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Driving Mangrove Recovery: Community Engagement and Socio-Economic Shifts in Aquaculture Areas

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Abstract

Land-use change and recovery patterns of mangroves in the Tha Sak subdistrict, Nakhon Si Thammarat, Thailand, were examined utilizing multi-temporal Landsat images and socio-economic data from 1988 to 2023. Land use was classified through visual interpretation, and potential changes were predicted using a Markov chain model. The results showed a significant expansion of mangrove forests (1.11 km² to 9.10 km²), indicating a clear recovery. At the same time, the aquaculture area decreased drastically (from 25.69 km² to 8.79 km²), indicating a significant change in land use. The recovery of mangroves is primarily attributed to the cessation of aquaculture and the active involvement of the Tha Sak subdistrict's Small-Scale Fishermen Group, highlighting the success of community-based restoration. This study provides evidence of the critical role local communities play in bringing about positive environmental change and enabling Sustainable Development Goals (SDGs) 15: Life on Land from ecosystem restoration, SDG 14: Life Below Water for conservation of coastal areas, and SDG 11: Sustainable Cities and Communities for increasing community resilience. Involving local communities in mangrove restoration and preservation is key to long-term sustainability.

Keywords:

Mangrove Restoration;
Land Use Change;
Community Participation;
Sustainable Development Goals.

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1- Introduction

Mangrove ecosystems provide a variety of critical services, acting as a vital defense for coastlines by guarding against erosion, serving as essential spawning and nursery areas for marine life and fish, and providing diverse habitats for flora and fauna [1-4]. Beyond their ecological roles, mangroves are a foundational source of nutritional sustenance and economic revenue for coastal communities [5]. Products such as mangrove wood and wild honey can be processed for local income [6]. Healthy mangrove forests also attract nature-focused tourists, thereby fostering ecotourism as a significant source of community income [7]. Furthermore, mangrove ecosystems are highly effective at long-term carbon storage, acting as critical agents of carbon sequestration by accumulating carbon in their biomass and, crucially, in their rich, waterlogged, and oxygen-poor soils, forming deep peat layers over millennia [8-10]. The conversion of mangrove forests for other purposes is a significant threat to the coastal environment. Several factors drive this change, and it has significant ecological and social implications. The leading anthropogenic causes of land use change in mangrove stands are the expansion of aquaculture [11], urban and local residential development, and tourism development. Ecotourism can generate income for the local population [12]. However, uncontrolled tourism has negative consequences, including environmental degradation resulting from road construction, waste disposal, and wildlife disturbance [13, 14].

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Climate change and extreme weather conditions are causing mangroves to degrade and decline [15, 16]. Driven by demand for political and economic reasons, human use and exploitation of mangrove resources, including direct logging of mangroves, seafood collection, and forest cultivation, have increasingly depended on and depleted these natural ecosystems, leaving the forests destroyed and degraded. This change in land use and the catastrophic deforestation of mangroves have their effects—loss of biodiversity is one consequence, as wildlife habitats and food sources are destroyed [17]. The destruction of mangroves also has an impact on coastal health. Mangroves are natural protective barriers, and their loss is therefore seen as a cause of vulnerability in coastal areas, exposing them to erosion [18]. Converting mangrove land contributes to pollution in these areas, particularly through soil and water pollution [19]. Deforestation also diminishes the ecosystem's capacity to store carbon [20, 21]. Furthermore, mangrove destruction has had adverse effects on numerous coastal communities, including the loss of natural protection, a decline in fisheries, loss of life, economic hardship, saltwater intrusion, resource depletion, and increased vulnerability to climate change [22, 23].

The rapid expansion of the aquaculture industry in Southeast Asia at the end of the 20th century resulted in large-scale mangrove deforestation for the construction of aquaculture facilities [12]. The loss of mangroves in Thailand has been similar, with mangroves being converted for aquaculture and turned into developed coastlines. The Tha Sak subdistrict of Nakhon Si Thammarat, in particular, has witnessed significant land-use changes; the increasing conversion of mangrove forests to shrimp ponds has led to a near-complete loss. While many studies have documented mangrove degradation due to aquaculture, fewer have systematically analyzed long-term recovery dynamics in such severely impacted areas, especially where a complex interplay of socio-economic shifts and active community participation drives recovery. Understanding the process of land-use change, its drivers, and how mangrove forests regenerate in this unique context is crucial for designing effective conservation and management strategies. Therefore, this study aimed to investigate the interrelationship among land-use change, mangrove forest degradation and recovery, community involvement, and socio-economic conditions, utilizing the socio-ecological systems (SES) perspective, which recognizes the complex and dynamic relationships between human communities and natural ecosystems [24, 25]. Through the SES perspective, mangrove degradation and recovery are considered not only ecological processes but are also closely linked to human actions and governance, i.e., the socio-economic environment.

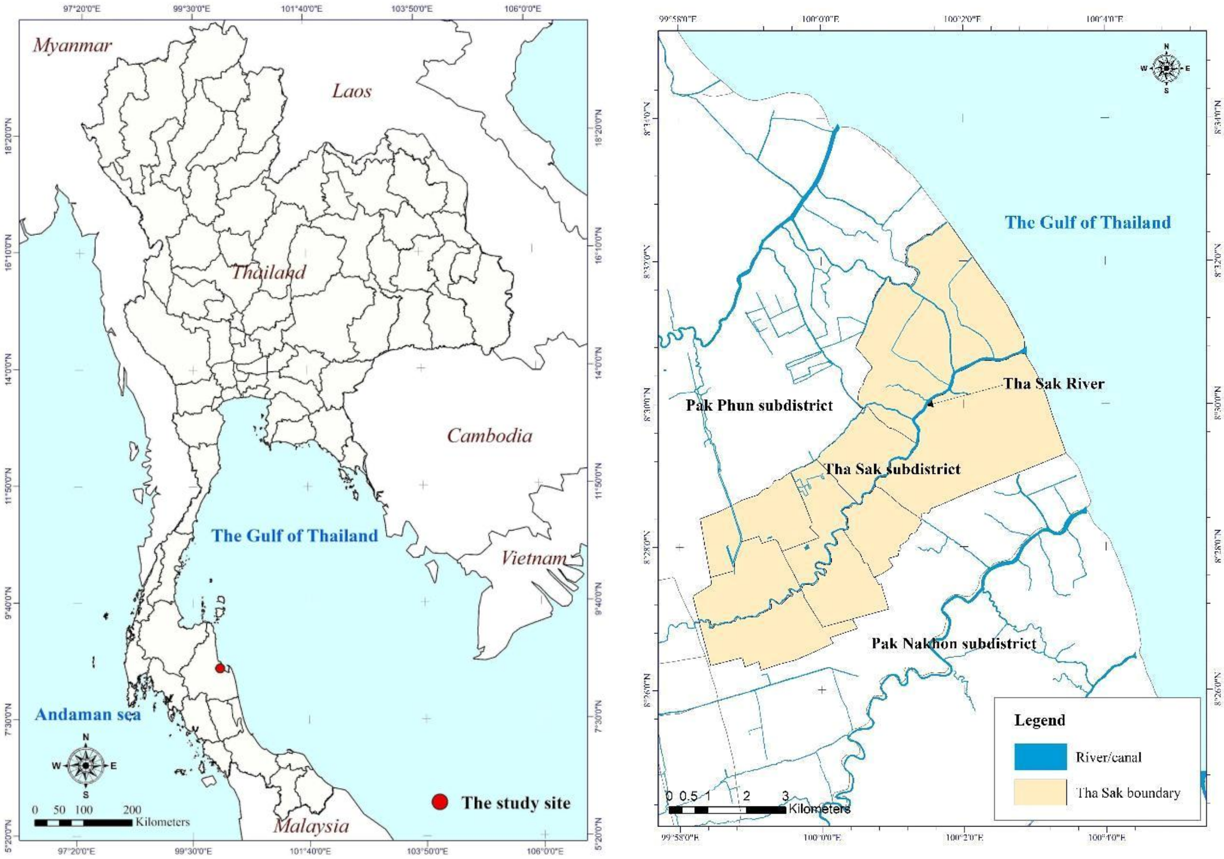
It is essential to understand how community participation in conservation influences community management of resources, specifically how communities can effectively coordinate and manage a shared natural resource to prevent its degradation and promote the sustainable use of that resource [26, 27]. To understand the processes and conditions necessary for a group's actions to have positive ecological consequences (e.g., the restoration of former unsustainable mangrove areas), this research study aimed to fill this gap by exploring long-term land-use change and mangrove forest recovery in the Tha Sak subdistrict from 1988 to 2023. This study aims to identify the socio-economic forces underlying these shifts and investigate the effects of community participation on the conservation and sustainable use of mangrove resources, providing novel insights into successful, community-led ecological recovery in former aquaculture areas.

2- Materials and Methods

2-1- Study Area

The Tha Sak subdistrict is located in the south-eastern part of Nakhon Si Thammarat Province, Thailand, between latitudes 8° 27.317′ N and 8° 29.309′ N, and longitudes 99° 59′ 144″ E and 100° 01′ 755″ E, covering 50 km² (Figure 1A, B). The area's topography is flat coastal plains with predominantly clay soils (Land Development Department: *https://dinonline.ldd.go.th/*). The Tha Sak River flows through the subdistrict, providing a crucial water source for the ecosystem and local communities. The study area's climate is influenced by the southwest and northeast monsoons, resulting in an average annual temperature of approximately 28°C and an average yearly rainfall of 2,429.04 mm (*https://www.tmd.go.th/*). The rainy season usually lasts from October to January, while the hot season lasts from March to May.

The Tha Sak subdistrict is similar to other Thai coastal communities, with a long history of mangrove conversion for exploitation and aquaculture development. Historically, mangroves were valued for their woody resources and fisheries [28, 29]. The gross deforestation of mangroves for aquaculture ponds, aimed at achieving nutritional security and improving livelihoods, was encouraged by several Asian governments from the 1970s [30]. This led to the rapid expansion of the fish and shellfish farming sector and, consequently, widespread mangrove clearing. The transformation of mangroves into culture ponds has led to several environmental issues, including shoreline erosion and water pollution [31, 32]. Over the last few years, community-based rehabilitation of mangrove forests in the subdistrict has begun [33]. The Tha Sak subdistrict was designated as the study area due to its documented history of extensive land use modifications, including the transition from mangrove forests to aquaculture and subsequent restoration. This makes it an excellent place for exploring the interplay between socio-economic drivers, community involvement, and mangrove ecosystem dynamics. The ongoing restoration initiatives in the area also provide an opportunity to evaluate the effectiveness of community-based conservation strategies.



(a) (b)

Figure 1. Location of the study site: (a) Map of Thailand highlighting the Tha Sak subdistrict (red), (b) An enlarged view of the Tha Sak subdistrict

2-2- Data and Software

Multitemporal Landsat images (from Landsat 5 and Landsat 8) obtained from the USGS Earth Explorer (*https://earthexplorer.usgs.gov/*) for path/row 129/54 were used in this study to analyse land use change. The selected images were acquired in 1988, 1993, 1997, 2002, 2007, 2013, 2018, and 2023. All photos were georeferenced and projected into the UTM zone 47N coordinate system, using the WGS84 datum to enable accurate spatial analysis. ArcGIS 9.2 and QGIS 2.18.23 were subsequently used to classify and predict land use patterns. The accuracy of the classification results was evaluated using high-resolution imagery sourced from Google Earth, pre-compiled land-use data, and data acquired through field reconnaissance. Secondary data was obtained from various sources, including the Royal Thai Survey Department, the Land Development Department, and the Tha Sak Subdistrict Administrative Organization. The analysis incorporated economic and social statistics, as well as relevant academic literature, to gain a comprehensive understanding of the drivers of land use change in the study area.

2-3- Methods

A four-step methodology was employed over a 35-year period to study mangrove recovery and associated land-use changes in a formerly aquaculture-dominated coastal area, focusing on the influence of community engagement and socioeconomic factors. These steps included: (1) acquisition and pre-processing of Landsat satellite data, (2) image classification to identify land use types, (3) projection of future land use scenarios using a Markov chain model, and (4) exploration of the underlying drivers of land use change (Figure 2).

2-3-1- Data Collection and Pre-processing

This study selected cloud-free images from Landsat 5 and 8 of Path 129 and Row 54, acquired at five-year intervals from 1987 to 2022, through the USGS Earth Explorer (*https://earthexplorer.usgs.gov/*). Bands 3, 4, and 5 of Landsat 5 and Bands 4, 5, 6, and 7 of Landsat 8 [34] were used to capture vegetation dynamics, especially in the near-infrared (NIR) region, which strongly correlates with chlorophyll content. Geometric correction and enhancement techniques, including sharpening and noise reduction [35], were then applied to optimize image quality for subsequent analysis of mangrove changes.

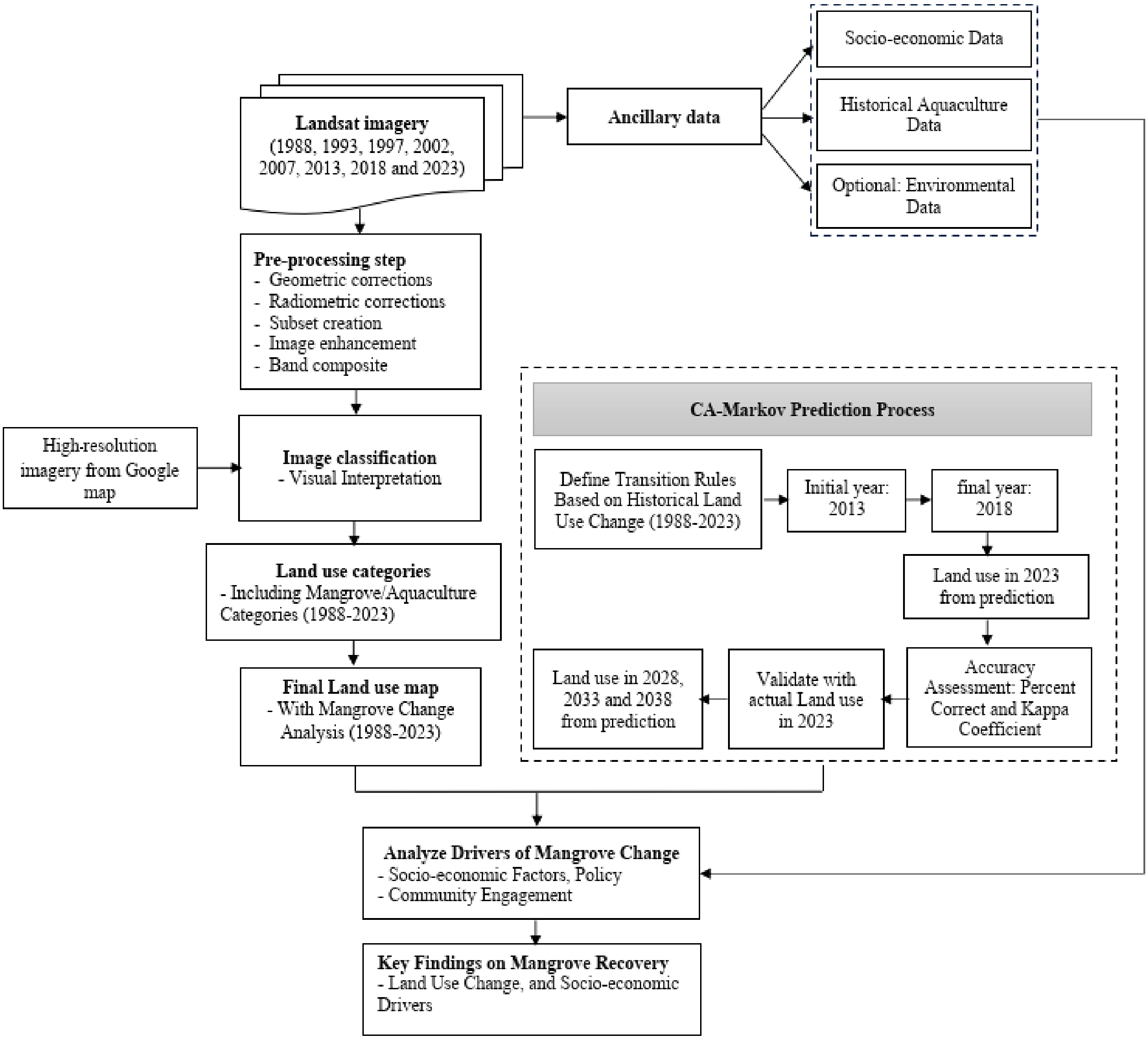


Figure 2. Research methodology schema

2-3-2- Visual Interpretation of Landsat Images

Land use classification was performed using Landsat 5 and 8 satellite imagery through visual interpretation. In this method, analysts directly interpret the images by examining color, brightness, shape, texture, and spatial patterns to identify different land cover types. This method was chosen due to its ability to incorporate local knowledge and expert judgment [36], which can be crucial for accurate classification in complex coastal environments, such as the Tha Sak subdistrict. While visual interpretation can be time-consuming, its accuracy is often higher than automated classification methods, especially in areas with heterogeneous land cover.

To enhance the interpretability of the Landsat imagery, false color composite images were generated using RGB band combinations of 453 for Landsat 5 and 564 for Landsat 8, following the methodology of Khairuddin et al. [34]. These band combinations optimize the visualization of vegetation, including mangrove forests, by maximizing contrast and spectral separability between different land use categories. Based on the Thai Ministry of Land Development's classification system, the Landsat imagery was classified into 11 land-use categories. The categories included: abandoned paddy fields (A100), active paddy fields (A101), perennial crops and orchards (A3), abandoned aquaculture land (A900), aquaculture land (A901), coconut plantations with integrated aquaculture (A95), mangrove forests (F3), grasslands/scrublands (M1), urban and built-up areas (U), natural water bodies (W1), and sea (W101).

The accuracy of the land use classification was assessed using a reference dataset of 150 randomly selected ground-truth points obtained from high-resolution imagery in Google Earth. An error matrix was constructed to compare the classified land use map with the reference data [37], and the overall accuracy and kappa coefficient were calculated. The kappa coefficient, measuring the agreement between the classified map and the reference data that accounts for chance agreement, was 0.85, indicating a high level of classification accuracy [38]. The assessment of the overall accuracy of our land use maps from 2007 to 2023 was well-defined based on the corresponding high-resolution Google Earth satellite images as ground-truth data. The classification accuracies were comparable in 2023 (92.00%), 2018 (90.67%), 2013 (87.33%), and 2007 (88.67%). The kappa coefficients for these comparisons were 0.91 (result for 2023), 0.98 (result for 2018), 0.85 (result for 2013), and 0.87 (result for 2007). For earlier years (1988, 1993, 1997, and 2002), it was challenging to obtain quantitative classification accuracy, such as kappa coefficients, as we lacked access to comparable fine-resolution, modern, or high-resolution satellite imagery and extensive field survey data for direct ground-truthing. To ensure the reliability of land use mapping of older periods, this visual interpretation was based on false color composite imagery (using R G B band combinations 453 for Landsat 5), which should improve visualization by maximizing contrast and spectral separation between the respective land use classes.

To increase confidence in these historical land use maps, we checked their interpretation against other available historical secondary sources. These were historical aerial photographs from the Royal Thai Survey Department (e.g., 1975) and historical land-use maps from the Land Development Department, the primary government organization responsible for land-use studies in Thailand (e.g., 1992 and 2000). Although a complete quantitative error analysis was not possible for these older maps, we employed rigorous comparisons to minimize potential interpretation errors and maintain consistency of classification over time, utilizing a variety of authoritative historical sources.

2-3-3- Prediction of Future Land Use Based on the First-order Markov Chain Model

Prospective land use changes were estimated using a first-order Markov model in Quantum GIS (Version 2.18.23). The Markov chain model simulates land use change, which estimates future land use status based on transition probabilities between land use types derived from historical data. For this study, land use maps from 2013 to 2018 were used to create a transition matrix. This matrix quantitatively represents the probability of each land use category transitioning to any other category, or remaining the same, over the five-year interval (2013-2018), based on the observed spatial changes between these two time points. This matrix was then used to model land use for 2022, 2028, 2033, and 2038. The accuracy of the Markov chain model prediction was validated by comparing the predicted land use map for 2023 with the actual land use map classified by visual interpretation for the same year. The validation results showed a high degree of accuracy for the model's projections. The overall correctness was 83.01%, with a kappa coefficient of 0.80. In addition, the kappa value (histo) was 0.90 and the kappa value (loc) was 0.86, confirming the robust performance of the model in simulating land use changes in the study area.

The Markov chain-based model with few constraints is sufficient for trend testing of land use and land cover. It presumes that future trends will resemble past trends and does not explicitly consider the impact of complex external factors, such as government policies, economic factors, and climate change [39]. These considerations may introduce some degree of ambiguity in the projections. To address this shortcoming, future work may need to combine the Markov chain model with other models, such as cellular automata or system dynamics models, that better represent these external drivers.

2-3-4- Community Participation and Socio-economic Factors Influencing Mangrove Regeneration

This part of the study examined the impact of community-based efforts and socioeconomic factors on mangrove regeneration in the Tha Sak sub-district. It is based on a review of academic papers, previous studies, and statistical sources, including government policy papers that focus on land use and related topics. This included examining trends in economic activities, such as changes in aquaculture and policy interventions, and integrating these findings with the spatial and temporal patterns of land use change derived from analyzing historical satellite imagery, as described in Section 2-3-2. This study investigated the role of community engagement in driving mangrove restoration, aiming to identify correlations and potential causal relationships. This analysis relied on existing documentation and spatial data; no primary data collection, such as questionnaires or surveys, was conducted. Therefore, the interpretation of the influence of societal engagement and socioeconomic factors is based on inferences from the literature, policy, and the correlation of these factors with observed changes in land use. This analysis, therefore, aimed to contextualise and explain the driving factors of the observed land use changes in the Results section.

3- Results

3-1- Image Classification and Analysis

The analysis of land use change data from 1988 to 2023 revealed significant shifts in land cover. Mangrove forests, urban and built-up areas, and perennial crops and orchards experienced substantial growth. The mangrove forest areas increased from 1.11 to 9.10 km^2, urban and built-up areas increased from 0.85 to 5.42 km^2, and the area of perennial crops and orchards increased from 1.05 to 7.12 km^2 (Table 1). This represents an approximate 720% increase in mangrove coverage over 35 years, highlighting a substantial ecological shift. In contrast to the increase in area for mangrove forest, urban and built-up areas, and perennial crops and orchards, the aquaculture area decreased significantly between 1988 and 2023, shrinking from 25.69 to 8.79 km^2. This 66% reduction in aquaculture area fundamentally altered the coastal land use composition. At the same time, abandoned aquaculture areas experienced a remarkable expansion between 1997 and 2007, increasing from 5.65 to 8.30 km^2. However, this trend reversed in the following decade, and the area decreased to 5.82 km^2 by 2023. Similarly, a continuous decline in the area with active paddy fields was observed, decreasing from 15.09 km² in 1988 to 2.17 km² in 2023. Conversely, abandoned paddy fields experienced a significant increase, from 0.01 km² in 1988 to 5.56 km² in 2007, before slightly decreasing to 2.55 km² in 2023. Finally, the emergence and subsequent expansion of coconut plantations with integrated aquaculture areas have been observed since 1997. The area dedicated to these systems increased from 0.84 km^2 in 1997 to 3.16 km^2 in 2018. However, a slight decrease to 2.90 km^2 in 2023 was observed (see Table 1).

Table 1. Total area and percentage of land use types in Tha Sak subdistrict, Mueang District, Nakhon Si Thammarat Province, Thailand, from 1988 to 2023

Land use types	Years															
	1988		1993		1997		2002		2007		2013		2018		2023	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Abandoned paddy fields (A100)	0.01	0.01	4.43	9.36	4.68	9.88	4.18	8.84	5.56	11.74	3.46	7.32	2.65	5.59	2.55	5.37
Active paddy fields (A101)	15.09	31.89	8.43	17.82	5.91	12.49	5.22	11.02	3.48	7.35	2.90	6.13	2.39	5.03	2.17	4.57
Perennial crops and orchards (A3)	1.05	2.21	1.74	3.68	3.34	7.06	3.71	7.85	3.68	7.77	7.07	14.95	6.99	14.73	7.12	15.01
Abandoned aquaculture land (A900)	0.00	0.00	0.00	0.00	5.65	11.93	6.29	13.30	8.30	17.54	8.25	17.44	6.43	13.55	5.82	12.27
Aquaculture land (A901)	25.69	54.27	26.19	55.36	18.98	40.10	17.72	37.45	11.44	24.18	7.84	16.57	8.61	18.15	8.79	18.53
Coconut plantations with integrated aquaculture (A95)	0.00	0.00	0.00	0.00	0.84	1.78	1.05	2.23	2.26	4.77	2.26	4.78	3.16	6.65	2.90	6.12
Mangrove forests (F3)	1.11	2.34	1.46	3.08	2.12	4.48	2.51	5.31	5.11	10.79	7.89	16.69	8.11	17.10	9.10	19.18
Grasslands and scrublands (M1)	2.38	5.02	1.64	3.46	1.83	3.86	2.55	5.38	2.59	5.47	1.60	3.38	2.26	4.76	1.99	4.19
Urban and built-up areas (U)	0.85	1.79	2.30	4.85	2.69	5.68	2.68	5.66	3.49	7.36	4.49	9.48	5.30	11.17	5.42	11.43
Natural water bodies (W1)	1.15	2.43	1.13	2.39	1.13	2.39	1.20	2.53	1.17	2.48	1.17	2.48	1.17	2.47	1.21	2.56
Sea (W101)	0.02	0.04	0.00	0.00	0.17	0.36	0.21	0.44	0.26	0.55	0.37	0.79	0.37	0.78	0.37	0.78
Total	**47.33**	**100**	**47.32**	**100**	**47.34**	**100**	**47.32**	**100**	**47.34**	**100**	**47.31**	**100**	**47.45**	**100**	**47.45**	**100**

The spatial analysis of the land use change maps for the Tha Sak subdistrict from 1988 to 2023 showed a consistent trend of mangrove forest expansion (Figures 3-A to 3-H). The inverse relationship between mangrove forest recovery and the decrease in aquaculture areas is shown in Figure 3. Initially, in 1988, mangrove forests first appeared in the central part of the study area as small, isolated patches with limited spatial continuity. Subsequently, from 1988 onwards, there was a gradual expansion of mangrove areas, which, until 1993, were mainly concentrated in areas adjacent to natural waters (light blue). This trend continued until 1997, with the dark green mangrove areas showing better spatial continuity and expanding inland, especially along existing canals or waterways. By 2002, the distribution of mangrove forests had become more evident and more pronounced. They formed larger contiguous patches with a considerable extent both laterally along the coast and inland. A phase of rapid expansion followed until 2007, mainly in the middle and higher regions of the study area. This steady expansion continued until 2018, covering a larger area, especially in formerly abandoned aquaculture areas (light purple).

Improved connectivity indicated higher ecological integrity. Finally, in 2023, mangrove forest areas reached their maximum extent compared to all other study years, covering most coastal and adjacent areas with a dense and continuous distribution. The dynamics of abandoned aquaculture areas (A900) are particularly significant, with their substantial expansion between 1997 and 2007 exhibiting a spatial correlation with areas of subsequent mangrove recovery, indicating a crucial intermediate step in land-use change. The observations in Figure 3 also show that the abandoned aquaculture ponds (light purple) were gradually filled in by expanding mangrove forests (dark green) during the entire study period, especially from 2002 onwards, which represents a direct spatial displacement process. At the same time, shifts in agricultural land use, including the notable decline in active paddy fields and the expansion of perennial crops, indicate a broader restructuring of economic activities and land management priorities within the subdistrict beyond the immediate coastal zone.

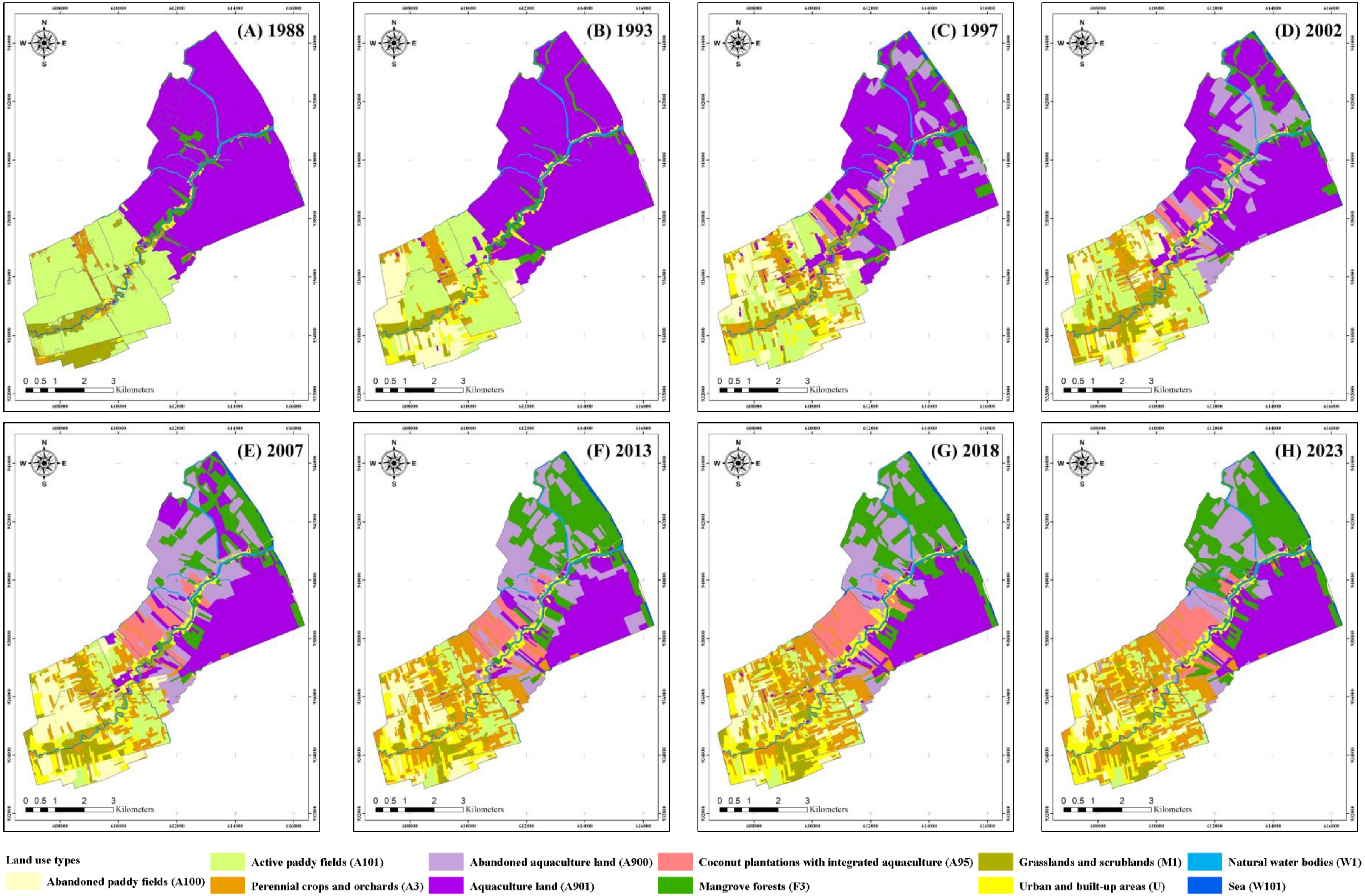


Figure 3. Historical Land Use and Mangrove Coverage Dynamics in Tha Sak Subdistrict, Thailand (1988–2023)

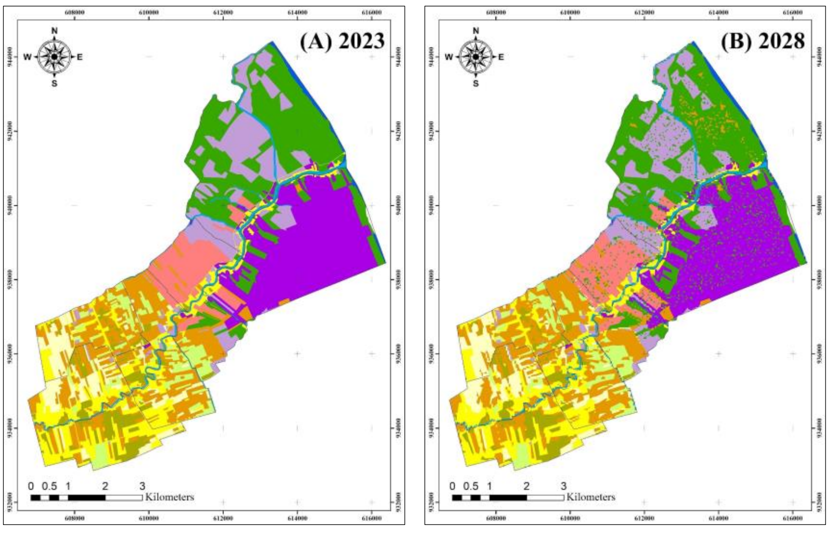
3-2- Land Use Prediction

The land use projections for 2028, 2033, and 2038 showed a continuous increase in mangrove forest area, rising from 10.28 km^2 in 2028 to 12.68 km^2 in 2038. Perennial crops and orchards are also projected to increase from 7.68 km^2 in 2028 to 8.05 km^2 in 2038. Conversely, the aquaculture land area is expected to decrease from 8.03 km² in 2028 to 6.71 km² in 2033 and further to 4.37 km² in 2038. The abandoned aquaculture land area also showed a downward trend, shrinking from 7.68 km^2 in 2028 to 4.37 km^2 in 2038 (Table 2).

Table 2. Comparison of the land use type areas and the percentage in 2023, and predicting the land use type areas and the percentages for 2028, 2033, and 2038

Land use types	Years							
	2023		2028		2033		2038	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Abandoned paddy fields (A100)	2.55	5.37	2.56	5.38	2.57	5.40	2.58	5.42
Active paddy fields (A101)	2.17	4.57	2.15	4.51	2.15	4.51	2.15	4.51
Perennial crops and orchards (A3)	7.12	15.01	7.68	16.13	7.93	16.66	8.05	16.91
Abandoned aquaculture land (A900)	5.82	12.27	5.27	11.07	4.83	10.14	4.37	9.19
Aquaculture land (A901)	8.79	18.53	8.03	16.88	7.42	15.60	6.71	14.09
Coconut plantations with integrated aquaculture (A95)	2.90	6.12	2.66	5.59	2.40	5.03	2.17	4.56
Mangrove forests (F3)	9.10	19.18	10.28	21.60	11.37	23.88	12.68	26.65
Grasslands and scrublands (M1)	1.99	4.19	2.03	4.27	2.06	4.33	2.07	4.34
Urban and built-up areas (U)	5.42	11.43	5.46	11.47	5.45	11.46	5.44	11.43
Natural water bodies (W1)	1.21	2.56	1.12	2.35	1.07	2.25	1.03	2.16
Sea (W101)	0.37	0.78	0.35	0.74	0.35	0.74	0.35	0.74
Total	**47.45**	**100**	**47.59**	**100**	**47.59**	**100**	**47.59**	**100**

Figures 4-A to 4-D shows the predicted spatial distribution of mangrove forests (dark green areas) in 2028, 2033, and 2038 and the actual spatial distribution in 2023. These spatial projections showed that future mangrove expansion is not random but is strategically predicted to occur. In 2028, mangrove forests are expected to be visible along the coastline, particularly at river mouths and along canals that lead to the sea (Figure 4-B). In 2033, the mangrove forest area (dark green) is predicted to expand more than in 2028, especially in regions where mangroves were already present in the sea (Figures 4-B and 4-C). The dark green areas appear denser and extend over a wider area along the coast and into adjacent zones. The trend of mangrove expansion is expected to continue until 2038, with dark green areas covering the most significant area compared to other periods (Figure 4-D). This indicates that mangroves are likely to fill in the remaining abandoned aquaculture ponds and reinforce existing mangrove fringes along river systems and canals. This will improve the overall ecological connectivity of the forest. This projected growth indicates an increase in environmental resilience and a greater potential for biodiversity as fragmented areas become more connected. The predicted continued decline in aquaculture areas suggests a sustainable trend that will reduce activity and strengthen the potential for further mangrove ecosystem restoration in these coastal regions in the future. This prediction means that former aquaculture sites will continue to be available for natural succession or active restoration measures, providing ongoing opportunities for coastal restoration.



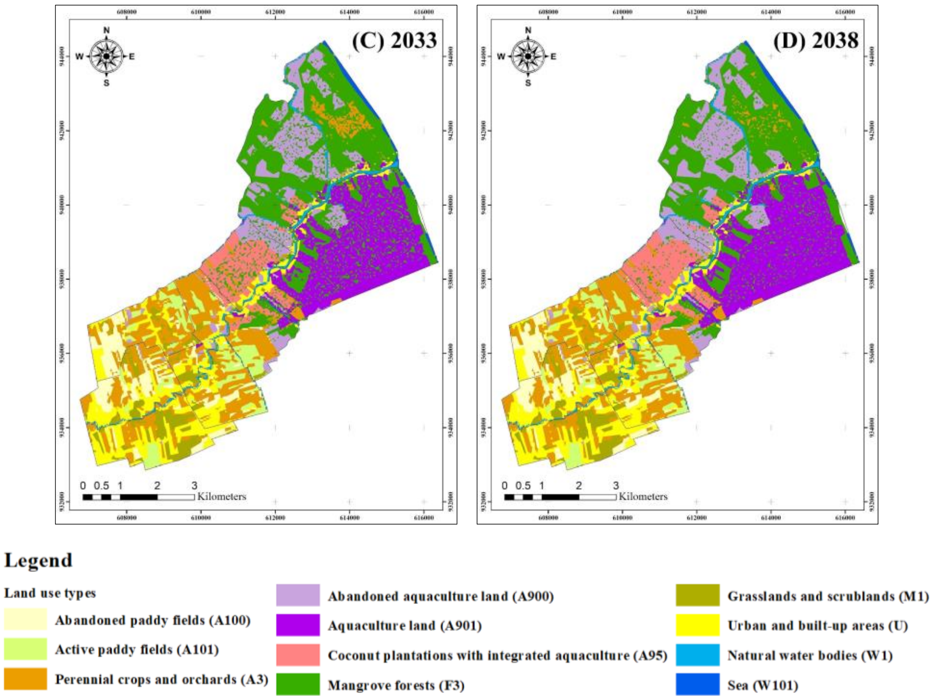


Figure 4. Actual (2023) and Predicted (2028, 2033, 2038) Land Use and Mangrove Trends in Tha Sak Subdistrict, Thailand.

4- Discussion

4-1- Image Classification and Change Detection

This study clearly illustrates the transformation of the coastal landscape in the Tha Sak subdistrict, particularly the remarkable recovery of the mangrove forest area, from 1.11 km² in 1988 to 9.10 km² in 2023. This finding aligns with the study's central hypothesis that the recovery of mangrove forests is primarily attributed to community engagement and socioeconomic changes in coastal areas previously dominated by aquaculture. This observed recovery represents a significant reversal of the widespread mangrove loss often documented globally, particularly in Southeast Asian coastal regions, which the expansion of aquaculture has heavily impacted. The scale of this recovery in the Tha Sak subdistrict contrasts with the continued degradation seen in many other aquaculture-dominated regions, providing a compelling case study of successful restoration efforts [11]. The focus of the present work is a comprehensive investigation of the interplay among these factors, examining their mutual relationships. Images of the coast around the Tha Sak subdistrict, taken by the Royal Thai Survey Authority in 1975, also showed that the coastal area was largely covered with mangrove forest. However, the rapid depletion of mangrove areas in this region in the late 1970s and early 1980s, primarily caused by the promotion of shrimp farming [40], highlighted the conflict between specific economic development and the conservation of a common resource. It was this essential connection that led to repeated recognition and restoration campaigns.

4-2- Socio-Economic Factors and Community Engagement

Building on the significant land use change and mangrove restoration patterns outlined in Section 3, this section focuses on the socio-economic factors and community engagement that emerged as key drivers of these changes through our analysis of secondary data and policy interventions. Interestingly, the loss of mangroves began to slow in the 1990s, possibly due to mangrove reforestation initiatives undertaken by both the public and private sectors, which started in 1991. This development shows the importance of proactive conservation measures. Although the mangroves did not recover significantly until later [41], these earlier efforts laid an essential foundation for mangrove area expansion observed in this study. The continuous upward trend in mangrove area growth since 1993, consistent with the research of Rattanarama et al. [41], supports our proposition that community participation and socio-economic developments are instrumental in advancing this recovery. This consistency reinforces that mangrove ecosystems, even after severe degradation, can exhibit significant recuperation, aligning with broader regional patterns of environmental rebound where supportive conditions emerge. Global studies also indicated that mangrove ecosystems can recover when effective management strategies are implemented. Specifically, successful mangrove restoration often requires the elimination of environmental stressors and the restoration of appropriate hydrological conditions, enabling mangroves to develop fully. Furthermore, practical restoration projects were found to be compatible with local resource use, integrating local knowledge, mobilizing community support, and supported by relevant policies [42].

Various political and legal frameworks have also played a key role in safeguarding and rehabilitating mangrove ecosystems. In 1938, the Royal Thai Government promulgated legislative instruments and regulatory frameworks for managing mangrove forests and natural resources, including the National Forest Protection and Reservation Act. A Cabinet decision on August 1, 1989, also designated Nakhon Si Thammarat Province as a mangrove forest conservation area. Additionally, the 2015 government project to resolve land disputes in mangrove areas of Nakhon Si Thammarat Province may have led to improved management and conservation of mangroves, which contributed to the expansion of the mangrove area in the Tha Sak subdistrict. Such policy actions provided a crucial enabling environment, demonstrating how governmental support, when aligned with local needs and leveraging community empowerment, could effectively underpin conservation efforts and facilitate community-led initiatives. This alignment is critical, as it indicates that governments were more likely to respond favorably to community demands when local people were empowered to participate in conservation. This pattern is observed in successful environmental programs globally, where alliances with governmental conservation agencies are crucial for securing support [43].

Community engagement has been a key mechanism in recovering mangroves in the Tha Sak subdistrict. The expansion of the mangrove forests was not spontaneous. Still, it resulted from the collective action by the "Tha Sak subdistrict Small-Scale Fishermen Group," which was formed in 2004 due to increased awareness of the coastal resource crisis. The group has continuously implemented mangrove protection and planting projects for over a decade (2004-2014), increasing the mangrove area. Despite unsuccessful attempts to expand the area seaward due to wave action, the group collaboratively planned and initiated "bamboo Barriers" in 2014 [33]. This innovation emerged from local understanding to counteract direct erosion, alongside the continuous planting of mangroves [44], emphasizing the use of appropriate species such as *Rhizophora*, which reflects local knowledge and wisdom. Consistent action through community collaboration and external support, such as the Rak Thai Foundation, the Nakhon Si Thammarat Provincial Administrative Organization, and the Department of Marine and Coastal Resources, underscores the inherent capacity of community-based organizations and the strategic importance of network development for achieving mutual objectives.

This finding aligns with previous research findings [45-48], emphasizing the critical role of community participation in ecosystem restoration. The Tha Sak case robustly reinforces this global understanding, showcasing how deep-seated local traditional knowledge, combined with a direct personal stake in resource health, empowers communities to become primary drivers of ecological change. The proactive problem-solving, such as the innovative use of bamboo Barriers [33], exemplifies how community-led initiatives can adapt to local challenges more effectively than top-down approaches —a characteristic crucial for successful restoration in diverse socio-ecological contexts. Information from these studies has shown that involving local communities in mangrove conservation can be applied in Tanzania [45], Ghana [46], Indonesia [47], and Sri Lanka [48], among others. The sustained ecological integrity of mangrove ecosystems necessitates the integral participation of local communities in their conservation. It acknowledges that local people living in and around mangrove forests often possess intimate traditional knowledge and a personal stake in the health of these habitats. In the Tha Sak subdistrict, the driving force behind community action was recovering aquatic resources from capitalist and commercial fishing, as well as rehabilitating and expanding mangroves by replacing unused shrimp ponds. Moreover, they hoped to prevent coastal erosion that had put their land and livelihoods at risk [49]. Mangrove restoration needs to be a proactive, sustainable, and locally relevant endeavor that involves community stakeholders. The involvement of local communities is crucial to long-term, effective mangrove conservation, leading to reduced conflict over resources, enhanced community stewardship, and improved monitoring and enforcement.

Some critical socio-economic changes accompanied the significantly higher mangrove forest recovery percentage in the Tha Sak subdistrict. The aquaculture area decreased from 25.69 km^2 in 1988 to 8.79 km^2 in 2023, representing a 66% reduction in area. This decline likely has multiple and intricate causes. There may have been economic drivers stemming from well-documented volatility in the shrimp market and seasonal disease outbreaks, which reduced the profitability of pond aquaculture and increased the risk of the activity, leading some farmers to abandon their ponds. For instance, research has shown that shrimp farming in this area is sensitive to market prices [50] and to disease [51, 52], which can lead to financial losses for farmers. Soil and water quality degradation due to intensive aquaculture were other factors that may have contributed to a decline in productivity and pond desertification [53]. Declining pond quality may induce a feedback loop, reinforcing the inconsistency in investing in aquaculture. Reducing the number of aquaculture sites has resulted in significant open space for potential mangrove growth. Draining of aquaculture ponds can serve as possible sites for the natural recolonization of mangrove habitats or restoration projects [54, 55]. This change in land use is a key factor in explaining the observed increase in mangrove forests. The observed abandonment of shrimp ponds in Tha Sak, driven by economic and environmental challenges within the aquaculture industry, aligns with patterns of aquaculture failure and land abandonment reported in other coastal regions [53, 54]. This highlights a critical socio-economic pathway through which land becomes available for natural recovery or active restoration. The subsequent utilization of these abandoned ponds as sites for mangrove recolonization or restoration projects further corroborates findings that such disturbed areas hold significant potential for ecological rehabilitation [55, 56].

The mangrove forest restoration in the Tha Sak subdistrict serves as evidence of the synergy between community engagement, socio-economic change, and ecological restoration. A shared awareness of the impact of coastal erosion on the livelihoods of local fishing communities has led to collective action to restore natural defenses, resulting in the continued expansion of conservation networks at the subdistrict level. At the same time, small-scale farmers have turned to alternative economic aquacultures, such as sea bass and mud crab farming (*https://www4.fisheries.go.th/*), possibly due to financial and environmental challenges, which freed up resources and land for more effective ecosystem restoration. External support has further strengthened the community's ability to achieve its goals. A clear result of mangrove restoration is the significant expansion of mangrove forests, which effectively control coastal erosion and help alleviate the severe erosion problems previously experienced [57]. Although the study provides a broad perspective on land use shifts and mangrove restoration in an area formerly dominated by aquaculture, an in-depth analysis of household-level socio-economic factors, the complex motivations for community participation, and the multiple economic and social impacts of mangrove restoration remains a topic for further study. The long-term sustainability of restoration and its performance under climate change and potential economic threats could be studied. Mangrove rehabilitation in the Tha Sak subdistrict is a good example of the need for synergy between community interaction and socio-economic transformation in mangrove restoration. This knowledge is therefore essential for developing sound policies to conserve and sustainably develop mangroves and coastal areas in similar settings worldwide.

4-3- Land Use Prediction

This study's future land use extrapolations offer instructive insights into the potential trajectory of landscape development within the Tha Sak subdistrict. The model predicted further expansion of mangrove forests, indicating that ongoing recovery appears imminent. This expansion is most conspicuous in former aquaculture ponds, suggesting that these aquaculture-impacted sites are potential restoration sites for mangroves [55, 56]. As the forecasts demonstrate, the greater connection of mangrove ecosystems suggests increased ecological integrity and ecosystem services. However, it is essential to note that the Markov chain model underpinning these forecasts suffers from well-known limitations. For example, it is not sufficiently flexible to incorporate exogenous pressures, such as climate incentives and policy shifts. The forecasting results should be carefully considered, as they are well-suited for short-term forecasts [58]. Felegari et al. [59] emphasized the importance of integrated modeling approaches in providing a comprehensive representation of land use change over time.

Although this study has provided quantitative evidence of the successful recovery of mangroves in the Tha Sak subdistrict and its link to a change in management approach and socio-economic trends, the prospects for long-term recovery of these new forest ecosystems are being challenged by new threats due to climate change. Rapid sea-level rise and more frequent and intense storm events pose a significant challenge. While the natural regeneration of mangroves is inherently resilient and an essential element of coastal defense in the country, it has its physiological threshold in adapting to rapid changes in inundation levels. Insufficient space for landward migration in response to sea level rise could lead to inundation stress for these restored forests [60, 61]. In addition, stronger storm events could also cause physical damage to the restored sites and promote erosion, which could undermine the support for community-based interventions (e.g., bamboo Barriers) [62]. A better understanding of the long-term performance and resilience of these restored mangroves under future climate change scenarios, along with measures that improve both ecological and social resilience to these stresses, is therefore a significant research gap. This could include the development of predictive models that take climate projections into account, as well as consideration of the socio-economic impacts of climate-induced changes on productive coastal regions.

The further reduction of the aquaculture area predicted by the model raises some essential questions about the industry's future in the study area. Although that drop could open up more room for mangrove recovery, it may also have socio-economic consequences for coastal communities that depend on aquaculture for income. Strong community institutions can effectively represent their needs, influence decision-making, and implement sustainable natural resource management [54, 63, 64]. Such community empowerment is essential to ensure that conservation initiatives align with local livelihoods and are sustainable in the long run. Further research is needed to explore other economy-generating activities that could be sustainable for these communities in the spirit of a just transition. Furthermore, mechanisms for sustainable land use in the evolving landscape should be identified, taking into account both environmental and socio-economic factors. Such a framework could entail the implementation of integrated coastal zone management protocols designed to achieve equipoise between conservation objectives and the socio-economic requirements of local populations.

5- Conclusion

Our study on land use change in Tha Sak subdistrict for the period 1988–2023 reveals a dynamic coastal landscape in transition, characterized by ecological and socio–economic changes. The most remarkable result is the astonishing growth of the mangrove forest from 1.11 km² in 1988 to 9.10 km² in 2023. This recovery has transformed a series of fragmented mangrove systems into a single, contiguous mega-forest that is far larger, better connected, and ecologically healthier. This recovery is linked to a simultaneous and significant reduction in aquaculture areas (from 25.69 km² to 8.79 km²), which made regeneration possible in the first place. Crucially, this ecological recovery was not 'voluntary' but was made possible by the active engagement of the local community, in particular the Tha Sak Subdistrict Small-Scale Fishermen Group, which was very active in the planting, conservation, and sustainable use of the mangroves. This is clear evidence of the success of community-based restoration of former aquaculture landscapes. These changes in land use demonstrate the recovery and resilience of mangrove ecosystems, which are supported by human endeavors. The observed recovery highlights the crucial role of local communities in fostering positive environmental change and serves as a valuable model for effective coastal management. Our findings are directly linked to several Sustainable Development Goals (SDGs): SDG 15 (Life on Land) for ecosystem restoration, SDG 14 (Life Below Water) for coastal protection and the preservation of healthy marine habitats, and SDG 11 (Sustainable Cities and Communities) for building community resilience through conservation efforts. Tha Sak's model, where local communities lead restoration and management, offers valuable lessons for similar coastal efforts worldwide and supports future sustainability. In addition to quantifying these large-scale changes and linking them to community action, future research could further explore the socio-economic motivations of households and the long-term performance of ecosystems under changing climatic and economic pressures.

6- Declarations

6-1- Author Contributions

Conceptualization, J.R., K.J., and M.J.; methodology, J.R., K.J., and M.J.; formal analysis, J.R., K.J., and M.J.; investigation, J.R., K.J., and M.J.; data curation, J.R.; writing—original draft preparation, J.R., K.J., M.J., and E.B.S.; writing—review and editing, J.R., K.J., M.J., and E.B.S. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6-3- Funding

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6-5- Institutional Review Board Statement

Not applicable.

6-6- Informed Consent Statement

Not applicable.

6-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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