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Mangrove Forest Landcover Changes in Coastal Vietnam: A Case Study from 1973 to 2020 in Thanh Hoa and Nghe An Provinces

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Abstract: Mangrove forests can ameliorate the impacts of typhoons and storms, but their extent is threatened by coastal development. The northern coast of Vietnam is especially vulnerable as typhoons frequently hit it during the monsoon season. However, temporal change information in mangrove cover distribution in this region is incomplete. Therefore, this study was undertaken to detect change in the spatial distribution of mangroves in Thanh Hoa and Nghe An provinces and identify reasons for the cover change. Landsat satellite images from 1973 to 2020 were analyzed using the NDVI method combined with visual interpretation to detect mangrove area change. Six LULC classes were categorized: mangrove forest, other forests, aquaculture, other land use, mudflat, and water. The mangrove cover in Nghe An province was estimated to be 66.5 ha in 1973 and increased to 323.0 ha in 2020. Mangrove cover in Thanh Hoa province was 366.1 ha in 1973, decreased to 61.7 ha in 1995, and rose to 791.1 ha in 2020. Aquaculture was the main reason for the loss of mangroves in both provinces. Overall, the percentage of mangrove loss from aquaculture was 42.5% for Nghe An province and 60.1% for Thanh Hoa province. Mangrove restoration efforts have contributed significantly to mangrove cover, with more than 1300 ha being planted by 2020. This study reveals that improving mangrove restoration success remains a challenge for these provinces, and further refinement of engineering techniques is needed to improve restoration outcomes.

Keywords: coastal Vietnam; Landsat; land-use change; mangrove forest; monitoring

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1. Introduction

Mangroves are intertidal wetlands occurring along tropical, subtropical, and warm-temperate coastlines. These forests provide valuable ecosystem services including preventing erosion [1], providing habitat for fisheries species [2], protecting coastal communities from extreme weather events [3,4], and storing large reserves of blue carbon, thus helping to mitigate global climate change [5]. The services provided by mangroves are threatened by anthropogenic processes, including deforestation [6] and sea-level rise [7,8]. Historically, mangroves were subject to high deforestation rates of up to 3.6% per annum [9]. However, since the turn of the millennium, global mangrove deforestation rates have slowed, with annual loss rates of 0.2–0.7% [10,11]. Lower rates of loss are due to near-total historical loss of forest patches in some regions, improved conservation practices [11] and improvements in large-scale monitoring techniques that provide more accurate estimates of cover and loss than were historically available [10,12]. The historic assessments contain reporting errors resulting from the inclusion of features without mangrove cover such as small creeks, mudflats, and salt pans. The majority of recent mangrove loss occurs in Southeast Asia, where ~50% of the remaining global mangrove forest area is located, with nations such as Indonesia, Malaysia, and Myanmar continuing to show losses of 0.26%, 0.41%, and 0.70% per year, respectively [10].

In Vietnam, mangroves were reported to cover 408,500 ha (1.2% of the country) in 1943 [13]. However, this area has declined dramatically over 50 years. In the northern parts of Vietnam, from Mong Cai to Do Son, the mangrove area decreased by 17,094 ha from 1964 to 1997 [14]. In the Red River plain, 4640 ha of mangroves were lost from 1975 to 1991, followed by a further 7430 ha in 1993 [14]. The coastal zone of southern Vietnam witnessed little change in mangrove area (from 250,000 to 210,000 ha) from 1950 to 1960; yet, the mangrove area declined to 92,000 ha by 1975 due to aerial spraying of herbicides by the American military in the period of 1962 to 1972 [15]. According to FAO [16], in the 1990s mangrove forests in Vietnam covered only 73,000 ha. In this context and to preserve this unique ecosystem, the authorities and NGOs have taken actions to replant the lost mangroves. Up to 2005, about 130,168 ha of mangroves were planted with state and NGO funds [17]. With reforestation and afforestation efforts, the total mangrove forests in Vietnam increased from 209,741 ha (0.63% of the country) in 2006 [18] to 262,000 ha (0.42% of the country) in 2010 [16], and 270,000 ha in 2015 [16]. An assessment of the status of the plantings [19] revealed that 65% were monocultures, and generally, they were poor in biomass and biodiversity. However, according to the Ministry of Agriculture and Rural Development (MARD [20]), the area of mangroves in Vietnam was only 235,569 ha in 2019. Discrepancies between reports in the total area of mangroves may reflect the methods used to audit the mangrove estate. In the past, spatial information on the status of mangroves was undertaken using traditional field surveys. Logistically and practically speaking, mangrove swamps are extremely difficult to access. Remote sensing technology is an effective solution to these problems of accessibility and accuracy. Accurate long-term monitoring and mapping of mangroves are essential to support coastal zone management and planning programs in Vietnam.

Mangrove forests in northern Vietnam play a vital role in reducing the impacts of natural disasters, for example, typhoons and storms, which are frequent occurrences in the monsoon season. According to Wang, Mahul [21], about ten tropical typhoons hit the Vietnamese coast every year, often causing severe damage. The Emergency Events Database indicates that the economic damage associated with storms has been rapidly growing in Vietnam [22]. From 1977 to 2017, typhoons with wind speeds above 20 knots struck the country 105 times. It is estimated that about 62% of the population and 44% of the country are affected by typhoons, which kill some 250 people every year [23]. Most large typhoons occur on the coast of northern Vietnam [24] and the landfall frequency of storms has risen significantly in this part of the country [22]. Consequently, mangrove restoration in this region has received special attention from the government and international organizations since the 1990s, and many restoration projects have been undertaken. However, there is a lack of reliable data on mangrove extent, mangrove loss, and assessment of restoration projects for much of the coastline in this part of Vietnam. Furthermore, the integration of mangrove restoration projects with engineering solutions is not well documented.

Remote sensing is an effective tool to characterize and monitor mangrove change over a range of spatial and temporal scales. Remote-sensing techniques have demonstrated a high potential to detect, identify, map, and monitor mangrove conditions and changes over the last three decades, which is reflected in the large number of scientific papers published on this topic [25–32]. In Vietnam, remote sensing is used to monitor and evaluate mangrove ecosystems for mangrove forest management. However, most of these activities have concentrated on mangroves in the Mekong Delta [30,33–45] and fewer studies have been conducted in northern Vietnam. Most projects in northern Vietnam are concentrated in the highly developed Red River delta (Region 1 [46]) [47–51] and Hai Phong (Region 1) [52–56]. In the less urbanized coastal southern part of Region 2, mangrove change has either not been documented (Nghe An province) or is limited to the reforestation of mangrove forests from 2005 to 2018 in two districts in Thanh Hoa province [57].

Thus, gaps remain in the documentation of mangrove extent and change for parts of northern Vietnam. While yearly reports on the status of mangroves are prepared by the Ministry of Agriculture and Rural Development, most of these reports are based on mapping using traditional rudimentary methods, which are complicated, laborious, and time-consuming [58,59]. For example, where it was not possible to undertake surveys by boat or by land grids, topographic maps were used with binoculars in the field to try to delineate mangrove boundaries. Furthermore, the construction of a mangrove forest map requires high accuracy and up-to-date information. Therefore, this study was carried out to understand how the mangrove ecosystems in Thanh Hoa and Nghe An provinces have been altered over the past 47 years. The outcomes will help local authorities to manage coastal mangrove forests more effectively and efficiently in the future. The objectives were to:

(i) determine the spatial extent of the mangrove forest in Thanh Hoa and Nghe An provinces using remotely-sensed satellite data;
(ii) estimate changes in the spatial extent of the forest in Thanh Hoa and Nghe An provinces from 1973 to 2020; and
(iii) document the factors responsible for the changes in the areal extent of the mangrove forest.

2. Materials and Methods

2.1. Study Area

The study covered all the mangrove areas in Thanh Hoa and Nghe An provinces in northern Vietnam. The coastlines of these provinces are vulnerable, and coastal erosion along with depositional forces have increased due to unusual climatic fluctuation and human activity. The provinces have a tropical monsoon climate that is influenced by the Gulf of Tokin and the North Central Coast's tropical climate, and they experience between six to eight typhoons annually. This area has an average annual precipitation of 1700 mm with distinct dry (November–April) and wet (May–October) seasons, and an average temperature from 23 to 24 °C. The lowest temperature in the study area can be <5 °C, and the highest temperature can reach 41 °C. The latitude range of the study's coastal line is 18°37′45″ N–19°54′42″ N.

There are 24 districts in Thanh Hoa and 18 districts in Nghe An, of which mangrove forests are found in eight, namely Hau Loc, Hoang Hoa, Nga Son, and Tinh Gia districts (Thanh Hoa province); and Vinh city, Nghi Loc, Dien Chau, and Quynh Luu districts (Nghe An province). The study accessed the change in mangrove cover and other land-uses related to mangroves in these eight districts. As the mangroves occupy two geographical regions in Hoang Hoa, Tinh Gia, Nghi Loc, and Quynh Luu districts, the study area was broken into 12 mangrove zones in this research (Figure 1).

2.2. Image Selection

Multiple temporal satellite images were used to classify land use and land cover (LULC) in 7 years (1973, 1988, 1995, 2005, 2010, 2015, and 2020) (Table 1). The oldest available Landsat image in the research location was in 1973. The year 1988 was selected around the Doi Moi Policy, which was executed in 1986. The third period (1995) related to changes in land policy (executed 1993) and the 327 Program (1993–1998). Changes in land policy (executed 2003), 661 Program (1998–2010), and the end of some NGO mangrove efforts were reasons for selecting the year 2005. The fifth period (2010) covered the early implementation of the Forestry Development Strategy (2006–2020). Most of the mangrove restoration projects funded by the Vietnam government commenced in 2015.

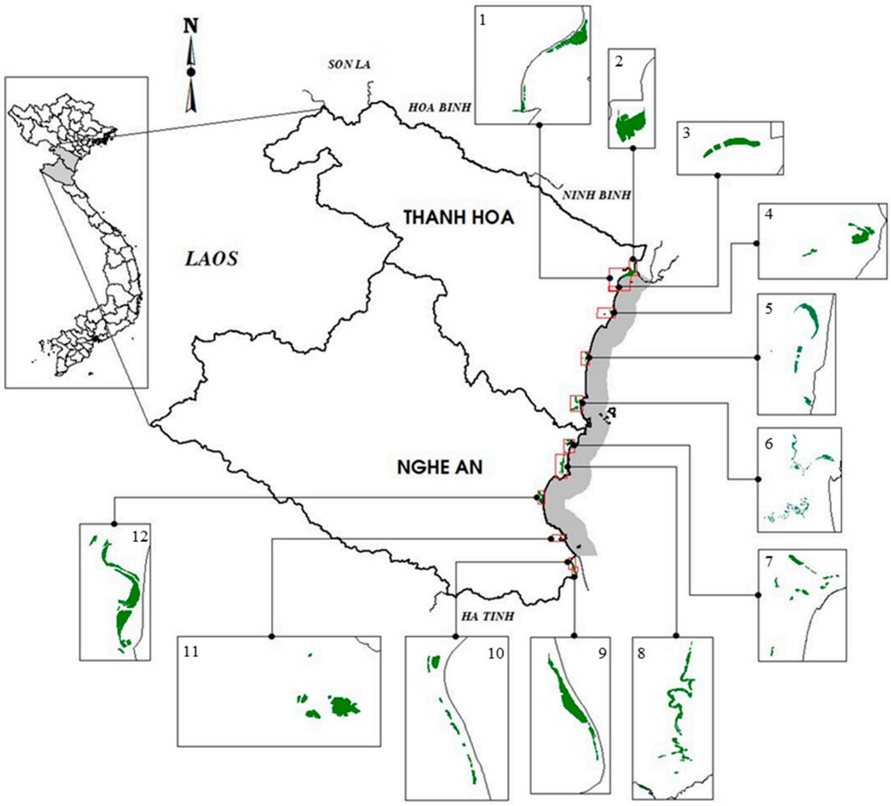


Figure 1. Location map of the study areas showing the distribution of the mangroves in green in 2020 (1—Hau Loc district; 2—Nga Son district; 3, 4—Hoang Hoa district; 5, 6—Tinh Gia district; 7, 8—Quynh Luu district; 9—Vinh city; 10, 11—Nghi Loc district; and 12—Dien Chau district); the coast is highlighted in grey.

Table 1. Landsat images used for the LULC change analysis.

Image Date	Image Number	Satellite (Resolution m)	Path/Row
21 July 1973	LM11360461973202AAA05	Landsat 1(60)	136/46
27 February 1973	LM11360471973058AAA05	Landsat 1(60)	136/47
4 November 1988	LT51260461988309BKT00	Landsat 5(30)	126/46
20 November 1988	LT51260461988325BKT01	Landsat 5(30)	126/46
28 May 1988	LT51260471988149BKT00	Landsat 5(30)	126/47
13 June 1988	LT51260471988165BKT01	Landsat 5(30)	126/47
1 September 1988	LT51260471988245BKT00	Landsat 5(30)	126/47
4 November 1988	LT51260471988309BKT00	Landsat 5(30)	126/47
6 December 1988	LT51260471988341BKT00	Landsat 5(30)	126/47
24 November 1995	LT51260461995328CLT00	Landsat 5(30)	126/46
8 January 1995	LT51260471995008BKT00	Landsat 5(30)	126/47
14 April 1995	LT51260471995104BKT00	Landsat 5(30)	126/47
24 June 1995	LT51270461995175BKT00	Landsat 5(30)	126/46
10 July 1995	LT51270471995191BKT00	Landsat 5(30)	127/47
3 January 2005	LT51260462005003BJC01	Landsat 5(30)	126/46
11 May 2005	LT51260462005131BJC00	Landsat 5(30)	126/46
14 July 2005	LT51260462005195BJC00	Landsat 5(30)	126/46
3 January 2005	LT51260472005003BKT00	Landsat 5(30)	126/47
11 May 2005	LT51260472005131BKT01	Landsat 5(30)	126/47
14 July 2005	LT51260472005195BKT00	Landsat 5(30)	126/47
1 November 2010	LT51260462010305BKT00	Landsat 5(30)	126/46
3 December 2010	LT51260462010337BJC00	Landsat 5(30)	126/46

Table 1. *Cont.*

Image Date	Image Number	Satellite (Resolution m)	Path/Row
12 July 2010	LT51260472010193BKT00	Landsat 5(30)	126/47
10 Jyly 2015	LC81260462015191LGN01	Landsat 8(15)	126/46
11 August 2015	LC81260462015223LGN01	Landsat 8(15)	126/46
7 May 2015	LC81260472015127LGN02	Landsat 8(15)	126/47
11 August 2015	LC81260472015223LGN01	Landsat 8(15)	126/47
30 May 2015	LC81270462015150LGN01	Landsat 8(15)	127/46
21 June 2020	LC81260462020173LGN00	Landsat 8(15)	126/46
20 May 2020	LC81260472020141LGN00	Landsat 8(15)	126/47
21 June 2020	LC81260472020173LGN00	Landsat 8(15)	126/47
27 December 2013	LC81260462013361LGN01	Landsat 8(15)	126/46
30 December 2014	LC81260462014364LGN01	Landsat 8(15)	126/46
1 July 2015	LC81270462015182LGN01	Landsat 8(15)	127/46
7 October 2016	LC81270462016281LGN02	Landsat 8(15)	127/46
31 July 2017	LC81260462017212LGN00	Landsat 8(15)	126/46
23 November 2018	LC81260462018327LGN00	Landsat 8(15)	126/46
10 November 2019	LC81260462019314LGN00	Landsat 8(15)	126/46
24 August 2020	LC81260462020237LGN00	Landsat 8(15)	126/46

The tidal cycle, tidal inundation, and cloud cover are important coastal features to consider before selecting remote sensing images for mangrove mapping. These factors have the potential to significantly bias mangrove mapping results [60]. Fortunately, optical remote sensing data, including Landsat data, offer time-series remotely-sensed images, which provide more options to avoid the effects of tidal inundation on the accuracy of mangrove mapping [60,61]. Additionally, knowledge of tidal levels at the time of the acquired remotely-sensed images can be used to help eliminate errors [62]. In this study, tidal tables together with information of local tidal regimes obtained from local people during the field survey were synthesized to help select images for mangrove mapping.

We also used secondary data for mangrove afforestation and change analysis. The 2015 land cover map and forest cover maps (1983, 1995, 2000, 2005, 2010 and 2015) with map scales of 1:50,000 were obtained from the Thanh Hoa and Nghe An departments of Agriculture and Rural Development. Legal documents [63–66] and other relevant documents [67,68] concerning mangrove management and development in the study area were reviewed. Also, to better understand the management status of mangrove forests and any historical changes across time, local records were examined to confirm the presence of mangroves in the past.

2.3. Data Pre-Processing

Landsat 1 Level-1 images were downloaded from the United States Geological Survey (USGS). Landsat (5 and 8) Level-2 images were obtained from EROS Science Processing Architecture (ESPA). The Landsat (5 and 8) Level-2 images were then used to classify the reflectance data using the NDVI method in combination with visual interpretation. Meanwhile, Landsat 1 Level-1 images were pre-processed using the linear contrast stretch and histogram equalization stretch methods [69] to improve the quality of images before visual interpretation. These processes were undertaken with ArcGIS 10.3.

A polygon was created and then used to define the areas of mangrove forests in the pre-processed Landsat images. These images were clipped to extract the areas of interest (the total AOI was about 32,000 ha) where mangrove forests were more likely to be present (e.g., low-lying areas, intertidal zones, estuaries, and rivers), and to exclude large areas where mangrove forests do not occur (e.g., far inland, highlands, and open ocean) before the image classification was undertaken.

2.4. Land Cover Classification

The mapping unit used for this study was at a scale of 1/150,000. This scale was chosen as it was most suitable for Landsat 8 and Landsat 5 images. To construct thematic land cover maps, including mangrove forest maps, this study mainly used NDVI [26] combined with the visual interpretation approach. NDVI was selected because it is one of the most widely used change detection indices for cultivated land [70] and vegetation monitoring [71]. Threshold values of NDVI for each land cover type were determined and then used to construct a thematic land cover map for each selected year with the support of the ground reference data. Firstly, we used Google Earth and ground data (field sample survey) to exactly define the presence of mangroves, mudflats, water surface, aquaculture, other forest, and other land use on Landsat Level—2 images (NDVI images). Then, we defined NDVI maximum and minimum values for each land cover type. Lastly, we used ArcGIS 10.3 software to classify the six land cover types. NDVI index values are usually divided into levels: a negative value to 0 refers to water; values of less than 0.1 usually represent soil, rock, sand, or snow; values from 0.2 to 0.5 are bushes, grass, or dry fields; and values of 0.6 to 0.9 or close to 1.0 are trees [72,73]. The NDVI output is a greyscale raster map with index values ranging from 1 to −1. These threshold values were then used to construct a thematic land cover map for each year. These thresholds were confirmed in previous studies [74–77].

In addition, the visual interpretation approach used expert knowledge and experience to separate the areas of mangrove forests and other classes from remote sensing imagery. This approach was used to support NDVI, and to identify NDVI thresholds and classify reference data by using higher spatial resolution Google Earth [78,79] (on Google Earth software, older images were given by using the 'show historical imagery' function) along with a data survey, forest cover map, and land cover maps The various steps taken in this study are summarized in the flow chart in Figure 2. The final classification result was the combined NDVI method and visual interpretation.

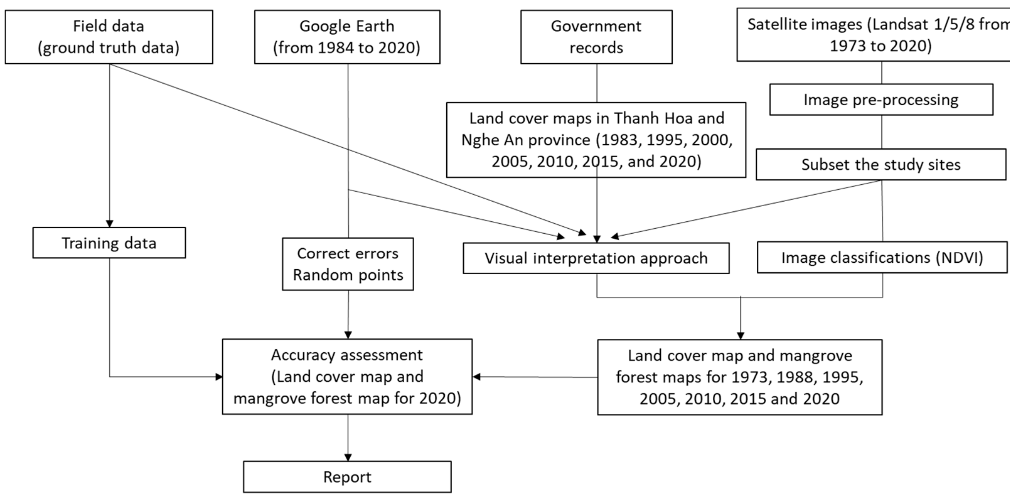


Figure 2. Chart of the methodology used for mapping mangrove extent and land cover.

2.5. Accuracy Assessment

In this study, a thematic land cover map derived with classification mainly according to NDVI values each selected year was considered to be accurate if it gave an unbiased representation of the land cover categories [80]. Accuracy assessments were conducted on the 2020 Landsat images by comparing the classification results with reference data that accurately reflected true land covers [80]. This study's 360 field sample points were acquired from a field investigation in August 2020 and recorded using the global positioning system (GPS). The field survey was conducted to collect ground information on LULC, including forest type, water bodies, aquaculture, bare land, and others.

We also collected 435 sample points from high-resolution images (Google Earth) for the classified images. The sample points were randomly distributed across the six land cover classes (Table 2). The 795 validation points were stratified randomly by a sampling approach by area and were then used to compare with the 2020 land cover map classifications based on NDVI thresholds. Moreover, reference data and maps (land cover maps in 2005, 2010, and 2015 with a scale of 1:50,000; forest cover maps in 1983, 1995, 2000, 2005, 2010, and 2015) were used.

Table 2. Description of the land cover categories.

Land Cover Type	Description
Mangrove forest	Inter-tidal, halophytic forests both natural and planted
Other forest	Non-mangrove forest
Aquaculture	Aquaculture ponds and salt pans
Other land use	Rice fields, urban areas, roads, and industrial zones
Mudflat	Tidal mudflats, sandy beaches, and other low-lying flooded areas
Water	Rivers/estuaries, lakes, canals, small water bodies, and sea

Validation points collected from the field data survey and Google Earth were used to assess only the accuracy of the 2020 classified map. The accuracy for earlier classifications were also assessed by using land cover maps, forest cover maps, Google Earth, and a data survey. The ground data for earlier years were not of high reliability, and this would have affected the accuracy of classification for that period. The field sample points were defined by using forest cover and land cover maps before conducting the field data survey. Of the 795 validation points collected from the ground reference data and Google Earth for six land-use classes (Table 2), 202 were in aquaculture, 166 were in mangrove forests, 68 were in mudflats, 73 were in other forests, 154 were in other land use, and 132 were in water. To evaluate the accuracy of land cover maps and assess the accuracy of the NDVI approach each selected year, users, producers, and overall accuracy with kappa statistics were derived from the error matrix. According to Anand [81], once a classification exercise has been carried out, there is a need to determine the degree of error in the end product, including identified categories on the map. Errors are the result of incorrect labelling of the pixels for a category. The most used method of representing the degree of accuracy of classification is to build a k × k array, where k represents the number of categories. The resulting error matrix is useful for determining overall errors for each category and misclassifications by category; as a result, it is also known as the confusion matrix. The strength of a confusion matrix is that it identifies the nature of the classification errors, and their quantities [81]. The kappa coefficient is a measure of the agreement between two maps considering all elements of the error matrix, and it is defined in terms of error matrix according to Anand [81]. Kappa values were categorized into groups by value where: kappa values that were zero indicated no agreement; from 0.41–0.6 were considered as moderate agreement; 0.61–0.8 were regarded as substantial agreement; and 0.81–1 referred to an almost perfect agreement [80,82–84].

3. Results

3.1. Classification and Accuracy Assessment

All the Landsat images in Table 1 were used to produce the NDVI LULC classification maps for the study area. NDVI thresholds for each land cover type were defined from the calculated ratio difference between the measured canopy reflectance in the red and near-infrared bands, as follows: mangrove forest (0.57–1.0); other forest (0.49–0.56); other land use (0.26–0.48); aquaculture (0.17–0.25); mudflat (0.01–0.16); and water (0.0–1.0). These threshold values were then used to construct a thematic land cover map for each assessed year.

The error matrix produced (Table 3) showed that results of the accuracy assessment for the 2020 classification indicate a high rate of classification accuracy with a user accuracy as follows: 100% for mapping mangrove forest; 98.6% for other forests; 94.7% for aquaculture;

100% for mudflat; 99.2% for water; and 94.2% for other land use, giving an overall accuracy of 97.2%. Also, the kappa coefficient of 0.97 revealed a substantial agreement between the classification results and reference data. The classification accuracy was averaged for twelve study areas. There were small differences in classification accuracy between the areas and the magnitude of the errors was ±2.7%. Thus, the results confirmed the potential effectiveness of using recent Landsat data for monitoring the spatiotemporal distribution of mangrove forests in the study areas.

Table 3. Error matrix based on a random sample of 795 points, which were cross-classified using the LULC map classified in 2020 and ground-truthing, in which each row and column represents one category in the interpreted map. The left-hand side of the table has the categories on the standard map/data. The top of the table comprises the k categories representing the product of the created map to be evaluated. The values in the matrix indicate the numbers of pixels.

	Ground Truth (References from GPS)								
	Classified Data	**MF**	**OF**	**Aq**	**OLU**	**MF**	**W**	**Total**	**User's Accuracy** [1]
Classification result	(MF)	166						166	100.0
	OF		71		1			72	98.6
	Aq			197	6	2	3	208	94.7
	OLU		2	5	147		2	156	94.2
	MF					65		65	100.0
	W					1	127	128	99.2
	Total	166	73	202	154	68	132	795	
	Producer's accuracy [2]	100	97.3	97.5	95.5	95.6	96.2		
	Overall accuracy [3]	97.2							
	Kappa [4]	0.97							

[1] User's accuracy (commission error), computed by dividing the number of correctly classified pixels in each category by the total number of pixels classified in that category (the row total). The user's accuracy represents the probability that a pixel classified into a given category represents that category on the ground. [2] Producer's accuracy (omission errors) results were calculated from dividing the number of correctly classified pixels in each category (on the major diagonal) by the number of reference pixels "known" to be of that category (the column total). This value represents how well reference pixels of the ground cover type are classified. [3] Total accuracy computed by dividing the total number of correctly classified pixels (the sum of the elements along the major diagonal) by the total number of reference pixels. The overall accuracy is calculated as given from dividing the sum of the diagonal elements by the total number of accuracy sites. [4] Kappa coefficient is a measure of the agreement between two maps taking into account all elements of the error matrix and it is defined in terms of the error matrix according to Anand [81]. Mangrove forest—MF, Other forest—OF, Aquaculture—A, Other land use—OLU, Mudflat—MF, and Water—W.

3.2. LULC Changes in Thanh Hoa and Nghe An Provinces from 1973 to 2020

Multi-temporal changes in the extent of mangrove forests in the study regions are detailed in Table 4. From 1973 to 2020, the overall mangrove forest area increased in Nghe An and Thanh Hoa by 256.5 and 431 ha (equivalent to 8.2% per year and 2.5% per year respectively. Over the same period, the aquaculture area increased by 1328 ha in Nghe An and 3333 ha in Thanh Hoa provinces. In contrast, the mudflat areas declined by 880 ha in Nghe An and 4572 ha in Thanh Hoa provinces.

In September 2020, there were 215.6 ha of mudflat cover in Nghe An province and 457.9 ha in Thanh Hoa province. The inter-tidal parts of the latter areas provide potential targets for future mangrove restoration projects. The areas of other forest, other land use, and water fluctuated slightly in Nghe An province, but they changed markedly for Thanh Hoa province. In particular, the area of other forest in Thanh Hoa province dropped from 3731.8 ha in 1973 to 660.8 ha in 2020, and the other land use category increased from 5992 ha to 8910 ha over the same period.

From 1973–1988, mangrove cover nearly doubled from 66.5 to 124.5 ha in Nghe An province, but it declined from about 366 ha to 120 ha in Thanh Hoa province. From 1988 to 1995, the mangrove area declined in both provinces, especially in Thanh Hoa, where it decreased to 62 ha in 1995. From 1995 to 2005, there was a marked increase in the area of mangroves to nearly 340 ha in Thanh Hoa and 282 ha in Nghe An by 2005. In the next five years, the mangrove cover in Thanh Hoa fell slightly, but it increased slightly in Nghe An. Between 2010 and 2015, about 40 ha in Nghe An province and 170 ha in Thanh Hoa province were planted to mangroves. By August 2020, mangrove cover in Thanh Hoa province was about 797 ha (increase of 431 ha over 1973), while the figure for Nghe An province was about 323 ha (increase of 257 ha over 1973).

Table 4. The estimated area of LULC (ha) and the land cover percentages in Nghe An and Thanh Hoa provinces for the years 1973, 1988, 1995, 2005, 2010, 2015, and 2020 obtained from Landsat images.

Province/ Classification	**1973**		**1988**		**1995**		**2005**		**2010**		**2015**		**2020**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
Nghe An [1]														
Mangrove forest	66.5	0.5	124.4	0.9	155.6	1.1	282.1	1.9	300.2	2.1	340.7	2.3	323	2.2
Other forest	647.3	4.5	814.9	5.6	629.1	4.3	594	4.1	600	4.1	612.5	4.2	603.9	4.2
Aquaculture	1487.9	10.2	1503.1	10.4	2159.9	14.9	2548.6	17.6	2702.1	18.6	2812.8	19.4	2816.1	19.4
Other land use	9046.8	62.3	8014	55.2	8851.4	61	8644.1	59.5	8501.4	58.5	8375.3	57.7	8329.5	57.4
Mudflat	1095.8	7.5	1885.1	13	591.1	4.1	354.7	2.4	265.3	1.8	239.7	1.7	215.6	1.5
Water	2176.8	15	2179.6	15	2134.1	14.7	2097.6	14.4	2152.1	14.8	2140	14.7	2233	15.4
Thanh Hoa [2]														
Mangrove forest	366.1	2.1	119.4	0.7	61.7	0.4	340	2.1	323.8	1.8	492.7	3.4	797.1	4.5
Other forest	3731.8	21.3	2079.1	11.8	686.2	3.9	629.9	3.6	637.8	3.6	660.8	4.6	660.8	3.8
Aquaculture	566.2	3.2	738	4.2	1152.3	6.6	3017.4	17.2	3485.6	19.9	3846.3	21.9	3898.9	22.2
Other land use	5992.3	34.1	8734.7	49.8	9992.5	56.9	9744.8	55.5	9355.2	53.3	8955.5	61.7	8910.6	50.8
Mudflat	5030.2	28.7	2467.6	14.1	3563.4	20.3	1516.2	8.5	849.8	4.8	801.7	5.5	457.9	2.6
Water	1864.4	10.6	3412.3	19.4	2095	11.9	2302.7	13.1	2898.8	16.5	2794.1	19.2	2825.8	16.1

[1] The total ha of the study area in Nghe An was 14,521.1 ha; [2] The total ha of the study area in Thanh Hoa was 17,551 ha.

3.3. Change in Mangrove Cover at the District Level from 1973 to 2020

Mangrove cover and change in mangrove cover differed between districts within the two provinces (Table 5). Mangroves were evident in Vinh city, Nghi Loc, Hau Loc, and Nga Son districts in 1973. In 1995, mangroves were present in Dien Chau and Tinh Gia districts, but had disappeared in Hoang Hoa district. The period from 1973–2020 witnessed fluctuations in mangrove cover in Hau Loc and Nga Son districts. By 2020, the mangrove cover in Nga Son district was similar to what it was in 1973. By contrast, there was almost constant mangrove cover (about 50 ha) in Vinh city from 1973 to 2020. By 2020, mangrove cover was greatest in Hau Loc (256.8 ha) and Nga Son (315.5 ha) and least in Nghi Loc district (47.1 ha) and Vinh city (55.2 ha) (Table 5).

Table 5. The estimated area of mangrove cover (ha) in coastal districts of Nghe An and Thanh Hoa provinces for years 1973, 1988, 1995, 2005, 2010, 2015, and 2020 * obtained from Landsat images.

Province	**District**	**1973**	**1988**	**1995**	**2005**	**2010**	**2015**	**2020**
Nghe An		66.5	124.5	155.6	282.1	300.2	340.7	323.0
	Dien Chau			6.4	99.8	101.8	110.7	105.0
	Nghi Loc	21.3	26.7	14.8	44.2	32.0	46.5	47.1
	Quynh Luu		47.7	68.3	80.9	111.3	128.4	115.7
	Vinh city	45.2	50.1	66.1	57.3	55.2	55.2	55.2
Thanh Hoa		366.1	119.4	61.7	340.0	323.8	492.7	797.1
	Hau Loc	47.4	12.7	20.2	95.5	80.2	181.6	256.8
	Hoang Hoa		42.9		84.5	23	35.2	69.2
	Nga Son	318.7	63.8	10.4	101.7	121.8	129.8	315.5
	Tinh Gia			31.1	58.3	98.8	146.1	155.6
Total		**437.9**	**243.0**	**219.3**	**643.8**	**626.8**	**829.6**	**1120.1**

* For Nghi Loc, Hoang Hoa, Quynh Luu, and Tinh Gia districts, the data were combined from the two sites.

3.4. Drivers of Change in Mangrove Cover

Changes in mangrove forest extent were observed across most districts (Table 5) because of both natural and anthropogenic drivers of change. The main drivers of change in mangrove forest in Thanh Hoa and Nghe An provinces were aquaculture, other land use, and afforestation projects. Whilst we did observe some natural seedling recruitment of mangroves along river edges and mudflats in our field surveys, most seedlings did not survive longer than a few months.

- Aquaculture

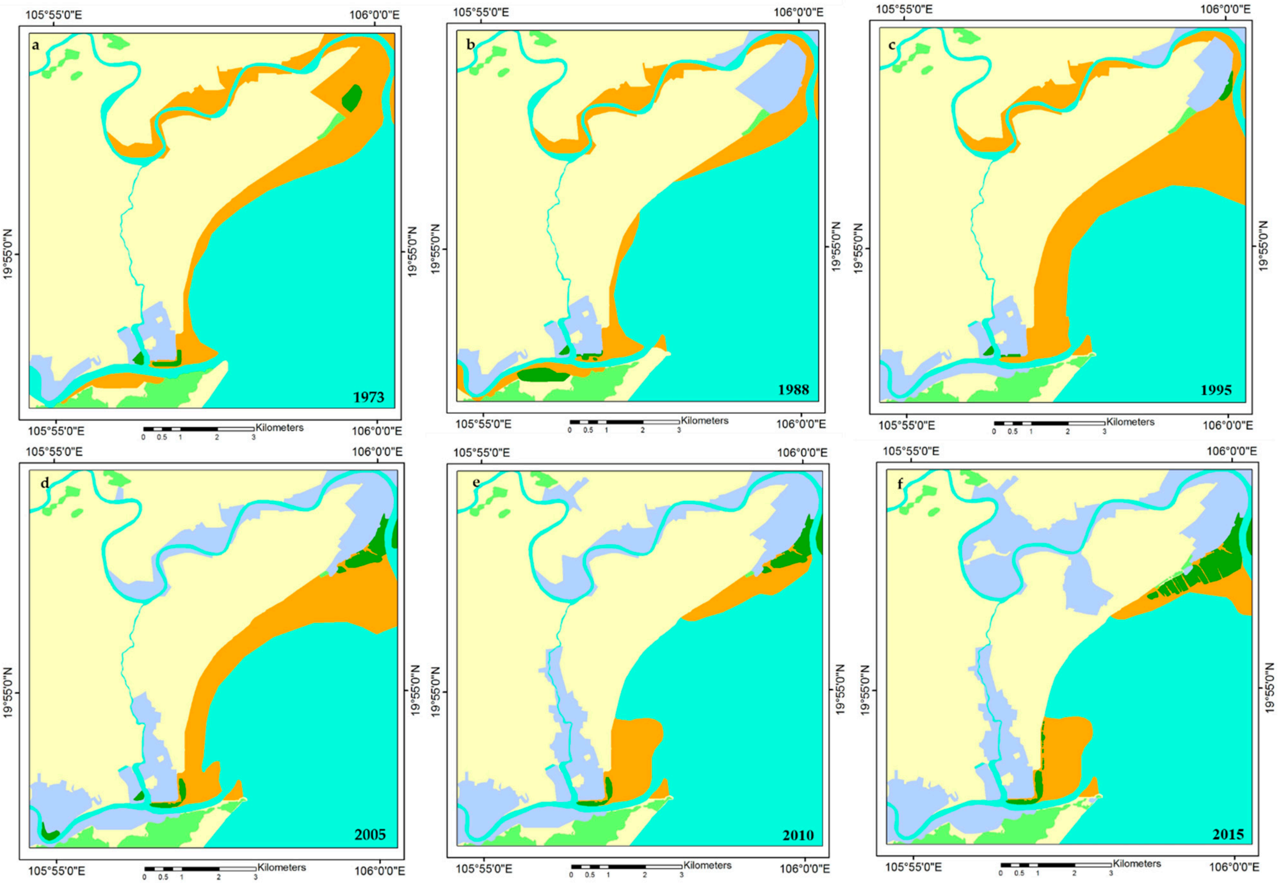
Mangrove cover in Thanh Hoa and Nghe An provinces was appreciably affected by aquaculture, which depended on the period and location. From 1973 to 1988, aquaculture had a small regional impact on mangrove extent in both provinces. The loss from aquaculture was only 8.2% (28.3 ha) in Thanh Hoa province, while the area of mangroves in Nghe An province was not affected by aquaculture. The percentage of conversion to aquaculture ponds increased steadily over the next five years. Aquaculture accounted for 31.3 ha (28.2%) loss of mangroves in Thanh Hoa, and 5 ha (21.9%) in Nghe An. It can be seen in Hau Loc district (Figure 3) that aquaculture was present in the northeast in 1988. This change resulted from the Doi Moi (Renovation) policy which was implemented in 1986. From 1995–2005, there were notable increases in the area of aquaculture in both Thanh Hoa and Nghe An provinces. This is illustrated (Figure S1) using Nga Son district, where aquaculture expanded in the north. On average, aquaculture accounted for 49.6% (28.8 ha) and 95.7% (16.2 ha) of the mangrove loss in Nghe An and Thanh Hoa provinces, respectively. Aquaculture remained the main reason for mangrove loss (89.2%) in Thanh Hoa province from 2005 to 2010 but was a smaller contributor (27.5%) in Nghe An province. Between 2010 and 2015, the rate of mangrove loss from the expansion of aquaculture was more than 70% in both provinces. Since 2015, conversion to aquaculture has continued at a constant rate in Thanh Hoa province but declined to about 50% in Nghe An province.

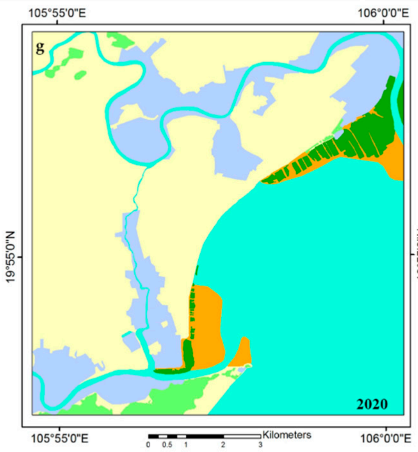
- Other land use

Other land use was also an important driver of mangrove deforestation. In particular, the study shows that the expansion of rice production was responsible for driving mangrove deforestation. On average, agriculture expansion for rice production accounted for 7.3% and 57.4% mangrove loss, respectively, in Nghe An and Thanh Hoa provinces from 1973 to 2020. The conversion rate to other land use was particularly dominant in Thanh Hoa province, especially from 1973 to 1995. The percentage of conversion to other land use was highest at about 300 ha (86.7%) in Thanh Hoa province in 1973 to 1988, then declined to 30.2% in 1995. The river mouth in Nga Son district (Thanh Hoa province) illustrates how rice production resulted in the area of mangroves dropping from 318.7 ha in 1973 to 63.8 ha in 1988 (Table 5).

- Afforestation

Afforestation projects contributed considerably to the change in mangrove area during the research period. In the river mouth in Nga Son district, in the five years from 2015–2020, more than 211 ha of mangroves were established on the mudflat area (Table 5, Figure 4). The change is apparent on Landsat images year by year (Figure 4). The satellite imagery revealed young mangroves, and hence mangroves planted in recent years were able to be included in the 2020 land use maps. We were able to detect 6 month old mangroves on Landsat and Google Earth images.





h

LULC	Mangroves	Other forest	Aquaculture	Other land use	Mudflat	Water
1973 (ha)	47.4	238.1	225	4907.8	1072.4	3673.5
1988 (ha)	55.6	238.1	490.7	4933.3	726.5	3719.9
1995 (ha)	20.2	250	535.2	5006.8	1400.9	2951.1
2005 (ha)	104.8	237.3	1026.6	4807.8	856.7	3130.9
2010 (ha)	93.1	237.3	1234.3	4614.9	468.9	3515.7
2015 (ha)	192.9	238.6	1593.3	4260.2	450.1	3429.1
2020 (ha)	270.5	238.6	1608.9	4243.1	320.8	3482.2

Figure 3. Land use and land cover classification map of the river mouth in Hau Loc district in Thanh Hoa province obtained from Landsat 1 for 1973 (**a**), Landsat 5 for 1988 (**b**), 1995 (**c**), 2005 (**d**), 2010 (**e**), and Landsat 8 for 2015 (**f**) and 2020 (**g**). Panel (**h**) provides the LULC (ha) for panels (**a**–**g**).

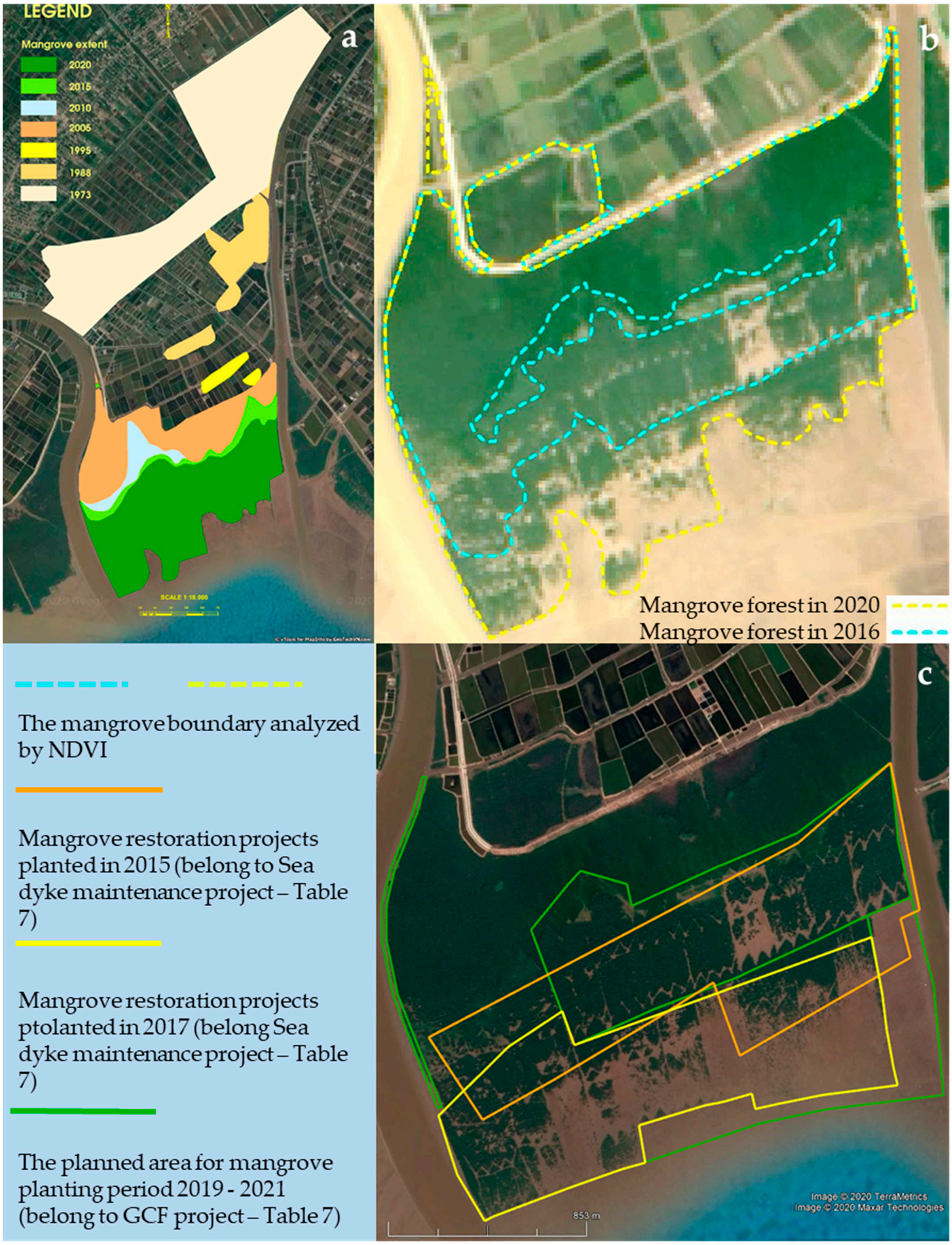


Figure 4. Mangrove restoration programs in Nga Son district. (**a**) Google Earth image of 2014 overlaid with mangrove extent obtained from Landsat images from 1973 to 2020; (**b**) Landsat image from 24/8/2020 showing boundaries for mangrove distribution in 2016 (light blue) and 2020 (yellow) obtained by NDVI; (**c**) Google Earth image of 26/7/2020 showing the extent of mangrove restoration projects planted in 2015 and 2017, and the planned area for mangrove planting from 2019 to 2021 sourced from [85]. Imagery in (**a**,**c**) copyright of Google Earth.

It is evident from the satellite imagery that not all afforestation projects were successful (example of Nga Son is illustrated in Figure 4). For example, from 1988 to 1995, parts of the afforestation estate disappeared to mudflat, totaling 45.3 ha (40.8%) and 15.5 ha (67.5%) in

Thanh Hoa and Nghe An provinces, respectively. This means that restoration efforts during this period in Thanh Hoa were not successful. According to local people in Minh Loc commune (Hau Loc district, Thanh Hoa province), some mangrove restoration programs failed in Minh Loc commune in 2015, 2017, and 2019. Likewise, survival rates of mangroves in other projects in Nga Son district were not high; thus, some projects had to be replanted (Figure 4). Reasons given for these failures include natural disasters and change in land use, and these are discussed in the following sections.

4. Discussion

4.1. Mangrove Extent

Mangrove cover fluctuated greatly in the two provinces over time. However, overall, the increase in the mangrove area of 584.2 ha in Thanh Hoa province and 124.2 ha in Nghe An province since 1973 is a successful outcome for protecting this vulnerable coastal region of Vietnam. In a previous study that covered a small part of the study region, Hoa et al. [57] concluded that mangrove forests in Hau Loc and Nga Son districts had increased by 278 ha between 2005 and 2018. Our assessment of these districts is marginally higher. As [58] used supervised classification techniques, this may have resulted in an underestimation of the mangrove area due to a higher occurrence of misclassification. Our study provides a detailed analysis of the areal extent and distribution of Thanh Hoa and Nghe An's mangrove forests. However, more qualitative and quantitative information concerning the composition and condition of mangrove forests is needed for planning future afforestation and conservation efforts. Remote sensing technology allows monitoring of mangrove forests to be faster, more efficient, and with a broader scope than with conventional methods [86]. Remote sensing has been used to identify attributes such as biomass [87–89], carbon stocks [90,91], species [92–95], and mangrove health [96–98].

4.2. Drivers of Change Over Time

The drivers of change on a hectare basis over the period of 1973 to 2020 were in the order of aquaculture > other land use > natural factors > afforestation.

- Aquaculture

Globally, mangrove forests have experienced extensive deforestation owing to the global demand for commodities such as farmed shrimp and fish [99,100]. In this study, aquaculture accounted for 42.5% and 29.8% of the mangroves lost in Nghe An and Thanh Hoa provinces, respectively, from 1973 to 2020. From 2005 to 2010, conversion to aquaculture caused significant mangrove loss in Than Hoa province. The aquaculture industry is primarily responsible for mangrove deforestation in Southeast Asia over the past 30 years [9,101]. Hence, this region is well known as a global hotspot of mangrove loss and fragmentation [102]. For example, aquaculture contributed to 33% loss of mangroves in Thailand and 63% in Indonesia [99]. In Vietnam, the Doi Moi Policy launched in 1986 encouraged trade liberalization and export growth, including planned and unplanned responses of the domestic agricultural sector to global markets. This led to the large-scale conversion of mangrove forests to shrimp farms [13,103]. An example of conversion to aquaculture and other land in Tinh Gia district in 2014, 2016, 2018, and 2020 is evident on satellite images (Figure S2).

- Other land use

The contribution of other land use to mangrove loss was about 7.3% and 57.8% in Nghe An and Thanh Hoa provinces, respectively, over the research period of 47 years. Rice production has been a major driver of mangrove loss in many countries. It is estimated that agriculture expansion for rice production, primarily in Southern Asia, accounted for more than 20% of the total mangrove change in the region from 2000 to 2012 [102]. The expansion of rice agriculture across Myanmar is responsible for driving the fastest rate of mangrove deforestation of any country in Southeast Asia, with 87.6% loss occurring in the

2000s [102,104]. In Vietnam, rice production is estimated to have contributed about 10% of the total loss of mangroves [102] including parts of northern Vietnam [80].

- Natural factors

In 2005, a peak tide and a river storm surge co-occurred as typhoons hit Thanh Hoa province. All shrimp farms were seriously damaged, and many shrimp farmers fell deeply into debt [105]. The surge destroyed 3.7 km of the coastal dike system protecting Da Loc (Hau Loc, Thanh Hoa). Floodwaters inundated seven out of ten villages, lasting for several hours. More than 100 houses were heavily damaged or destroyed, with all shrimp farms and 500 hectares of crops lost. The loss of mangroves was not recorded, but community members later discovered that the only section of dike spared by the storm was the 4.7 km section protected by mangroves [105]. Therefore, since 2005, local people have realized the essential roles of mangrove forests in protecting the dike system and their livelihoods against typhoons. Engineering actions such as concrete barriers have been implemented to reduce storm damage. The planting of mangrove forests in vulnerable areas and the protection of older mangroves subsequently received more active local participation. Consequently, mangrove forests have expanded due to active local participation in mangrove forest management in close cooperation with the local authorities.

Significant areas of mangroves (36%) were transformed to mudflats in Nghe An province, and nearly 14% changed to water. Factors that contributed to this include failed mangrove restoration projects, coastal erosion, storms, and typhoons. Sea level rise may also be a contributing factor [106] but there is no reliable information for this part of Vietnam. Due to coastal erosion, mangroves tend to move landward or die due to bank slumping, especially in deltaic regions [107,108]. The loss of mudflat areas through erosion decreased the number of potential areas for planting mangroves in both Thanh Hoa and Nghe An provinces. For example, in the river mouth in Nga Son and Hau Loc districts (Figures 3 and 4), the total mudflat area decreased by over 4000 ha from 2005 to 2010. Loss of mangroves in Nghe An in 2015 to 2020 has been attributed to the frequency of storms in the area [109]. However, policies on coastal forest management, protection, rehabilitation, and development in response to climate change were also launched in this period [63,64].

Damage sustained by mangrove forests from storms and tsunamis has been documented in other studies. For instance, after examining the extent of mangrove destruction and subsequent recovery in Thai Lan after the 2004 Indian Ocean tsunami, Kamthonkiat, Rodfai [110] found that the tsunami reduced the mangrove area by 5% (1054 ha). Smith, Anderson [111] estimated that 1250 ha of mangroves were initially lost from the impacts of Hurricane Wilma in 2005 on Florida mangroves. They also reported that frequent hurricanes hitting the area have drastically altered the mangrove ecosystems by changing some of them to mudflats.

- Afforestation

Development projects, as well as increasing local participation [67] in mangrove management, have helped to increase mangrove cover. For example, community members planted 277 ha of mangrove in Hau Loc and 181 ha in Nga Son in 2007, with a survival rate of 70 to 90% [105]. The participation of local people in planting, maintaining, and protecting the young forests has also led to cost savings, efficiency gains, and strong community buy-in for forest protection. In the 1990s, the coastal zone in Hoang Hoa, Hau Loc, Tinh Gia, and Nga Son districts (Thanh Hoa province), and Nghi Loc, Vinh city, Dien Chau, and Quynh Luu districts (Nghe An province) was the focus of a project entitled Environmental Preservation Project, implemented by NGOs. Furthermore, to increase the resilience of communities to natural disasters and with support from IFRC/JRC, 1245 ha in Thanh Hoa province and 1096 ha in Nghe An province were planted from 1997 to 2010. These projects had individual agreements with households who participated in the planting and protection of mangrove forests. Also, the provincial Red Cross chapter made direct payments to local households.

Mangrove forests in Nghe An increased from 1973 to 1995 due to mangrove afforestation programs funded by NGOs. International involvement in mangrove planting projects became more evident from 1990 to 2005, and thousands of hectares of mangroves were planted in Thanh Hoa and Nghe An provinces (Table S1). However, over the decade from 2010 to 2020, there was only a moderate increase in the mangrove area of 170 ha and 40 ha in Thanh Hoa and Nghe An provinces, respectively, despite new mangrove planting projects (funded by the IFRC/JRC and CARE, Table S1) and implementation of the national plan for forest protection and development for 2010 to 2020 (Table S2) [63]. Over the last decades, the area of aquaculture increased greatly, including 286 ha in the river mouth in Nga Son and 359 ha in Hau Loc, which impacted some mangrove plantings.

From project documents, it is estimated that about 6318 ha of mangrove will be planted by funds from NGOs and the state from the early 1990s to 2023 in Thanh Hoa and Nghe An provinces. This estimate is subject to change as it depends on many factors. For example, according to the National Target Program to Respond to Climate Change (Table S2), 300 ha of mangroves were to be planted in Thanh Hoa province from 2014 to 2015 [64]. However, only 194.4 ha of mangroves were planted as the approved budget was not fully allocated [112]. By contrast, programs for sea dyke maintenance in Thanh Hoa (Table S2) were fully implemented as in the approved plans [109,113].

By comparing the data in project documents and government audits, we estimate that the average rate of success of mangrove restoration programs in the two provinces is about 30%. Furthermore, nearly 5000 ha of mangroves scheduled to be planted in the next three years will help to redress the historic loss of mangroves. The survival rate of mangrove restoration projects in this area has been a challenge. Therefore, engineering solutions to improve the survival rate of mangrove restoration programs should be considered as priority studies.

- Classification and accuracy assessment

Regarding LULC classification, differences in the area of water in Thanh Hoa and Nghe An overtime could be due to water level variations from the low and high tide regimes in two images collected for comparison [33,61,114], and temporal differences between the two images [61]. In fact, there was a tidally temporal difference between images captured over the years in this study. As the tide came in or out of the study areas, some areas that belonged to mudflats or water, were covered by water or mudflats, thus narrowing or expanding its areas. However, this did not affect the mapping of mangroves.

In this study, accuracy assessment showed that it was possible to estimate mangrove cover and other LULC classes in Thanh Hoa and Nghe An provinces using Landsat data. The accuracy of the individual classes showed that NDVI was effective in separating mangroves and LULC classes. Mangroves produced higher user and producer accuracies than other LULC classes, indicating that mangroves were well classified. The producer and user's accuracies of other land use were lower than the other classes, which could be due to spectral similarity between other land uses (such as rice fields) and other forests. However, the kappa coefficient was 0.97 (Table 4), showing that there was a substantial agreement between the classification results and reference data [83,84,115].

5. Conclusions

The present study used multi-date Landsat imagery, processed using the NDVI method, to quantify changes in the distribution of mangroves in Thanh Hoa and Nghe An provinces. The main drivers of mangrove change were: aquaculture > other land use > natural factors > afforestation. The study estimated that over the last 47 years (from 1973 to 2020), mangrove forests increased by approximately 2.5% to 797.1 ha in Thanh Hoa province and 8.2% to 323 ha in Nghe An province due to the deposition of sediment and mangrove plantation programs. The success of mangrove restoration efforts relies heavily on the involvement of local communities. We suggest that agencies engaged in managing coastal infrastructure and mangroves should employ remote sensing approaches for sustainable planning and management of mangrove forests in tandem with the local communes.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12050637/s1, Figure S1: NDVI LULC classification map of the river mouth in Nga Son district, Thanh Hoa province obtained from Landsat 1 for 1973 (a); Landsat 5 for 1988 (b); 1995 (c); 2005 (d); 2010 (e); and Landsat 8 for 2015 (f) and 2020 (g). Figure S2: Loss of planted mangroves by aquaculture in Tinh Gia district, Thanh Hoa province from 2014 to 2020; loss of mangrove by aquaculture—a; and loss of mangroves by other land uses—b and c. Table S1: Mangrove restoration areas are funded by NGOs in Thanh Hoa and Nghe An provinces from the 1990s to 2020. Table S2: Mangrove restoration areas are funded by the Vietnam government in Thanh Hoa and Nghe An provinces from the 1990s to 2020.

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