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Building Sustainable Indicators for Mangrove Forests Based on a Survey to Determine Forest Erosion in the Southwestern Sea of Vietnam

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ABSTRACT

The increased erosion of mangrove forests has alarmed the government about the damage to both the economy and livelihoods. To evaluated forest and land erosion the coast. Based on survey data is divided into five levels (F1: no erosion; F2: little erosion; F3: moderate erosion; F4: high erosion; F5: strong erosion), and ecological conditions, the coast is divided into sub-regions for investigation. From the surveyed indicators at each erosion level, forest structure is analyzed for comparison. The erosion level is defined as an erosion function (Er) from 1 to 5 (+), where (1) parameters include the number of trees per hectare (Ntr/ha), height to top (Ht), trunk diameter at 1.3 m (D1.3), tree canopy diameter (Dc), and width of the forest range (Wf); (2) land erosion is a function (Erl = Erlte + Erlsa + Erlsi + Erlcl), with parameters including erosion by terrain (Erlte), sand (Erlsa), silt (Erlsi), and clay (Erlcl); and (3) climate change leading to erosion is an inverse function (Cl) from 1 to 5 (–), with parameters including erosion by rainfall (Clra), wind (Clwi), waves (Clwa), and tide (Clti). The resulting function output is Er = (Erf + Erl)–Cl. On eroded forest land, species were tested under climate change conditions and their growth in the next rainy season to assess survival rates affected by rainfall, waves, wind, and tides. These results help to plan planting mangrove forest anti-erosion models and construct a theoretical function of mangrove erosion and proposes restore forests using pioneer species.

Keywords: Mangroves Forest; Forest Erosion; Coastal Erosion; West Sea; Vietnam

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1. Introduction

Kien Giang and Ca Mau provinces in the Southwestern Sea of Vietnam. In recent years, erosion of coastal and sea dykes has increased. Kien Giang and Ca Mau with the coastal length is 300 kilometer (km), on August 5th 2020, in Ca Mau province the storm No. 2 was damaged section to 700 meter (m) of the sea dyke and the width of forest was lost 20–25 meter (m) a section 500m [1]; in Kien Giang province is lost a section 500 m of the mangrove forest [2]. The damage caused by Storm No. 2 in the rainy season of 2020 shows that it is necessary to study the impact of climate change factors on mangrove forests and sea dykes in the Southwest coastal region of Vietnam.

After that event, the research team was supported by the Department of Agriculture and Rural Development in two provinces to investigate the erosion situation to find the scientific basis for the erosion of mangrove forests and sea dykes. The investigated indicators are the current status of forest erosion with levels divided into five levels. Forest data will be constructed into a function, and the survey indicators are parameters.

The structural factors of the mangrove forest range from levels 1 to 5. The average soil terrain was calculated, and soil samples were collected to analyze the sand, silt, and clay components of the ecological sub-regions. The data of soil terrain and soil physical factors are constructed into functions; the indicators are parameters. The factors of climate change and sea-level rise were collected in the last 5 years to synthesize into factors affecting forest and sea dike erosion including monthly and annual average data such as rainfall, waves, wind and tides; synthesize these factors into a function and the collected parameters.

The research results will provide a theoretical basis and practical experience to develop criteria for coastal protection forests to prevent erosion by climate change and rising sea levels [3]. Through research and assessment of forest structure to divide the level of erosion with width forest range to find control criteria for less erosion by the impact of climate change and sea level rise [4].

Based on the results of the study on eroded areas, the reforest station is considered a sustainable solution. This study also experiments with a list of forest species to trial on eroded forest land to help develop a model of these species into a future forest that can adapt to climate change.

2. Research Methods

2.1. Methods

2.1.1. Methods of Forest

Survey three sample plots for each sub-region to calculate the coefficient of variation in the height of the sample plots, and determine the relevant values for calculation [5]. The directions of the survey lines are arranged from the land to the sea and are evenly spaced. The lines and plots on the base map to determine the outside the field. Each sample plot is designed with three plots, the number tested is 18 plots and the number investigated is 68 plots, the total number plots collected is 96 plots.

Determine indicators: Number of trees per hectare (N/ha), the trunk diameter at 1.3 m (D1.3), height to top (Ht), the canopy diameter (Dc), the width of forest ranges (Wfr).

Erosion due to forest structure is designed by Erf: (0–1), (0.1, 0.2, 0.3, 0.4, 0.5…).

Where Erf indicates Erosion by forest structure; Erfnt denotes Erosion by the number of trees per area; Erfd1.3 stands for Erosion by the effect of trunk diameter at 1.3 m; Erfht points to Erosion by the effect of the height of the tree to the top; Erfdc represents Erosion by the effect of the canopy diameter; Erfwr denotes the Width of the forest range.

2.1.2. Methods of Land Terrain and Properties

Applying the FAO soil survey method [6]; Based on the map of the current status of forest protection in Kien Giang province in the western sea of the Mekong Delta prepared by the Southern Forest Investigation and Planning Sub-Institute (2010) and annual forest resource reports 2010–2022 (Kien Giang), maps of Kien Giang; Each soil site from 0–80 cm to take three soil samples; total five sub-regions; Each region one types of land: total number of soil samples taken for analysis is 15 samples for forest objects. All the above samples were brought to the Intensive Laboratory of Kien Giang University for analysis [7].

Erl: (0–1), (0.1, 0.2, 0.3, 0.4, 0.5…)

The collected and analyzed indicators include soil terrain (te), sand (sa), silt (si), and clay (cl). Erte indicates erosion of soil terrain, Ersa represents erosion of sand, Ersi signifies erosion of silt, and Ercl stands for erosion of clay.

2.1.3. Methods of Climate Change

Synthesize monthly and annual average data on rainfall, wind, waves, and tides of Kien Giang [8].

Based on the collection of monitoring data from the hydro-meteorological stations of Kien Giang province, on wind speed, wave height, and hydrological water level, to find out the risk of erosion, analysis, and assessment of climate change and sea level rise in the west coast of Kien Giang province.

Rainfall (Clr) Collect data and documents on the rainfall, consider rules of rainfall change, maximum and minimum according to the months of the year, and compare the change over the 5-year period on the basis of the data collected.

Wind (Clwi): Collect data and documents on wind supply, the rules of wind supply, maximum and minimum wind speeds for each month of the year, and compare changes in 5-year period on the basis of available data.

Waves (Clwa): Collect data and documents on wave height evolution, the maximum and minimum follow the months of the year, and compare the changes over the 5-year period on the basis of available data.

Tides (Clti cm): Collect data and documents on tides for 5 years, maximum and minimum levels by months of the year, and compare changes in 5 years on the basis of available data.

Cl stands for Climate change by erosion; Clr represents Climate change by erosive rainfall; Clwa indicates Climate change by wave erosion; Clwi means Climate change by wind erosion; Clti signifies Climate change by tidal erosion.

2.2. Species Trial Method

The experiment was performed on nine species:

(1) *Soneratia alba*: Formula 1 (Fo1) (Soa)
(2) *Lumnitzera litorea*: Fo 2 (Luf)
(3) *Ceriops zippeliana*: Fo 3 (Cez)
(4) *Rhizophora apiculata*: Fo 4 (Rhf)
(5) *Avicennia marina*: Fo 5 (Avm)
(6) *Avicennia officinalis*: Fo 6 (Avo)
(7) *Avicennia alba*: Fo 7 (Ava)
(8) *Bruguiera cexangula*: Fo 8 (Brc)
(9) *Xylocarpus grannatum*: Fo 9 (Xyg)

Planted seven tree x 7 tree (49 trees per plot), distance between rows and trees is 1 meter, made seedling in plastic bags, 20 cm height and 10 cm diameter. There are three experiments with a water level of 20 cm, each experiment 4 repeated four times (**Figure 1**). The experiment was measured twice after 3 months planted at the end of the dry season, and the second time in September the end of the rainy season, to check the adaptability of the species to rainy, wave, wind and tides conditions. The indicators measured are tree height growth and survival rate [9].

Figure 1. Seedling of Experimental Species Prepared in the Nursery.

3. Results

3.1. Results on Mangrove Erosion

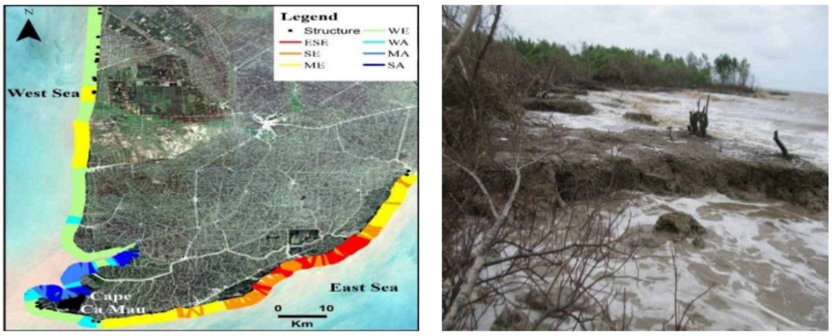
3.1.1. Theoretical Study on Sustainability in Forest Erosion

Theoretical research on forest and sea dyke erosion is illustrated in **Figure 2** and **Figure 3**.

Forest erosion:

$$Erf = (Erfnt + Erfd1.3 + Erfht + Erfdc + Erfwr) \quad (1)$$

Erf: Erosion by forest structure; Erfnt: Erosion by the number of trees per area; Erfd1.3: Erosion by the effect of trunk diameter at 1.3 m; Erfht: Erosion by the effect of the height of the tree to the top; Erfdc: Erosion by the effect of the canopy diameter; Erfwr: Width of the forest range.



(**a**) Erosion Status of West Sea of Vietnam. (**b**) Erosion in An Minh.

Figure 2. Forest and Sea Dyke Erosion. (a) Erosion Status of West Sea of Vietnam (Source of Landsat, 2020); (b) Erosion in An Minh (Section 5, 2020).

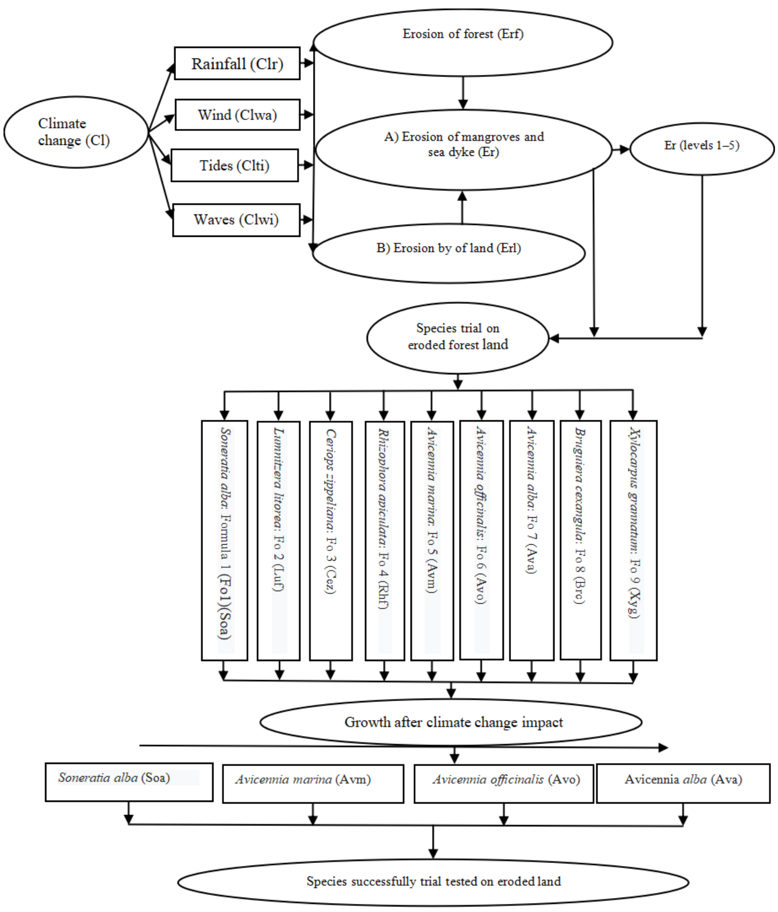


Figure 3. Theoretical Research Diagram on Erosion of Mangrove Forests in the West Coast of Vietnam.

Land erosion:

$$\mathrm{Erl} = (\mathrm{Erlte} + \mathrm{Erlsa} + \mathrm{Erlsi} + \mathrm{Erlcl}) \quad (2)$$

Erl: Land erosion level; Erlte: Erosion by affected land terrain, Erlsa: Erosion affected by sand ratio; Erlsi: Erosion affected by silt ratio; Erlcl: Erosion affected by clay ratio.

$$\mathrm{Cl} = (\mathrm{Clr} + \mathrm{Clwa} + \mathrm{Clwi} + \mathrm{Clti}) \quad (3)$$

Cl: Climate change by erosion; Clr: Climate change by erosion rainfall; Clwa: Climate change by erosion waves; Clwi: Climate change by erosion wind; Clti: Climate change by erosion tidal.

$$\mathrm{Erfl} = \mathrm{Erf} + \mathrm{Erl} \quad (4)$$

where Erfl stands for Mangrove erosion, Erf means forest structure erosion, and Erl denotes land structure erosion.

Case (0) means the forest is not eroded; case (1) represents complete erosion.

$$\mathrm{Er} = (\mathrm{Erf} + \mathrm{Erl}) - (\mathrm{Cl}) = \mathrm{Efl} - \mathrm{Cl} \quad (5)$$

Erfl = 1 and Cl = 0 indicate no erosion; Erlf = 0 and Cl = 1 represent total erosion.

Er is total erosion, as calculated by formula (5).

3.1.2. Growth of Mangrove Forests with Erosion

- **Comments (Table 1)**

The results in **Table 1** show that: In terms of time to complete erosion, there are five sections: section 1 has no erosion, section 2 has slight erosion, section 3 has moderate erosion, section 4 has high erosion, and section 5 has severe erosion for the forest. Forest erosion by forest structure in the system studied with indicators like the forest density (Ntr/ha), the tree height (Ht), the tree trunk diameter (D1.3), the tree canopy diameter and width forest range (Wfr).

Table 1. Average Growth Indicators of Mangrove on Erosion Level on the Fields.

No.	Sections	Ntr/ha	Ht (m)	D1.3 m (cm)	Dc (m)	Wfr (m)	Erosion of Forest (Erf)
1	Ha Tien	7,200	4.01	4.88	1.76	148	1–2
2	Kien Luong	4,350	6.21	8.53	2.95	94.64	2–3
3	Hon Dat	3,704	7.12	9.51	3.59	32.63	3–4
4	An Bien	4,350	6.21	8.69	2.95	94.64	2–3
5	An Minh	2,407	5.70	9.86	2.56	33.1	5
	Average	4,196	5.61	8.28	2.61	73.28	
	P > 0.01	> 0.01*	> 0.01*	> 0.01*	> 0.01*	> 0.01*	

Note: N/ha (Number of tree per hectare); Ht (the height to top); Dc (the canopy diameter of tree); Wfr (The width forest range). >0.01: Significant difference between regions; P > 0.01: With significance level P smaller>0.01.*

This division is found in the field; the sustainability of forests can be divided into 5 levels as follows: Section 1 – no erosion; Section 2 – slight erosion; Section 3 – moderate erosion; Section 4 – heavy erosion; Section 5 – severe erosion[10].

The results of the investigation in the specific case are as follows: Ha Tien (section 1) with density number of trees per hectare (ha) (Ntr/ha) is 7,200 trees (tr), height to top of tree (Ht) is 4.01 meter(m), the trunk diameter of tree at 1.3 m (D1.3) is 4.88 centimeter (cm), the canopy diameter of tree (Dc) is 1.76 meter (m), Width of the forest range is 148 meter (m), erosion (Erf) is (no erosion). Kien Luong (section 2) Ntr/ha is 4,350tr, Ht height to top (Ht) is 6.21m, D1.3 is 8.53 cm, Dc is 2.95 m, Wfr is 94.62 m, Erf is (little erosion). Hon Dat (section 3) Ntr/ha is 3,704tr, Ht is 7.12m, D1.3 is 9.51 cm, Dc is 3.59 m, Wfr is 32.63 m, Erf is (heavy erosion). An Bien (section 4) Ntr/ha is 4,350tr, Ht is 6.21m, the diameter at 1.3 m (D1.3) is 8.69 cm, the canopy diameter (Dc) is 2.95 m, Width of the forest range is 94.64, erosion (Erf) is (average erosion). An Minh (section 5) Ntr/ha is 2,407tr, Ht is 4.40 m, D1.3 is 8.22 cm, Dc is 2.61 m, Wfr is 31.1m, Erf is (strong erosion)[11].

- **Comments (Table 2)**

The structure of the survey average data indicators (**Table 2**) for each forest section is divided into five levels based on structural characteristics, as follows.

Section 1: the forest density was 9560 tr/ha, Ht is 12.53 m, D1.3 is 19.4 cm, Dc is 5.14 m, Wf is 271.5 m, Er is 1–2, indicating no erosion.

Section 2: Ntr/ha is 7680 tr/ha, Ht is 10.56 m, D1.3 is 16.08 cm, Dc is 3.76 m, Wfr is 214.8 m, Erf is 2–3, indicating little erosion.

Section 3: Ntr/ha is 5800 tr/ha, Ht is 8.59 m, D1.3 is

12.63 cm, Dc is 3.44 m, Wfr is 157.5 m, Erf is 3–4, indicating moderate erosion.

Section 4: Ntr/ha is 3920 tr/ha, Ht is 6.62 m, D1.3 is 9.25 cm, Dc is 2.61 m, Wfr is 100.5 m, Erf is 4, indicating high erosion.

Section 5: Ntr/ha is 2040 tr/ha, Ht is 4.65 m, D1.3 is 5.86 cm, Dc is 1.77 m, Wfr is 43.3 m, Erf is 5, indicating strong erosion.

Table 2. Maximum Growth Structure of Mangrove Forest Divided on the Status of Erosion.

Section	Ntr/ha (tr)	Ht (m)	D1.3 (cm)	Dc (m)	Wfr (m)	Erf (1...5)
Section 1	9560	12.526	19.398	5.139	271.5	1–2
Section 2	7680	10.558	16.077	3.757	214.8	2–3
Section 3	5800	8.59	12.63	3.445	157.5	3–4
Section 4	3920	6.622	9.246	2.613	100.5	4–5
Section 5	2040	4.654	5.862	1.771	43.5	5
Average	5800	8.59	12.64	3.34	157.56	
$P > 0.01$	> 0.01*	> 0.01*	> 0.01*	> 0.01*	> 0.01*	

Note: > 0.01: Significant difference between regions; P > 0.01: With significance level P smaller > 0.01.*

The sustainability of forests in terms of erosion depends on five factors: density, forest height, tree trunk diameter at 1.3 m forest canopy diameter and forest range width; the formula Erf is the forest erosion, Erfnt is the density coefficient, Erfht is the erosion of forest height, Erfd1.3 is the erosion of diameter at 1.3 m, Erfdc the erosion of the tree canopy diameter, Erfwr is erosion of the width forest range, these impact coefficients contribute to the impact on sustainability against erosion[12].

Erosion with direct forest to sea level can be simulated:

Erf: (0–1) (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1)

Case (0) is the forest is not eroded; case (1) is the case of complete erosion.

3.2. Land Erosion of Mangrove Forest

- **Comments (Table 3)**

The soil map of the mangrove forest (**Table 3**) shows that erosion caused by soil factors is determined by elements such as terrain, sand, silt, and clay. Determining soil types on the map and verifying in the field shows: Ha Tien (Section 1) has potentially deep, salty acid soil under the mangrove forest, with terrain at 0.8–1.0 m. Kien Luong (Section 2) has acid-alkaline soil that is deeply active in mangroves, and acid soil with potential for deep saline intrusion under mangroves, with terrain at 0.6–0.8 m. Hon Dat (Section 3) has potential acid soil that is deep and salty under the mangrove forest, with terrain at 0.4–0.6 m. An Bien (Section 4) has saline soil typical of mangroves, with terrain at 0.2–0.4 m. An Minh (Section 5) also has saline soil typical of mangroves, with terrain at 0.2–0.4 m[13].

In these terrains, it shows that Section 1 has no erosion due to high terrain; Section 2 has little erosion; Section 3 has moderate erosion; Section 4 has high erosion; and Section 5 has strong erosion (**Figure 4**).

Section 1 in Ha Tien: sand ratio (sa%) is 79.38%, silt (si%) is 17.08%, and clay (cl%) is 3.54%, erosion level is 1–2.

Section 2 in Kien Luong: sa% is 17.32%, si% is 60.28%, cl% is 8.89%, erosion level is 2–3.

Section 3 in Hon Dat: sa% is 6.6%, si% is 62.8%, cl% is 30.58%, erosion level is 3–4.

Section 4 in An Bien: sa% is 1.02%, si% is 92.66%, cl% is 6.31%, erosion level is 4–5.

Section 5 in An Minh: sa% is 1.5%, si% is 69.41%, cl% is 29.08%, erosion level is 5[14].

Table 3. Land Erosion of Mangrove Forest.

No.	Locations	Types of soil	Terrain (te)	Sand sa%	Silt (si%)	Clay (cl%)	Land Erosion (Erl)
1	Ha Tien	Sj2Mm	0.8–1.0 m	79.38	17.08	3.54	1–2
2	Kien Luong	Sp2Mm	0.6–0.8 m	17.32	60.28	8.89	2–3
3	Hon Dat	Sp2Mm	0.4–0.6m	6.6	62.8	30.58	3–4
4	An Bien	Mnh	0.2–0.4 m	1.02	92.66	6.31	4–5
5	An Minh	Mnh	0.0–0.2 m	1.5	69.41	29.08	5
	Average			21.16	69.45	15.68	
	$P > 0.01$			> 0.01*	> 0.01*	> 0.01*	

Source: Soil map of Department of Agriculture and rural Development, Kien Giang, 2020
Note: > 0.01: Significant difference between regions; P > 0.01: With significance level P smaller > 0.01.*

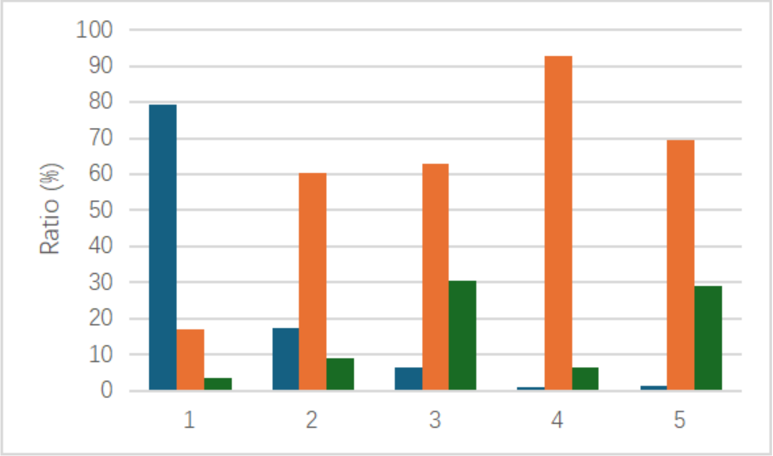


Figure 4. Ratio of Sand, Meat, Clay with Erosion.

This result shows that the higher the sand content in the soil, the greater the compactness, the lower the soil erosion and vice versa. The higher the silt content in the soil, the softer the soil and the more susceptible to erosion by external factors[15].

The Status of Land Erosion

- **Comments (Table 4)**

Land eroded status (**Table 4**, **Figure 5**) shows:

- Section 1 in Ha Tien: Terrain Te is 0.9 m (standard water level), property is tight, physic is sand, land erosion (1–2).
- Section 2 in Kien Luong: Te is 0.7 m, property is slightly tight, physic is silt–sand, land erosion (2–3).
- Section 3 in Hon Dat: Te is 0.5 m, property is moderately tight, physic is clay–sand, land erosion (3–4).
- Section 4 in An Bien: Te is 0.3 m, property is soft, physic is silt, land erosion (4).
- Section 5 in An Minh: Te is 0.2 m, property is very soft, physic is silt, land erosion (5)[16].

Table 4. The Status of Land Erosion.

No.	Section	Average Terrains	Property of Land	Physical of Land Soil	Land Erosion
1	Section 1	0.9	Tight	Sand	1–2
2	Section 2	0.7	Little tight	Silt - sand	2–3
3	Section 3	0.5	Moderate tight	Clay - sand	3–4
4	Section 4	0.3	Soft	Silt	4
5	Section 5	0.2	Very soft	Silt	5

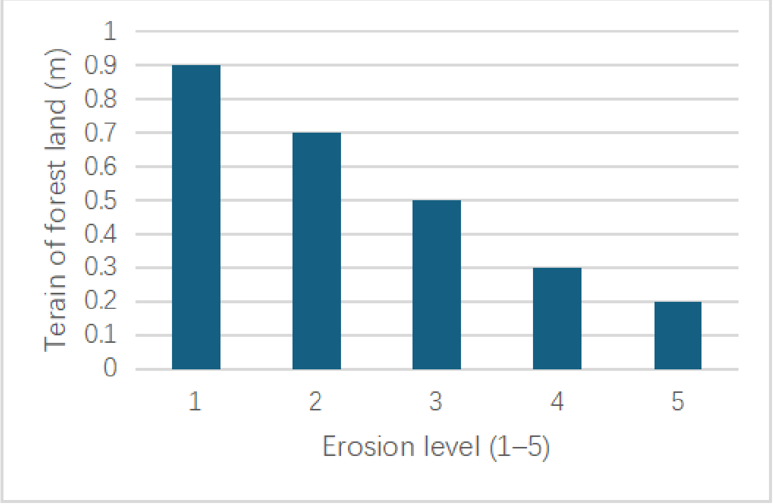


Figure 5. Terrain of Forest Land with Erosion Level.

3.3. Climate Change of Rainfall, Wind Level, Waves and Tide

3.3.1. Climate Change

Climate change is cause of erosion which is modeled by the formula (3).

Cl: Climate change by erosion; Clr: Climate change by erosion rainfall; Clwa: Climate change by erosion waves; Clwi: Climate change by erosion wind; Clti: Climate change by erosion tides.

3.3.2. Rainfall in Year and in Months

- **Comments (Table 5)**

Rainfall in the year (**Table 5**, **Figure 6**) shows:

Average rainfall in 2016 was 2,268 mm; in 2017, 2,510 mm; in 2018, 2,631 mm; and in 2019, 2,420 mm. Among these, 2016 had the lowest and 2018 had the highest rainfall. Over the past 5 years, average annual rainfall has tended to increase.

Average monthly rainfall in 2016 was 189 mm; in 2017, 209 mm; in 2018, 219 mm; in 2019, 202 mm; and in 2020, 295 mm. Average monthly rainfall in recent years also shows an increasing trend[17].

Clr: (−0–−1)—This indicator represents erosion over time. (4.1)

Table 5. Average Rainfall in Years and in Months.

Year	Average Rainfall in a Year (mm)	Average Rainfall per Month (mm)
2016	2268.00	189
2017	2510.20	209
2018	2631.00	219
2019	2420.10	202
2020	2344.30	195

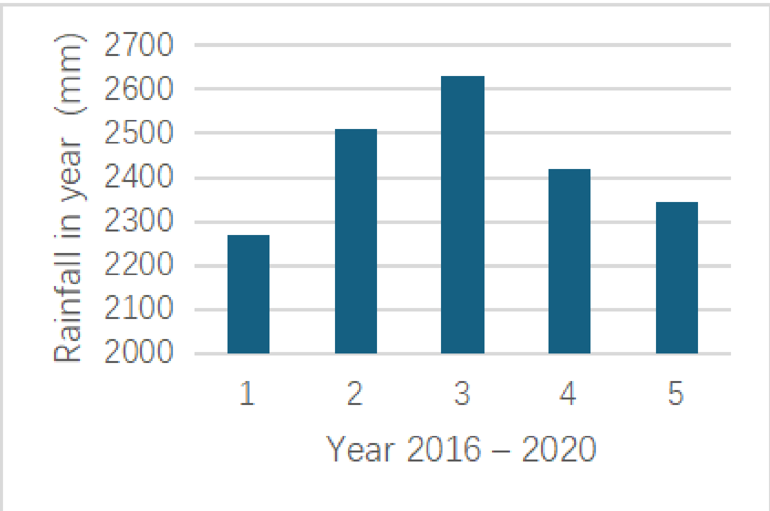


Figure 6. Average Rainfall in Year (2016–2020).

- **Comments (Table 6)**

Average monthly rainfall in Year 5 (**Table 6**, **Figure 7**) shows:

February has the lowest rainfall at 0 mm. Rainfall in May is 204.4 mm, and the highest rainfall is in September at 359 mm. The rainy season lasts from May until January of the following year. The average rainfall in January is 102.2 mm.

Forest erosion begins from May to October, with the most severe erosion occurring in September and October, because the average rainfall during these months exceeds 350 mm, indicating that erosion increases with rainfall[17].

Table 6. Average Rainfall of Months in Year from 2016–2020.

Year	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
2016	0.0	0.0	0.0	0.0	377.9	271.4	265.4	193.1	308.4	431.4	295.4	125
2017	152.2	65.9	87.3	204.3	254.6	128.7	294.3	339.7	224.5	408.3	218.6	131.8

Table 6. *Cont.*

Year	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
2018	221.8	9.7	74.0	95.5	203.1	284.5	493.0	356.6	297.9	236.5	156.0	202.4
2019	26.6	26.9	40.9	53.4	215.6	412.1	306.9	481.0	473.7	239.9	152.9	0.2
2020	8.1	1.6	10.9	106	151	306.8	229	300.7	490.3	478	167.2	94.7
Average	102.2	18.8	53.3	91.8	204.4	280.7	317.7	334.2	359	358.8	198	110.8
Statistical indicators	Min = 0; Max = 359											

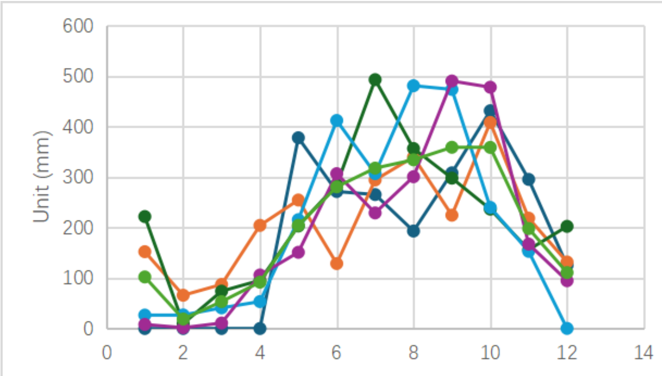


Figure 7. Rainfall of Months in Years (2016–2020).

3.3.3. The Waves Per Month in Year

- **Comments (Table 7)**

The wave levels in the months during the five years from 2016 to 2020 (**Table 7**, **Figure 8**) show that the lowest average wave height in January is 1 m. The waves start to increase in April, with the highest waves reaching 2 m. The highest waves occur in May at 3.5 m, followed by strong waves from June to October. The strongest waves are in September, reaching 3.8 m. Waves continue as northeast winds descend from November to January each year. Statistical indicators: Min = 1 m, Max = 3.8 m [18].

Table 7. Waves Level Height Month in Five Year from 2016–2020.

Year	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
2016	1.0	1.0	1.0	2.0	4.5	4.0	4.0	4.0	4.0	4.0	2.0	1.0
2017	1.0	1.0	2.0	2.0	4.0	3.0	4.0	3.0	3.0	4.0	2.0	2.0
2018	1.0	1.0	2.0	2.0	2.0	4.0	4.0	4.0	3.0	1.0	2.0	2.0
2019	2.0	1,0	2.0	2.0	3.0	4.0	3.0	4.0	4.0	2.0	2.0	2.0
2020	1.0	1.0	2.0	2.0	4.0	3.0	3.0	4.0	4.0	3.0	2.0	2.0
BQ	1.2	1.0	1.8	2.0	3.5	3.6	3.6	3.8	3.6	2.8	2.0	1.8
Statstical indicators	Min = 1; Max = 3.8											

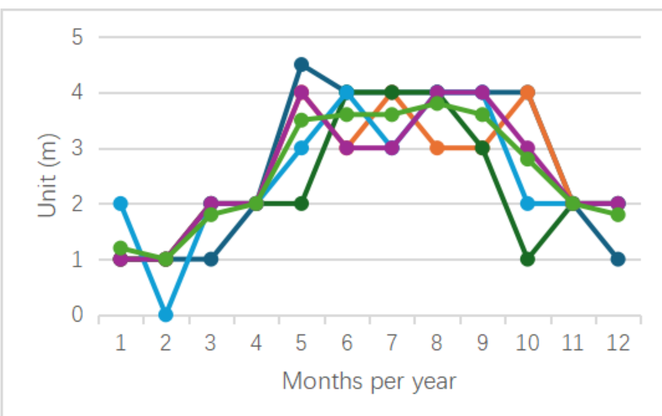


Figure 8. The Waves Per Month in a Year.

Clwa: (−0–−1)—This indicator represents the risk of wave erosion over time. (4.2)

3.3.4. The Wind Per Mocc

- **Comments (Table 8, Table 9)**

The wind per month over the years (**Table 8**, **Table 9**, **Figure 9**):

The lowest average monthly wind speed over the five years is in February, at 6.8 m/s. Wind speeds begin to increase in May, reaching 14 m/s, and remain strong through September, at 13.4 m/s. In December, due to the northeast monsoon, wind speed reaches 12.4 m/s. The highest wind speed of the year is in August, at 14.8 m/s.

Statistical indicators: TgMin = 6.8 m/s; TgMax = 14.8 m/s.

Extremely strong winds can cause sedge trees to fall, leading to coastal erosion and damage to coastal structures[19].

Clwi: (−0–−1)—This indicator represents the risk of wind erosion over time. (4.3)

Table 8. Statistical Maximum Average Wind Speed of Months in Five Years from 2016 to 2020.

Year	**Wi (M1)**	**Wi (M2)**	**Wi (M3)**	**Wi (M4)**	**Wi (M5)**	**Wi (M6)**	**Wi (M7)**	**Wi (M8)**	**Wi (M9)**	**Wi (M10)**	**Wi (M11)**	**Wi (M12)**
2016	7	7	7	8	19	17	16	16	14	15	9	7
2017	7	6	8	8	14	13	16	13	12	14	9	10
2018	7	7	8	9	10	14	15	16	13	6	8	16
2019	8	7	8	9	13	14	13	15	14	9	8	15
2020	7	7	8	12	14	13	12	14	14	11	9	14
Average	7.2	6.8	7.8	9.2	1.4	14.2	14.4	14.8	13.4	11.0	8.6	12.4
Statistical indicators	Min = 6.8 m/s; Max = 14.8 m/s											

Table 9. The Wind Level Per Month in Five Years 2016–2020.

Year	**Wi (M1)**	**Wi (M2)**	**Wi (M3)**	**Wi (M4)**	**Wi (M5)**	**Wi (M6)**	**Wi (M7)**	**Wi (M8)**	**Wi (M9)**	**Wi (M10)**	**Wi (M11)**	**Wi (M12)**
2016	4	4	4	5	8	7	7	7	7	7	5	4
2017	4	4	5	5	7	6	7	6	6	7	5	5
2018	4	4	5	5	5	7	7	7	6	4	5	5
2019	5	4	5	5	6	7	6	7	7	5	5	5
2020	4	4	5	6	7	6	6	7	7	6	5	5
Average	4.2	4.0	4.8	5.2	6.6	6.6	6.6	6.8	6.6	5.8	5.0	4.8
Statistical indicators	Min = 4; Max = 6.8											

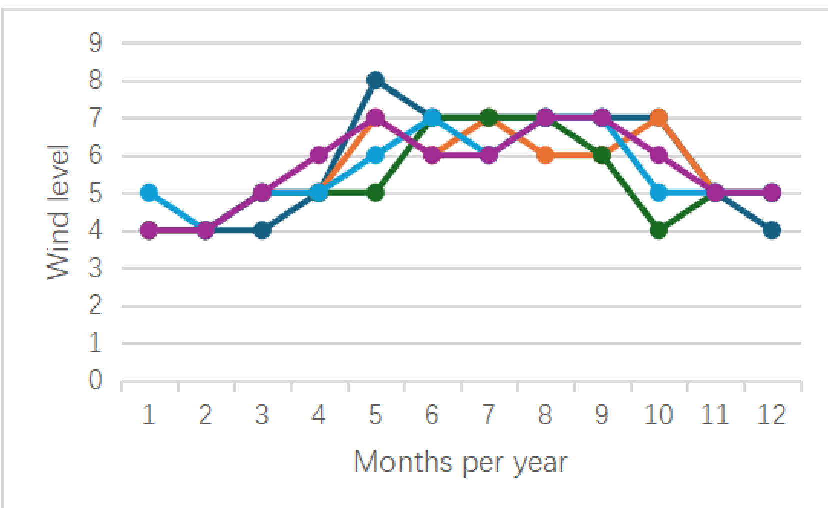


Figure 9. The Wind Level Per Month in Years.

3.3.5. Tides Per Month in Years

- **Comments (Table 10)**

The monthly tides over the years (**Table 10**, **Figure 10**) show that the lowest average tide in the five years is in April at 61.1 cm. Tide levels increase from June to January, with the highest average tide in September at 88.2 cm (Min = 61.1 cm; Max = 89.8 cm). High tidal levels cause erosion and damage to mangrove plantings and sea dykes.

Table 10. Tidal Levels Per Months in Five Year from 2016–2020 (Unit: cm).

Year	Ti (M1)	Ti (M2)	Ti (M3)	Ti (M4)	Ti (M5)	Ti (M6)	Ti (M7)	Ti (M8)	Ti (M9)	Ti (M10)	Ti (M11)	Ti (M12)
2016	83	77	70	51	93	78	74	68	80	87	91	81
2017	79	81	59	71	72	95	83	81	73	65	85	96
2018	91	87	71	55	51	95	105	99	75	88	77	78
2019	92	59	57	61	61	102	71	104	91	85	86	77
2020	75	75	54	67	60	67	66	73	122	106	110	93
Average	84	75.8	62.2	61.1	67.4	87.4	79.8	85.0	88.2	86.2	89.8	85.0
Statistical indicators	Min = 61.1 cm; Max = 89.8 cm; Unit: centimeter (cm)											

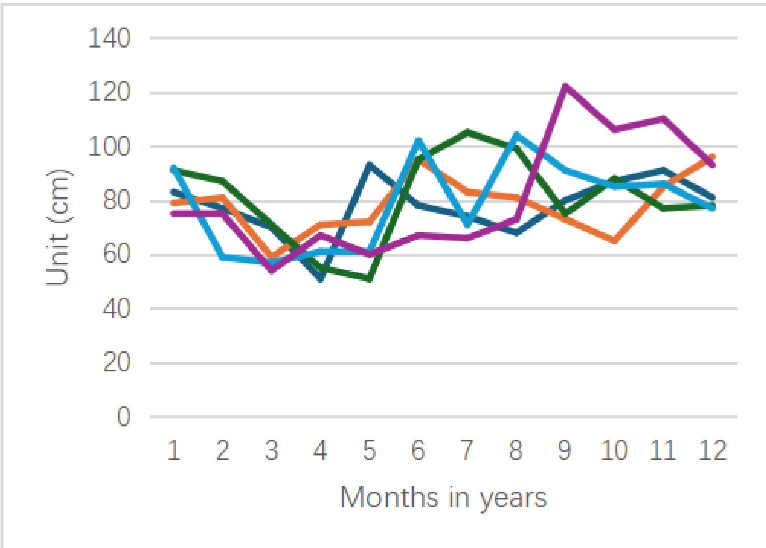


Figure 10. The Tides Per Month in Years.

Erosion levels are: January — Level 2; February and March — Level 1; April — Level 2; May — Level 4; June to September — Level 5; October — Level 4; November and December — Level 3.

From January to April, erosion levels range between 1 and 2. From May to October, the southwest wind blows strongly, combined with low pressure, storms, and heavy rain, resulting in erosion levels 4 and 5, which are very dangerous. November and December experience level 3 erosion due to the influence of northeast winds, considered moderately dangerous [20].

Clti: (−0–−1)— This indicator represents erosion over time. (4.4)

3.4. Species Trial for Forest Restoration in Eroded Areas

- **Comments (Table 11, Figure 11, Figure 12)**

In three experiments, forest was planted in January during the dry season on land directly eroded by the sea surface and impacted by tides, waves, and wind during the rainy season. The forest was first measured after three months (January to March) (**Table 11**, **Figure 11**, **Figure 12**). The results show:

Table 11. The Height Growth of Species in 3 Experiments at 3 Different Sites (Unit: cm).

No	Species	Experiment 1		Experiment 2		Experiment 3	
		3/2022	9/2022	3/2022	9/2022	3/2022	9/2022
1	*Sonneratia caseolaris*	58.30 ± 0.41^b	161.30 ± 3.01^a	59.95 ± 0.30^a	164.75 ± 2.80^a	59.69 ± 0.22^a	155.27 ± 3.05^b
2	*Lumnizera littorea*	59.85 ± 0.26^a	70.95 ± 0.95^a	58.51 ± 0.16^b	68.22 ± 0.42^b	58.35 ± 0.19^b	69.07 ± 0.30^b
3	*Ceriops decandra*	60.77 ± 0.45^a	66.00 ± 0.43^b	59.75 ± 0.51^b	67.35 ± 0.42^a	58.87 ± 0.45^c	65.00 ± 0.94^b
4	*Rhizophora mucronata*	58.97 ± 0.71^b	69.82 ± 1.31^a	60.72 ± 0.41^a	70.82 ± 0.88^a	60.07 ± 0.43^a	69.27 ± 1.35^a
5	*Avicennia marina*	58.85 ± 0.66^a	71.32 ± 1.31^b	58.95 ± 0.52^a	77.32 ± 0.88^a	59.70 ± 0.89^a	72.57 ± 1.35^b
6	*Avicennia officinalis*	59.95 ± 0.93^a	93.02 ± 1.31^b	57.87 ± 0.76^b	98.72 ± 0.88^a	58.35 ± 0.77^b	91.37 ± 1.35^b
7	*Avicennia alba*	59.35 ± 0.55^a	86.75 ± 1.17^a	58.82 ± 0.73^a	84.15 ± 0.59^b	59.12 ± 0.50^a	87.25 ± 1.41^a
8	*Bruguiera sexangula*	57.92 ± 0.53^b	72.22 ± 1.31^a	57.80 ± 0.69^b	71.02 ± 0.88^a	59.87 ± 0.29^a	71.12 ± 1.35^a
9	*Xyclocarpus grannatum*	58.35 ± 0.46^b	69.72 ± 0.31^a	59.12 ± 0.60^{ab}	70.47 ± 0.97^a	59.35 ± 0.38^a	69.55 ± 1.25^a

Note: (a, b, c) indicate no statistically significant difference at the 5% level (Duncan test). Unit: cm.

(**a**) Species Trial

(**b**) Measure of Mangrove Growth

Figure 11. (**a**) Species Trial; (**b**) Measure of Mangrove Growth.

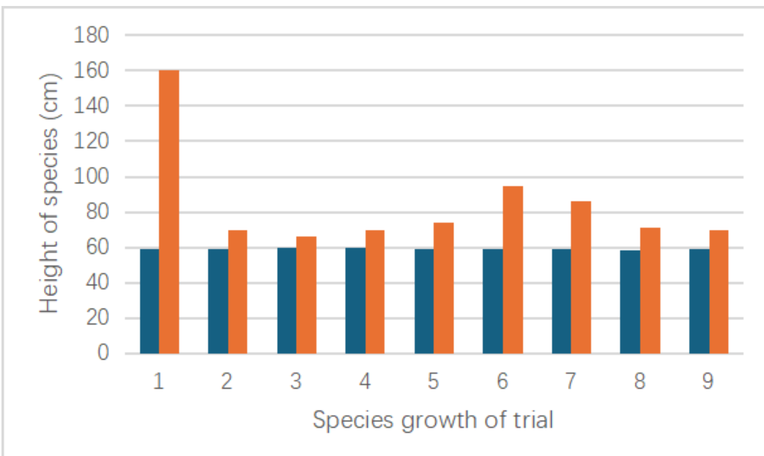


Figure 12. The height growth of species of Mangroves trial.

The species tested for adaptation were *Sonneratia caseolaris*, *Lumnizera littorea*, *Ceriops decandra*, *Rhizophora mucronata*, *Avicennia marina*, *Avicennia officinalis*, *Avicennia alba*, *Bruguiera sexangula*, *Xyclocarpus grannatum*. After three months, the height of all tested species ranged from 58.30 cm to 60.77 cm[21,22].

All species in the three experiments were measured for height at the end of the rainy season. The results are as follows:

- *Sonneratia caseolaris*: 161 cm, 164 cm, 155 cm
- *Lumnitzera littorea*: 70.95 cm, 68.22 cm, 69.07 cm
- *Ceriops decandra*: 66 cm, 67.35 cm, 65 cm
- *Rhizophora mucronata*: 69.82 cm, 70.82 cm, 69.27 cm
- *Avicennia marina*: 71.32 cm, 77.32 cm, 72.57 cm
- *Avicennia officinalis*: 93.02 cm, 98.72 cm, 91.37 cm
- *Avicennia alba*: 86.75 cm, 84.15 cm, 87.25 cm

- *Bruguiera sexangula*: 72.22 cm, 71.02 cm, 71.12 cm
- *Xylocarpus granatum*: 69.72 cm, 70.47 cm, 69.55 cm

The results of this experiment show the growth and survival rates during the first year of forestation under conditions affected by erosion[23].

Among these, two species that grew taller than the others were *Sonneratia caseolaris* and *Avicennia officinalis*. These are promising species for mangrove planting to prevent forest erosion.

- **Comments (Table 12)**

In the nine species planted on eroded forest land as follows: *Sonneratia caseolaris*, *Lumnizera littorea*, *Ceriops decandra*, *Rhizophora mucronata*, *Avicennia marina*, *Avicennia officinalis*, *Avicennia alba*, *Bruguiera sexangula*, *Xyclocarpus grannatum*. Plants planted at the end of the dry season were not affected by rain, waves and wind and experienced a rainy season combined with high tides. The end of the rainy season resulted in a very high survival rate in the experimental species.

After planting forests following a rainy season with high tides, heavy rain, strong waves, and wind, the surveyed species show the following percentage of surviving plants per plot:

- *Sonneratia caseolaris* — 35 out of 36 trees (97%),
- *Avicennia officinalis* — 34 out of 36 trees (94.44%),
- *Avicennia alba* — 33 out of 36 trees (91.67%),
- *Avicennia marina* — 32 out of 36 trees (88.88%),
- Other species — about 26 to 27 trees (72.92%–75%).

This result allows us to select species with a survival rate greater than 90% for large-scale planting (**Table 12**), aimed at developing forests to combat rapid erosion caused by climate change and rising sea levels in the Southwest region of Vietnam[24].

Table 12. Survival Rate of Species in 3 Experiments at 3 Different Sites (Unit %).

No	Species	Experiment 1		Experiment 2		Experiment 3	
		N (tree)	Sur. (%)	N (Tree)	Sur. (%)	N (Tree)	Sur. (%)
1	*Sonneratia caseolaris*	35.00a	97	34.75 ± 0.25a	96.53	34.50 ± 0.28a	95.83
2	*Lumnizera littorea*	27.00a	75	27.00a	75	26.25 ± 0.50b	72.92
3	*Ceriops decandra*	27.00a	75	27.00a	75	26.75 ± 0.50a	74.30
4	*Rhizophora mucronata*	27.00a	75	27.00a	75	26.25 ± 0.50b	72.92
5	*Avicennia marina*	32.00	88.88	32.00	88.88	31.00	86.11
6	*Avicennia officinalis*	34.00	94.44	33.00	91.67	32.00	88.88
7	*Avicennia alba*	33.00a	91.67	32.00a	88.88	32.75 ± 0.50a	90.97
8	*Bruguiera sexangula*	27.00a	75	26.75 ± 0.50a	74.30	26.50 ± 0.57a	73.61
9	*Xyclocarpus grannatum*	27.00a	75	26.75 ± 0.50a	74.30	26.75 ± 0.50a	74.30

Note: (a, b, c) indicate groups with no statistically significant difference at the 5% level (Duncan test). Unit: cm.

3.5. Discussion

3.5.1. Indicators for Mangrove Erosion

By investigating the erosion caused by storms, waves, and rising sea levels, it was found that part of the forest has been eroded, causing damage at varying levels[25]. The authors have divided this erosion damage into five levels: no erosion, little erosion, moderate erosion, high erosion and strong erosion.

Forest structure includes density, height, trunk diameter, canopy diameter, and width. For soil erosion indicators such as terrain, soil physical properties such as sand, silt and clay, the results can be obtained using the formulas (1), (2), and (4).

3.5.2. Indicators for Climate Change

Besides, the indicators of climate change, which are contrary to the sustainability of the forest, change daily or even hourly during the rainy season, eroding horizontally the forest range that we build[26]. These indicators are expressed according to the formula (3).

3.6. Indicators for Erosions

Erosion is the opposite of forest succession formation.

According to formula (5), the following conditions are satisfied:

If the forest is sustainable, Er = 1; if the forest is completely eroded, Er = 0, to know the level of erosion, investigate the current situation to calculate the level of damage in terms of area for assessment. When the area is eroded by 10%, the level of erosion to the forest is 0.1.

This formula is built to evaluate the mangrove forests of the western coast of Vietnam; it can also be used as a reference to evaluate other coastal mangrove forests, in which the parameters of forest, land and climate change conditions can be changed to suit specific conditions.

3.6.1. Hard Indicators of Southwestern Vietnam

Experience shows that in the investigation of forest erosion in the southwest coast of Vietnam, the density of forest planting to ensure erosion resistance requires (**Table 2**, Section 1 in Ha Tien) a density of 9560 trees per hectare of forest, and the forest range to ensure that the forest is not completely eroded is a minimum width of rang forest is 150 m for type soil sand ratio over 75% and 270m for type soil silt ratio over 75%.

3.6.2. For Species Selection and Future Afforestation to Limit Erosion

For planting forest after a rainy season to heavy rain, high waves, strong wind, and high tides the species grow high survival are *Sonneratia caseolaris* is 35/36 tree by 97% per plot, *Avicennia officinalis* is 34/36 by 94.44 % per plot, *Avicennia alba* is 33/36 tree by 91.67 %, *Avicennia marina* is 32/36 tree by 88.88 %; this result planting new forest on the eroded land.

In this group, these species have aerial roots. They grow upward from the ground; the root system adapts to high tidal levels, and they can live in saline water up to 2%, so they grow well in waves, wind, and tides on the new land.

The remaining group is five species, most of them are taproot system, live in areas with light salinity and high terrain, so they live in conditions of waves, wind and high tides; they are not adapted, so they grow slowly and have a low survival rate.

This method could limit erosion caused by climate change and rising sea levels in the future.

4. Conclusions

This study has established the initial theoretical basis for the formula to predict the current state of forest erosion from 1–5 level (1 is no erosion, 5 is strong erosion) with formula (1) assessing the state of forest erosion, formula (2) assessing the state of land erosion, formulas (3–5) assessing the impact of climate change the current state of erosion is a function (Er = Erfl (Erf + Erl)–Cl) in which Erfl (Erf + Erl) and the impact factors Cl, between Erfl–Cl, if Cl = 0 then there is no erosion, if Cl = 1 then the forest is eroded at level 5.

Mangrove forest in the case of surveying the southwest sea of Vietnam shows forest cover erosion at five different levels. There is sustainable forest without erosion when there are hard criteria such as forest density (N/ha) reaching 9,560 trees/ha, Ht of 12 m, D1.3 of 19cm, Dc of 5 m and Wfr of 270 m; Erosion reaches levels 4–5 when N/ha is 4,654 trees/ha, D1.3 is 5.9 cm, Dc is 1.7 m, and Wfr is 43 m.

Nine tree species experimental design research to find out the adaptability to climate change conditions were tested through a flood season, high rainfall, big waves, strong winds, and rising sea levels, but the experiment showed that four mangrove species that adapted after the rainy season still grew and developed well in high-density planting conditions, with a survival rate of over 90%; the remaining five species grew more slowly with a low survival rate of less than 75%. This result shows the prospect of building a high-density forest of 10,000 trees per hectare in the area of erosion that is taking place in the West Sea of Vietnam.

Author Contributions

Conceptualization, M.D., L.T.T. and N.T.H.D.; methodology, L.T.T.; validation, M.D., L.T.T., N.T.H.D. and B.M.N.N.; formal analysis, M.D., L.T.T., N.T.H.D. and B.M.N.N.; investigation, M.D., L.T.T., N.T.H.D. and B.M.N.N.; data curation, M.D., L.T.T., N.T.H.D. and B.M.N.N.; writing—original draft preparation, M.D. and L.T.T.; writing—review and editing, M.D., L.T.T. and N.T.H.D.; visualization, M.D. and B.M.N.N.; project administration, M.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The databases were created by us. Thus, they were used for our study and for the preparation of this article. They can be shared by the authors' group upon publication in the journal.

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Conflicts of Interest

The authors declare no conflict of interest.

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