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Research paper

# Site Classification and Ecological Solutions for Mangrove Forest Development in the Red River Delta Biosphere Reserve of Vietnam

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## ABSTRACT

The classification of mangrove sites within the Red River Delta Inter-Provincial Wetland Biosphere Reserve provides an essential scientific foundation for the effective and sustainable management of coastal mangrove ecosystems. The primary objective of this study is to apply a standardized mangrove site classification framework to identify suitable species for mangrove planting, restoration and conservation in coastal areas. The study employs a quantitative approach incorporatin key mangrove site classification indicators: sub-soil type, soil layer thickness, sub-terrain type, rainfall, and forest vegetation status. The resulting framework was applied to evaluate previous studies on mangrove site classification both globally and within Vietnam. Changes in the mangrove forest area within the study area from 1990 to 2025 were assessed. Notably, Hung Yen Province experienced substantial mangrove loss between 1990 and 2005, with more than 4,768 hectares converted to aquaculture. Currently, the alluvial area is 9,780.6 ha, of which 7,411.4 ha is mangrove forest. Based on site classification criteria, the area has been categorized into three levels of suitability for mangrove development: favorable (4,491.3 ha), moderate (6,338.83 ha), and difficult (4,809.87 ha). These assessments provide a foundation for proposing solutions for mangrove forest development suitable to site conditions.

**Keywords:** mangroves, salt-marsh, salt-marsh site classification, planting techniques

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## INTRODUCTION

Vietnam lies in the tropical monsoon climate zone, with a coastline of over 3,260 km, stretching from Quang Ninh province in the north to An Giang province in the south. Of Vietnam's 34 provinces and municipalities, 22 have coastal mangrove forests and mangrove soils. According to statistics from the Ministry of Agriculture and Environment, the total area of mangrove forests in Vietnam exceeded 151,481 hectares in 2024 (MAE 2025).

The Red River Delta Inter-Provincial Wetland Biosphere Reserve commonly referred to as the Red River Biosphere Reserve was designated by UNESCO in 2004. The reserve encompasses two provinces: Hung Yen (formerly Thai Binh Province) and Ninh Binh (formerly including Nam Dinh and Ninh Binh provinces). The Red River Biosphere Reserve has a total area of over 105,558 hectares. Division: Coastal mainland: 66,256 hectares and sea surface water: 39,302 hectares. Among which, there are over 7,081 hectares of mangrove forest.

With its diverse ecosystems, including the mangrove systems which serve as habitat, transition center, and dispersal center for numerous biological groups, the reserve plays an essential ecological role. Notably, the Ramsar site in Xuan Thuy National Park and the Wetland Nature Reserve in Hung Yen Province are considered internationally significant waterbird stations. These sites support important nearly 60 recorded migratory bird species and provide habitat for more than 50 species of waterfowl species. With substantial biodiversity potential, this area also provides livelihoods for local communities and demonstrates strong advantages for ecotourism, aquaculture, maritime services and processing industries. Consequently, this important ecosystem provides a wide range of valuable products and services to coastal communities, including timber and non-timber forest products, aquatic resources, recreation opportunities, biofiltration functions, and coastal protection. In particular, mangroves contribute significantly to sea-dyke reinforcement, soil stabilization, carbon sequestration and $CO_2$ absorption.

Hung Yen and Ninh Binh are agriculturally intensive provinces within the Red River Delta. Hung Yen contains one of the largest area of mangroves and freshwater marshes in the Red River Delta, with more than 4,099.7 hectares of mangroves. Mangroves in this area provide substantial opportunities for tourism development and aquaculture. However, the mangrove ecosystem faces numerous challenges. Conditions challenging development include saline wet soils are typically concentrated in alluvial areas, river mouths, and sandbanks, which often change significantly over time and space. These areas are also highly susceptible to strong winds, large waves, and nutrient-poor substrates. In the context of climate change and rising sea levels, the region has also experienced fluctuations–and declines–in both the quantity and quality of mangroves. At the same time, constraints in forest restoration efforts persist. Although mangrove planting and restoration activities have been conducted, systematic and detailed site-specific research remains limited, even though such knowledge is essential for implementing effective forest restoration measures. In recent years, mangrove planting and restoration work has also lacked technical guidance for species selection, planting methods and appropriate measures to enhance growth, development and survival rates. As a result, the ability to achieve forest establishment defined as a survival rate of 60% remains limited. The core challenge is to scientifically classify mangrove sites and from there propose technical guidance to support restoration and reforestation. The proposed solutions are substantiated by afforestation results after 48 months, demonstrating a tree survival rate exceeding 50%, with even spatial distribution of trees, no canopy gaps exceeding 1,000 $m^2$, and a canopy cover (or crown closure) greater than 0.3.

To this end, the main objective of this study is to evaluate and classify mangrove site conditions in the Red River Delta Biosphere Reserve focusing on two representative areas, Hung Yen and Ninh Binh–based on scientific criteria, to identify characteristic mangrove site types in the research area. A secondary objective is to develop specific ecological engineering solutions, suitable for each site type to improve the afforestation rate and quality of mangroves.

Scientifically, this study provides a robust foundation and systematic data for mangrove site characterization, addressing gaps in ecological zoning for mangrove restoration and reforestation. In terms of practice, the study presents a set of ecological engineering solutions–including species selection, planting techniques, and impact measures–specifically designed for the challenging site conditions of the Red River Delta Biosphere Reserve. The outcomes are significant for achieving stable and sustainable mangrove restoration and contributing to proactive adaptation to global climate change and rising sea levels in this critical coastal region.

## MATERIALS AND METHODS

### Materials

Mangrove forests and mangrove soils located in coastal communes of the two provinces of Hung Yen and Ninh Binh were used as the primary material for this study.

### Methods

Secondary data related to terrain characteristics, natural conditions (including rainfall and hydrological regimes, such as inundation levels of mangrove soils), and forest status (mangrove forest area and bare soil area), were compiled from the 2024 Statistical Yearbooks of Thai Binh, Nam Dinh and Ninh Binh provinces.

Guidelines for planting mangrove species were based on procedures from the Ministry of Agriculture and Environment: Decision 1205/QĐ-BNN-TCLN; 4147/QD-BNN-TCLN, MARD (2016, 2021).

**1. Methods of investigating the current status of mangrove forest**

Mangrove forest inventory was conducted using the sample plot method, with a total of 35 sample plots (OTC). These plots were representative of two main types of planted forests: pure stands of *Sonneratia caseolaris* (L.) Engl. or *Kandelia obovata* Sheue, H.Y.Liu & J.W.H.Yong, and mixed stands of *S. caseolaris* and *K. obovata*. Survey locations were distributed across the mangrove forest areas of Hung Yen and Ninh Binh provinces.

OTCs were established to investigate mangrove plantations characteristics. Each OTC covered an area of 100 $m^2$ (10 m × 10 m). Within each OTC, all trees were identified and measured. The following criteria and measurements were applied:

(1) Species identification: Individual trees within each OTC were identified to species level.
(2) Root diameter (Doo, cm): For *S. caseolaris* and *K. obovata* aged 1-3 years, diameter was measured 10 cm above the ground. For trees older than three years, diameter was measured 10 cm above the buttress.
(3) Tree height (Hvn, m) was measured with

a graduated pole ruler.

(4) Diameter of the canopy (Dt, m) was measured with a tape measure according to the vertical projection of the edge of the canopy onto the ground. Measurements were taken in two directions east-west and north-south and the mean was calculated.

(5) Tree quality was evaluated using morphological comparison based on three classes (good, average, and poor). Assessment criteria integrated standard indicators for protective mangrove trees, including branch thickness, leaves, branching angle, number of breathing roots and root type.

**2. Methods of soil sampling and analyzing saline soils in the laboratory**

At each OTC location established for mangrove assessment, soil samples were taken to analyze specific characteristics: Five soil profiles were excavated at each OTC (four in the corners and one in the center), each measuring 1.2 m long and 1.0 m wide. Samples were collected from three depths: 0-20 cm, > 20-40 cm, and > 40 cm. Soil samples from five positions were thoroughly mixed at the same depth, and each depth constituted one sample. Consequently, a total of 105 soil samples were collected, calculated as: 3 depths times 35 sample plots.

All samples were labeled and accompanied by a brief description of the soil profile characteristics, including color, properties, and moisture. The soil samples were taken back to the Soil and Environment Laboratory of the Vietnam Institute of Agricultural Planning and Design for detailed analysis of particle size, composition and physical properties according to Vietnamese and international standards.

For saline soils, soil layer thickness (cm), total soluble salts (EC), chloride content (Cl, %), particle size distribution, pH KCl, total nitrogen content (N, %), phosphorus ($P_2O_5$), and potassium ($K_2O$).

**3. Analytical Hierarchy Process (AHP)**

A matrix of factors for classifying mangrove sites was drawn up and all criteria were scored using a weighted scoring method. Site types were then grouped according to their cumulative weighted scores.

Principle of weighted scoring: Weighted scoring was applied based on the research findings regarding the relative level of influence of site criteria on the growth of mangrove forests. Each indicator and criterion was assigned a weight proportional to its impact. Factors that have a large and clear influence on the growth of mangrove forests were given a higher weight than other factors, Expert elicitation methods were used to determine the final weighting scheme.

Site classification by score: Each site type was determined from the composite score of the criteria and indicators. Based on the score of each site type, the relative level of ease or difficulty to restore mangrove forests for each site type was assessed. Higher scores indicate more favorable conditions for mangrove establishment and recovery, whereas lower scores reflect more challenging site conditions.

Determining weights for mangrove site criteria: The AHP (Analytical Hierarchy Principles) method developed by Thomas L. Saaty (1980) was used to classify mangrove site types.

Specific objectives were to classify the mangrove site and to organize the 5 criteria into 5 target groups, establishing a multi-layered structural system for each target group.

Comparisons were conducted to evaluate the relative importance of each pair of criteria of the same rank, expressed as the comparison value $C_{ij}$. Assuming the weight $A_k$ is the norm, the criteria of the lower rank $C_1$,

$C_2 \ldots C_{11}$ are linked as branch relationships. Experts assessed the importance of each pair of criteria $C_i$ and $C_j$ with respect to weight $A_k$ providing the basis for conducting quantitative comparisons, and to support the comparison and evaluation process across the following ranks: A-B; $B_1$-C; $B_2$-C; $B_3$-C; $B_4$-C and $B_5$-C.

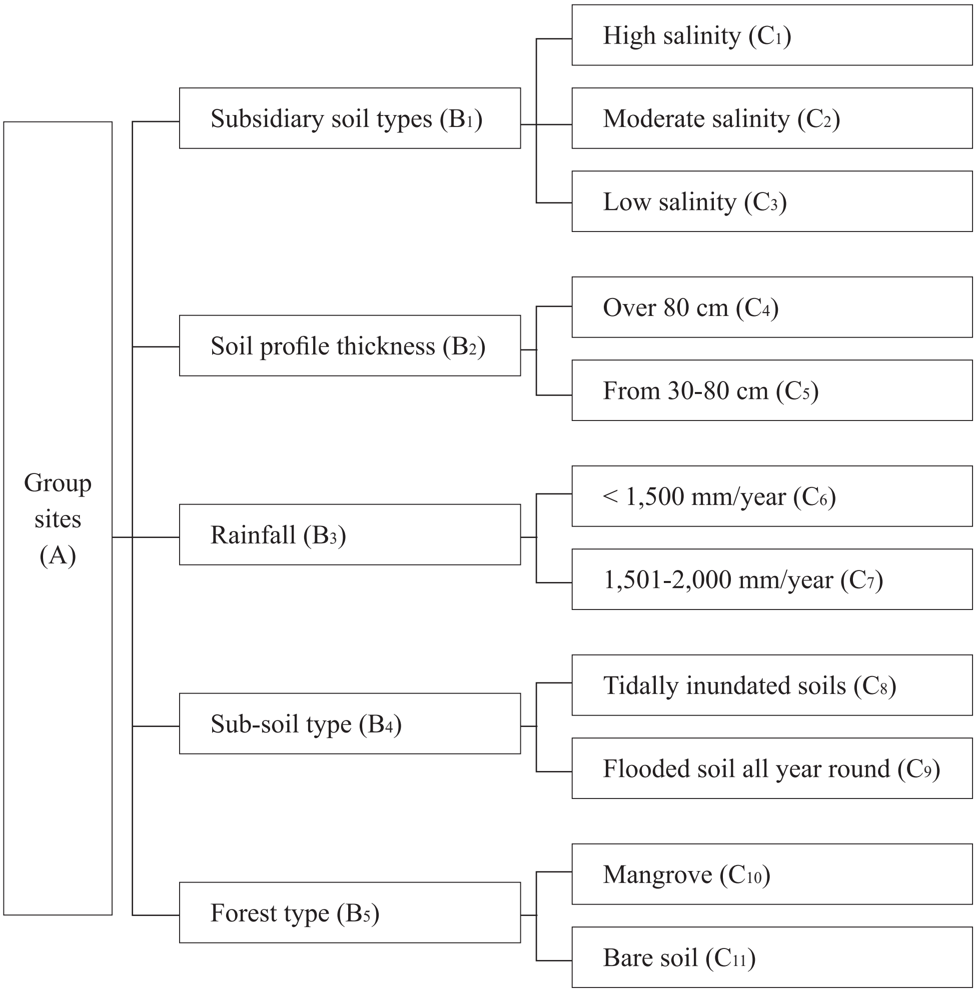
Calculate the single class by comparing pairs, and modifying the pairs until an acceptable comparison value is achieved.

Summary of criteria for classifying mangrove areas is determined by the following formula:

$$E = \sum_{i=1}^{n} B_i C_i$$

In which: $E$ is the result of evaluating the site type group
$B_i$ is the evaluation weight of criterion $i$
$C_i$ is the score of criterion $i$
$n$ is the number of evaluation criteria.

**Classification process of criteria for evaluating the division of site type groups**



**4. Proposed scale for evaluating criteria**

Criteria were coded and a scoring system was applied based on the relative difficulty of each criterion to propose an evaluation scale. Factors with a larger and obvious impact on the growth of mangrove forests were assigned higher weights than other factors, incorporating expert methods for scoring. Scores were assigned from high to low in 3 levels (2, 1, and 0). These weighted scores were then used to evaluate the level of influence of each criterion on afforestation, forest restoration, and mangrove development as well as the overall growth and development of mangrove trees.

Each site was evaluated based on its composite score to determine the relative level of convenience or difficulty to restore mangrove forests on that site type. The higher the score of the site type, the higher the level of convenience and vice versa.

**5. Method of constructing level II topographic maps:**

Applying Vietnamese standard TCVN 12630-2: 2019 Site Map-Rules for the Structure and Content Part 2: Site Map Class II.

* Proposed scale to evaluate the criteria:

(1) Criteria were coded and scored according to their difficulty to establish an evaluation scale. Factors that have a large and obvious impact on the growth of mangrove forests were assigned a higher weight than other factors, combining expert methods to score. Scores were assigned on a four-level scale from high to low (3, 2, 1, and 0). These weighted scores were then used to evaluate the level of influence of each criterion on afforestation, forest restoration, and mangrove development as well as the overall growth and development of mangrove trees.

(2) Field surveys were conducted to determine soil type, soil maturity, and the tidal flooding regime. At each survey area, soil samples were collected and analyzed in the laboratory to determine their mechanical composition according to current TCVN standards. Data from field surveys, combined with laboratory analysis data, were then used to classify sites for planting and development of mangroves within the research area.

ArcGIS was used to edit maps and Microsoft Office Excel to calculate and process collected and surveyed data. The calculated and processed data is presented through tables, diagrams and graphs.

**6. Data collection and processing methods**

Data were compiled and analyzed according to the research purposes using mathematical statistics in biology. Specialized statistical software such as Excel, and R were used to assess changes in mangrove forest area in the study area over time, Tuan (2014). Matlab was used to analyze data and draw charts according to the research objectives.

## RESULTS

### Worldwide

In the Soviet Union, a site is defined as the habitat conditions–the sum of external factors that form forest types and influence the growth and development of forest plants. In Germany, a site is defined as a specific geographical area including external factors that influence the growth of trees. In the United States, a site is all the external factors such as climate, hydrology, soil, organisms and humans that regularly affect the life of organisms.

Several studies have shown that rainfall and temperature significantly affect the growth and development of mangroves.

Chapman (1976) noted that temperature is an important factor affecting the growth and distribution of mangroves. Mangroves grow well in warm environments, where the temperature of the coldest month does not fall below 20℃, and the seasonal temperature range does not exceed 10℃. Saenger et al. (1983) and Tri (1999) explained that the presence of mangroves in a certain area depends on air temperature and water temperature. Studies on the division of coastal mangrove planting sites in the world mainly focuses on ecological factors affecting the formation and development of mangroves, including: Chapman (1976, 1977), Tomlinson (1986).

According to Choudhury (1994), it is essential to conduct a careful site assessment before forest restoration, to determine whether the soil needs improvement or not, whether it can be afforested, and to determine the form of soil preparation or soil improvement that can increase the success of forest restoration.

According to Field (1998), soil and substrate have an impact on the distribution of mangrove species. Mangrove ecosystems are uniquely adapted to intertidal zones and generally thrive in environments where hydrodynamic energy is managed or naturally low. Stable, non-erodible soils with suitable depths are favorable environments for mangrove growth. In addition, the substrate is a source of nutrients and supports the trees, which also has an important impact on tree growth.

Research on mangrove site conditions in India and Bangladesh has focused primarily on the Sundarbans, the transboundary mangrove system formed at the confluence of the Ganges–Brahmaputra–Meghna river system. This region exhibits a highly complex site gradient, including alluvial plains, sand dunes, tidal creeks, brackish marshes, and extensive mangrove forests. Studies have evaluated a range of environment conditions, most notably salinity, which is considered the dominant limiting ecological factor influencing mangrove distribution in the Sundarbans. Increasing salinity–largely associated with upstream freshwater diversion from the Ganges in India–has had significant negative impacts on mangrove biodiversity and species composition (Gijón Mancheño et al. 2021). This long-term selective pressure has led to the formation of mangrove assemblages capable of tolerating hypersaline conditions, which often occur in regions with high seasonal rainfall variability or where evaporation exceeds precipitation (Goodell et al. 2022). Tidal dynamics and sediment processes also play critical roles in shaping local site conditions Owing to the continuous tidal forcing from the Bay of Bengal, sedimentation rates in the Sundarbans are considered high relative to other mangrove regions globally, in some areas even exceeding the current rate of sea-level rise (Setyadi et al. 2022). Based on these environmental gradients, researchers have classified site types according to salinity regimes to explain spatial patterns of vegetation distribution.

Indonesia has the largest mangrove forest area in the world and supports exceptionally high biodiversity (Alongi et al. 2005). Site-based studies in this region emphasize tides and salinity as primary environmental drivers influencing mangrove distribution, owing to the ability of mangroves to tolerate frequent tidal flooding and broad high salinity ranges. Substrate characteristics and forest structural attributes also influence species composition, with mangrove species such as *Rhizophora apiculata* Blume and *Bruguiera gymnorrhiza* (L.) Lam. occurring widely across the archipelago (cifor-icraf.org, Setyadi et al.

2022, Alongi et al. 2005). However, mangrove restoration projects in Indonesia often fail due to a lack of comprehensive assessment of site conditions including geomorphological features, physical and chemical soil properties, and sediment dynamics (Utami et al. 2024). These limitations highlight the critical need for detailed site classification prior to afforestation or restoration activities

**In Vietnam**

The term *site* is a noun used in Sino-Vietnamese vowels, originating from China, derived from German, *Standort*, a compound noun *Stand* meaning state and *Ort* meaning locality; referring to the natural conditions in a specific locality or area. According to the viewpoint of German site developers, "Site a terrain range with all external factors–climate, soil, and topography–that affect plant growth". Thus, site originates from the concept of regional ecology.

Therefore, to determine site conditions in a specific area, we must fully determine external factors including: climate, terrain, soil and expressed through the characteristics of natural plant communities. Site is the habitat of a species or a group of plant species under the influence of all external factors affecting them. Thus, site is not only understood as a simple soil factor, but also associated with external conditions such as terrain, soilscape, climate (temperature, light, air humidity, rainfall, ...). The site is a certain territorial scope including all external factors affecting the growth of organisms, mainly plants. In a broad sense, site is a synthesis of factors that create the living environment of plants, including the four components: climate, terrain, soil and the world of animals and plants (Que and Quat 2012).

According to Decision No. 5365/QD-BNN-TCLN dated December 23, 2016 of the Ministry of Agriculture and Rural Development, a site for growing mangrove trees is understood as "the climate, hydrology, terrain, soil and vegetation conditions at and around the location where the tree grows." Although different in terms of expression, the term site is understood uniformly worldwide.

When talking about a site, two key issues should be mentioned: geographical location of the site, and the environmental conditions existing at the site. In forestry, site is understood as a forest site. Site quality refers to the productivity of forest trees or different types of vegetation on that site. Therefore, site quality is always associated with a certain tree species or group of tree species. There are suitable sites, and there are sites that are not suitable for tree species. Site quality is determined by factors: climate, terrain, soil and organisms. If a site is planted with different tree species, the site quality may vary, depending on the tree species. Site conditions refers to the synthesis of factors that make up the site.

Site quality, planting conditions and site conditions are terms that are often used interchangeably. When assessing site quality, it is often necessary to make judgments or forecasts about the current production of the site. The purpose of assessing site quality is to forecast crop yields, quantify soil productivity or divide the site into units with uniform productivity (Que and Quat 2012). The basic unit and also the final unit of the site is the site type. It is a piece of soil with a defined location and has relative uniformity in each of its constituent elements, including climate, terrain, soil, and vegetation. The site type is the final unit of the site division system and is determined on a small unit (commune level, forestry farm, production team) with a map scale of 1/10,000 or 1/5,000 to serve the work of designing afforestation techniques. The collection of similar site types is called a site type group or site type. This is the basis for determining the type of plant and determining the technical measures for planting and caring for forests. In the current forest planting conditions, going deep into intensive cultivation, including natural forests and planted forests, determining clear economic and environmental efficiency, so the division of site types is extremely necessary, is the basis for selecting suitable plant types and applying measures to increase the productivity of planted forests. According to Decision No. 5365/QD-BNN-TCLN dated December 23, 2016 of the Ministry of Agriculture and Rural Development, MARD (2016), the site type in the condition of growing mangrove trees is understood as "The basic, final unit of the site division system for arranging plants and designing forest planting techniques".

In the study of mangrove forests, some factors (indicators) that make up the type of mangrove site are often used to divide mangrove sites: Current status of forests and mangrove soil (soil with mangrove forest and bare soil); characteristics of mangrove soil (maturity, % sand, some other soil chemical characteristics, ...); salinity of coastal seawater; beach exposure time; wave height; beach elevation, ... Through these factors, different types of sites and groups of site types will be combined and will be the basis for selecting plant species suitable for growing conditions, ensuring a high forest formation rate.

The basic viewpoint when studying the restoration and development of mangroves in Vietnam is based on site conditions to determine the site type and select tree species suitable for planting conditions. In the coastal area of the Mekong Delta, three important factors related to the growth of mangrove forests are used to divide sites, including: (i) Soil type; (ii) Tidal flooding regime (tidal flooding time and highest tidal flooding); and (iii) Soil maturity (n). Que (2003) divided the whole region into 14 site types, of which, saline soil has 8 site types and potential saline soil has 6 site types. Based on the ecological characteristics of tree species, research results and production practices in localities, the author proposed directions for use according to site type groups (A, B, C, and D).

Que and An (2001) studied the criteria for dividing the site types for the coastal mangrove area of Vietnam and explained the construction of a site map for the coastal mangrove area of Thanh Phu district, Ben Tre province. For the division of the site of the coastal mangrove strip of Vietnam, the author classified the subdivisions into site regions, sub-regions, site regions, sub-regions and site types. The study proposed the criteria for dividing the site for the coastal mangrove area of the Mekong Delta, with 1 factor chosen as the criteria for division: soil type, tidal flooding regime, and soil maturity. The author identified 14 site types in this area, of which 8 are mangrove soil types and 6 are potential mangrove soil types.

Tam (2012) divided the sites for the Northern coastal region based on 04 main criteria: (a) Soil type; (b) Tidal regime; (c) Soil maturity; and (d) Mechanical composition. Accordingly, the Northern coastal region has 18 main site types of 02 soil types (saline wetsoil without potential alum and saline wetsoil with medium and weak potential alum). The author applied this division criterion to the very difficult site type in the area with a mechanical composition of sticky sand.

Thoi (2014) divided the southern coastal issoils, the particularly difficult mangrove area, gravel, sand, coral debris, high salinity into 03 regions including: (1) South Central coastal issoils and offshore issoils; (2) Southeastsea issoils; and (3) Mekong Delta issoils. Each region is divided into 20 types of sites based on the combination of 3 main factors: Tidal flooding regime, subgrade and salinity. The whole region has 6 main groups of site types: Group A (2 sites), B (4), C (2), D (6), E (2), and F (4). On that basis, the author presents the mangrove plant species distributed according to each group of site types for the southern coastal issoils.

According to Giang (2015), in the coastal areas of Quang Ninh and Hai Phong, there are 3 main types of saline soil, type 1 is strongly acidic and salty saline soil, type 2 is acidic and moderate saline soil, type 3 is weakly acidic and slightly salty saline soil. The author relies on 6 specific criteria to divide the saline soil for the study area, which are soil type, current soil use status, tidal depth, maturity, salinity, mechanical composition and applies the results of site division to build a saline soil map for Dong Rui commune, Tien Yen district, Quang Ninh province. However, the division of soil and saline soil has only been applied experimentally in 1 commune, and has not yet studied in depth the solutions for mangrove restoration in different site conditions and in different ecological zones.

Manh (2019) when studying the division of saltwater site conditions in Thai Binh province based on the factors (i) Soil type, (ii) Current status of saltwater and mangrove (iii) Exposure time, (iv) Soil maturity, (v) Percentage of sand grains, and (vi) Saltwater elevation. Based on the establishment of saltwater site maps for commune-level units, appropriate silvicultural technical solutions for each site type group were proposed.

Thus, the above research results on site zoning and site type division are the basis for contributing to the development of standards on coastal mangrove site division to serve the planning, selection of plant species, planting techniques, restoration and development of mangrove forests in our country, especially in response to climate change and rising sea levels. The above authors used site constituent factors such as tidal regime, maturity, mechanical composition, soil type, salinity, and current status of mangrove soil use.

However, the factors that strongly affect the existence of mangrove plants are the elevation of the mangrove soil that has not been used for site research in the mangrove areas of Vietnam. This is a factor that includes the factors of the tidal regime that directly affect the growth of trees mangrove. The shallow, medium and deep tidal flooding levels used by previous authors are based on the number of tidal flooding days in a month. This is a very difficult task and without a series of monitoring data, it cannot be determined in practice because the water cycle is usually repeated every 14 days. If you go to the tidal flat to check at a time and a space, you cannot detect which tidal flat has shallow, medium and deep tidal flooding. Meanwhile, the elevation of the mangrove soil is a fixed indicator, less affected by the tide, and easy to determine in practice.

**General comments**

Studies on site factors such as substrate, salinity, tides, current status of mangrove forests, weather and climate, wave regime, beach elevation, tidal flooding time are basic factors of site types that have been studied by many authors in the world and Vietnam. However, studies in each region, each area and specific characteristics of each vegetation have been generalized about the site, mangrove sites have received less attention due to the nature, characteristics, and area of mangroves as a special type of forest, affected by tides, small scale, and strong fluctuations due to frequent impacts of coastal natural disasters and human production, business, and socio-economic activities. Therefore, it is necessary to focus on research and development of criteria for dividing mangrove sites in degraded mangrove areas of the Red River Biosphere Reserve as a basis for dividing mangrove sites and proposing technical measures to restore and develop stable mangroves.

## Assessment of the current status of mangrove forests in the Red River Delta Biosphere Reserve

### 1. Current status of mangroves area

According to statistics from the Forest Protection Department for the period 1990-2024, the area of mangrove forests in the Red River Delta Biosphere Reserve has tended to decrease significantly and continuously over this period, while the area of coastal alluvial soil has increased rapidly. In the whole region, the area of mangrove forests has decreased by about 40.1%, equivalent to 4,953.2 ha, with an average decrease rate of 145.7 ha/year; in contrast, the area of alluvial soil has increased by 107% (an average increase of 148.7 ha/year) over the past 30 years. This fluctuation shows a nearly symmetrical replacement relationship in ecological space between the two types of mangrove forests and coastal alluvial soil.

Specifically, in the period 1990-2005, the mangrove forest area decreased slightly from 12,364.6 ha to 12,252.7 ha (a decrease of 111.9 ha, equivalent to 0.9%), reflecting a relatively stable state. However, in the period 2005-2020, the forest area decreased sharply from 12,252.7 ha to 7,484.1 ha (a decrease of 4,768.6 ha, equivalent to 38.9%), showing great pressure from coastal socio-economic development such as converting forest soil to aquaculture, expanding residential areas, developing coastal infrastructure, along with the impact of climate change and coastal erosion. By 2024, the forest area will be only 7,411.4 hectares, a further decrease of 72.7 hectares compared to 2020 (equivalent to 0.97%), showing that the decline trend continues but has slowed down, partly reflecting the effectiveness of recent afforestation and forest restoration programs.

Coastal alluvial area tends to increase strongly and continuously, opening up great potential for mangrove restoration and expansion if properly planned. However, the symmetrical trend between forest reduction and alluvial increase shows that newly formed soils have not been effectively converted into mangrove areas, due to the lack of integration between coastal spatial planning and mangrove restoration plans.

By locality, Hung Yen province recorded the largest forest decline, from 7,500 ha (1990) to 4,099.7 ha (2024) (a decrease of 3,400.3 ha, equivalent to 45.3%), while the alluvial area increased sharply from 1,927 ha to 5,429.3 ha (an increase of 3,502.3 ha, equivalent to 181.7%), demonstrating significant forest restoration potential. Ninh Binh province had a milder fluctuation, with the forest area decreasing from 4,864.6 ha to 3,311.8 ha (a decrease of 1,552.8 ha, equivalent to 31.9%), while the alluvial area increased from 2,798.4 ha to 4,351.4 ha (an increase of 1,553 ha, equivalent to 55.5%).

In the whole region, by 2024, the area of mangrove forests decreased from 12,364.6 ha to 7,411.4 ha, while the area of alluvial plains increased from 4,725.4 ha to 9,780.6 ha. This opposite fluctuation reflects a clear trend of mangrove degradation, and also points out the potential of new ecological space to restore forests on newly formed alluvial plains. The assessment results show that mangrove forests in the Red River Delta Biosphere Reserve are rapidly and alarmingly declining, in parallel with the strong increase in the area of coastal alluvial plains. This has important implications for planning and managing coastal resources. If we know how to take advantage of newly formed alluvial areas to plant and restore mangrove forests, it will contribute to enhancing coastal protection, minimizing the impact of climate change, conserving biodiversity and developing sustainable livelihoods for local communities.

**2. Characteristics of saline soil**

(1) Soil characteristics in mangrove forests

**Table 1. Changes in soil area and coastal mangrove forests of the Red River Delta Biosphere Reserve (Unit: ha)**

| Year | Soil type | Hung Yen | Ninh Binh | Total |
|---|---|---|---|---|
| 1990 | Mangroves | 7,500.0 | 4,864.6 | 12,364.6 |
| | Alluvial soil | 1,927.0 | 2,798.4 | 4,725.4 |
| 2005 | Mangroves | 7,304.0 | 4,948.7 | 12,252.7 |
| | Alluvial soil | 2,123.0 | 2,715.8 | 4,838.8 |
| 2020 | Mangroves | 4,170.6 | 3,313.4 | 7,484.1 |
| | Alluvial soil | 5,303.5 | 4,349.6 | 9,653.0 |
| 2024 | Mangroves | 4,099.7 | 3,311.8 | 7,411.4 |
| | Alluvial soil | 5,429.3 | 4,351.4 | 9,780.6 |

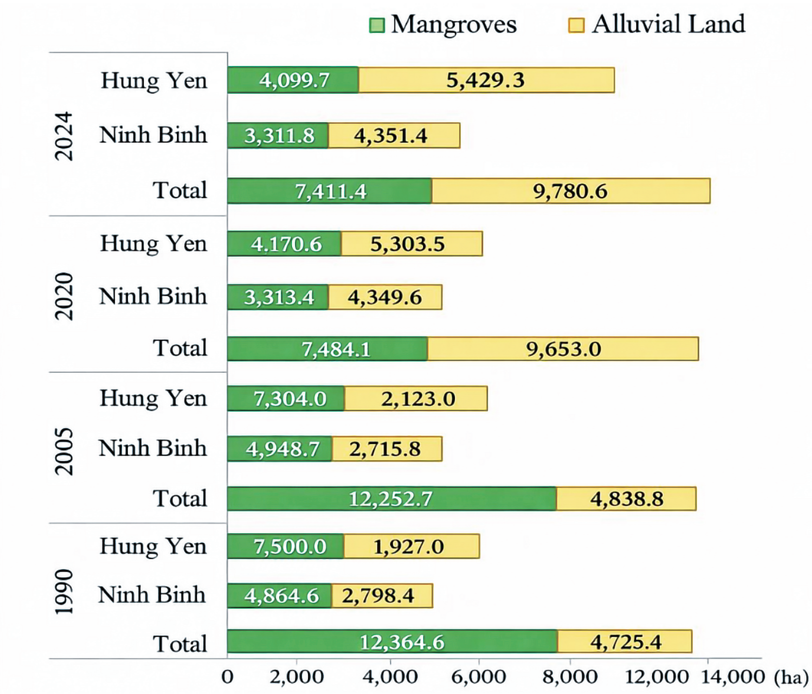



**Figure 1. Mangrove forest and alluvial bare soil areas for several years in Hung Yen and Ninh Binh provinces**

The sand grain size (0.02-2.0 mm) tends to have a high proportion as the soil depth increases. The sand grain ratio at different soil depths in the coastal area of Thai Binh province fluctuates greatly, ranging from 6.27-83.66% and there is no clear difference between different forest planting methods (*K. obovata*, *S. caseolaris* and mixed *S. caseolaris* + *K. obovata*) (Thai Binh Provincial Forest Protection Department. 2023).

$pH_{KCl}$ index in cashew stands at different soil depths in the pure *K. obovata* forest stands fluctuated between 5.59 and 6.70. In the pure *S. caseolaris* forest stands, the $pH_{KCl}$ index fluctuated between 5.04 and 6.80.

Total nitrogen content (N, %) in the investigated forest stands fluctuated between 0.05-0.19%. Total $P_2O_5$ content in the investigated forest stands was at an average level, ranging from 0.09-0.24%. Total $K_2O$ content (%) in all investigated forest stands was at a fairly good level of 1.81-3.86%.

(2) Characteristics of flooded barren soil

The sand grain size (0.02-2.0 mm) tends to have a high proportion as the soil depth increases. The sand grain percentage ranges from 51.90% (0-20 cm) to 73.64% (> 40 cm). The sand grain percentage accounts for a relatively large proportion (over 50%) in the grain size composition of the bare saline soil in the coastal area of Thai Binh province. The $pH_{KCl}$ index at the survey points of the bare saline soil has no clear difference between the sampling depths, the average $pH_{KCl}$ ranges from 5.61 (0-20 cm) to 6.76 (20-40 cm); the bare saline soil in the coastal area of the SouthCentral Coast has a reaction from slightly acidic to acidic, belonging to the types of highly saline, moderately saline and slightly saline soil.

Total nitrogen content (N, %) at sampling points of bare saline soil in the study area ranged from 0.05% (> 40 cm) to 0.08% (20-40 cm). Bare saline soil in the study area, at different sampling depths, was poor in nitrogen (N, % < 0.15%).

$P_2O_5$ content is at a poor phosphorus level, $P_2O_5$ content ranges from 0.09% (0-20 cm) to 0.10% (20-40 cm and > 40 cm).

Total $K_2O$ content (%) is at a fairly good level, ranging from 1.36% (> 40 cm) to 2.20% (20-40 cm).

Comments: The characteristics of mangrove soil in the coastal area of Thai Binh province have a mechanical composition from soft clay to sandy loam, quite rich in mud and clay, the proportion of clay particles is quite high in the standard plots of soil analysis, compared with the areas of Quang Ninh and Hai Phong, Thanh Hoa. Thai Binh mangrove forest is in a form of rich potential, favorable for the growth and development of mangrove forest, the content of nitrogen, phosphorus, potassium from total to easily digestible from rich to medium level. Meanwhile, these contents in other areas are at poor to fair level. Mangrove forest is in the form of low salinity to high salinity, concentrated in the form of medium salinity, this type of salinity is chlorine salinity, this is consistent with the natural law because the mangrove forest in Thai Binh is affected by 5 large river mouths flowing into the sea. However, this area is also influenced by the terrain, so the areas near the national dike (in the form of high beach elevation) are often in the form of sandy loam, quite high salinity, the content of nutrients is at medium and low levels.

**3. Selection of criteria for dividing mangrove sites**

In addition to factors such as soil characteristics in mangrove forests, the correlation between mangrove trees and soil characteristics analyzed above, some other factors affecting the growth of mangrove trees are based on the following criteria classified according to

Vietnamese standard TCVN 12630-2: 2019 Site Map-Rules for the Structure and Content Part 2: Site Map Class II:

(1) Sub-soil type ($B_1$)

Low saline areas are located near river mouths and alluvial areas without forests. Medium saline areas are often very suitable for planting mangrove trees in areas with mangroves and in aquaculture ponds. High saline areas are located 1 km from the forest to the sea and in deep tidal areas.

**Table 2. Classification criteria for saline soils**

| Indicators | Value | Symbol |
|---|---|---|
| + High salinity | TMT > 0.7%, $Cl^-$ > 0.5%, | $C_1$ |
| + Moderate salinity | TMT from 0.5 to 0.7%, $Cl^-$ from 0.3 to 0.5% | $C_2$ |
| + Low salinity | TMT < 0.5%, $Cl^-$ < 0.3% | $C_3$ |

(2) Soil profile thickness ($B_2$)

The research area includes two main soil layers: the area with a thickness of 30-80 cm, including plots of soil in the area adjacent to the sea dike, in the mangrove forest, the alluvial area in Hung Yen province, Ninh Binh province and soil with a thickness of over 80 cm in the alluvial areas along the river, Ninh Binh province.

**Table 3. Classification criteria for soil layer thickness**

| Indicators | Value | Symbol |
|---|---|---|
| + Thick soil | Over 80 cm | $C_4$ |
| + Thin soil | From 30-80 cm | $C_5$ |

(3) Rainfall ($B_3$)

Rainfall has a great influence on the growth, species composition, and size of mangrove trees. According to hydrological assessments, the entire study area receives an average rainfall ranging from 1,500 to 2,000 mm per year.

**Table 4. Rainfall per year**

| Indicator | Value | Symbol |
|---|---|---|
| + Little rain | Less than 1,500 mm | $C_6$ |
| + Heavy rain | From 1,500 to 2,000 mm | $C_7$ |

(4) Sub-soil type ($B_4$)

The study area has saline soils affected by cyclic tides and year-round saline soils.

**Table 5. Sub-soil type index**

| Indicators | Symbol |
|---|---|
| + Tidally inundated soil | $C_8$ |
| + Flooded soil all year round | $C_9$ |

(5) Forest type ($B_5$)

The current status of coastal mangrove soil use, especially the planting and restoration of mangroves, has clearly affected the growth and development of crops. Mangroves are a mirror reflecting the potential of mangroves, and vice versa, mangroves also change the physical and chemical properties of mangroves. Therefore, the current status of soil and mangroves plays a decisive role in the selection of mangrove plant species and appropriate technical measures for planting, caring for and protecting mangroves. In particular, the current status of forests and mangrove soil use is the basis for proposing solutions for mangrove restoration. The study area includes two main vegetation states: alluvial plains, areas without mangroves, and areas with mangrove forests.

**Table 6. Current status indicators of soil and mangrove forests**

| Indicators | Symbol |
|---|---|
| + Mangroves | C10 |
| + Bare soil (no mangroves) | C11 |

(6) Synthesize criteria for soil type division for the research area

With the above analyzed criteria/indicators, the following criteria/indicators are synthesized according to the type of site:

**Table 7. Summary of criteria for classifying salt marsh sites**

| Criterion A | Criterion B | Criterion C | Weight | Point |
|---|---|---|---|---|
| Group sites | Sub-soil type | High salinity ($C_1$) | 0.3 | 2 |
| | | Moderate salinity ($C_2$) | | 1 |
| | | Low salinity ($C_3$) | | 0 |
| | Soil prolile thickness | Over 80 cm ($C_4$) | 0.2 | 1 |
| | | From 30-80 cm ($C_5$) | | 2 |
| | Rainfall | from 1501-2000 mm/year ($C_7$) | 0.15 | 2 |
| | Sub-soil type | Tidally inundated soil ($C_8$) | 0.15 | 2 |
| | Forest type | Mangroves ($C_{10}$) | 0.2 | 1 |
| | | Bare soil ($C_{11}$) | | 2 |

## 4. Soil types of the coastal alluvial areas of the Red River Delta Biosphere Reserve

The above criteria division table is the basis for determining each type of saline soil, which can be applied to build large-scale saline soil maps and plan for sustainable and effective use of coastal saline soil.

Based on the score of each site type, the level of favorableness for afforestation and mangrove restoration is divided into 3 groups as follows:

(1) Group I: Favorable: over 1.6 points;
(2) Group II: Average: 1.4-1.6 points;
(3) Group III: Difficult: under 1.4 points.

**Table 8. Results of site level assessment of the study area**

| Provinces | Area (ha) | | |
|---|---|---|---|
| | Group I | Group II | Group III |
| Hung Yen | 1045.35 | 3378.95 | 3694.68 |
| Ninh Binh | 3445.96 | 2959.88 | 1115.19 |
| Total | 4491.31 | 6338.83 | 4809.87 |

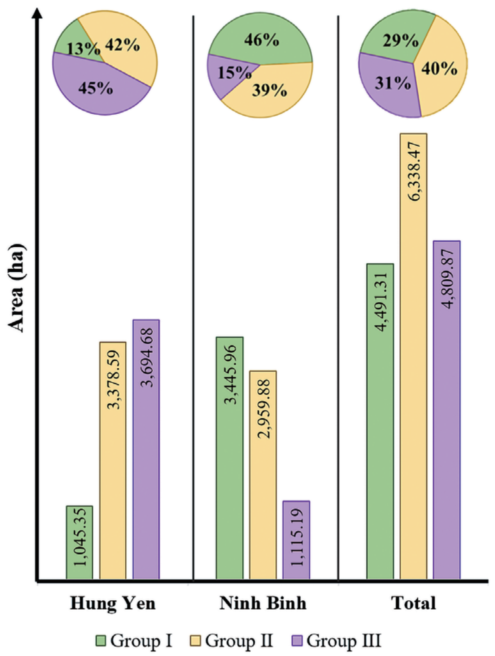



**Figure 2. Area Chart of site groups**

The results of the site-based mangrove forest classification show that group II occupies the largest area with 6,338.83 ha, followed by group III (4,809.87 ha) and group I (4,491.31 ha). Ninh Binh province has the largest area of group I (3,445.96 ha). Meanwhile, Hung Yen province has a prominent area of group II mangrove forest with a total of 3,379.04 ha, showing that the site conditions here are more suitable for intermediate forest groups. Group III - which often has more limited growing conditions - is still widely distributed, showing the potential for forest restoration but requires appropriate management and rehabilitation.

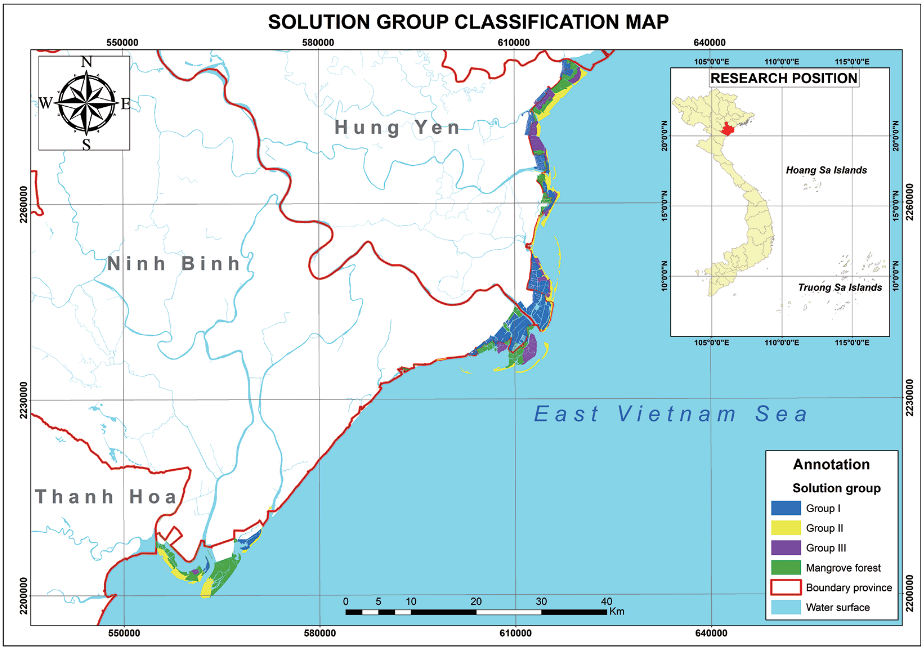



**Figure 3. Solution group classification map**

## DISCUSSION

In the world, Aksornkoae (1996) identified two primary *R. mucronata* Lam. species in Thaisoil, with high survival rates (> 80% for planted seedlings and > 94% for mangrove forest planting). Chan (1996) reported that Malaysia successfully cultivated 4,300 hectares of mangroves, notably *Rhizophora* spp., from 1987 to 1992. Similarly, Soemodihardo et al. (1996) noted four main species in Indonesia: *Rhizophora* spp., *Bruguiera* spp. In Indonesia, Soemodihardjo et al. (1996) employed two methods–direct planting and planting with seedlings–at a density of 2,500 trees/ha, with survival rates of 55-70% and 85%, respectively. Siddiqi and Khan (1996) highlighted the importance of tidal flooding and salinity levels for seedling survival, citing survival rates of 29-52% for *Bruguiera* spp. and 70% for mangrove. In India, direct planting with seedlings and nursery-grown plants (size 4 cm × 10 cm) involved species like *Avicennia* spp., with a planting density of 1.5 m × 1.5 m (Untawale 1996). In Thaisoil, success rates exceeded 80%, with *Rhizophora* spp. surviving over 94% when planted with seedlings or saplings (Aksornkoae 1996). Various protective measures, such as constructing sea walls, sand dunes, and barriers, are vital during seedling establishment to mitigate wave action and erosion. Overall, restoration strategies focus on re-establishing mangrove structure and functions, including shoreline stabilization and habitat provision (Lewis 2005, Gilman and Ellison 2007). Techniques such as selective planting, staged reforestation, and ecosystem management are recommended, considering biological and physical site conditions (Chan and Baba 2009). Many countries implement policies encouraging research, awareness, and legal protection for mangrove ecosystems.

Based on the division of 3 groups of site types, which is the basis for selecting mangrove species to restore and develop mangroves, technical measures applied to each group of site types. Proposed directions for using macro-level sites are as follows:

Group I: Planting mangrove forests using conventional technical measures, can be planted with propagules such as Rhizophora species, or seedlings in pots such as Sonneratia species. In which, the standard of seedlings required is at a low level such as seedlings are incubated for 8-12 months. No need for stakes to protect the trees, can be planted with pure species, or mixed species.

Group II: Afforestation using seedlings in pots, with or without engineering measures such as: site improvement, planting with qualified seedlings, etc. depending on the specific conditions of each locality.

Group III: Forest planting must combine technical measures: Seedlings with standard pots, site improvement, tree stakes, wave-reducing fences, and sedimentation depending on specific conditions.

However, in particular, the selection of tree species and planting and care techniques are the factors that are raised. Through expert consultation and discussion:

Select native tree species such as: *K. obovata*, *Sonneratia caseolaris*, *A. marina* (Forssk.) Vierh., *R. stylosa* Griff. and imported species such as *S. caseolaris*. In which, *K. obovata*, *S. caseolaris* are used to plant in alluvial areas without mangroves or with mangroves that need additional planting. However, in reality, *S. caseolaris* grows stronger, the tree height and breathing roots as well as the development time of *S. caseolaris* are 1.5 times faster than *K. obovata* after 1 year of planting. *S. caseolaris* grows strongly in areas with few waves. Select mangrove, *S. caseolaris* species to plant in aquaculture ponds to restore mangroves.

**1. Technical standards for mangrove seedlings:**

(1) Seedling age: Mangrove seedlings are grown in pots from 12-18 months old, depending on growing conditions. For favorable conditions, it is necessary to sow and care for at least 12 months. For difficult conditions, it is necessary to sow and care for 18 months old so that the tree trunk can become woody and withstand adverse conditions well.

(2) Seedling growth indicators: Root collar diameter from 0.8-1.2 cm; height from 0.8 to 1.2 m; Seedlings have breathing roots; Plants grow well and are not affected by pests or diseases.

(3) Mangrove trees must be transplanted at least 1 month before planting. For species that can sprout branches early and quickly such as *Sonneratia*, *Avicennia*, etc., mechanical treatment should be done by cutting and pruning branches and leaves before planting to increase the survival rate of the trees and minimize the impact of waves and sea winds on newly planted trees before they have time to take root.

**2. Method of planting mangroves**

Planting pure or mixed species of *K. obovata* and *Sonneratia caseolaris* or in high soil areas should be supplemented with planting of *Rhizophora stylosa*. In the aquaculture pond, plant pure *R. stylosa* or *S. caseolaris*. Areas with *R. stylosa* fruit should be used in place for incubation and planting in place, suitable for supplementary planting in aquaculture ponds with regular water retention. On the other hand, *R. stylosa* is a fast-growing species, with roots, foliage, and trunk suitable for protecting the banks of aquaculture ponds.

**3. Mangroves planting method**

(1) Forest planting season: Choose the time of year with the least waves to plant forests. Avoid the South wind season. In addition to choosing a time with less waves and

wind, tree planting must be completed 3 months before the season with strong winds and big waves. The suitable forest planting season is from May to September.

(2) Technique of digging holes before planting: the alluvial area for planting forests is often flooded with tides, has big waves, and strong winds, so dig holes and plant forests accordingly. Do not dig holes in advance, because if you dig holes in advance, the soil will cover the holes later when the tide floods.

(3) Planting technique: When planting forests with polyethylene-potted seedlings in tidal flats, the entire potted seedling must be brought onshore one week prior to planting to allow the soil in the pot to drain, ensuring that the root ball becomes firm and stable and reducing the risk off pot breakage during transportation. When transporting seedlings to the planting site, they should be placed in a tray, basket or other locally appropriate carrying tool. Seedlings must not be lifted by the stem or crown, as this may cause pot rupture or root breakage. Planting technique: Before planting, remove the pot casing. Position the seedling vertically, ensuring that the top of the root ball sits 3-5 cm below the surface of the planting hole. After backfilling, firmly compact the mud and soil around the root ball using hands or feet to stabilize the seedling. Collect all pot casing waste and transport it to the designated mainland disposal or soil- fill collection area.

(4) Staking technique: Stakes should be constructed from locally available materials, such as bamboo, piles, cajuput, or other suitable wooden poles. The number of stakes may be either one or three. Stakes should be 70-150 cm in height and 1-3 cm in diameter. If using a single stake, it should be driven into the ground at a 45-degree angle, with the stake head facing seaward (opposite the wave direction). The stake should contact the seedling stem at a height of 15-20 cm, and the connection should be secured with a soft rope at the point of contact. If using three stakes, they should also be driven at a 45-degree angle, forming a tripod configuration such that the meeting point of the three stakes lies 15-20 cm above the base of the seedling stem. One end of the soft rope should first be tied to the seedling, after which the remaining rope is used to secure the three stakes at their convergence point, ensuring that all stake heads are fixed firmly. The rope must be tightly fastened to prevent any movement of the seedling, which could cause abrasion against the stake, leading to bark damage, mortality, or increased susceptibility to infection at the wound site.

**4. Care and protection of mangrove forests after planting**

After 1-2 months of planting, check the dead trees, the rate is over 10%, so you should replant. Healthy seedlings of similar size to the surviving trees should be selected for replacement. The standards for seedlings, planting season, and planting techiques must follow the same requirement as those applied in initial mangrove establishtment (replanting should be conducted within the first three years). Forest maintenance must be carried out during the first three years after planting. During the first three months, in areas with substantial debris accumulation or exposure to strong wave, the site should be inspected every 10 days to remove debris, re-fix stakes, and re-tie support ropes. Thereafter, care activities should be conducted every three months, including weeding, debris removal, and supplementary planting, where necessary.

Signs prohibiting the exploitation or harvesting of aquatic species within the planted forest area must be installed. It is essential to prevent tree cutting, forest destruction, land encroachment, and the presence of harmful organisms and pests. Soil filling or the installation of nets that obstruct water flow within the planted forest area is prohibited during the first four years, whether for aquaculture or combined production purposes. In subsequent years, if aquaculture activities are permitted, a management plan must be implemented to ensure no damage occurs to the established mangrove forest.

## CONCLUSIONS

Criteria/indicators for dividing coastal mangrove sites in the Red River Delta Biosphere Reserve include: (i) Sub-soil type, (ii) Soil thickness (iii) Rainfall, (iv) Sub-terrain type, and (v) Forest status. Based on the establishment of mangrove site maps for commune-level units, appropriate silvicultural technical solutions for each site type group are proposed.

Based on the criteria, the research area is divided into 3 types: favorable, average, and difficult. Each type of site has an assessment and proposed appropriate technical solutions.

Initially propose solutions for developing mangrove forests for each type of site. In particular, solutions for selecting species, technical standards for seedlings to be planted (seedling age, height, root diameter, and tree quality), and techniques for transferring seedlings before planting are mandatory requirements. Planting techniques such as choosing the planting season, digging holes before planting, planting techniques, caring for and protecting trees after planting must be carried out in accordance with the above instructions.

## ACKNOWLEDGMENTS

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研究報告

# 紅河三角洲生物圈保護區紅樹林立地分類及其恢復造林生態工程對策之研究

Do Quy Manh[1], Nguyen Quoc Huy[1], Nguyen Minh Duc[1], Ha Tra My[1], Nguyen Thanh Luan[2,3], Pham Ngoc Tu[2]

## 摘 要

### 背景

越南擁有超過3,260 km的海岸線，處於熱帶季風氣候區，全國34個省市中有22個擁有沿海紅樹林。本研究的重點區域─紅河三角洲省際濕地生物圈保護區(簡稱紅河生物圈保護區)，於2004年被聯合國教科文組織指定，涵蓋興安省和寧平省，總面積超過105,558 ha，其中紅樹林面積超過7,081 ha。此區域的紅樹林生態系統具有重要的生態功能，包括作為眾多生物群體的棲息地和過渡中心，並提供木材、水產資源、生物過濾等寶貴的產品和服務，尤其對海堤加固、土壤穩定及碳吸存具有顯著貢獻。

然而，該地區的紅樹林生態系統正面臨嚴峻挑戰，包括：鹽鹼濕地土壤的時空變化、易受強風大浪侵襲、基質養分貧乏、氣候變遷和海平面上升的影響，導致紅樹林數量和品質下降。過去的紅樹林種植和恢復活動缺乏系統性、針對具體立地的研究、物種選擇和種植方法的技術指導，使得造林成活率(定義為存活率達60%)受到限制。

本研究之挑戰在於科學地劃分紅樹林立地類型，並據此提出支持恢復和重新造林的技術指南。因此，本研究的主要目標是基於科學標準，評估和分類紅河三角洲生物圈保護區(以興安和寧平兩省為代表)的紅樹林立地條件，以識別出具代表性的立地類型。次要目標是針對每種立地類型，開發適當的生態工程解決方案，以提高紅樹林的造林率和品質。本研究成果將為紅樹林生態分區提供科學基礎和系統性數據，並為該關鍵沿海地區應對氣候變遷和海平面上升提供穩定且永續的恢復措施。

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## 材料與方法

本研究以興安省和寧平省沿海公社的紅樹林和濕地土壤作為主要材料。研究方法採用量化途徑，整合了多種調查和分析技術：

1. 文獻搜尋與數據蒐集：彙整且評估了1990-2024年間研究區域內紅樹林面積變化的次級資料，以掌握生態系統的時空動態。
2. 紅樹林現況調查：在選定的紅樹林和濕地地區設立35個標準樣區(10 m × 10 m)，用於調查林分組成、物種鑑定、樹高、根徑、樹冠直徑等林分特性。
3. 土壤採樣與分析：在每個樣區設置土壤剖面，採集三個深度(0-20 cm、20-40 cm、> 40 cm)的土壤樣本進行實驗室分析。分析指標包括：顆粒大小、pH值、總可溶性鹽(EC)、氯化物含量及總氮、磷、鉀等含量，以評估土壤的鹽鹼和養分狀況。
4. 立地分類與評估：採用層次分析法(AHP)作為多準則決策工具，根據對紅樹林生長影響的重要性，賦予各指標不同的權重和分數。立地分類的核心指標包括：次生土壤類型、土層厚度、次生地形類型、降雨量和林分現狀。最終，根據累積加權分數E，將研究區域劃分為三種立地適宜性組別，即第一組：有利；第二組：一般；第三組：困難。

## 結果與討論

1. 紅樹林面積變化

   1990-2024年間，紅河三角洲生物圈保護區的紅樹林面積顯著減少了約40.1% (相當於4,953.2 ha)，與此同時，沿海沖積土面積增加了107%。其中，2005-2020年間森林面積急劇減少了4,768.6 ha，主要原因是將林地轉為水產養殖和沿海基礎設施建設。興安省的森林減少幅度最大，達45.3%，但其沖積土面積也大幅增加，顯示出巨大的潛在恢復空間。至2024年，紅樹林面積為7,411.4 ha，沖積平原面積為9,780.6 ha。

2. 紅樹林立地分類結果

   本研究應用層次分析法，並基於五個核心指標(次生土壤類型、土層厚度、次生地形類型、降雨量、林分現狀)的加權評估，將紅河三角洲生物圈保護區的紅樹林立地條件劃分為三種適宜性類別，其分佈呈現出顯著的地域差異。分類結果如下：

   (1) 第二組(一般)：佔據了最大的面積，達6,338.83 ha，其中興安省的面積尤為突出(3,379.04 ha)，此為顯示研究區域普遍存在，如：養分不足和中等程度的鹽分等「一般」限制條件。

   (2) 第三組(困難)：面積為4,809.87 ha，主要分佈在興安省的前海和太水等極限環境區域，凸顯了紅河三角洲沿海環境的嚴苛性。然而，這廣大的困難立地面積也同時證明了透過精準的生態工程措施，該地區仍具備巨大的森林恢復潛力。

   (3) 第一組(有利)：面積最小，為4,491.3 ha，但其分佈高度集中，其中寧平省的面積最大，達到3,445.96 ha。

整體而言，立地分類結果為後續制定針對性的生態解決方案，提供了詳實的科學基礎。

3. 針對不同立地條件的生態解決方案與技術規範

基於上述的立地分類結果，本研究提出了針對性的生態工程解決方案與技術規範，其目的為在提升紅樹林造林的成功率和永續性。這些技術建議根據立地條件的複雜程度分為三級，以指導現場的物種選擇、苗木準備與工程防護措施。

(1) 第一組立地：有利條件區域的常規造林方案

對於被劃分為「有利條件」的第一組立地(主要集中在寧平省，面積達4,491.31 ha)，其環境限制最小，因此可採用常規技術方法進行造林。在物種選擇上，既可使用繁殖體(如：紅海欖(*Rhizophora stylosa* Griff.)的胎生苗)，也可使用盆栽苗如：海桑(*Sonneratia caseolaris* (L.) Engl.)。由於環境穩定，對苗木標準的要求也較為寬鬆，僅需選用生長8-12個月的幼苗。此類區域的造林無需額外設置木樁或減浪柵欄進行保護，可根據生態目標選擇單一物種或多物種混養。此方案具備操作簡便、成本較低的優勢。

(2) 第二組立地：一般條件區域的適度工程介入

第二組立地(佔研究區域最大面積6,338.83 ha，集中於興安省)屬於「一般條件」，面臨中等程度的環境壓力，因此造林技術需進行適度調整。必須使用盆栽苗進行定植，以確保幼苗具備更高的存活率。根據當地具體的鹽分、養分或水流狀況，可考慮結合適當的工程措施。這些措施包括：小規模的場地改良，或是採用更高標準的苗木。關鍵在於根據現場評估，靈活決定是否需要額外的工程支撐，以確保紅樹林能夠在這些限制性條件下成功建立。

(3) 第三組立地：困難條件區域的多重工程結合策略

第三組立地(面積4,809.87 ha，廣泛分佈於興安省前海和太水)面臨嚴苛的「困難條件」，通常具有強浪衝擊、土壤貧瘠或鹽分極高的特點。因此，此類區域的造林成功必須依賴於多重技術措施的系統性結合。具體策略包括：

a. 使用標準盆栽苗木：必須選用具備更長苗齡(建議12-18個月)和更強壯規格的標準苗木，確保樹幹木質化程度高，足以抵抗惡劣環境。

b. 場地改良：針對土壤理化性質進行針對性改良，如調整土壤酸鹼度或增加基質有機質。

c. 設置木樁固定：必須使用木樁(如竹樁)以單樁或三腳架形式，牢固地固定樹木基部，防止幼苗因強風大浪而搖晃或被拔除。

d. 設置減浪柵欄與促進淤積：必須在造林區域外圍設置減浪柵欄(如竹製或木製柵欄)，以有效消減波浪能量，同時促進泥沙淤積，為紅樹林提供一個更穩定的生長基質和營養來源。

總而言之，第三組立地的解決方案強調從物種準備、環境基質到物理防護的全面干預，是確保紅樹林在最具挑戰性的沿海環境中實現永續恢復的關鍵。

## 結論

本研究成功建立了紅河三角洲生物圈保護區紅樹林立地分類的科學框架，並據此將研究區域精確劃分為「有利、一般、困難」三種立地類型。此劃分為將紅樹林恢復工作提供了至關重要的分區基礎。

研究成果證實，針對不同立地條件，必須採取差異化的生態解決方案。對於困難立地，必須綜合應用標準化幼苗、場地改良、木樁固定和減浪促淤柵欄等多項技術措施，才能有效提高造林成功率。本研究不僅為紅河三角洲提供了具體的紅樹林恢復技術指南，也為越南沿海地區應對氣候變遷和海平面上升的長期永續管理策略提供了強有力的科學支持。

**關鍵詞：**紅樹林、鹽沼、鹽沼棲地分類、造林技術

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