

Article

Typhoon-Driven Shifts in Dissolved Organic Carbon Across Mangrove Ecosystems of Varying Restoration Age

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Abstract

Mangrove ecosystems are vital to coastal carbon cycling, yet their response to extreme climatic events remains underexplored. This study assesses dissolved organic carbon (DOC) dynamics across four ecosystem types—primary mangrove, restored (5-year and 8-year), and bare land—during three typhoons (Maliksi, Yagi, and Trami) that occurred in 2024. DOC concentrations ($\text{mol m}^{-2} \text{ s}^{-1}$) were measured across pre-, during-, and post-event phases and analyzed using boxplots, heatmaps, and ANOVA. Results show that primary mangroves maintained stable DOC levels, indicating strong biogeochemical resilience. Restored plots exhibited phase-dependent DOC variability, with older restoration age linked to improved carbon retention. Bare land showed consistently high DOC release, especially post-event, reflecting vulnerability to hydrological stress. DOC peaks occurred after typhoons, suggesting delayed carbon mobilization via microbial turnover and detrital input. These findings highlight the role of restoration age and vegetation cover in stabilizing coastal carbon under intensifying climatic extremes.

Keywords: mangrove restoration; dissolved organic carbon (DOC); typhoon disturbance; carbon flux; ecosystem resilience; bare land; restoration age; coastal carbon cycling; extreme climatic events; post-disturbance response



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1. Introduction

Mangrove ecosystems, situated at the dynamic interface between land and sea, play a pivotal role in carbon sequestration and the regulation of coastal biogeochemical cycles. Recognized as one of the most carbon-dense terrestrial systems, mangroves store substantial amounts of carbon both in vegetative biomass and sediment deposits. Their complex root architecture and high primary productivity contribute to the stabilization of soil organic carbon (SOC) and the accumulation of dissolved organic carbon (DOC) in interstitial waters [1,2]. These carbon pools, collectively referred to as “blue carbon”, are essential for mitigating climate change, with mangroves sequestering carbon at rates that often exceed those of tropical rainforests [3]. In this context, understanding the dynamics of DOC in mangrove pore waters is critical for evaluating their role in global carbon cycling and climate regulation.

DOC serves as a key component of the coastal carbon cycle, acting as a substrate for microbial communities and facilitating organic matter turnover and productivity within the water column [4]. Its concentration in pore waters is governed by a suite of interacting factors, including microbial degradation, root exudation, tidal exchange, and seasonal variations in hydrology and temperature [5]. While considerable research has focused on SOC accumulation in mangrove soils, the temporal and spatial dynamics of DOC—particularly in relation to seasonal fluctuations and restoration practices—remain less well understood.

Mangrove restoration has emerged as a prominent strategy for rehabilitating degraded coastal zones and enhancing carbon sequestration in tropical regions. Restoration approaches vary, ranging from active planting of seedlings to passive natural regeneration, and have demonstrated potential for gradually rebuilding carbon stocks over time. However, the recovery trajectory of DOC concentrations in pore waters following restoration is still unclear. Some studies suggest that restored mangrove forests can attain carbon storage capacities comparable to those of natural stands, while others report greater variability in DOC recovery [6,7]. In contrast, unvegetated or disturbed coastal areas typically exhibit lower and more erratic DOC levels due to the absence of root systems and vegetative cover that stabilize carbon inputs.

Seasonal variation further influences DOC dynamics in coastal ecosystems. In tropical climates, pronounced shifts in rainfall and temperature between wet and dry seasons affect the leaching, decomposition, and concentration of organic materials. During the rainy season, increased precipitation enhances the mobilization of organic matter from soils, elevating DOC concentrations in pore waters. Conversely, the dry season often leads to reduced water levels and more concentrated DOC pools [5]. These seasonal patterns have important implications for the stability of carbon reservoirs, particularly in ecosystems undergoing restoration or subject to anthropogenic disturbance.

In this study, we investigate dissolved organic carbon (DOC) concentrations in pore water across four coastal ecosystem types in Sanya, Hainan: natural mangrove forests, restored mangroves (5 and 8 years post-restoration), crab burrows, and bare land. Our primary objective is to assess how restoration age and seasonal variation influence DOC dynamics under typhoon disturbance. We hypothesize that older restored mangrove sites exhibit enhanced DOC stability due to improved canopy structure and microbial buffering, while bare land shows greater DOC fluctuation due to limited organic input and reduced retention capacity. This research provides field-based evidence for the role of mangrove restoration in regulating coastal carbon fluxes and highlights its ecological significance in the context of climate change resilience.

2. Materials and Methods

This study was conducted in four coastal regions of Sanya, Hainan Province, China: Haitang Bay, Yalong Bay, Sanya Bay, and Yazhou Bay. These sites represent a gradient of mangrove restoration stages and natural conditions, including primary mangrove forests, restored mangroves (5 and 8 years post-restoration), bare land, and crab burrow zones. The climate in Sanya is tropical monsoon, with distinct rainy (May–October) and dry (November–April) seasons. Mean annual precipitation ranges from 1300 to 2000 mm, and mean annual temperature is approximately 26 °C [6].

2.1. Experimental Sites

The study site is located in a typical tropical mangrove area of Sanya, Hainan Province, in southern China (109°41'56" E, 18°17'15" N) (Figure 1). We have installed small weather stations and other instruments related to measuring environmental factors, which can

measure the local environment (Tables 1 and 2). The average annual temperature is 23.8 °C, with a mean monthly maximum temperature of 28.4 °C in July and a mean monthly minimum temperature of 16.9 °C in January. The annual precipitation is 431.2 mm, and it is mostly concentrated from May to October. The annual total sunshine hours are 6.9 h in one day, and the annual UV index range is 10.9 in the region [6].



Figure 1. The experiment in the costal sample plot.

Table 1. Sediment information for experimental sites.

Research Area	0–20 (cm Depth)	20–40 (cm Depth)
Sand (%)	30.7	73.9
Silt (%)	0.22	0.57
Clay (%)	2.57	2.39
Organic (%)	3.42	2.52
Bulk Density (g/cm ³)	1.69	1.42

Table 2. Data collection instruments in this study.

Environmental Factor	Instrument	Height (+) or Depth (–)	Accuracy/Limitations
Air temperature/humidity	Campbell Scientific HMP45C capacitance hygrometer and thermistor (Logan, UT, USA)	+8 m	± 0.2 °C (temp), $\pm 2\%$ RH; may drift under prolonged exposure
Wind speed	Met One Instruments 014A 3-cup anemometer (Grants Pass, OR, USA)	+1, +3, +5, +8 m	± 0.5 m/s; sensitive to turbulence and debris
Wind fluctuations	Campbell Scientific CSAT3 ultrasonic anemometer (Logan, UT, USA)	+8 m	± 0.05 m/s; affected by rain and signal noise
Vapor fluctuations	Campbell Scientific KH ₂ O hygrometer (Logan, UT, USA)	+8 m	± 0.02 g/m ³ ; performance may vary with humidity extremes
Radiation (incoming/outgoing shortwave and longwave)	Kipp & Zonen CNR4 pyrgeometer and pyranometer (Delft, The Netherlands)	+8 m	$\pm 10\%$ (shortwave), $\pm 15\%$ (longwave); cloud cover may affect readings
Soil moisture	Campbell Scientific CS616 water content reflectometer (Logan, UT, USA)	–0.05, –0.1, –0.2, –0.4 m	$\pm 2.5\%$ VWC; salinity may interfere in coastal soils
Soil temperature	Omega Engineering Type-T thermocouple wire (Norwalk, CT, USA)	–0.05, –0.1, –0.2, –0.4 m	± 0.5 °C; response time may vary with soil type
Ground heat flux	Hukseflux HFT1 heat flux plate (Delft, the Netherlands)	–0.05, –0.1, –0.2, –0.4 m	$\pm 5\%$; sensitive to soil contact and compaction

The main coastal forests in Sanya City have been damaged and are currently in the recovery stage. The area of the remaining mangroves in Sanya is less than 258.69 hm². The middle part and the outer bank are dominated by mangroves, which are in clusters, accounting for 70% of the total. The mangrove restoration area is dominated by *Sonneratia apetala*, *Avicennia corniculatum*, *Avicennia marina*, and *Laguncularia racemosa* L. Among them, the *Laguncularia racemosa* L. accounts for 5% and is dominant locally, and *Avicennia corniculatum* is more scattered, accounting for 2% to 3%.

Located in a low-lying coastal zone, the study area contains a significant number of ancient mangrove trees, many over 50 years old. These trees are distributed across primary forest patches and exhibit extensive aerial root systems, thick trunk diameters, and high canopy coverage, all of which contribute to the site's ecological resilience. Among the mangrove wetlands in China, the largest individuals of *Lumnitzera racemosa* Willd., *Lumnitzera littorea* (Jack) Voigt, *Xylocarpus granatum* J. Koenig, *Bruguiera sexangula* (Lour.) Poir., *Casuarina equisetifolia*, and *Bruguiera gymnorhiza* (L.) Savigny are all distributed in this tidal flat. It is one of the oldest mangrove forests in China. The sediment depth of mangrove wetlands is about 30–40 cm, with a top organic layer that is between 0.05 and 0.2 m thick; furthermore, the sediment layer is a mixture of sandy clay, gravel, and an organic layer (Table 2). A systematic sampling method was conducted because of the homogenous distribution of the plant species in small sub-strata.

Environmental conditions across the study period were monitored to account for seasonal and interannual variability that may influence DOC responses. As shown in

Table 3, the mangrove sites experienced pronounced fluctuations in precipitation and sea temperature, particularly during the typhoon season (May–October), which coincides with peak DOC activity and disturbance exposure.

Table 3. Inter-annual dynamics of mangrove forest environment at different recovery stages (30 October 2022 to 30 October 2024).

	Environmental Factors (Mean $\pm$ SD)					
	Average Maximum Temperature/ $^{\circ}$ C	Average Minimum Temperature/ $^{\circ}$ C	Average Precipitation/mm	Average Rainy Days/Day	Average Sea Temperature/ $^{\circ}$ C	Average Sunshine Duration/h
January	26.1 $\pm$ 1.5	18.5 $\pm$ 1.7	8.2 $\pm$ 0.4	2.4 $\pm$ 1.3	20.4 $\pm$ 2.4	11.2 $\pm$ 0.6
February	26.8 $\pm$ 1.2	19.8 $\pm$ 1.3	12.8 $\pm$ 0.7	1.6 $\pm$ 1.8	19.7 $\pm$ 1.9	11.6 $\pm$ 0.7
March	28.6 $\pm$ 1.7	21.9 $\pm$ 1.1	19.2 $\pm$ 1.3	3.9 $\pm$ 1.4	21.4 $\pm$ 3.7	12 $\pm$ 0.8
April	30.7 $\pm$ 1.3	24.2 $\pm$ 1.8	43.3 $\pm$ 4.9	5.6 $\pm$ 1.3	23.1 $\pm$ 0.4	12.6 $\pm$ 0.4
May	32 $\pm$ 1.9	25.6 $\pm$ 1.6	202.3 $\pm$ 17.8	10 $\pm$ 1.5	28.9 $\pm$ 0.9	13 $\pm$ 0.3
June	31.9 $\pm$ 1.5	26.1 $\pm$ 1.2	397.5 $\pm$ 35.7	14 $\pm$ 3.1	29.7 $\pm$ 1.3	13.2 $\pm$ 0.5
July	31.7 $\pm$ 1.9	25.9 $\pm$ 1.1	592.6 $\pm$ 24.2	13.8 $\pm$ 4.8	29.8 $\pm$ 1.2	13.1 $\pm$ 0.7
August	31.4 $\pm$ 2.6	25.5 $\pm$ 1.5	421.5 $\pm$ 39.6	16 $\pm$ 3.9	28.8 $\pm$ 1.5	12.7 $\pm$ 0.3
September	31.2 $\pm$ 2.3	24.7 $\pm$ 1.6	451.4 $\pm$ 53.5	17 $\pm$ 2.2	28.3 $\pm$ 2.4	12.2 $\pm$ 0.3
October	30.2 $\pm$ 2.1	23.4 $\pm$ 1.3	334.5 $\pm$ 14.1	13.5 $\pm$ 3.8	27.2 $\pm$ 3.5	11.7 $\pm$ 0.5
November	28.5 $\pm$ 1.7	21.3 $\pm$ 1.3	78.3 $\pm$ 2.7	3.6 $\pm$ 1.9	22.6 $\pm$ 2.3	11.3 $\pm$ 0.2
December	26.6 $\pm$ 1.8	19 $\pm$ 1.4	10.7 $\pm$ 1.5	2.1 $\pm$ 1.3	21.5 $\pm$ 1.6	11 $\pm$ 0.6

2.2. Plot Design and Sampling Methods

Field sampling was conducted in Sanya, Hainan, across four coastal ecosystem types: natural mangrove forests, restored mangrove plots (5 and 8 years post-restoration), crab burrow zones, and bare land. Restored sites were rehabilitated in 2015 and 2022 using native mangrove species (*Rhizophora stylosa* and *Avicennia marina*) to enhance habitat structure and carbon sequestration. Crab burrow plots represent areas of active bioturbation, while bare land plots serve as degraded controls lacking vegetation and root systems.

Sampling occurred over two seasonal periods—rainy season (May–October) and dry season (November–April)—with three sampling trips per season, totaling 12 events between 30 December 2022 and 30 December 2024. Seasonal classification was based on meteorological data from a flux tower (8 m height) and the nearby Tielu Bay Forest Ecosystem Research Station. The dry season spanned 21 November 2023 to 28 April 2024, and the rainy season from 1 May 2024 to 28 March 2025. Environmental parameters, including rainfall, temperature, tidal cycles, and atmospheric pressure, were monitored throughout the study. Instrumentation details and site coordinates are provided in Table 1, and the environmental monitoring setup is summarized in Table 2. Site locations are illustrated in Figure 1.

2.3. Sampling Locations and Methods

At each site, three replicate sampling points were established to account for spatial variability within the ecosystem. Sampling points were selected to represent the dominant environmental conditions at each site, such as near mangrove roots, crab holes, and open bare land. The sampling locations were distributed along a transect that included the edge, mid, and inner parts of the mangrove forest to capture variability due to distance from the shoreline and the root zone.

Pore water was extracted from the upper 30 cm of the sediment, as this layer is known to contain the majority of organic material in mangrove ecosystems and is where microbial and root interactions primarily occur. A hand-held soil auger (diameter: 5 cm) was used to extract sediment cores, which were placed in pre-cleaned polyethylene bags

for transportation to the laboratory. To minimize contamination, the auger was cleaned thoroughly between sampling points using distilled water.

Once in the field, the pore water was extracted using a vacuum filtration system. A vacuum pump was used to draw the pore water from the sediment core into pre-cleaned glass bottles, which were stored on ice and transported immediately to the laboratory for analysis.

2.3.1. DOC Analysis

The collected pore water samples were analyzed for dissolved organic carbon (DOC) concentrations in the laboratory. DOC is a key indicator of organic matter in aquatic systems and is primarily derived from decomposing plant material, root exudates, and microbial activity. DOC analysis was performed using a total organic carbon analyzer TOC-V CPN (Shimadzu Corporation, Kyoto, Japan), which utilizes combustion and detection of carbon dioxide to quantify organic carbon.

2.3.2. Preparation and Calibration

Prior to analysis, samples were filtered through 0.45 μm Whatman cellulose acetate membranes (Whatman, Cytiva, Maidstone, UK) to remove particulate matter and ensure that only dissolved organic carbon was measured. A calibration standard was prepared using potassium hydrogen phthalate (KHP), a stable organic compound with a known carbon content [3,5]. A blank sample containing deionized water was also prepared to assess background contamination.

DOC concentrations were measured using the following procedure: 1 mL of each sample was injected into the analyzer, where it was combusted at 680 $^{\circ}\text{C}$ in a quartz combustion tube. The combustion gases, primarily carbon dioxide, were measured by a non-dispersive infrared detector [2,6]. To ensure the precision of the measurements, each sample was analyzed in triplicate [5,6]. Data from these analyses were used to calculate the average DOC concentration for each sample point [3].

2.3.3. Environmental Variables

To understand the factors influencing DOC concentrations, several environmental variables were monitored during the sampling. All instruments were calibrated prior to deployment following manufacturer guidelines. Regular calibration checks were conducted throughout the sampling period to ensure data reliability. The analytical accuracy of each instrument is summarized in Table 2. For example, the HMP45C (Campbell Scientific Inc., Logan, UT, USA) sensor measures air temperature with ± 0.2 $^{\circ}\text{C}$ accuracy and relative humidity with $\pm 2\%$ RH. Soil moisture sensors (CS616) (Campbell Scientific Inc., Logan, UT, USA) have an accuracy of $\pm 2.5\%$ volumetric water content, while radiation sensors (CNR4) (Kipp & Zonen B.V., Delft, The Netherlands) report shortwave and longwave fluxes with $\pm 10\%$ – 15% accuracy under field conditions. These included:

- (1) Temperature and Salinity: Water temperature and salinity were measured using a portable multi-parameter probe (YSI ProDSS, YSI Inc., Yellow Springs, OH, USA). These variables affect microbial activity and the solubility of organic compounds, thus influencing DOC concentrations. Measurements were recorded in situ at each sampling point.
- (2) pH: The pH of pore water was measured using a pH meter (Mettler Toledo, Columbus, OH, USA) to assess the acidity of the sediment and pore water. pH can influence the speciation of organic carbon and microbial processes.

- (3) Tidal Height: Tidal cycles can influence pore water dynamics through the movement of organic matter and the inundation of sediments. Tidal height was recorded using a local tide gauge to determine the influence of tidal fluctuation on DOC concentrations.
- (4) Rainfall: Rainfall data were obtained from the local meteorological station. Rainfall significantly influences DOC concentrations by altering freshwater input, which can leach organic carbon from the soil.

2.3.4. Data Analysis

DOC concentrations and environmental variables were averaged across replicates and expressed as mean $\pm$ standard deviation. Statistical comparisons among ecosystem types, seasons, and regions were performed using one-way ANOVA followed by Tukey's HSD post hoc tests. Pearson correlation analysis was used to assess relationships between DOC and environmental parameters. Principal component analysis (PCA) was conducted to explore multivariate patterns in environmental drivers. All statistical analyses were performed using R software (version 4.2.0), with significance set at $p < 0.05$.

2.4. Typhoon Disturbance Parameters

Data regarding the typhoon event was obtained from the Sanya Meteorological Bureau. Key disturbance parameters, including maximum wind speed, rainfall intensity, and storm surge, were recorded. The specific typhoon events considered for this study were Typhoon Maliksi (31 May 2024–1 June 2024), Typhoon Yagi (30 August 2024–9 September 2024), and Typhoon Trami (27 October 2024–30 October 2024), which occurred in 2024. These typhoons were chosen because of their significant impact on the study region, with wind speeds exceeding 21–89 km/h, rainfall of 568.4–722.8 mm, and storm surge levels reaching 3–6 m.

3. Result

During the study period, the dynamic characteristics of seasonal environmental changes among mangroves at different stages of recovery are illustrated in Table 3. According to the results in Table 3, it is evident that from November to March, average temperatures are relatively low, and rainfall is minimal, characterizing the dry season in Hainan. Conversely, from April to October, average temperatures are higher, and rainfall is substantial, marking the rainy season in Hainan. During the rainy season, the number of rainy days is relatively high, whereas in February, there is almost no rainfall.

3.1. Seasonal and Interannual Variation in Porewater DOC

Porewater DOC concentrations varied significantly across land use types, seasons, and years (Figure 2). Across all years (2022–2024), primary mangrove plots consistently exhibited the highest DOC concentrations, with rainy season values reaching up to 18.5 mg/L in 2024. These concentrations were significantly higher than those observed in restored 5-year plots and bare land ($p < 0.05$), indicating strong carbon retention and microbial activity in mature mangrove systems.

Restored 5-year plots showed intermediate DOC levels, with a gradual increase over time, suggesting progressive recovery of biogeochemical functions. However, their DOC concentrations remained significantly lower than those of primary mangroves, especially during the dry season (e.g., 2022 dry season: ~9.2 mg/L vs. 13.6 mg/L in primary mangroves). Bare land plots consistently exhibited the lowest DOC concentrations, with minimal seasonal variation and values rarely exceeding 8 mg/L. This reflects limited organic input and poor retention capacity in unvegetated substrates. Seasonally, DOC concentrations were significantly higher during the rainy season.

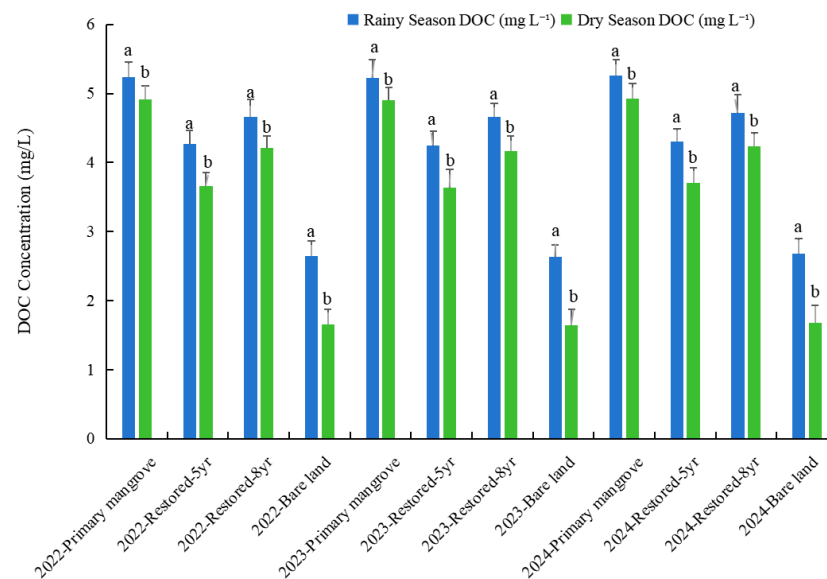


Figure 2. Seasonal and interannual variation in porewater DOC concentrations ($\text{mg}\cdot\text{L}^{-1}$) across primary and restored mangrove ecosystems from 2022 to 2024. Bar chart showing dissolved organic carbon (DOC) concentrations (mg/L) in porewater across primary mangrove and 5-year restored sites from 2022 to 2024, during the rainy season (blue) and dry season (green). Error bars represent standard error. Letters above the bars indicate statistically significant differences based on one-way ANOVA with Tukey's HSD post hoc test ($p < 0.05$). Different lowercase letters denote significant seasonal differences within the same site-year group.

3.2. Environmental Drivers of DOC Variation

Redundancy analysis (RDA) revealed distinct ecological separation among land types based on DOC-environment relationships (Figure 3). Primary mangrove plots were strongly associated with elevated dissolved oxygen and phosphate levels, indicating mature systems with active microbial and nutrient cycling. Restored 8-year plots aligned with temperature and nitrate vectors, suggesting transitional carbon dynamics influenced by nitrogen availability. In contrast, restored 5-year plots showed weaker associations with environmental drivers, while bare land samples clustered near salinity and suspended solids, reflecting physical rather than biological control over DOC. Environmental parameters varied in their influence on DOC concentrations (Figure 3). Dissolved oxygen and phosphate exhibited the strongest positive correlations with DOC, while salinity and total suspended solids were negatively associated. These patterns underscore the role of vegetation cover and restoration age in shaping DOC-environment interactions, with mature mangroves exerting greater biological regulation compared to younger or unvegetated systems.

3.3. Spatial Variation Across Regions

Porewater DOC concentrations varied significantly across the four coastal regions—Haitang Bay, Yalong Bay, Sanya Bay, and Yazhou Bay—between 2022 and 2024 (Table 4). One-way ANOVA revealed statistically significant differences in DOC concentrations among regions for all ecosystem types and seasons ($p < 0.05$). Primary mangrove plots in Haitang Bay consistently exhibited the highest DOC concentrations, with rainy-season values significantly greater than those in Yazhou and Sanya Bays ($F = 6.42$, $p = 0.003$). Similar patterns were observed during the dry season ($F = 4.87$, $p = 0.009$), where Haitang Bay exceeded Yalong and Yazhou Bays.

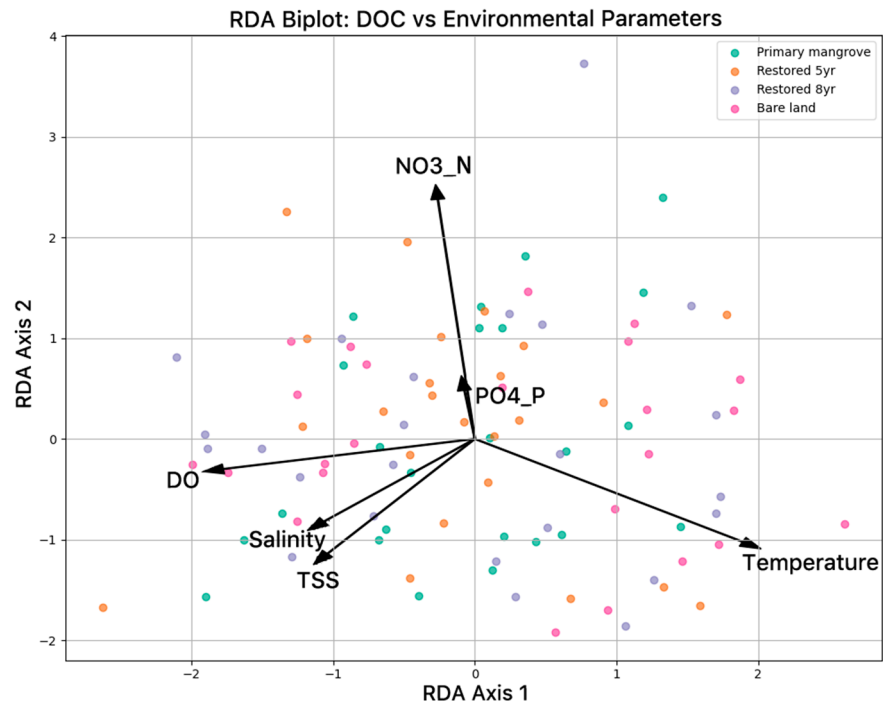


Figure 3. Redundancy analysis (RDA) biplot showing the relationship between porewater DOC concentrations and environmental parameters across mangrove ecosystems from 2022 to 2024.

Table 4. Statistical test results of DOC concentrations in different regions (2022–2024).

Ecosystem Type	Season	Region Comparison	Mean DOC (mg/L) ± SD	ANOVA F-Value	ANOVA p-Value	Tukey HSD Result (p < 0.05)
Primary mangrove	Rainy	Haitang Bay	5.61 ± 0.13	6.42	0.003	Haitang > Yazhou, Sanya
		Yalong Bay	5.20 ± 0.14			
		Sanya Bay	5.36 ± 0.12			
		Yazhou Bay	5.29 ± 0.15			
Primary mangrove	Dry	Haitang Bay	5.04 ± 0.09	4.87	0.009	Haitang > Yalong, Yazhou
		Yalong Bay	4.91 ± 0.11			
		Sanya Bay	4.89 ± 0.10			
		Yazhou Bay	4.84 ± 0.12			
Restored 8yr	Rainy	Haitang Bay	4.76 ± 0.18	5.91	0.005	Haitang > Sanya, Yazhou
		Yalong Bay	4.59 ± 0.20			
		Sanya Bay	4.53 ± 0.19			
		Yazhou Bay	4.46 ± 0.27			
Restored 8yr	Dry	Haitang Bay	4.22 ± 0.14	3.76	0.021	Haitang > Yazhou
		Yalong Bay	4.09 ± 0.15			
		Sanya Bay	4.06 ± 0.16			
		Yazhou Bay	3.97 ± 0.25			
Restored 5yr	Rainy	Haitang Bay	4.31 ± 0.21	4.33	0.014	Haitang > Sanya
		Yalong Bay	4.13 ± 0.22			
		Sanya Bay	4.06 ± 0.23			
		Yazhou Bay	4.01 ± 0.32			
Restored 5yr	Dry	Haitang Bay	3.71 ± 0.17	2.98	0.041	Haitang > Yazhou
		Yalong Bay	3.56 ± 0.18			
		Sanya Bay	3.53 ± 0.19			
		Yazhou Bay	3.46 ± 0.30			

Table 4. Cont.

Ecosystem Type	Season	Region Comparison	Mean DOC (mg/L) $\pm$ SD	ANOVA F-Value	ANOVA <i>p</i> -Value	Tukey HSD Result (<i>p</i> < 0.05)
Bare land	Rainy	Haitang Bay	2.79 $\pm$ 0.31	7.15	0.002	Haitang > all other regions
		Yalong Bay	2.56 $\pm$ 0.33			
		Sanya Bay	2.49 $\pm$ 0.34			
		Yazhou Bay	2.43 $\pm$ 0.52			
Bare land	Dry	Haitang Bay	1.75 $\pm$ 0.34	6.88	0.003	Haitang > Sanya, Yazhou
		Yalong Bay	1.66 $\pm$ 0.36			
		Sanya Bay	1.59 $\pm$ 0.37			
		Yazhou Bay	1.53 $\pm$ 0.50			

Restored mangrove plots also showed regional variation. Eight-year restored sites in Haitang Bay had significantly higher DOC concentrations than those in Sanya and Yazhou Bays during the rainy season ($F = 5.91$, $p = 0.005$) and higher than Yazhou Bay during the dry season ($F = 3.76$, $p = 0.021$). Five-year restored plots followed a similar trend, with Haitang Bay showing elevated DOC levels compared to Sanya and Yazhou Bays ($p < 0.05$).

Bare land plots exhibited the most pronounced spatial differences. Rainy-season DOC concentrations in Haitang Bay were significantly higher than in all other regions ($F = 7.15$, $p = 0.002$), and dry-season values were also elevated compared to Sanya and Yazhou Bays ($F = 6.88$, $p = 0.003$). These results indicate strong spatial heterogeneity in DOC concentrations, with Haitang Bay consistently supporting higher carbon levels across ecosystem types and seasons.

3.4. Impact of Mangrove Restoration on DOC Stabilization

Boxplot analysis revealed distinct patterns in DOC concentration distributions across mangrove ecosystems with varying restoration ages from 2022 to 2024 (Figure 4). Primary mangrove plots exhibited the narrowest interquartile ranges and consistent medians in both rainy and dry seasons, indicating low variability in DOC concentrations. Eight-year restored plots showed intermediate dispersion, with slightly wider boxes and occasional outliers, particularly during the rainy season. Five-year restored plots displayed broader interquartile ranges and greater seasonal spread, suggesting higher variability in DOC levels. Bare land plots had the widest boxes and most frequent outliers, especially in the dry season, reflecting pronounced fluctuations in DOC concentrations.

Within-year comparisons of DOC concentrations revealed consistent and significant differences among mangrove ecosystem types. In all three years (2022–2024), primary mangrove sites exhibited the highest DOC levels, with median values ranging from 5.01 to 5.27 mg·L^{−1}, significantly exceeding those of bare land plots, which remained the lowest across all years (3.41–3.57 mg·L^{−1}; $p < 0.05$). Restored 5-year plots showed intermediate DOC concentrations (4.03–4.26 mg·L^{−1}), significantly lower than primary mangroves but higher than bare land. Restored 8-year plots demonstrated progressive improvement in DOC retention, with 2024 values (5.00 mg·L^{−1}) statistically indistinguishable from primary mangroves, indicating near-complete recovery of carbon stabilization function (Table 5). In 2022 and 2023, restored 8-year plots occupied an intermediate position, not significantly different from either primary mangrove or restored 5-year plots. These findings underscore the importance of restoration age in enhancing DOC stability and suggest that mangrove ecosystems require at least eight years to approach the carbon retention capacity of mature forests.

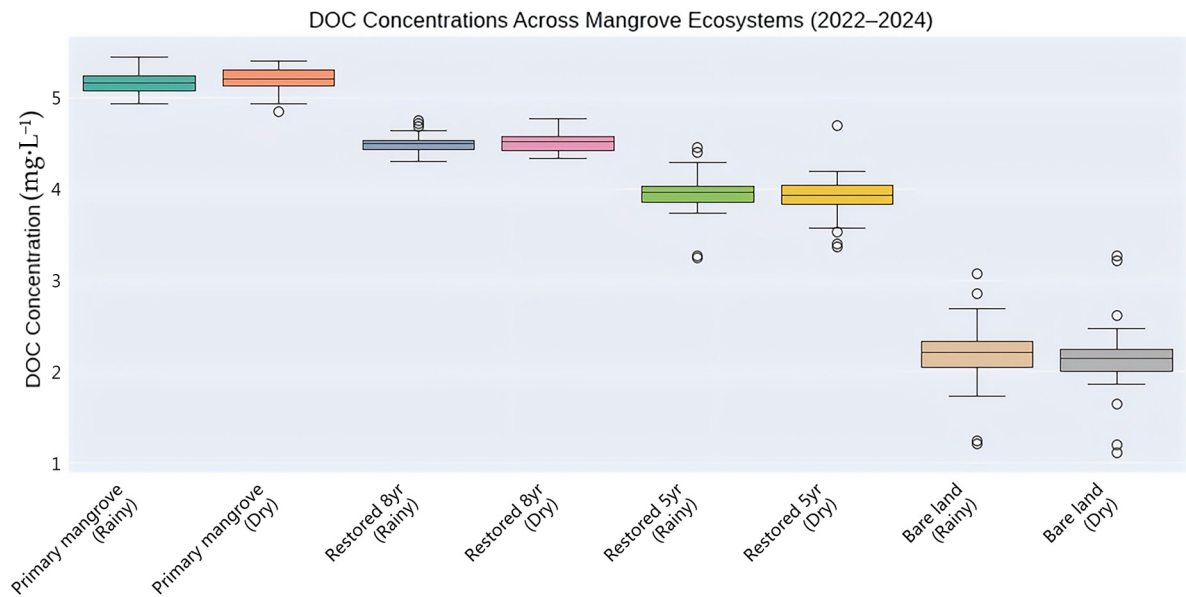


Figure 4. Boxplot showing DOC concentration distributions (mg·L^{−1}) across mangrove ecosystems with varying restoration age from 2022 to 2024.

Table 5. DOC concentrations across mangrove ecosystem types within each year (2022–2024). Values represent the median ± interquartile range (IQR) of dissolved organic carbon (DOC) concentrations in porewater. Statistical comparisons were conducted using one-way ANOVA followed by Tukey’s HSD test ($p < 0.05$) within each year. Different letters indicate significant differences among ecosystem types in the same year.

Year	2022	2022	2022	2022	2023	2023	2023	2023	2024	2024	2024	2024
Ecosystem Type	Primary mangrove	Restored 5-yr	Restored 8-yr	Bare land	Primary mangrove	Restored 5-yr	Restored 8-yr	Bare land	Primary mangrove	Restored 5-yr	Restored 8-yr	Bare land
DOC Concentration (Median ± IQR, mg·L ^{−1})	5.12 ± 0.38 a	4.03 ± 0.47 b	4.76 ± 0.34 ab	3.57 ± 0.52 c	5.27 ± 0.31 a	4.18 ± 0.42 b	4.89 ± 0.28 ab	3.48 ± 0.49 c	5.01 ± 0.33 a	4.26 ± 0.39 b	5.00 ± 0.30 a	3.41 ± 0.46 c

3.5. DOC Response to Extreme Climatic Events

Dissolved Organic Carbon (DOC) concentrations (mol m^{−2} s^{−1}) varied significantly across ecosystem types and typhoon phases. Heatmap analyses revealed distinct temporal and spatial patterns in DOC response to Typhoon “Maliksi”, Typhoon “Yagi”, and Typhoon “Trami”.

DOC responses following extreme climatic events varied significantly across land types, as shown in both Table 6 and Figure 5. Bare land exhibited the strongest DOC increases after all three events, with highly significant changes of +1.03 (Maliksi), +1.12 (Yagi), and +0.96 (Trami) ($p < 0.01$), consistent with the intense orange shading in the heatmap. These elevated responses likely reflect the lack of vegetation and poor carbon retention capacity, making bare land highly susceptible to organic matter mobilization during disturbances (Figure 5 and Table 6).

Primary mangrove and restored 8-year plots showed moderate but statistically significant DOC increases after Maliksi and Yagi ($p < 0.05$), with values ranging from +0.72 to +0.84. The heatmap illustrates these responses with lighter orange tones, indicating stable but responsive carbon dynamics. In contrast, restored 5-year plots showed minimal DOC changes (+0.02 to +0.07), with no statistical significance, suggesting limited resilience and buffering capacity at early restoration stages (Figure 5 and Table 6).

Table 6. DOC response magnitude across land types following three extreme climatic events. Values represent the net change in standardized dissolved organic carbon (DOC) response (post-event minus pre-event) for each land type after Maliksi, Yagi, and Trami. Asterisks denote statistical significance based on repeated measures ANOVA followed by Tukey’s HSD test ($p < 0.05$, $p < 0.01$).

	Primary Mangrove	Restored 8 Yr	Restored 5 Yr	Bare Land
Maliksi	0.722 *	0.83 *	0.066	1.03 **
Yagi	0.841 *	0.79 *	0.020	1.12 **
Trami	0.04	0.38	0.026	0.96 **

$p < 0.05$: *, $p < 0.01$: **.

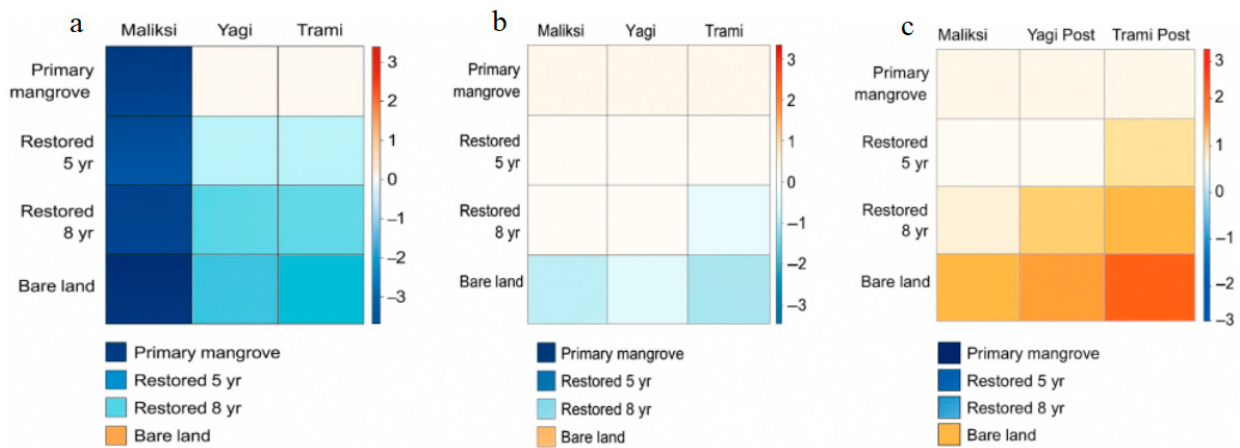


Figure 5. Heatmap showing DOC concentrations ($\text{mol m}^{-2}\cdot\text{s}^{-1}$) across mangrove ecosystems in the aftermath of three typhoon events (a): pre-event; (b): during event; (c): after event.

Trami induced weaker DOC responses overall, with only bare land showing a significant increase (Figure 5 and Table 6). This pattern may reflect differences in storm intensity, timing, or antecedent soil conditions. Together, these results highlight that restoration age and vegetation structure strongly influence DOC sensitivity to climatic stress, with older restored sites approaching the functional stability of primary mangroves.

4. Discussion

This study provides new insights into how mangrove ecosystems of varying restoration ages respond to extreme climatic events in terms of dissolved organic carbon (DOC) dynamics. By analyzing DOC concentrations across three typhoon events—Maliksi, Yagi, and Trami—our results highlight the stabilizing role of mature mangroves and the vulnerability of younger restored plots and bare land to post-disturbance carbon fluxes.

Primary mangrove ecosystems exhibited remarkable DOC stability across all typhoon phases. This resilience is consistent with previous findings that mature mangrove forests possess complex root structures and microbial communities capable of buffering hydrological and biogeochemical disturbances [1]. Their ability to maintain near-zero DOC fluctuations even under intense typhoon conditions reinforces their role as long-term carbon sinks [2].

In contrast, restored mangrove plots showed phase-dependent DOC variability, with restoration age emerging as a key factor. Restored 5-year and 8-year plots exhibited elevated DOC concentrations post-event, particularly following Typhoon Trami. This pattern suggests that while restored mangroves begin to recover carbon sequestration functionality within a few years, full equivalence to primary systems may require longer timescales [3,7]. Lin et al. [6] demonstrated that restoration age significantly influences

carbon resilience under typhoon stress, with older restored plots showing improved DOC retention and reduced post-event volatility.

Bare land plots consistently showed the highest DOC release, especially in the post-event phase. The absence of vegetation likely accelerates surface runoff and organic matter leaching, resulting in pronounced carbon loss. These findings align with broader studies on carbon emissions from unvegetated or degraded coastal zones [5,8]. The deep red zones observed in post-event heatmaps for bare land underscore the ecological cost of deforestation and the urgency of reforestation efforts in typhoon-prone regions.

Temporal analysis revealed that DOC responses were most pronounced after typhoon events, rather than during. This delayed response likely reflects post-storm changes in soil saturation, microbial turnover, and detrital decomposition [4]. Such lag effects are critical for understanding carbon flux timing and for designing monitoring protocols that extend beyond the immediate disturbance window. Typhoon-induced canopy damage and leaf litter deposition likely contribute to increased organic matter input into mangrove soils. The physical disturbance from high winds and rainfall accelerates defoliation, branch breakage, and surface runoff, delivering fresh detritus to the soil surface. This influx of labile organic substrates enhances microbial activity and decomposition rates, leading to elevated DOC concentrations in the post-event phase. Similar mechanisms have been observed in tropical forests and coastal wetlands following storm events, where organic carbon pulses are linked to vegetation damage and litterfall [3,5–7]. Although direct measurements of litter input were not conducted in this study, the observed DOC peaks align with this disturbance-driven enrichment pathway.

Furthermore, the molecular composition of DOC may shift under typhoon influence, with increased mobilization of labile compounds and altered microbial processing [9]. These biochemical changes, though not directly measured in this study, warrant further investigation using advanced molecular and isotopic techniques. Notably, in Figure 5, some DOC values appear negative. These do not represent actual concentrations below zero but rather reflect standardized or centered values used in multivariate ordination. Such transformations are common in ecological analyses and indicate relative deviations from the mean, allowing clearer visualization of sample-level differences in DOC dynamics.

In addition to typhoon-induced disturbances, long-term sea level rise may further alter DOC dynamics in mangrove ecosystems. Rising sea levels can increase tidal inundation frequency and salinity intrusion, which in turn affect soil redox conditions, cation exchange processes, and organic matter decomposition rates. These shifts may enhance the mobilization or retention of dissolved organic carbon, depending on site-specific hydrological and geomorphological settings. Moreover, changes in cation dynamics—such as sodium and calcium displacement—can influence DOC solubility and microbial processing. Although sea level rise was not directly assessed in this study, its potential to compound typhoon-driven DOC fluctuations highlights the need for integrated, climate-resilient restoration strategies in coastal zones.

Collectively, our findings emphasize the ecological value of mangrove conservation and the strategic importance of long-term restoration. Mature mangroves offer robust DOC stability under climatic stress, while younger restored plots show promising but incomplete resilience. Bare land, by contrast, remains highly susceptible to DOC loss, reinforcing the need for targeted restoration in vulnerable coastal zones.

In addition to hydrological and microbial drivers, typhoon-induced organic matter input likely plays a central role in post-event DOC enrichment. High winds and intense rainfall during typhoons cause widespread canopy damage, defoliation, and branch fragmentation, resulting in substantial litterfall deposition onto the soil surface. This sudden influx of fresh detritus—rich in labile carbon compounds—acts as a substrate for microbial

decomposition, thereby accelerating DOC release into porewater. The effect is particularly pronounced in vegetated plots, where structural biomass is available for redistribution. In restored mangrove sites, the accumulation of leaf litter and organic debris may temporarily exceed the system's stabilization capacity, leading to elevated DOC concentrations despite partial recovery of carbon retention functions.

Bare land plots, although lacking standing vegetation, may still receive organic inputs via lateral transport, wind-driven deposition, or runoff from adjacent vegetated zones. However, the absence of root uptake and microbial buffering mechanisms in these plots facilitates rapid DOC mobilization and loss. This disturbance-driven enrichment pathway has been documented in other coastal and tropical systems, where storm events trigger carbon pulses linked to vegetation damage and detrital influx [3,5,7,8]. Although direct measurements of litter input were not conducted in this study, the observed DOC peaks and temporal patterns strongly support this mechanism.

Furthermore, the molecular composition of DOC may shift under typhoon influence, with increased mobilization of labile compounds and altered microbial processing [9]. These biochemical changes, though not directly measured in this study, warrant further investigation using advanced molecular and isotopic techniques. Collectively, our findings emphasize the ecological value of mangrove conservation and the strategic importance of long-term restoration. Mature mangroves offer robust DOC stability under climatic stress, while younger restored plots show promising but incomplete resilience. Bare land, by contrast, remains highly susceptible to DOC loss, reinforcing the need for targeted restoration in vulnerable coastal zones.

5. Conclusions

This study highlights the critical role of mangrove ecosystem structure and restoration age in regulating dissolved organic carbon (DOC) dynamics under extreme climatic disturbances. By examining DOC responses across three typhoon events—Maliksi, Yagi, and Trami—and three disturbance phases, we demonstrate that primary mangroves maintain exceptional DOC stability, while restored plots and bare land exhibit increasingly volatile carbon fluxes, particularly post-event.

Our results confirm that restoration age is a key determinant of carbon resilience. Restored 8-year plots showed improved DOC retention compared to 5-year plots, yet neither matched the buffering capacity of mature mangroves. Bare land, in contrast, consistently released the highest DOC concentrations, underscoring the ecological vulnerability of deforested coastal zones.

Temporal analysis revealed that DOC responses were most pronounced after typhoon events, suggesting that post-disturbance processes—such as microbial turnover, detrital decomposition, and hydrological shifts—play a dominant role in carbon mobilization. These findings emphasize the need for long-term monitoring strategies that extend beyond the immediate storm window.

Collectively, this research reinforces the importance of conserving mature mangrove forests and accelerating restoration efforts in typhoon-prone regions. Enhancing restoration age and structural complexity can significantly improve carbon stability and mitigate climate-driven DOC losses. As extreme weather events intensify under global climate change, mangrove ecosystems will remain indispensable for coastal carbon management and resilience.

In light of these findings, we suggest that restoration activities—particularly planting—should be timed with caution following typhoon events. Given the observed DOC volatility and biogeochemical instability in the immediate aftermath of storms, delaying planting until the system begins to stabilize may enhance restoration success and carbon retention.

This insight offers practical guidance for optimizing restoration strategies in disturbance-prone coastal zones.

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Data Availability Statement: The data supporting the findings of this study are available upon reasonable request. Due to the proximity of the research site to a military base, access to the data is subject to restrictions and requires either an individual usage application or an institutional request. Upon approval, the data and related analysis files will be shared via downloadable links (e.g., Baidu Netdisk).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Alongi, D.M. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci.* **2008**, *76*, 1–13. [\[CrossRef\]](#)
2. Murdiyarso, D.; Donato, D.C.; Kauffman, J.B.; Kurnianto, S.; Stidham, M.; Kanninen, M. Carbon storage in mangrove and peatland ecosystems: A review. *Wetl. Ecol. Manag.* **2010**, *18*, 443–458. [\[CrossRef\]](#)
3. Donato, D.C.; Kauffman, J.B.; Murdiyarso, D.; Kurnianto, S.; Stidham, M.; Kanninen, M. Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.* **2011**, *4*, 293–297. [\[CrossRef\]](#)
4. Koch, B.P.; Kattner, G.; Witt, M.; Passow, U. Molecular insights into the chemical composition of dissolved organic matter in the ocean. *Mar. Chem.* **2007**, *105*, 240–251. [\[CrossRef\]](#)
5. Borges, A.V.; Darchambeau, F.; Teodoru, C.R.; Marwick, T.R.; Tamooch, F.; Geeraert, N.; Omengo, F.O.; Guérin, F.; Lambert, T.; Morana, C.; et al. Globally significant greenhouse-gas emissions from African inland waters. *Nat. Geosci.* **2015**, *8*, 637–642. [\[CrossRef\]](#)
6. Lin, Y.; Liu, R.; Shi, Y.; Han, S.; Zhao, H.; Peng, Z. Resilience of Mangrove Carbon Sequestration Under Typhoon Disturbance: Insights from Different Restoration Ages. *Forests* **2025**, *16*, 1165. [\[CrossRef\]](#)
7. Bosire, J.O.; Dahdouh-Guebas, F.; Walton, M.; Crona, B.I.; Lewis, R.R.; Field, C.; Koedam, N. Functionality of restored mangroves: A review. *Aquat. Bot.* **2008**, *89*, 251–259. [\[CrossRef\]](#)
8. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **2013**, *3*, 961–968. [\[CrossRef\]](#)
9. Kristensen, E.; Bouillon, S.; Dittmar, T.; Marchand, C. Organic carbon dynamics in mangrove ecosystems: A review. *Aquat. Bot.* **2008**, *89*, 201–219. [\[CrossRef\]](#)

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