Ecological Assessment and Proposed Solutions for Mangrove Conservation and Restoration: A Case Study of Dong Thuy Anh Commune, Hung Yen Province, Viet Nam

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ABSTRACT: *Mangroves are vital coastal ecosystems that provide shoreline protection, biodiversity conservation, carbon sequestration, and climate change adaptation. This study assessed the current status of mangrove forests in Dong Thuy Anh Commune, Hung Yen Province, within the Red River Delta Biosphere Reserve, and proposed ecological solutions for their conservation and sustainable development under difficult site conditions. The research integrated literature review, field surveys, environmental and socioeconomic investigations, expert consultation, and site suitability evaluation using the Analytic Hierarchy Process (AHP). Results showed that the study area supported approximately 1,294.79 ha of predominantly protective plantation mangroves in 2025, dominated by Sonneratia caseolaris, Kandelia obovata, Aegiceras corniculatum, and Avicennia marina. Forest degradation is mainly associated with coastal erosion, sediment dynamics, ecological succession, and human activities such as aquaculture expansion. Based on site suitability assessment, the study proposes an ecological restoration framework that combines nature-based wave attenuation measures, site-specific species selection, natural regeneration, and community-based sustainable forest management. These findings provide a scientific basis for mangrove restoration and coastal resilience enhancement in the Red River Delta Biosphere Reserve under climate change and sea-level rise.*

KEYWORDS: *Mangroves; ecological restoration; difficult site conditions; Analytic Hierarchy Process (AHP); ecological engineering; Red River Delta Biosphere Reserve; climate change.*

I. INTRODUCTION

Mangrove forests are among the most important coastal ecosystems, playing a vital role in environmental protection and socioeconomic development. They not only protect coastlines from the impacts of waves, wind, and storms but also sequester carbon, mitigate greenhouse gas emissions, conserve biodiversity, and enhance resilience to climate change. However, driven by rapid urbanization, aquaculture expansion, and coastal resource exploitation, the global extent of mangrove forests has declined substantially over recent decades, particularly in Southeast Asia. This trend highlights the urgent need for sustainable mangrove conservation and restoration.

In Viet Nam, mangrove forests are primarily distributed along estuaries and coastal areas, covering more than 150,000 ha in 2025. They play a crucial role in protecting sea dikes, reducing coastal erosion, conserving biodiversity, and supporting the livelihoods of coastal communities. In the context of climate change and sea-level rise, mangroves are widely recognized as an effective "biological shield." Although mangrove area has shown signs of recovery since the implementation of large-scale afforestation programs in the early 2000s, both the extent and quality of these forests continue to be affected by natural factors and socio-economic development activities.

The coastal estuarine area of Dong Thuy Anh Commune, Hung Yen Province, is part of the Red River Delta Biosphere Reserve, which was designated by UNESCO in 2004. The area possesses favorable natural conditions for mangrove development, with an estimated mangrove area of approximately 1,333 ha in 2025. Nevertheless, mangrove growth and development are influenced by environmental factors such as salinity, tidal inundation regime, soil characteristics, land-use practices, and aquaculture activities. Moreover, studies on the current status of mangrove forests, community structure, and the key factors influencing their development in this area remain limited, posing challenges to the formulation of appropriate management strategies.

Notably, the study area is a high-conservation-value zone within both the Red River Delta Biosphere Reserve and the Hung Yen Provincial Wetland Conservation Area. Consequently, conventional hard-engineering interventions are considered inappropriate. Instead, mangrove conservation and development should be guided by ecosystem-based approaches that are compatible with local environmental conditions and the conservation objectives of the ecosystem.

Based on the above considerations, this study, entitled "Ecological Assessment and Proposed Solutions for Mangrove Conservation and Restoration: A Case Study of Dong Thuy Anh Commune, Hung Yen Province, Viet Nam" was undertaken. The findings are expected to provide a scientific basis for the sustainable conservation and restoration of mangrove forests, while improving the effectiveness of coastal resource management and strengthening resilience to climate change.

II. MATERIALS AND METHODS

2.1. Study area

The study was conducted in Dong Thuy Anh Commune, Hung Yen Province, Viet Nam, located within the Red River Delta Biosphere Reserve, which was designated by UNESCO in 2004. The study area represents a typical estuarine mangrove ecosystem along the northern coast of Viet Nam and plays a crucial role in coastal protection, biodiversity conservation, carbon sequestration, and enhancing resilience to climate change.

Mangrove forests are primarily distributed seaward of the coastal dyke system on intertidal mudflats directly influenced by tidal inundation, wave action, and sediment accretion. The study area is characterized by challenging site conditions, including soft to fluid muddy substrates, an intertidal elevation of approximately 0.3–0.5 m above mean sea level, and nearshore salinity ranging from 10 to 18‰. In addition, continuous exposure to waves and tidal currents substantially constrains natural regeneration and the successful restoration of mangrove forests.

By 2025, the total mangrove forest area in Dong Thuy Anh Commune had reached 1,294.79 ha, consisting predominantly of planted protection forests. The dominant mangrove species include *Sonneratia caseolaris*, *Kandelia obovata*, *Aegiceras corniculatum*, and *Avicennia marina*. The study area was selected because of its high conservation value and its exposure to the combined impacts of natural environmental stressors and coastal socio-economic development, making it representative of the challenging ecological conditions of mangrove ecosystems in the Red River Delta.

2.2. Research objectives and scope

This study aimed to assess the current status of mangrove forests in Dong Thuy Anh Commune and to propose ecological solutions for their restoration, conservation, and sustainable development under challenging site conditions. Specifically, the study focused on: (i) assessing the current distribution, forest area, species composition, community structure, and natural regeneration of mangrove forests; (ii) identifying the natural and anthropogenic drivers of mangrove degradation; (iii) evaluating site suitability using the Analytic Hierarchy Process (AHP); and (iv) proposing ecological restoration strategies based on site characteristics, natural successional processes, and nature-based engineering measures to enhance the effectiveness of mangrove conservation and management.

The study was conducted within the mangrove ecosystem and adjacent intertidal mudflats of Dong Thuy Anh Commune. The research encompassed assessments of forest resources, ecological conditions, environmental factors, and socio-economic conditions affecting mangrove conservation, restoration, and sustainable development. Field surveys and data analyses primarily represent the period 2024 - 2025.

2.3. Research methodology

2.3.1. Collection, Compilation, and Analysis of Secondary Data

Secondary data were collected, compiled, and analyzed from reports, scientific publications, and national and international research programs related to mangrove forests. The data sources included forest status reports, meteorological and hydrological records, land-use planning documents, local socio-economic reports, and specialized publications on ecological solutions, mangrove restoration techniques, and integrated hydraulic engineering–forestry models. Only published studies that had undergone scientific review or had been validated by competent authorities were selected. The study selectively incorporated findings from Do Quy Manh et al. (2020, 2026), reports of the Institute of Ecology and Works Protection (2023, 2026), data from the Viet Nam Forest Information System (Ministry of Agriculture and Environment), the 2026 forest change report of the Forest Protection Sub-department, Decision No. 575/QD-UBND (2026) on the announcement of the forest status of Hung Yen Province, and other relevant planning documents. Following data collection, the documents were categorized by thematic groups, synthesized, cross-compared, and analyzed to ensure systematic organization and reliability, while providing a scientific basis for developing the theoretical framework and conducting a preliminary assessment of the study area.

2.3.2. Field Survey Method

Field surveys were conducted within the study area to collect information on the current status of mangrove forests and site conditions. Sample plots were established to represent different mangrove community types and land-use categories, including aquaculture areas, degraded mangrove forests, and tidal flats. A total of 30 sample plots, each measuring 100 m², were established across different forest conditions (pure and mixed stands). Within each plot, the following parameters were measured and recorded: species composition, tree density, growth characteristics (tree height (Hvn), diameter at breast height (DBH, D1.3), basal diameter (Dbase), and canopy diameter (Dc)), as well as tree health and natural regeneration status. In addition, site characteristics, including tidal inundation regime, tidal exposure duration, salinity, and soil properties, were observed and documented. Representative soil and water samples were collected for environmental analyses to support the quantitative assessment of ecological conditions in the study area.

2.3.3. Sociological Survey and Expert Consultation

Interviews were conducted with local residents and management authorities to collect information on the current status of land use, production activities, and mangrove forest protection. Data were collected using structured questionnaires combined with group discussions, comprising 35 survey questionnaires with 15 assessment indicators. In addition, consultations were conducted with three experts in forestry, ecology, and hydraulic engineering to validate the current status assessment, identify the causes of mangrove degradation, and propose appropriate ecological solutions.

2.3.4. Data Analysis and Processing

The collected data were compiled and processed using Microsoft Excel. Mangrove forest structural and growth parameters were calculated from the field survey data. Statistical analyses were subsequently applied to compare characteristics among the study sites and to examine the relationships between environmental conditions and mangrove growth.

III. RESULTS

3.1. Current Status of Mangrove Forests in the Study Area

3.1.1. Distribution and Area of Mangrove Forests

Dong Thuy Anh Commune is located in the coastal area of Thai Thuy District, Hung Yen Province, and is part of the Red River Delta Biosphere Reserve. Characterized by extensive intertidal mudflats, direct tidal influence, and active coastal sediment accretion, the area provides favorable conditions for the establishment and development of mangrove ecosystems. The mangrove forests serve as a transitional zone between the marine and terrestrial environments and constitute one of the key ecological components of the northern coastal region of Viet Nam.

The results of field surveys and data analysis indicate that mangrove forests in Dong Thuy Anh are distributed relatively continuously along the coastal intertidal zone and estuarine areas. Most of the forest area is located seaward of the sea dike system, directly adjacent to the intertidal zone and newly accreted coastal land. This distribution forms a continuous ecological belt along the coastline, enhancing habitat connectivity while strengthening the protection of inland areas behind the sea dikes against wave action, strong winds, and extreme weather events.

In addition, the mangrove forests exhibit close spatial relationships with other land-use types within the study area. Considerable portions of the forests are interspersed with or adjacent to aquaculture ponds, natural resource harvesting areas, and coastal ecotourism sites. This distribution pattern reflects the multifunctional land-use characteristics of the Thai Thuy coastal zone, where mangrove forests perform essential ecological functions while simultaneously supporting the livelihoods of local communities.

During the 2024 - 2025 period, the mangrove forest area in Dong Thuy Anh Commune underwent notable changes. The total forest area decreased from 1,333.51 ha in 2024 to 1,294.79 ha in 2025, representing a reduction of 38.72 ha. However, this decline does not necessarily indicate overall forest degradation. Over the same period, the area classified as established forest increased by 5.97 ha, whereas the area of immature forest decreased substantially to 90.30 ha. These changes suggest that a proportion of the planted mangrove forests continued to grow and transitioned from the immature forest stage to established forest.

By 2025, the total forest area of the commune reached 1,294.79 ha out of a total natural area of 6,624.20 ha, corresponding to a forest cover of approximately 18.18%. All existing forest areas were planted forests, including 1,204.49 ha of established forest and 90.30 ha of unestablished forest, while no natural forest was recorded. This forest structure reflects that the formation and development of mangrove forests in the locality have been driven primarily by long-term restoration, afforestation, and forest protection and management programs.

In terms of land-use objectives, protection forests accounted for 1,277.38 ha, representing almost the entire forest area of the commune. An additional 17.41 ha of forest lies outside the official forestry planning area but has nevertheless been identified as serving a protection function. The predominance of protection forests indicates that the principal ecological role of the mangrove ecosystem in Dong Thuy Anh is to protect sea dikes, dissipate wave energy, mitigate coastal erosion, and contribute to maintaining the ecological stability of the coastal zone.

3.1.2. Species Composition and Community Structure of Mangrove Forests

The mangrove flora in Dong Thuy Anh Commune exhibits the typical characteristics of estuarine and coastal ecosystems in northern Viet Nam. A total of 38 vascular mangrove plant species have been recorded within the biosphere reserve, including both true mangrove species and mangrove-associated species. The dominant true mangrove species comprise *Aegiceras corniculatum*, *Kandelia obovata*, *Avicennia marina*, and *Sonneratia caseolaris*. The mangrove flora of Dong Thuy Anh Commune is primarily composed of these species, reflecting the characteristic ecological features of the Thai Binh coastal region.

Mangrove species in the study area exhibit distinct distribution patterns according to site conditions, particularly tidal inundation regimes and substrate development. On newly accreted mudflats with unconsolidated sediments that are frequently inundated by tides, *Sonneratia caseolaris* and *Kandelia obovata* are the predominant species due to their high tolerance of unstable substrates. On recently deposited alluvial flats with either soft or more compact mud, *Kandelia obovata* and *Aegiceras corniculatum* develop extensive stands. In contrast, *Aegiceras corniculatum* and *Excoecaria agallocha* dominate high intertidal areas characterized by soft or compact clay soils. This zonation reflects the close relationship between habitat conditions and the ecological adaptation of individual mangrove species.

In terms of community structure, the mangrove forests of Dong Thuy Anh comprise both monospecific and mixed-species communities. Monospecific communities are mainly found in planted forests, where extensive stands of *Sonneratia caseolaris* or *Kandelia obovata* have been established on riverine and coastal mudflats. These communities generally exhibit a simple structure with a single dominant canopy layer, characteristic of protection forests established for coastal defense.

Mixed-species communities are also widely distributed, with a typical assemblage consisting of *Sonneratia caseolaris*, *Kandelia obovata*, and *Aegiceras corniculatum*. Within these communities, vertical stratification is relatively well developed. *Sonneratia caseolaris* generally occupies the upper canopy layer, reaching heights of approximately 1.8 m to more than 7 m, whereas *Kandelia obovata* and *Aegiceras corniculatum* are mainly distributed in the middle and lower strata. The coexistence of species with diverse morphological and ecological characteristics enhances community stability and improves resilience to the dynamic environmental conditions of coastal ecosystems.

Species distribution within the mangrove communities demonstrates a clear pattern of ecological succession. *Sonneratia caseolaris* commonly functions as a pioneer species on newly formed mudflats and estuarine zones, where tidal influence and sediment deposition are most pronounced. As the substrate gradually stabilizes and the ground surface becomes elevated, species such as *Kandelia obovata*, *Excoecaria agallocha*, and *Acanthus ilicifolius* become increasingly abundant on higher mudflats and along sea dikes. In addition, species such as *Acrostichum aureum* and *Acrostichum speciosum* are typically distributed on sandy mounds and relatively elevated areas within the intertidal zone. This distribution pattern reflects the ecological adaptation and successional dynamics of mangrove vegetation in response to variations in topography, hydrological conditions, and coastal sediment accretion.

3.1.3. Current Status of Mangrove Forest Quality and Restoration Potential

Overall, the mangrove forests in Dong Thuy Anh Commune are predominantly plantation forests characterized by a relatively simple species composition, with most stands established as monocultures. Tree density remains low in some areas, and the rate of successful forest establishment is still limited. These characteristics reflect the challenges associated with mangrove development in coastal environments, where planted trees are continuously exposed to wave action, tidal inundation, unstable sediment conditions, and various coastal economic activities.

The dominant mangrove species in the study area are Sonneratia caseolaris and Kandelia obovata, both of which are widely used in mangrove afforestation and restoration programs along the Thai Binh coast. However, tree growth performance varies considerably among sites due to heterogeneous site conditions. In newly accreted and unstable tidal flats exposed to strong waves and currents, seedling survival rates are generally low, requiring repeated replanting or supplementary planting. In addition, predation by crustaceans and disturbances associated with aquaculture activities significantly constrain the survival and growth of young mangrove trees.

In addition to plantation forests, natural regeneration has been observed in several locations with favorable site conditions. Woody species dominate the vegetation in the study area, accounting for approximately 47.36% of the recorded flora. The density of naturally regenerated seedlings varies markedly among habitat types. On stable tidal flats adjacent to sea dikes, regeneration density can exceed 15,040 individuals ha^{-1}, whereas in aquaculture areas subjected to intensive human disturbance, regeneration density is only about 50 individuals ha^{-1}. These findings indicate that the natural recovery potential of mangrove forests is strongly dependent on site conditions and the intensity of anthropogenic disturbances.

Overall, although the mangrove forests in Dong Thuy Anh still exhibit several limitations, including a simple species composition, low tree density, and spatially variable recovery capacity, the ecosystem retains substantial potential for natural regeneration and further development on stable tidal flats. This provides an important scientific basis for implementing appropriate technical measures to enhance the effectiveness of future mangrove restoration and sustainable development efforts.

3.1.4. Overall Assessment of the Current Status of Mangrove Forests

The assessment results indicate that the mangrove forests in Dong Thuy Anh Commune constitute an important coastal ecosystem that plays a significant role in protecting sea dykes, attenuating wave impacts, reducing coastal erosion, and maintaining the ecological stability of the coastal environment. The mangrove forests are distributed relatively continuously along the intertidal zone and seaward side of the sea dyke system, forming an important ecological belt along the coast of Thai Thuy District.

In terms of forest resources, the entire forest area within the study site consists of planted forests, with protection functions being predominant. Although the forest area remains relatively extensive, the total forest area has shown a declining trend in recent years. In addition, species composition remains relatively simple, consisting mainly of several characteristic mangrove species, including Sonneratia caseolaris, Kandelia obovata, Aegiceras corniculatum, and Avicennia marina. Large areas of mangrove forest have developed as monospecific stands, resulting in limited biodiversity and reduced ecological stability of the ecosystem.

The quality of mangrove forests varies considerably among different areas. Some stable accretional mudflat areas exhibit relatively good natural regeneration capacity, whereas many other areas continue to face difficulties in recovery due to exposure to wave action, fluctuations in intertidal topography, aquaculture activities, and other anthropogenic pressures. Consequently, considerable differences in tree density, the proportion of established forest area, and natural recovery capacity are observed among different site conditions.

Overall, the mangrove ecosystem in Dong Thuy Anh continues to maintain important ecological and protective functions for the coastal zone. However, the declining trend in forest area, simplified stand structure, and limited recovery capacity in certain areas indicate that this ecosystem is under increasing pressure from both natural factors and coastal economic development activities. These findings provide an important basis for proposing sustainable measures for the conservation, restoration, and development of mangrove forests in the subsequent period.

3.2. Major Causes of Mangrove Forest Degradation in the Study Area

Do Quy Manh identified two major groups of factors contributing to mangrove forest degradation across 22 mangrove areas in Thai Binh Province: natural factors and anthropogenic factors. The relative contribution of these factors varies among sites; while some degraded areas are affected by a single factor, others experience degradation resulting from the cumulative and interacting effects of multiple factors.

Among the identified causes, some may be interpreted as having a positive ecological implication from the perspective of seaward mangrove expansion and coastal afforestation. Specifically, the research team observed that *Kandelia obovata* and *Aegiceras corniculatum* in several areas had died as a result of senescence and changes in their habitat conditions, including increased ground elevation, soil compaction and hardening, and substantially reduced tidal inundation periods. These observations provide evidence of the role of mangrove vegetation in sediment trapping and accretion. Over their growth cycle, these species may have largely fulfilled their ecological function in facilitating seaward land accretion and mangrove expansion, thereby contributing to the gradual formation and stabilization of newly emerged intertidal substrates.

Based on the statistical assessment of the causes identified across the 22 surveyed areas, the major groups of factors affecting mangrove forests were ranked according to their frequency of occurrence, as presented below:

Table 1. Ranking of the major groups of factors contributing to mangrove forest degradation

Causes	Frequency of occurrence	Rank
Natural factors: storms and strong winds, wave action, changes in water flow, sand burial, etc.	15/22	1
Anthropogenic activities: livestock grazing, fishing activities, etc.	9/22	2
Natural ecological succession: forest degradation resulting from natural succession processes.	5/22	3
Other causes: waste accumulation, pests and diseases.	3/22	4

According to Table 1, natural factors constitute the primary causes contributing to mangrove forest degradation.

3.2.1. Causes Associated with Natural Factors

The results of the study and field surveys indicate that natural factors were the most frequently identified causes of mangrove forest degradation, occurring in 15 out of the 22 surveyed areas. These factors are largely uncontrollable and exert direct and substantial impacts on both forest area and forest quality, particularly in newly planted mangrove stands. The specific factors include:

- **Impacts of storms and abnormal high tides:** Strong storms not only directly cause tree breakage and uprooting but also alter flow regimes, resulting in localized erosion or sediment deposition. At many coastal sites, erosion caused by waves, coastal currents, and particularly storms has led to shoreline erosion and tree uprooting, especially in newly planted stands and those established using propagules.

Figure 1. Mangrove trees affected by strong winds, storms, and high tides

(Source: Do Quy Manh, 2024)

- Sand burial: Driven by wind and wave action, mobile sand can alter tidal-flat topography through surface accretion, scouring, or changes in sand-dune morphology. Sand burial can cover the root collar and impede physiological and metabolic processes, thereby reducing plant growth and potentially causing extensive mortality when burial is severe and prolonged.

Figure 2. Mangrove trees buried by sand

(Source: Do Quy Manh, 2024)

- Extreme weather conditions (severe cold and hailstorms): Although these events occur relatively infrequently, prolonged severe cold spells can cause substantial damage. A notable example was the severe cold spell in early 2016, which severely affected the province's mangrove forests. According to the report of the Department of Agriculture and Rural Development (Report No. 50/BC-SNNPTNT, dated 16 March 2016), approximately 218 ha of mangrove forests were damaged by this cold spell, including 26.3 ha of newly planted young forests (Report No. 39/BC-BQLDA-QLTC, dated 10 March 2016, issued by the Provincial Management Board for Investment and Construction Projects in Agriculture and Rural Development). Severe cold causes leaf scorching and defoliation, death of apical meristems, and drying of branches and shoots down to the main stem, thereby severely impairing tree growth.

Figure 3. Mangrove trees affected by prolonged severe cold

- Flow regime fluctuations and surface erosion: The formation of strong surface flows during ebb tide, commonly caused by obstruction of natural flow pathways or water discharge from aquaculture ponds, can cause erosion and expose tree roots. This process also removes fine sediments, resulting in a hardened clayey substrate that impedes root anchorage and inhibits natural regeneration by washing away seeds and propagules.

Figure 4. Surface flow and surface erosion

- Localized waterlogging: In low-lying areas, impeded drainage caused by obstructed flow pathways can result in prolonged and deep tidal inundation, causing waterlogging and tree mortality due to insufficient oxygen for root respiration.

Figure 5. Mangrove trees affected by prolonged waterlogging

- Natural succession: Mangrove forest degradation associated with natural succession occurs when site conditions change, particularly when sediment accretion raises ground elevation and reduces the duration of tidal inundation. As a result, some species become less adapted to the altered site conditions and gradually decline or die. In addition, senescent trees and poor growth, combined with adverse weather conditions such as prolonged severe cold, may further accelerate forest degradation.

The survey results indicate that some degraded areas are undergoing secondary succession, occurring on previously established forest stands where community structure has been altered by environmental changes. In particular, areas formerly dominated by *Kandelia obovata* are gradually being replaced by species better adapted to the altered site conditions, such as *Sonneratia caseolaris*, *Excoecaria agallocha*, *Thespesia populnea*, and *Nypa fruticans*. This process proceeds gradually over periods ranging from several years to several decades. At the same time, the senescence of existing populations, together with insufficient recruitment through natural regeneration or supplementary planting, contributes to changes in species composition and further accelerates mangrove forest degradation.

3.5.2. Causes Associated with Anthropogenic Activities

In addition to natural disturbances, economic and livelihood activities of coastal communities are important drivers of the decline in mangrove forest area and quality in Thai Binh Province. The survey results indicate that this group of factors was identified in 9 out of the 22 surveyed areas. The major anthropogenic impacts include:

- Aquaculture and fisheries activities: These are considered the most common socioeconomic drivers of mangrove degradation. Mangrove clearing, embankment construction, and dike construction for aquaculture ponds obstruct natural seawater circulation, alter hydrological regimes, and consequently contribute to tree mortality. In addition, digging and harvesting shellfish and other aquatic organisms, such as *Sinonovacula constricta*, directly damage mangrove root systems. Oyster farming can increase the density of fouling organisms that adversely affect trees, while water retention in aquaculture ponds disrupts natural tidal inundation regimes and may cause tree mortality due to prolonged waterlogging.

Figure 6. Mangrove forest degradation within aquaculture ponds

- Sand pumping for tidal-flat elevation and aquaculture pond improvement: Sand pumping activities to raise the elevation of clam-cultivation areas or to renovate aquaculture ponds can discharge large quantities of sediment into adjacent mangrove areas. Direct discharge of pond-bottom sediment and anthropogenically induced sand deposition can bury tree bases, cause root suffocation, and result in extensive mangrove mortality.

Figure 7. Sand deposition affecting mangrove trees

- Livestock and poultry grazing: Due to the lack of designated grazing areas, local residents commonly allow buffaloes, cattle, goats, and ducks to graze freely within mangrove forests. These animals can damage vegetation by feeding on leaves, rubbing against tree trunks, and trampling young trees and propagules. Prolonged grazing pressure can suppress tree growth and impair the natural regeneration capacity of mangrove forests.

Figure 8. Livestock and poultry grazing causing damage to mangrove vegetation

- Pressure from domestic and production-related waste: Waste originating from inland areas is transported seaward through river mouths and subsequently trapped within mangrove forests during incoming tides. The waste comprises a wide range of materials, including inorganic and organic waste, domestic waste, and construction debris. Such materials can become entangled in branches and tree crowns under wave action, causing branch breakage and tree collapse. This substantially affects mangrove growth, particularly that of naturally regenerating seedlings and newly planted trees.

Figure 9. Waste affecting mangrove vegetation

- Overexploitation of forest products: The extraction of timber, fuelwood, and other forest products to meet local livelihood needs, although reduced compared with previous periods, continues to contribute to declines in tree density and alterations in the vertical structure of mangrove forests.

3.5.3. Pest and Harmful Organisms

Several harmful organisms have been recorded in the mangrove forests of Hung Yen Province, including shipworms, tube worms, stem borers, defoliating caterpillars, and mangrove crabs that feed on tree bark. Among these, shipworms mainly damage young trees, attaching densely to the stems and impeding growth, and may cause trees to break or fall, particularly during the dry season when seawater salinity is high. Tube worms primarily attack woody trees through wounds in the bark, boring into the stems and reducing tree growth, increasing the risk of breakage and mortality. They are commonly observed in areas subject to frequent tidal inundation. Although stem borers, defoliating caterpillars, and mangrove crabs generally occur at relatively low densities, they can still reduce tree vigor and the resistance of mangrove stands to environmental stress. In addition, reduced sediment supply from upstream areas and increasing salinity during the dry season are also unfavorable factors affecting the growth and development of mangrove forests.

Figure 10. Barnacles attached to and damaging mangrove trees

3.3. Proposed Ecological Solutions for Mangrove Conservation, Restoration, and Development in the Study Area

3.3.1. Ecological Zoning Based on Site Conditions

Numerous studies on mangrove site conditions in Viet Nam have shown that the distribution and growth of mangrove vegetation are closely dependent on natural factors such as soil type, tidal inundation regime, soil maturity, soil texture, salinity, and coastal hydrological conditions. Nguyen Ngoc Binh (1996) reported that mangrove species exhibit different levels of adaptation to different types of mangrove soils; pioneer species generally occur on newly deposited, unconsolidated mudflats, whereas other species develop more effectively on relatively stable substrates with a higher degree of soil maturity. Similarly, Ngo Dinh Que et al. (2003), Do Dinh Sam et al. (2008), Doan Dinh Tam (2012), and Dinh Thanh Giang (2015) emphasized that site classification is an important basis for the planning, restoration, and development of mangrove forests, as different site types require different species assemblages and silvicultural practices.

Based on the identified site-condition criteria, the Analytic Hierarchy Process (AHP) developed by Thomas L. Saaty [18] was applied to evaluate and classify site conditions. The assessment results were determined using the following formula:

$$E = \sum_{i=1}^{n} Q_i P_i$$

Where:

E is the overall evaluation score for the site-condition group;
Qi is the weighting factor assigned to criterion *i*;
Pi is the evaluation score for criterion *i*;
N is the total number of evaluation criteria.

The study by Do Quy Manh (2018) demonstrated that the growth and survival rates of mangrove trees are closely dependent on site conditions. To assess site suitability, the author applied the Analytic Hierarchy Process (AHP) based on seven criteria: (1) mangrove soil type; (2) nearshore seawater salinity; (3) exposure duration of the tidal flat; (4) degree of soil maturity; (5) sand content; (6) mangrove ground elevation; and (7) existing conditions of mangrove soil and forest.

The assessment results indicated that Dong Thuy Anh Commune falls within the category of difficult mangrove site conditions, predominantly distributed across tidal flats, accretion areas, and unvegetated sites without mangrove forests or areas where existing mangrove stands have insufficient density to form stable plant communities. The area is directly exposed to the sea and is frequently affected by waves and currents, which constrain the natural regeneration of mangrove vegetation.

The soil texture is predominantly clay loam, with additional areas of silty clay and sandy clay. The ground elevation of the tidal flats ranges from 0.3 to 0.5 m, representing a medium elevation, while nearshore seawater salinity ranges from approximately 10 to 18‰. Given the weak substrate and frequent exposure to waves and tidal fluctuations, the study area is classified as soft mud to fluid mud according to the maturity classification of mangrove soils.

The hydrodynamic conditions are also relatively unfavorable, as offshore waves directly affect the area with limited attenuation. Wave-height statistics show that 75% of observations recorded significant wave heights (Hs) of 0.0-0.2 m, with the 0.0-0.1 m range accounting for 45.19% and the 0.1-0.2 m range accounting for 29.71% of observations. Notably, waves exceeding 0.2 m still accounted for nearly 25% of all observations. These findings indicate a relatively high intensity of nearshore wave action, which further increases the severity of site limitations and creates substantial challenges for mangrove forest restoration and development.

3.3.2. Ecological Approach to Mangrove Forest Restoration

+ Prioritizing pioneer species on newly accreted tidal flats and selecting silvicultural and nature-based hydraulic measures to support natural regeneration

Ecological mangrove restoration is a process of recovering the natural functions and structure of mangrove ecosystems by harnessing the principles of ecological succession, rather than focusing solely on conventional tree-planting activities. Numerous studies have shown that the failure of mangrove planting programs in coastal areas is often not primarily attributable to seedling quality, but rather to unsuitable site conditions, particularly wave action, tidal inundation regimes, and the instability of tidal-flat substrates.

According to Winterwerp et al. (2013), nature-based engineering approaches to mangrove restoration should follow five fundamental principles: (1) maintaining natural water exchange without disrupting tidal regimes; (2) reducing wave height; (3) enhancing the natural trapping and accumulation of sediment on tidal flats; (4) restoring the original hydrological and hydrodynamic conditions; and (5) planting suitable mangrove species in restored and protected areas. Based on these principles, mangrove restoration in Dong Thuy Anh Commune should prioritize the improvement of site conditions before planting, particularly in newly formed accretion areas or sites exposed to strong wave action.

To stabilize tidal-flat substrates and create favorable conditions for vegetation re-establishment, nature-based hydraulic measures should be implemented to reduce wave energy, promote sediment deposition, and restore natural hydrodynamic conditions. One suitable approach is the construction of permeable, low-crested wave-reduction barriers using bamboo piles combined with biodegradable materials, with the design adapted to the specific conditions of each coastal site. In Dong Thuy Anh Commune, Do Quy Manh applied a permeable barrier consisting of rows of bamboo piles with bundled branches used as filling material. The structure had a height of 1.5 m, bamboo piles 4.5 m in length driven 3 m into the substrate, a density of 6 piles per meter, and three rows of piles spaced 0.5 m apart and interconnected using horizontal and longitudinal braces. The model was implemented over an area of 2.0 ha. Field observations indicated that this measure contributed to reducing wave impacts, enhancing sediment retention, and stabilizing the accretion area, thereby creating more favorable conditions for subsequent mangrove establishment.

After site conditions have been improved, species selection should be based on the ecological characteristics of each site and the natural succession patterns of mangrove ecosystems. According to TCVN 10405:2020 on Hydraulic

Structures - Wave-Protection Vegetation Belts - Survey and Design and TCCS 08:2011, mangrove species should be arranged from the seaward side toward the inland side into three main ecological belts. The first belt comprises pioneer species such as *Avicennia marina*, which is suitable for sandy-muddy substrates with salinity exceeding 30‰, and *Sonneratia caseolaris*, which is well adapted to muddy and sandy substrates in estuarine areas with salinity of approximately 5-15‰ during the rainy season. The second belt comprises species with stilt or prop roots, such as *Rhizophora stylosa*, *Kandelia obovata*, and *Lumnitzera racemosa*, which grow well on relatively stable sandy-muddy substrates. The third belt comprises species such as *Thespesia populnea*, *Bruguiera gymnorhiza*, and *Phoenix paludosa*, which are adapted to areas within the mean tidal elevation zone. Within the same planting site, mixed-species stands comprising multiple age classes can be established to enhance ecosystem stability and resilience. Seedlings used for planting should meet the required quality standards and be raised in polyethylene containers in accordance with TCVN 10405:2020.

The investigation of natural conditions and mangrove species composition in Dong Thuy Anh Commune by Do Quy Manh indicates that *Sonneratia caseolaris* and *Kandelia obovata* are two suitable species for use as primary planting species on coastal accretional mudflats. *Sonneratia caseolaris* is a pioneer species with well-developed pneumatophores and is highly adapted to soft muddy substrates, where it contributes to sediment retention and promotes sediment accretion. Meanwhile, *Kandelia obovata* exhibits high tolerance to salinity and prolonged inundation. Its well-developed stilt roots and lateral roots help stabilize muddy and sandy substrates, reduce erosion, and create favorable conditions for the stable development of mangrove forests. For the 2.0-ha forest plantation model in the study area, a planting density of approximately 4,400 trees ha^{-1} may be applied. The optimal planting period is from August to October, taking advantage of favorable hydrological and climatic conditions to improve seedling survival and growth.

Table 2. Selected technical specifications of mangrove seedlings used for planting in the Dong Thuy Anh Commune model

No.	Tree species	Hvn (cm)	Doo (cm)	Dt (cm)	Quality
1	*Kandelia obovata*	62.0	0.74	26	Meets requirements
2	*Sonneratia caseolaris*	84.0	0.83	36	Meets technical requirements

Note: Hvn, Doo, Dt represent mean values; measurements were taken on 8 October 2024.

In addition, support stakes should be used to stabilize newly planted trees during the initial establishment phase, thereby minimizing the impacts of waves and enhancing root establishment and subsequent growth. Following planting, periodic maintenance should be undertaken, including the removal of debris entangled around trees, repositioning and securing leaning or uprooted trees, and replanting seedlings following periods of strong waves, high winds, or storms. Regular monitoring and protection are also necessary to minimize damage caused by human activities, livestock, and pests and diseases. These measures not only improve the survival rate of planted trees but also facilitate natural regeneration and ecological succession within the mangrove ecosystem.

+ Gradual Transition toward Stable Species in Favorable Estuarine, Coastal, and Accretional Mudflat Areas to Establish Species-Diverse and Stable Ecosystems

Following the restoration phase dominated by pioneer species, mangrove development should be guided by the principles of ecological succession to establish a diverse, stable, and self-sustaining plant community. Pioneer species such as *Sonneratia caseolaris* and *Kandelia obovata* play important roles in trapping sediments, reducing the impacts of waves and currents, promoting sediment accretion, improving site conditions, and creating favorable environments for the establishment and development of mangrove species characteristic of subsequent successional stages.

Before proceeding to the stage of introducing later-successional and more stable species, the current forest condition should be assessed based on indicators such as the survival and growth rates of pioneer trees, canopy cover, the extent of sediment accretion or erosion, substrate characteristics, and natural regeneration capacity. Restoration measures at the subsequent stage should only be considered when the substrate has become relatively stable, the pioneer community is well developed, and natural regeneration has been established. If these conditions have not yet been met, gap planting should be continued, wave-attenuation and sediment-retention structures should be maintained, and existing forest stands should be protected to further improve site conditions.

The choice between natural regeneration and supplementary planting should be based on the regeneration capacity of each site. In stable accretional mudflats with high natural regeneration density (>15,040 trees ha^{-1}), priority should be given to protection, monitoring, and facilitating natural succession, with supplementary planting limited to gaps or areas where tree density is unevenly distributed. In contrast, in areas formerly occupied by aquaculture ponds where natural regeneration density is low (approximately 50 trees ha^{-1}), supplementary planting of native mangrove species suited to local site conditions should be combined with natural regeneration to accelerate ecosystem recovery.

In stabilized estuarine, coastal, and accretional mudflat areas where natural regeneration remains insufficient to meet restoration objectives, native mangrove species characteristic of later successional stages may be gradually introduced to facilitate the transition from monospecific plantations toward multispecies mixed communities. Species selection should be based on site conditions, tidal inundation regimes, salinity, substrate characteristics, and the existing distribution of native species. In areas where the substrate has stabilized, wave energy has decreased, and the muddy substrate has become relatively firm, later-successional species such as *Rhizophora stylosa*, *Lumnitzera racemosa*, and *Bruguiera gymnorhiza* may be considered for supplementary planting in forest gaps or landward of pioneer belts to increase canopy cover and structural diversity. In areas with higher ground elevations, moderate tidal influence, and progressively improving site conditions, *Aegiceras corniculatum*, *Excoecaria agallocha*, and *Acanthus ilicifolius* may be considered to establish a multilayered mangrove community, increase species diversity, and enhance ecosystem resilience to waves, storms, and climate change. However, supplementary planting should only be undertaken following a comprehensive assessment of natural regeneration capacity and the ecological suitability of each species to local site conditions. Priority should be given to species naturally distributed along the coastal areas of Thai Binh to maintain native species composition and minimize the risk of altering the structure of natural plant communities.

Throughout the restoration process, vegetation succession and natural regeneration should be monitored periodically using indicators such as regeneration density, species composition, community structure, and changes in site conditions, thereby enabling timely adjustment of management interventions. The ultimate goal is to restore the structure and functioning of the mangrove ecosystem toward a state resembling natural conditions, establishing a diverse, stable, and self-sustaining plant community that contributes to improved coastal protection, biodiversity conservation, and enhanced ecosystem resilience to climate change.

3.3.3. Solutions for Mangrove Conservation, Management, and Sustainable Development

For Dong Thuy Anh Commune, which encompasses extensive coastal intertidal areas, mangrove forests play a critical role in coastal dike protection, biodiversity conservation, greenhouse gas emission reduction, and livelihood provision for local communities. However, the area remains subject to coastal erosion, climate change, aquaculture activities, and increasing pressure from economic development. Therefore, an integrated set of measures should be implemented as follows:

(1) Mangrove conservation and restoration: Conduct systematic surveys and assessments of the current status of mangrove forests; restore degraded areas using suitable native species; combine soft engineering structures for wave attenuation and sediment accretion to facilitate mangrove establishment and protect areas undergoing natural regeneration.

(2) Sustainable management: Improve coastal land-use planning; strengthen coordination between local authorities and communities; apply GIS, remote sensing, and UAV technologies to monitor changes in mangrove extent and condition; establish a comprehensive forest database and strictly enforce regulations against activities that damage or encroach upon mangrove forests.

(3) Sustainable livelihood development: Promote integrated mangrove–aquaculture systems; develop environmentally friendly products and ecotourism; establish benefit-sharing mechanisms to improve local livelihoods while creating economic incentives for mangrove conservation.

(4) Climate change adaptation: Integrate mangrove conservation into climate change adaptation and disaster risk reduction programs; prioritize mangrove restoration in areas serving as natural buffers against waves and protecting coastal dikes; investigate and select mangrove species with greater tolerance to changing climatic and environmental conditions.

(5) Institutional and policy mechanisms: Mobilize financial resources from government budgets, REDD+ programs, carbon credit mechanisms, and international cooperation; encourage private-sector and community participation in mangrove protection and development through appropriate support mechanisms and co-management arrangements.

(6) Science and technology: Apply GIS, remote sensing, and other advanced technologies to monitor and forecast changes in mangrove forests; develop, test, and scale up mangrove restoration models adapted to local environmental conditions.

(7) Community awareness and participation: Strengthen communication and environmental education on the ecological and socioeconomic importance of mangrove forests; promote the active participation of local communities and organizations in forest monitoring, protection, and restoration.

(8) Priority directions for Dong Thuy Anh Commune, Hung Yen Province, Viet Nam: In Dong Thuy Anh Commune, priority should be given to an integrated coastal zone management approach that combines wave attenuation and sediment accretion structures, mangrove restoration, and ecological aquaculture. In intertidal areas strongly exposed to wave action, systems of bamboo pile fences or other soft engineering structures should be established to reduce wave energy and promote sediment accretion before planting suitable native mangrove species. At the same time, digital technologies should be increasingly applied to forest management, while community participation should be strengthened and sustainable livelihood models developed to enhance both conservation effectiveness and local incomes. This integrated approach would contribute to coastal dike protection, enhance carbon sequestration, conserve biodiversity, and promote sustainable socioeconomic development in the coastal areas of Dong Thuy Anh Commune.

IV. CONCLUSIONS

This study provides an overview of the current status of mangrove forests in Dong Thuy Anh Commune, Hung Yen Province, showing that the forest area reached 1,294.79 ha in 2025. The mangrove forests are predominantly planted protection forests, with *Sonneratia caseolaris*, *Kandelia obovata*, *Aegiceras corniculatum*, and *Avicennia marina* as the dominant species; however, overall forest quality remains limited. The study identified the major drivers of mangrove degradation, among which wave action, storms, hydrodynamic fluctuations, and unfavorable site conditions were the primary factors, together with the impacts of aquaculture, fisheries, and other anthropogenic activities.

The AHP-based assessment classified the study area as a difficult mangrove site, providing a scientific basis for selecting appropriate restoration measures. Accordingly, the study proposes an ecological approach to mangrove restoration, prioritizing the improvement of site conditions through soft engineering structures for wave attenuation, species selection based on ecological requirements and natural succession, combined with the protection of natural regeneration, supplementary planting of native species, and strengthened management integrated with sustainable livelihood development.

The findings contribute to the scientific and practical knowledge base for the conservation, restoration, and sustainable development of mangrove forests in Dong Thuy Anh Commune, as well as in other coastal areas with similar site conditions.

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