, global mangrove forest area loss has declined, but human activities still pose dangers. In contrast, converting mangrove forests to aquaculture ponds and oil palm plantations remains a significant driver of forest loss in Southeast Asia (Cameron *et al*., 2021). In addition, the prediction of mangrove forest areas in Southeast Asia suggested that the decline resulted from reduced sediment yield, salinity increase, and rising sea levels (Alongi, 2015).

Our findings highlight the ability of mangrove forest areas to migrate seaward over the last decade. A case study in Surat Thani Province in the Lower Gulf of Thailand discovered that the sea level has risen at 5.28 mm/year in the last decade. However, the mangrove forests were able to build elevation at a rate exceeding sea level rise. Our study predicts that rising sea levels and limited inland

Table 2: Mangrove forest areas in Thailand and Surat Thani Province between 2015 and 2025 (2015-2020 data from JAXA, 2020-2025 prediction)

Year	Thailand (km²)	Surat Thani Province (km²)
2015	2,481.36	85.25
2016	2,483.65	84.22
2017	2,494.88	83.87
2018	2,492.73	83.63
2019	2,506.41	83.35
2020	2,527.99	83.06
2021	2,531.11	82.70
2022	2,540.18	82.34
2023	2,549.25	81.99
2024	2,558.32	81.63
2025	2,567.38	81.28

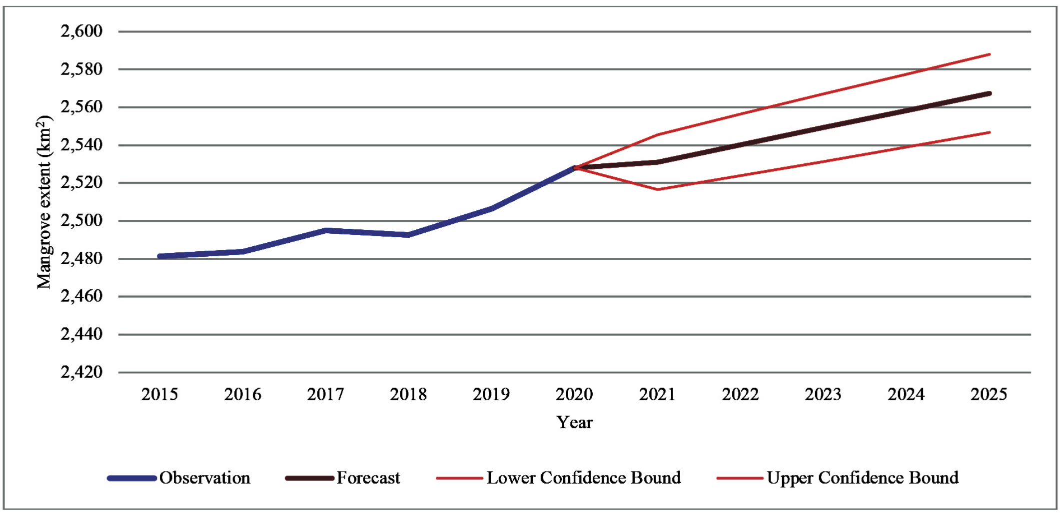


Figure 7: Mangrove forest areas in Thailand from 2015 to 2020 (data from JAXA) and 2021 to 2025 (prediction)

migration will put mangroves in Surat Thani Province at risk of drowning over the next five years. This finding aligns with observations from other regions facing similar challenges.

In areas with more rapid sea level rise and landward migration obstructed by coastal development, mangrove forests have become locally extinct and drowned along the shoreline, as seen in many Pacific islands (Ward *et al*., 2016) and the Mekong Delta (Dang *et al*., 2022). Mangrove forests in the Mekong Delta have recorded an average annual area loss of 0.54% to 0.22%. The main driver responsible for mangrove forest loss by the end of this century will be inundation (Dang *et al*., 2022).

Meanwhile, the Mngazana Estuary in South Africa showed SLR at 0.9 mm to 1.4 mm over the last century, with substrate elevation thresholds estimated to be positive over the short term until 2020 after which forests are expected to shrink

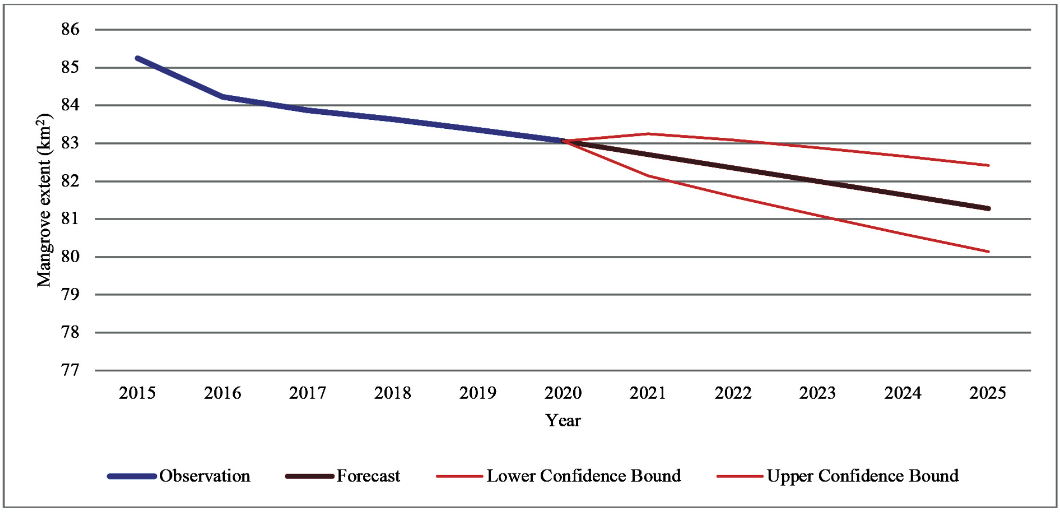


Figure 8: Mangrove forest areas in Surat Thani Province from 2015 to 2020 (data from JAXA) and 2021 to 2025 (prediction)

due to the prevention of landward migration (Naidoo, 2016). These observations highlight the vulnerability of mangroves to combined pressures from sea level rise and limited inland migration opportunities, emphasising the need for proactive conservation strategies in Surat Thani Province and the Lower Gulf of Thailand. To address this issue, we suggest implementing an approach by establishing new mangrove plantations within the fringing zone. Hence, careful planning and selection of appropriate plant species are necessary for the success of this approach.

Conclusions

Mangrove forest areas covering Chaiya, Tha Chang, Phunphin, and Mueang Districts in Surat Thani Province have gradually changed from 2011 to 2021. The main findings were as follows: (i) A significant decrease in mangrove forest area was recorded between 2011 and 2021, (ii) agriculture and aquaculture were the main reasons for the mangrove forest area decline, (iii) mangrove forest areas inland adjacent to communities showed similar decreases to mangrove forests along the coastline, (iv) greater mangrove forest expansion was recorded toward the sea (seaward migration) than toward the land (inland migration) with statistical significance ($p < 0.05$), (v) the rate of sea level increase was linear at 5.28 mm/year, and (vi) mangrove forest areas in Chaiya, Tha Chang, Phunphin, and Mueang District, Surat Thani Province adapted to the current rise in sea level.

Further research on other climate change impacts such as surface elevation and soil cores is needed to better understand the vulnerability of mangrove forests to sea level rise. Mangrove forest trees that can adapt to sea level rise from climate change present a significant topic for further research.

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Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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