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ORIGINAL PAPER

Distribution and drivers of Vietnam mangrove deforestation from 1995 to 2019

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Abstract

Vietnam mangrove forests have long been recognized to play important roles in coastal protection against soil erosion and storms/strong waves, supplying seafood, land reclamation, and carbon accumulation. Mangrove forests were severely damaged by the Second Indochina War and the shrimp aquaculture boom of the 1980s and 1990s. In recent decades, the rate of mangrove forest decline has been reduced due to increased efforts in mangrove restoration, though mangrove conversions to other land uses still occur locally. In this study, we analyzed Landsat data using the Google Earth Engine (GEE) platform to (1) determine the national distribution of mangroves; (2) identify the spatiotemporal change of mangrove cover; and (3) quantify the proportional conversion of mangroves to different land uses in Vietnam between 1995 and 2019. Vietnam lost 13,261 ha (7.3%) of its mangrove forest during the study period at a rate of 0.3% per year. Mangrove extent decreased 24,966 ha during 1995–2010, but increased 11,705 ha during 2010–2019. Spatially, mangrove extent decreased in southern regions, but increased in northern and central regions. Aquaculture and agriculture expansion were the major drivers that accounted for 43.4% and 24.8% of the total mangrove loss, respectively. In northern and central regions, infrastructure development was also identified as an additional driver of mangrove deforestation, while in the southern regions, erosion was identified as an increasing threat to mangroves. These results can assist managers and decision makers in mangrove, management, and ecological service evaluations as well as in forest inventories and national reporting. Our findings also suggest using the GEE platform to analyze public archive satellite images is an effective tool to monitor nationwide mangrove forest change over time in Vietnam.

Keywords Aquaculture · Agricultural expansion · Development · Mangrove forest cover · Mangrove loss · Deforestation

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1 Introduction

Vietnam has well-developed mangrove forests along its 3,260 km of coastline, from Mong Cai of Quang Ninh province in the north to Ha Tien of Kien Giang province in the south (Hong and San 1993; Sam et al. 2005). Mangrove forests play a vital role in providing ecosystem services such as coastal protection from storms, floods, and erosion as well as the provision of fuel and raw material products, habitat for aquatic and terrestrial species, and carbon sequestration (Rönnbäck 1999; Hawkins et al. 2010; Tuan and Kuenzer 2012). Most local people in the coastal provinces of Vietnam rely on these mangrove ecosystem services (Hawkins et al. 2010; Hai et al. 2020). Vietnam mangrove forests covered an area of 408,500 ha in 1943, but 40% of those mangroves were destroyed during the Second Indochina War (Hong and San 1993) from 1955 to 1975. From 1977 to 1995, 23% of the remaining mangrove area was converted to shrimp farms (de Graaf and Xuan 1998). Recent decades (1995 to present) have seen a reduction in the rate of mangrove deforestation. Although the area of newly planted mangroves has increased due to mangrove rehabilitation efforts, the existing mangrove area continues to be lost due to both natural and anthropogenic causes (Lebel et al. 2002). Accurate national estimates of mangrove losses and gains are currently lacking and needed to update annual national forest inventories by the Vietnam Ministry of Agriculture and Rural Development (MARD 2008) that lack analyses of mangrove coverage, mangrove forest change, and deforestation causes.

The innovations and new tools in the field of remote sensing and satellite image analysis, such as Google Earth Engine (GEE), have allowed us to systematically and rapidly assess the changes of mangrove forests at the national and subnational levels (Chen et al. 2017; Portengen 2017; Tieng et al. 2019; Jahromi et al. 2021). The GEE platform combines vast amounts of satellite datasets and planetary-scale computational capabilities. Moreover, it is freely accessible (upon registration) to scientists and non-profit users. Users can run geospatial analysis and process satellite imagery or other geospatial data from the database on the cloud (Liu et al. 2018). The GEE Engine Code Editor is based on JavaScript application programming interface, which can be used for writing and running scripts for complex geospatial analysis (Zurqani et al. 2018). As a cloud-based platform for planetary-scale geospatial analyses with massive computational capabilities, GEE can be a valuable tool to analyze a variety of high-impact societal issues that include monitoring forest change (Gorelick et al. 2017).

In this study, we utilized GEE to analyze Landsat images to quantify mangrove forest change across all of Vietnam during the period 1995–2019. We identified the land use types that were converted from mangroves and vice versa by categorizing land uses into categories that proximate drivers of mangrove deforestation (agriculture, aquaculture, infrastructure, waterbody, mudflat, and others). We analyzed the mangrove forest change at both the national and subnational levels to determine the distribution and drivers of mangrove deforestation. The results from this study are useful for Vietnam in developing mangrove rehabilitation and conservation strategies, biodiversity loss mitigation efforts, and mangrove monitoring and analysis in the future.

2 Materials and methods

2.1 Study area

This study was carried out across a total area of 2,581,853 ha that includes the mangrove-covered coastal regions of 28 coastal provinces of Vietnam (Fig. 1). Annual

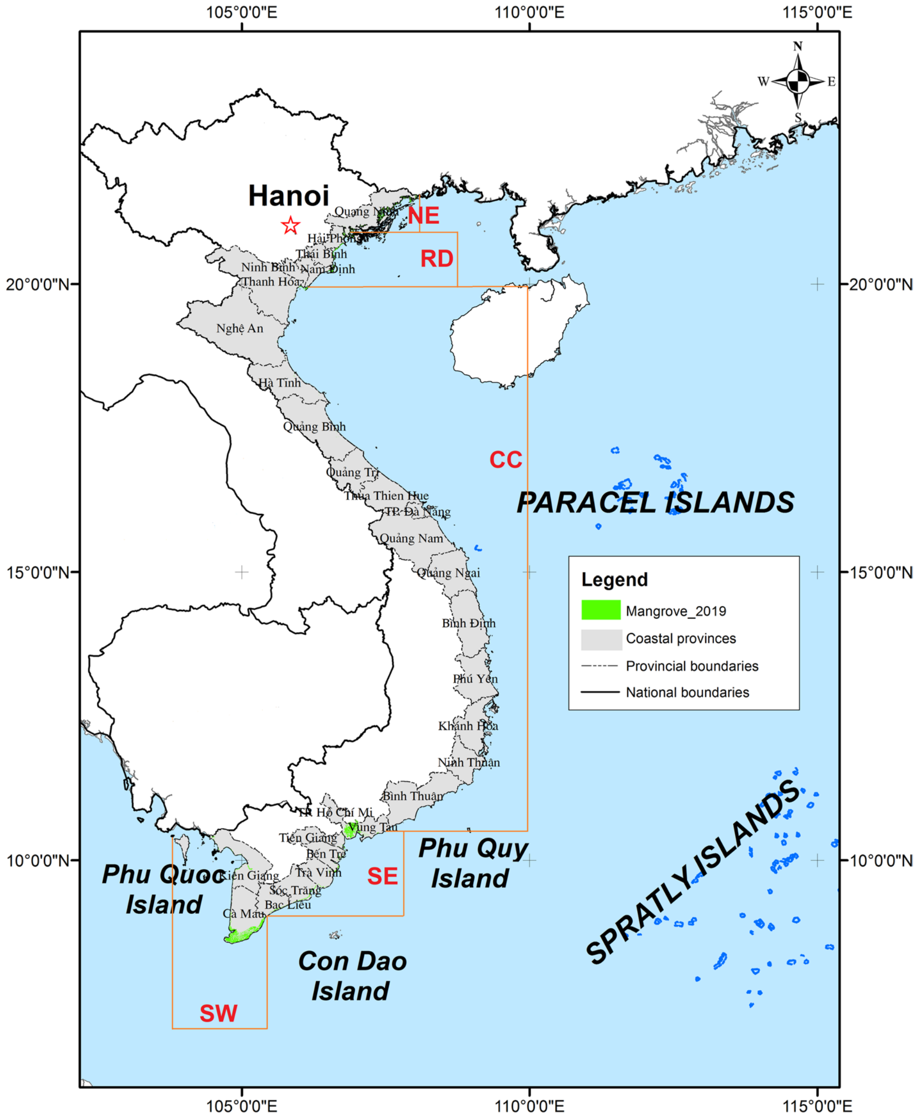


Fig. 1 Study area

average temperatures range from 22.7 to 27.6 °C and rainfall from 1500 to 2500 mm/year along the coast, which also has 114 estuaries and two large and fertile coastal deltas: the Red River Delta in the North and the Mekong River Delta in the South. Vietnam has 113 mangrove species, including 42 true mangrove species and 71 mangrove associates (Hong and San 1993). The geographical distribution of mangrove species regionally varies with 69 species found in the south and 34 species in the north. *Rhizophora apiculata*, *R. mucronata*, *Bruguiera cylindrica*, *B. parviflora*, *Avicennia alba*, *A. officinalis*, and *Sonneratia alba* are only found in the south, while *Myoporum bontioides* and *Scaevola hainanensis* are only found in the north (Tri 1999). Based on the differences in geomorphology, hydrology, climatic conditions, and mangrove structure, Hong and San (1993) divided Vietnam mangroves into 4 zones: Northeast Coast (NE), Red River Delta (RD), Central Coast (CC), and Southern Coast, and 12 subzones belonging to those zones. In this study, we divided the Southern Coast into Southeast Coast (SE) and Southwest Coast (SW) to easily perform satellite image analysis and mangrove deforestation assessment (Fig. 1).

2.2 Satellite data and reprocessing

Previous studies confirmed that Landsat data is effective at capturing mangrove distribution and dynamics (Long et al. 2014); approximately 85% of the studies that employed the GEE platform have used Landsat data (Jahromi et al. 2021). Landsat images have other advantages such as they are free, easily accessible, and are available as time-series (Elmahdy et al. 2020). In this study, the Landsat Thematic Mapper (TM) data for the periods 1995 and 2010 and the Operational Landsat Imager (OLI) Landsat 8 data for the period 2019 were acquired for the entire study area. In certain areas, the multiyear Landsat images were intermittently required to classify a single path/row due to the persistent cloud cover. A total of 16 Landsat path/rows were acquired for each period.

A flow chart of the satellite data processing methods used in this study is illustrated in Fig. 2. Landsat data was preprocessed by using the cloud-computing technology in the GEE platform (Zurqani et al. 2018). A JavaScript code was developed in GEE to assemble all the archived Landsat images covering study area, produce a spatially continuous image for each period, and then clip the images according to the study area boundaries. As cloud cover was present in many of the images, an algorithm was programmed in GEE using JavaScript function to clone information from cloud-free patches to their corresponding cloud-contaminated patches (Lin et al. 2013). This process reduced cloud coverage in Landsat images to less than 5%.

2.3 Image classification

In this study, supervised classification using the Random Forest (RF) algorithm was applied for binary land cover classification. The RF algorithm has been proven as a suitable method for a land cover classification strategy using medium and high-resolution satellite data (Gislason et al. 2006; Hayes et al. 2014; Thanh Noi and Kappas 2018). This algorithm has also been successfully applied to classify mangroves based on Landsat data (Kamal and Phinn 2011; Kamal et al. 2015; Elmahdy et al. 2020; Tieng et al. 2019). The RF algorithm was constructed by 50 random decision trees systematically operating as an ensemble (Cutler et al. 2007; Duan et al. 2019). Each decision tree was generated by sampling a random vector independently from a training dataset, then a classifying vote was computed, and finally, the most popular class, among the trees, became a classification model (Breiman 2001). The whole RF classification process (e.g., from creating training data, image classification, and evaluating model performance) was entirely deployed in the GEE platform. The classified maps were then overlaid in ERDAS IMAGINE (ERDAS 2014) to detect mangrove forest change between 1995 and 2019.

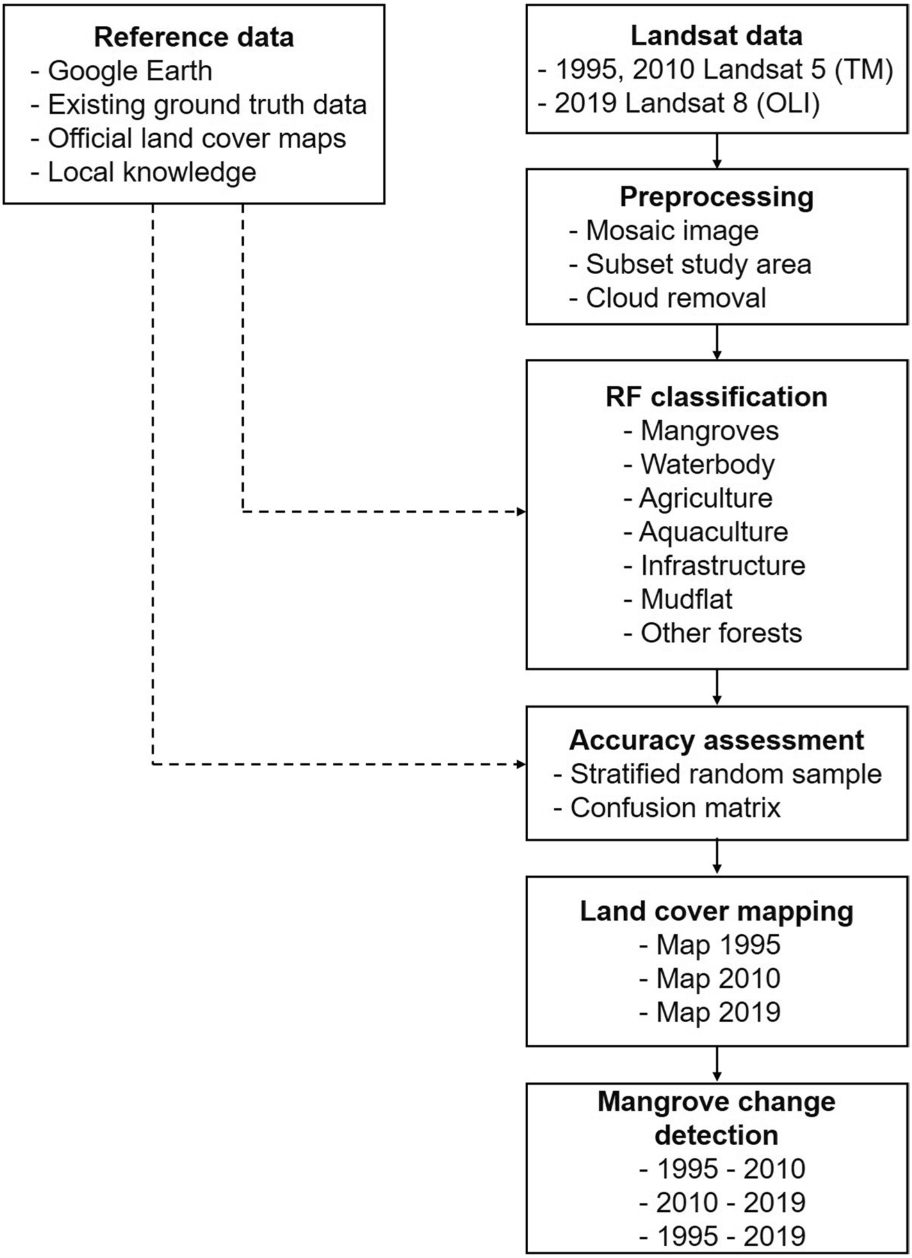


Fig. 2 Flowchart of the Landsat data processing method

2.4 Training data

The supervised classification approach requires the user to select representative training data that should be representative and homogeneous for the classes to be modelled (Mather and Tso 2009). The training data were generated by selecting a sample of pixels from each of seven land cover classes, namely mangroves, waterbody, agriculture, aquaculture, infrastructure, mudflat, and other forests. The training areas were selected from visual interpretation of true color (RGB 321) and pseudo-color (RGB 432) image composition of Landsat 5 or true color (RGB 432) and pseudo-color (RGB 543) image composition of Landsat 8 and high-resolution imagery from Google Earth, field survey data collected from previous studies/projects, and existing land cover maps (Long et al. 2014; Nguyen et al. 2020a). The total of 30 training areas for each land cover class and 50 pixels for each training area were selected to ensure classification accuracy (Nguyen et al. 2020a).

2.5 Accuracy assessment

An accuracy assessment of the produced classification maps was conducted using the confusion matrix with a stratified random sampling design. This technique is necessary to determine the reliability of the classified maps (Zurqani et al. 2018). The reference data on land use and land cover, including mangroves, waterbody, agriculture, aquaculture, infrastructure, mudflat, and other forests, were randomly selected using high-resolution satellite imagery from Google Earth, field survey data collected from previous studies/projects, existing land cover maps, and local knowledge regarding land cover (Hong et al. 2019; Nguyen et al. 2020a). All reference data used in the accuracy assessment of classified map of each year (1995, 2010, and 2019) were captured from its corresponding period. Then, these stratified points were randomly selected for each land cover class and compared with the classified map of each year. A confusion matrix of land cover maps was constructed to validate the image classified data with the reference data (Congalton 1991) using producer's accuracy, user's accuracy, and Kappa statistics (Long et al. 2014; Zurqani et al. 2018; Hong et al. 2019). The overall accuracy of the classified maps for the year 1995, 2010, and 2019 was 82.6%, 85.0%, and 85.6%, respectively, and the kappa coefficient were 0.78, 0.80, and 0.83, respectively (Table 1). This shows an acceptable agreement between the classification results and reference data where a value of 1 would be a perfect agreement (Dan et al. 2016; Nguyen et al. 2020b). However, some limitations must be noted that this study used training data obtained from visual interpretation and other existing sources (as described in the previous section) as well as a mapping unit of 30×30 m (that corresponded to the 30-m resolution of the Landsat images) to produce the classification maps that could miss some small, fragmented land use and land cover.

3 Results and discussion

3.1 Area and spatial distribution of mangroves in Vietnam

In this study, the Google Earth Engine platform and Landsat data provided up-to-date land cover and mangrove maps at both the national and subnational scales. In 2019, Vietnam had 168,538 ha of mangrove forests distributed along its coastlines, but mainly in the southern regions (Table 2). The SE had 56,727 ha (33.7% of total area) of mangroves mainly distributed in the Can Gio biosphere reserve of Ho Chi Minh city (Fig. 3d), and the SW had 84,670 ha (50.2% of total area) of mangroves mainly distributed in Ca Mau

Table 1 Averaged producer accuracy, user accuracy, overall accuracy, and kappa coefficient for land cover classification

No	Land use classes	1995		2010		2019	
		Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)
1	Other forests	81.1	80.0	81.7	83.3	83.5	84.0
2	Infrastructure	80.9	82.0	88.0	82.7	88.5	86.0
3	Waterbody	87.2	85.3	87.5	88.0	88.8	89.3
4	Agriculture	83.3	82.0	84.3	82.7	84.6	83.3
5	Mudflats	81.1	80.0	86.3	88.0	84.3	84.7
6	Aquaculture	82.5	84.7	86.9	84.7	88.7	88.0
7	Mangroves	82.4	84.0	81.4	85.3	81.9	84.0
Overall accuracy		82.6		85.0		85.6	
Kappa coefficient		79.7		0.80		83.2	

Table 2 Distribution of mangroves in different zones along the coast of Vietnam

Zone	1995		2010		2019	
	ha	(%)	ha	(%)	ha	(%)
Northeast (NE)	16,809	9.2	16,866	10.8	16,583	9.8
Red River Delta (RD)	4,712	2.6	5,864	3.7	8,918	5.3
Central Coast (CC)	1,371	0.8	803	0.5	1,641	1.0
Southeast (SE)	64,339	35.4	54,747	34.9	56,727	33.7
Southwest (SW)	94,569	52.0	78,552	50.1	84,670	50.2
Total	181,799	100	156,833	100	168,538	100

province (Fig. 3c). In other regions, mangrove forests were spatially distributed as linear and curvilinear strips with lengths of 3–5 km and widths of 200–1000 m (Fig. 3a,b).

Until this study, there have been few if any publications reporting total areal estimates of mangrove forest for the entire country of Vietnam. Most existing figures have been reported by Vietnam's Ministry of Agriculture and Rural Development (MARD) in decisions related to national forest inventories and monitoring (Sam et al. 2005; Thinh and Tuan 2019; Hai et al. 2020). The most recent is decision No. 1558/QD-BNN-TCLN dated April 13, 2021, announcing the state of national forests in 2020. However, these decisions only referred to the total area of flooded forests. Specific data on mangrove forest area for the entire country was not included. The forest definition in the forest monitoring system has also differed over time. Since 1984, forest was defined as minimum of 30% tree cover (Decision No. 682B/QDKT QPN 6–84). In 2009, Vietnam changed its definition of forest as minimum 10% tree cover, at a minimum height of 5 m, over a minimum area of 0.5 ha (Circular No. 34/2009/TT-BNNPTNT). With those definitions, many areas of dwarf mangroves in the NE and RD zones (Hong and San 1993) could not have been measured in the national forest inventories. This has created uncertainties in previously reported figures

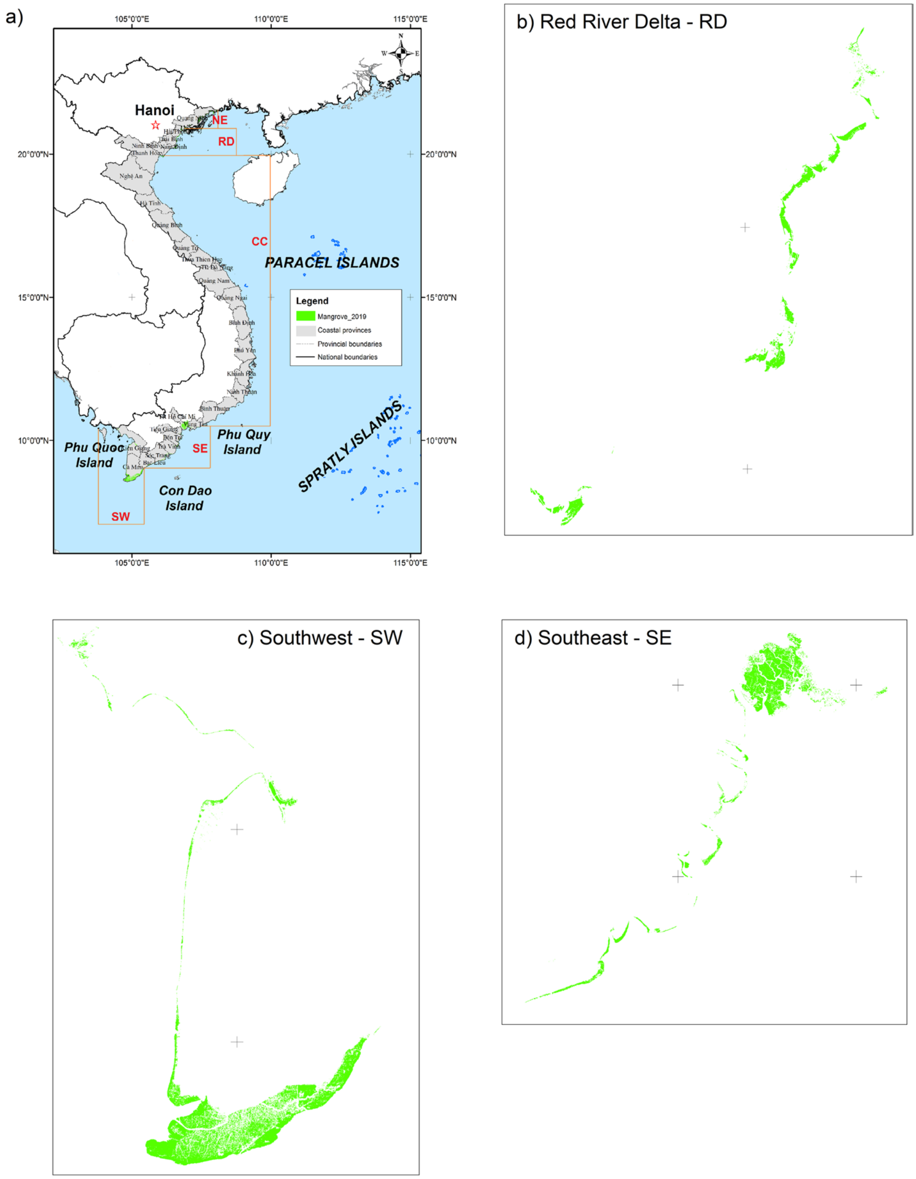


Fig. 3 Spatial distribution of Vietnam mangroves in 2019 (a), and zoom views in Red River Delta, RD (b); Southeastern, SE (c); and Southwest, SW (d) zones where mangroves are highly concentrated

of total mangrove area. Thus, Decree 156/2018/ND-CP dated November 16, 2018, added a separate minimum height of 1 m for mangrove forests. In this study, we first used the GEE platform to analyze Landsat data to classify and estimate nationwide mangrove area of Vietnam for the periods 1995, 2010, and 2019. These results have provided a full assessment of national mangrove extent and can be easily updated and used to monitor mangrove change in Vietnam.

3.2 Spatiotemporal changes of mangroves in Vietnam

The magnitude of mangrove changes in Vietnam from 1995 to 2019 is shown in Table 2, Fig. 4, and Fig. 5. Vietnam experienced a decrease of 24,966 ha of mangrove forests in the period 1995–2010 and an increase of 11,705 ha of mangrove forests in the following period 2010–2019. In total, Vietnam lost 13,261 ha (7.3%) of its mangrove forest between 1995 and 2019 at a rate of 0.3%/year (Table 2, Fig. 4). The magnitude of mangrove change was highest in RD followed by CC, SE, SW, and NE. From 1995 to 2019, the mangrove area has increased in RD and CC by 89.3% and 19.7% respectively, but decreased in SE, SW, and NE by 11.8%, 10.5%, and 1.3% respectively (Fig. 4).

In RD, the mangrove area increased by 22.6% during the period 1995–2010 and 52.3% during the period 2010–2019. This result is consistent with Nguyen et al. (2020b) and Pham and Yoshino (2015). Pham and Yoshino (2015) reported that mangrove area in Hai Phong (a province of RD) increased by 16% during the period 2001–2013. Meanwhile, Nguyen et al. (2020b) found that the mangrove area in some specific communes of Hai Phong increased up to 667.7% during the period 2000–2018. Although, there are some variations in mangrove change estimates among studies due to the different scope of study, Pham and Yoshino (2015), Nguyen et al. (2020b), and this study have all confirmed the trend of increasing mangrove area during the study period. The mangrove increase in RD resulted from mangrove and afforestation efforts by the Vietnam government, support from international donor agencies and non-governmental organizations (Jhaveri et al. 2017), and active participation of local people in mangrove management over the past decades (Hong 2008; IFRC 2012; Nguyen et al. 2020b).

In CC, the mangrove area decreased 41.5% during the period 1995–2010, but increased 45.2% during the period of 2010–2019. In previous studies conducted at several sites within this zone such as Thanh Hoa (Nguyen et al. 2020a, 2021), Nghe An (Nguyen et al. 2021), and Quang Nam (Mai et al. 2019), a similar trend of change in

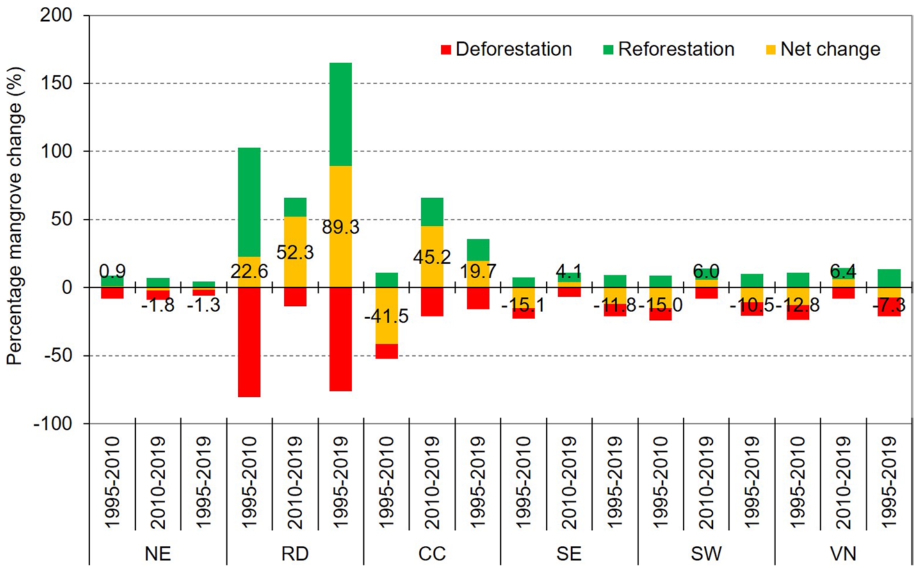


Fig. 4 Percentage of mangrove loss and gain by zone in Vietnam between 1995 and 2019

Fig. 5 Spatiotemporal distribution of mangrove changes between 1995 and 2019 in Red River Delta, RD (a, b); Southeastern, SE (c, d); and Southwest, SW (e, f) zones where mangroves are highly concentrated ▶

mangrove area was also reported. The recent increase of mangroves resulted from mangrove rehabilitation projects funded by state and local government for climate change mitigation and adaptation (Thu and Populus 2007). In this zone, most mangrove rehabilitation projects focused on coastal protection and stabilization due to its vulnerability to natural disasters (Hai et al. 2020).

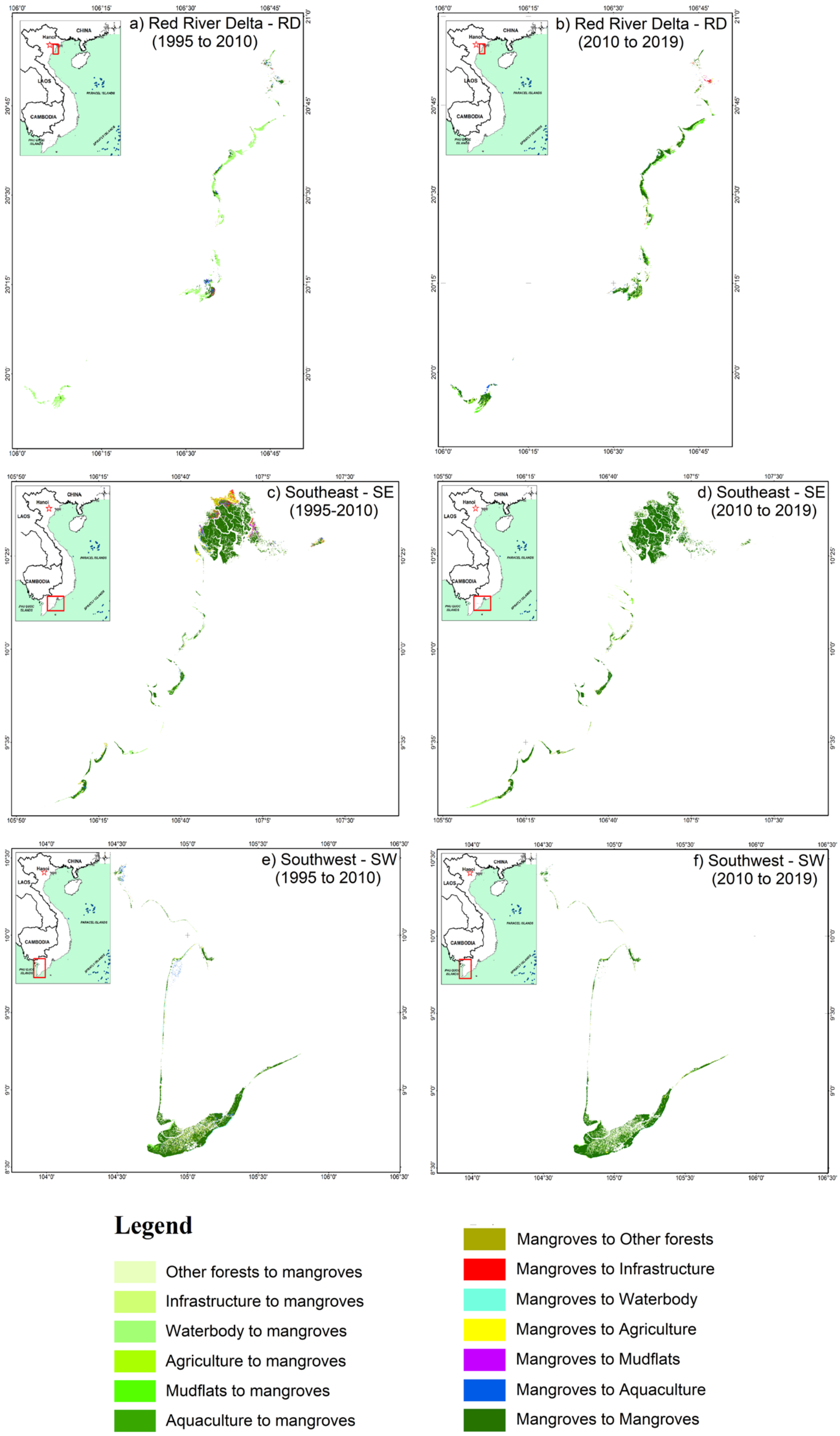
In SE and SW, approximately 15% of mangrove forests of each zone were lost during 1995–2010; however, each zone gained only about 5% of its mangrove forests over the period 2010–2019. These results are also consistent with the findings of Mokievsky et al. (2020). The authors analyzed the change in mangrove area of the Mekong River Delta (a large region that covers almost SE and SW zones) during the period 1988–2018 and found that mangrove area decreased 68% over a 30-year period, but the specific analysis performed every 10–15 years showed the negative trend of the dynamics has changed to a positive one. As compared to the RD or CC zones, the rates of mangrove decline in SE and SW were low, but the areas of mangroves lost were much greater (due to most of Vietnam's mangroves being distributed in these zones as mentioned above) and significantly affected the mangrove ecosystem services (Quoc Vo et al. 2015; Tuan and Kuenzer 2012). In recent years, mangrove rehabilitation projects in Vietnam have focused more on the south and include the SE and SW due to increased concern about climate change and sea level rise (Hai et al. 2020).

In NE, the area of mangrove forests changed the least during our study period. Specifically, the mangrove area increased 0.9% during 1995–2010, but decreased 1.8% during 2010–2019. Within this zone, Bui et al. (2014) estimated the land cover change of Ha Long and Mong Cai during 1999–2008 and found that mangrove area of these two cities decreased 34.9% and 28.2%, respectively, while Quyet et al. (2021) reported a decrease of 7.3% of mangrove area in Tien Yen during 2005–2020. Although previous studies indicated a decrease of mangrove area, these studies did not reflect the general trend of mangrove area change of the whole NE zone due to only focusing on some specific sites. Early efforts to restore mangroves by the Vietnamese Red Cross and Women's Union since the 1980s (Jhaveri et al. 2017), and Red Cross Japan, ACTMANG of Japan and UNDP in the late 1990s (Thuy et al. 2019) have significantly contributed to the increase of mangroves. However, conversions to shrimp ponds, farmland, and other land uses, which still have occurred locally over the past decade, were the main drivers of mangrove deforestation in the period 2010–2019 (Quyet et al. 2021).

This study confirmed that the mangrove deforestation in Vietnam was uneven across zones and changed over time. Mangrove deforestation was closely related to the socio-economic development strategies of the state and local governments, and the efforts of Vietnam and international organizations in mangrove afforestation, and conservation. Although mangrove loss still locally occurs along the coast of Vietnam, its rate has significantly decreased and the total area of mangroves has increased in recent years.

3.3 Drivers of mangrove deforestation in Vietnam

The nationwide analysis indicated that from 1995 to 2019, Vietnam mangrove forests were converted mainly to aquaculture and agriculture uses (e.g., rice, soybean, and medicinal plants) with conversion rates of 43.4% and 24.8% respectively (Table 3). This trend was


a) Red River Delta - RD
(1995 to 2010)
b) Red River Delta - RD
(2010 to 2019)
c) Southeast - SE
(1995-2010)
d) Southeast - SE
(2010 to 2019)
e) Southwest - SW
(1995 to 2010)
f) Southwest - SW
(2010 to 2019)
CHINA
LAOS
CAMBODIA
Hanoi
Legend
Other forests to mangroves
Infrastructure to mangroves
Waterbody to mangroves
Agriculture to mangroves
Mudflats to mangroves
Aquaculture to mangroves
Mangroves to Other forests
Mangroves to Infrastructure
Mangroves to Waterbody
Mangroves to Agriculture
Mangroves to Mudflats
Mangroves to Aquaculture
Mangroves to Mangroves

found in all zones. In NE, RD, CC, SE, and SW, conversion rates to aquaculture were 47.6%, 54.6%, 42.3%, 37.4%, and 45.4%, respectively, and to agriculture were 14.6%, 12.6%, 14.1%, 29.1%, and 24.7%, respectively (Table 3). In the northern zones such as NE, RD, and CC, infrastructure development was also an important cause of mangrove decline with conversion rates of 15%, 15.8%, and 21.2%, respectively; while in the southern zones such as SE and SW, coastal erosion significantly reduced mangrove area (as represented by the conversion to waterbody) by 12.3% and 21.2% respectively (Table 3). These results indicated that at the national level, the conversion rates of mangroves to other land uses over the past decade (2010–2019) did not differ significantly from those in the previous period (1995–2010). However, in different zones, conversion rates varied over the different time periods. In NE and RD, conversion to aquaculture and agriculture decreased but conversion to infrastructure increased, while in SE and SW, conversion to aquaculture increased slightly, along with the mangrove loss due to coastal erosion (Table 3). Thus, in addition to converting mangroves to aquaculture, other activities such as agricultural expansion, infrastructure, urban, and industrial development were key drivers of mangrove deforestation. This was also observed and reported by Hawkins et al. (2010). Coastal erosion that also resulted in loss of mangroves as reported in this paper was also recorded by Tien and Van Cu (2005) and Cat et al. (2006) at Hải Phong, Thai Bình, Nam Dinh (in RD zone), Thanh Hoa, Quang Nam, Quang Ngai, Phu Yen (in CC zone), Ho Chi Minh city (in SE zone), Bac Lieu, Ca Mau, and Kien Giang (in SW zone).

Previous studies identified the expansion of shrimp farms was one of the major drivers of mangrove deforestation in Vietnam (Richards and Friess 2016; Hamilton 2011; de Graaf and Xuan 1998; Clough et al. 1999; Rönnbäck 1999; Tuan and Kuenzer 2012; Le et al. 2020; Truong et al. 2017; Quyen 2011; Friess et al. 2019; Thomas et al. 2017), but our results suggest this may be on the decline. Compared to published estimates before 1995

Table 3 Percentage of mangrove forest converted to other land uses in Vietnam between 1995 and 2019

Zone	Time	Agriculture	Aquaculture	Infrastructure	Waterbody	Mudflats	Others
Northeast (NE)	1995–2010	30.4	48.0	2.8	5.6	6.6	6.5
	2010–2019	25.4	37.5	14.5	3.4	10.9	8.4
	1995–2019	14.6	47.6	15.0	5.5	12.4	4.8
Red River Delta (RD)	1995–2010	10.7	62.6	7.9	6.1	6.5	6.1
	2010–2019	16.9	48.0	15.4	5.8	4.2	9.7
	1995–2019	12.6	54.6	15.8	7.9	4.9	4.3
Central Coast (CC)	1995–2010	13.2	35.1	16.5	14.7	7.3	13.2
	2010–2019	13.6	37.2	18.1	12.0	7.8	11.4
	1995–2019	14.1	42.3	21.2	5.6	4.6	12.2
Southeast (SE)	1995–2010	29.2	38.5	8.8	10.2	4.5	8.9
	2010–2019	33.1	43.4	8.4	7.3	1.8	6.1
	1995–2019	29.1	37.4	11.6	12.3	1.6	8.0
Southwest (SW)	1995–2010	39.3	38.3	2.6	16.0	0.9	2.9
	2010–2019	29.5	45.4	0.7	18.8	0.2	5.3
	1995–2019	24.7	45.4	6.3	21.2	0.3	2.2
Total	1995–2010	32.7	40.8	5.4	12.8	2.9	5.5
	2010–2019	29.1	43.9	5.8	12.6	2.3	6.2
	1995–2019	24.8	43.4	9.4	16.3	1.6	4.6

(Tong et al. 2004; Hong and San 1993; Veettil et al. 2019), the conversion rate of mangroves to shrimp farms decreased from 1995 to 2019. Before 1995, the Vietnam government encouraged the development and rapid expansion of coastal aquaculture that resulted in the conversion of large areas of mangrove forests to shrimp farms (Hong and San 1993; Thu and Populus 2007; Van et al. 2015). In 1994, Decree 773-TTg was issued to let household contractors use open coastal areas and water bodies near or within mangroves for aquaculture (Nguyen et al. 2013). After that, provincial land use decisions were also issued that focused more on shrimp farming (Van et al. 2015). This resulted in a mangrove-shrimp model that flourished in Vietnam during the 2000s to create a win–win situation between conserving mangroves and improving livelihoods for local communities. In contrast to these decrees, a model named "land use allocation for forestry production purposes" was also adopted during this period allowing the farmers to use 30% of mangrove area for aquaculture (Truong and Do 2018). As farmers found that mangrove forest coverage negatively affected their aquaculture production, they continued to illegally cut down mangroves or gradually cut down the roots of mangroves to make them weak or dead (Hong et al. 2019). In the coming years, fisheries will continue to play an important role and account for a high proportion of the gross domestic product (GDP) of Vietnam (Khanh Nguyen et al. 2019). Thus, the maintenance of existing shrimp farms and development of new farms are still of great interest. This will be a challenge for mangrove conservation.

In addition to aquaculture development, agriculture expansion was also one of the key drivers of mangrove deforestation (Hong and San 1993; Richards and Friess 2016; Le et al. 2020; Hai et al. 2020; Bui et al. 2014; Thomas et al. 2017). Hong and San (1993) and Blasco et al. (2001) described the expansion of agricultural land to cultivate rice, soybeans, and other crops as one of the main causes of the loss of mangroves in Vietnam. However, it has also been an important solution to ensure food security and improve local people's livelihood since the late 1980s. A theory of "rice expanding to grass, grass expanding to mangroves and mangroves expanding to the sea" has been put into practice (mainly in RD and CC) in the process of seaward land reclamation to expand agriculture and other land uses (Nguyen et al. 2019). This process was observed by Hong and San (1993) in northern Vietnam, that mangrove species (e.g., *Avicennia marina*, *Aegiceras corniculatum*, and *Sonneratia caseolaris*) colonized the newly accreted mudflats. The accumulation of sediments and mangrove tree debris over a long period of time gradually solidified and elevated the mudflats. Then, mangroves would be replaced by a field of grass (e.g., *Cynodon dactylon*, *Sporobolus virginicus*, and *Cyprus stoloniferus*) when the land was not in tidal inundation. Finally, this grassland was converted to rice field or other land uses.

Infrastructure, urban, and industrial areas have also replaced a large area of mangroves (Le et al. 2020; Truong et al. 2017; Hong et al. 2019; Mackenzie et al. 2016; Thomas et al. 2017; Richards and Friess 2016). In our current study, we found that the conversion rate to infrastructure during the period 1995–2019 was 9.4% for all of Vietnam. However, this rate differed considerably by zone (Table 3). This result corresponded to the rapid socioeconomic development and infrastructure construction along the coast during the study period (Rentschler et al. 2020). In Vietnam, land use plans, at both the central and local levels, are prepared and approved every 10 years, with updates and adjustments every 5 years (Government of Vietnam 2014). In the process of implementing these plans, conservation of natural ecosystems, including mangroves, is always prioritized over other land uses (Government of Vietnam 2019). However, due to limitations in management and enforcement, along with the immediate economic benefits, mangrove forests have continued to be replaced by infrastructure, industrial parks, seaports, urban, or tourist areas. The rapid industrial development and urbanization in the coastal areas in the coming years

(Rentschler et al. 2020) as determined in the strategy for the sustainable development of Vietnam's marine economy to 2030 and vision to 2045 (Party's Resolution No. 39-NQ/TW), and the policy inconsistencies, conflicting governance aspects and lack of monitoring and enforcement of regulations (World Bank 2019) will continue to threaten mangroves if there is a lack of close collaboration among stakeholders in mangrove conservation and management.

Another important driver of mangrove loss was coastal erosion due to sea level rise, other natural disasters, or human activities (Ward et al. 2016; Truong et al. 2017; Anthony et al. 2015; Phan et al. 2014). Our results indicated this is an increasingly growing problem in SE and SW (Table 3), which were also observed in previous studies (Cat et al. 2006; Anthony et al. 2015; Besset et al. 2019). Although Vietnam has successfully implemented mangrove rehabilitation projects (from government and international fundings) to protect the coast and adapt to climate change (Hai et al. 2020), coastal erosion due to extreme storm waves, tides, surges, and sea level rise will still be one of the greatest future threats to mangroves in the region (Cat et al. 2006).

4 Conclusion

We have provided the first national estimate of mangrove area for Vietnam, information that can be used for more accurate forest inventories, forest reference emission levels, and other national reports. As of 2019, Vietnam had 168,538 ha of mangrove forests, a decrease of 7.3% compared to the area in 1995 (approximate 0.3% per year). Mangrove area increased in RD and CC, but decreased in other zones, especially in SE and SW, where mangrove forests account for 83.9% of national mangrove area. Aquaculture was the most important cause of mangrove loss and will continue to pose a major threat to mangroves due to its important role in the national economy and rapid growth potential in coming years. Agricultural development and infrastructure construction are quickly becoming serious threats to mangroves, especially in the context of rapid social-economic development along the coastal regions. Coastal erosion due to extreme storm waves, tides, surges and sea level rise is also threatening mangroves. The GEE platform was successfully used to develop a national mangrove map and identify the key drivers of mangrove deforestation. The government of Vietnam should use this approach to continue to monitor mangrove change, then integrate the results into strategies for the mangrove conservation/restoration and sustainable economic development. More national efforts and international collaborative initiatives will be also needed in mangrove rehabilitation as well as climate change mitigation and adaptation.

Author contribution P.H.T. and R.A.M. conceived the study, performed data analysis, wrote, and edited the manuscript draft. P.H.T. and T.D.H. collected and analyzed satellite images. N.T.H.H., N.H.H., D.Q.M, H.T.H., and M.S.T. assisted in gathering literature and writing the manuscripts draft. All authors reviewed and contributed to the manuscript's final draft.

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Declarations

Competing interests The authors declare no competing interests.

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