Restoration plan for the Little River mangrove ecosystem: guiding early-stage restoration through diagnostic assessment

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DEDICATION

To my family, my friends, and to myself—
In gratitude for your support, love, and encouragement,
and in recognition of the commitment and
perseverance that brought me here.

ACKNOWLEDGMENTS

I extend my heartfelt gratitude to my family in Jamaica and Colombia for their unwavering patience and constant encouragement throughout this journey. Your support helped me push forward, even during challenging times, and reminded me that growth often comes from embracing changes.

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Thanks to the University of the West Indies, Department of Life Sciences, for your seminar series, which offered research insights and network opportunities, and for providing me access to laboratories and equipment. Professor Mona Webber, who introduced me to the MSc. Environmental Management- Costal Restoration course in August 2024, which broadened my perspective and provided valuable tools for restoration work in Jamaica.

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Artículo 23 de la Resolución No. 13 de julio de 1946.

RESUMEN

Los ecosistemas de manglar ofrecen servicios fundamentales como la protección costera, el soporte de biodiversidad y el secuestro de carbono. Sin embargo, muchos están amenazados por alteraciones hidrológicas y presiones derivadas del uso del suelo. Este estudio evalúa el estado ecológico del manglar de Little River en St. James, Jamaica, con el objetivo de orientar futuras acciones de restauración. A través de evaluaciones de la estructura de la vegetación, niveles de salinidad y contenido de carbono orgánico en el suelo, se compararon los sitios con parcelas de control (C) y degradadas/confines de restauración (RE) para analizar su funcionalidad ecológica y potencial de recuperación.

Se encontraron diferencias significativas entre los sitios en la altura de los árboles y el diámetro a la altura del pecho (DAP). Las parcelas de control presentaron árboles más altos (hasta 10 m) y DAP promedio mayores (~10 cm), mientras que las parcelas degradadas mostraron árboles más jóvenes y de menor tamaño. No obstante, la densidad de plántulas fue mayor en las parcelas en restauración, especialmente en áreas con mejor conexión hidrológica, lo que indica un potencial de regeneración natural. Los niveles de salinidad variaron según el sitio, pero no mostraron diferencias significativas, probablemente debido a factores estacionales. El contenido de carbono osciló entre 41.26 y 219.57 Mg C/ha, con un promedio ligeramente mayor en las parcelas con fines de restauración (124.3 Mg C/ha ± 65) (promedio ± desviación estándar) comparadas con las parcelas de control (107 Mg C/ha ± 83) (promedio ± desviación estándar). Los valores de densidad de carbono se encontraron dentro del rango moderado y no mostraron diferencias significativas entre los sitios. Se desarrollaron un modelo lógico y un marco de teoría del cambio para guiar la rehabilitación hidrológica, monitorear los indicadores ecológico y fomentar la participación de los actores locales.

Este estudio propone un plan integral de restauración para el ecosistema de manglares de Little River, integrando actividades ecológicas, socioeconómicas, económicas y político-legales a lo largo de un período de veinticinco años. El enfoque por fases incluye un período de implementación de cinco años, desde 2025 hasta 2030, y un período de monitoreo de veinte años, desde 2031 hasta 2050, con un costo total estimado entre JMD $34,488,500 y JMD $49,818,000. Los resultados sugieren que la rehabilitación hidrológica dirigida puede facilitar los procesos de regeneración natural, reforzando el potencial para iniciativas de restauración de manglares escalables y adecuadas en ecosistemas costeros caribeños similares que se encuentran degradados.

ABSTRACT

Mangrove ecosystem offer critical services such as shoreline protection, biodiversity support, and carbon sequestration. However, many are under threat from hydrological alterations and land-use pressures. This study assessed the ecological condition of the Little River mangrove forest in St. James, Jamaica, to inform future restoration planning. Using field-based assessments of vegetation structure, salinity, and soil organic carbon (SOC), this case study compared control and degraded/restoration plots to evaluate ecosystem function and restoration potential.

Significant differences were found between sites in tree height and diameter at breast (DBH), with control plots (C) containing taller, more trees (up to 10m) and larger DBH values (averaging ~10 cm), while degraded/restoration plots (RE) had generally younger and shorter trees. However, seedling density was higher in restoration plots, especially in areas with hydrological connections, indicating natural regeneration potential. Salinity levels varied widely but showed no significant differences between sites, likely due to seasonal factors. SOC content ranged from 41.26 to 219.57 Mg C/ha, with restoration plots showing slightly higher average storage (124.3 Mg C/ha ± 65) (mean ± SD) compared to control plots (107 Mg C/ha ± 83) (mean ± SD). Carbon density values fell within the moderate range and did not differ significantly between sites. A logic model and theory of change framework were developed to guide hydrological rehabilitation, monitor ecological indicators, and engage local stakeholders.

This study proposes a comprehensive restoration plan for the Little River mangrove ecosystem, integrating ecological, socio-economic, economic and political/legal activities over a twenty-five-year period. The phased approach includes a five-year implementation period from 2025 to 2030 and a twenty-year monitoring period from 2031-2050, with a total projected cost ranging between JMD $34,488,500 and JMD $49,818,000. Findings suggest that targeted hydrological rehabilitation can facilitate natural regeneration processes, reinforcing the potential for scalable and suitable mangrove restoration efforts across similar degraded Caribbean costal ecosystems.

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1. Introduction

Mangroves are essential coastal ecosystem that thrive in tropical and subtropical regions where land meets the sea. These unique plants are specially adapted to saline and intertidal environments, with features like prop roots, aerial pneumatophores, and salt-excreting gland that allows them to survive in oxygen-poor, saline soils (Youssef and Saenger, 1996). Their thick, waxy leaves also aid in filtering out pollutants and excess nutrients from surrounding water, improving overall water quality (Boto, 2018).

These forests occupy a range of coastal zones, from river mouths and estuaries to lagoons, depending on factors such as tidal influence and surface drainage. Globally, mangroves consist of around 73 tree and shrub species across 29 genera and 21 families, including 11 known natural hybrids (Kindgard et al., 2023; Ragavan et al., 2017). In Jamaica, the dominant species include the red mangrove (*Rhizophora mangle*), Black mangrove (*Avicennia germinans*), and White mangrove (*Laguncularia racemosa*), alongside transitional mangroves associate like Buttonwood (*Conocarpus erectus*) (Forestry Department of Jamaica, 2025; Caldera and Ranathunga, 2023).

Mangroves are connected to adjacent marine environments through ocean currents that support nutrient exchange and organic matter flow, strengthening nearby ecosystems like coral reefs and seagrass beds (Lewis et al., 2008). These ecosystems work together to stabilize coastlines, reduce erosion, and provide habitat for numerous marine organisms. Additionally, mangroves play a key role in carbon sequestration, storing atmospheric carbon dioxide in their biomass and soils, which helps mitigate the effects of climate change (Sathirathai, 1998).

Beyond their ecological importance, mangroves serve critical socio-economic functions. Their roots trap sediments, reduce eutrophication risks, and remove up to 90% of dissolved inorganic nitrogen, improving water clarity (Moroyoqui-Rojo et al., 2015). The habitats they create support a wide range of species, including fish, crustaceans, mollusks, and birds, many of which relay on mangroves for breeding, shelter, and feeding (Cedeño et al., 2010; Arcero-Carranza et al., 2016). Moreover, this biodiversity is essential for monitoring restoration success, especially when assessing conditions before and after natural disturbances like hurricanes (Azimah and Tarmiji, 2018; McNair, 2008).

For many coastal communities, mangroves also represent a critical economic asset. In some regions, up to 68% of household gain revenue from mangrove-related activities such as crab harvesting, fishing, charcoal production, and wood collection. The mangrove crab (*Ucides cordatus*) is especially valuable, representing the primary income for over a third of households at the Brazilian North Coast (Glaser, 2003). However, mangroves fragmentation, often caused by roads and developments, reduce the ecosystem´s ability to delivery services such as fisheries support and coastal protection (Brander et al., 2012).

The economic worth of mangrove ecosystem services is considerable. In Southeast Asia alone, the average estimated value in 2007 was $4,185 USD per hectare per year, and if mangroves loss continues unchecked, projected annual losses by 2050 could total $2.2 billion USD (Brander et al., 2012). These values underscore the importance of preserving and restoring mangroves not only for ecological sustainability but also for long-term economic stability (Cesar et al., 2000).

Despite their value, mangroves are threatened from human activities including coastal development, pollution, overharvesting, and aquaculture. Globally, over 35% of mangrove forests have disappeared within just the last two decades (Valiela et al., 2001), largely due to the rapid expansion of aquaculture. Aquaculture´s contribution to total fisheries production increased from 16% in 1991 to one-third by 2005 (Primavera, 2005), with countries such as the Philippines, Malaysia, and Indonesia heavily utilizing mangroves areas for aquaculture development (Chong, 2006; Ilman et al., 2016, Tahiluddin et al., 2025). However, in response to mangrove forest decline, Indonesia has shown leadership in multiple large-scale restoration projectsto reverse this trend and restore critical coastal ecosystems. These include the National Mangrove Rehabilitation program, which aims to restore 600,000 hectares by 2024 (World Bank, 2022), and the expansion of Ecological Mangrove Restoration (EMR) practices in North Kalimantan by Wetlands International, targeting up to 33,000 hectares (Wetlands International Indonesia, 2025).

Restoration, as commonly envisioned, goes beyond merely planting trees; it requires a multidimensional approach that includes ecological, economic, social and political factors, enabling communities to reconnect with nature while also benefiting from its services. Ecological restoration focuses on assisting the natural recovery of a degraded ecosystem, whereas rehabilitation prioritizes restoring ecosystem services, even if the original biodiversity isn´t fully regained (SER, 2004). In the context of mangrove ecosystems, a shift in approach emerged in the

1980s that emphasized restoring natural hydrology over traditional “mangrove gardening” techniques (Lewis, 2005). This method, centered on reestablishing natural water flow and sediment dynamic, has proven to be effective in facilitating long-term recovery (López-Portillo et al., 2021). However, despite its success, hydrological restoration remains underrepresented in many managements plans due to its high cost and complexity (Beeston et al., 2023).

The mangrove ecosystem in Little River, Jamaica, illustrates the urgent need for restoration due to ongoing degradation from multiple human-induced stressors, including altered hydrology, deforestation, informal settlements, charcoal burning, pig farming and pollution. pens. Despite these cumulative effects of these pressures, no management actions have been taken to address or mitigate the damage (Campbell et al., 2023). Therefore, this study focuses on guiding early-stage restoration of the Little River mangrove ecosystem by conducting a diagnostic assessment that reviews hydrological issues, evaluates ecological status, and measures carbon content to support the development of a comprehensive restoration plan that integrates ecological, socio-cultural, economic and legal considerations.

2. Theoretical and Conceptual Framework

This research is grounded in the field of restoration ecology, focused on the ecological restoration of the mangrove ecosystem in the Little River Community, St. James, Jamaica. The theoretical underpinnings involve several interrelated concepts: restoration ecology, hydrology connectivity, ecosystem services, ecological resilience, and global, regional and national policy frameworks. These frameworks provide a lens through which to assess past efforts, guide data collection, and shape recommendations for future restoration planning.

2.1. Restoration Ecology

Restoration ecology offers a foundation for understanding how degraded and ecosystems can recover through either passive (natural regeneration) or active (human intervention) approaches. In mangrove systems, passive restoration may occur when threats are reduced, and there is a high potential for recovery, while active restoration often involves reintroducing species or modifying site conditions by human assistance. Robert Lewis (2005) introduced the concept of Ecological Mangrove Restoration (EMR), emphasizing the importance of restoring natural tidal hydrology rather than focusing solely on planting trees. EMR has been widely adopted as best practice because it supports natural regeneration and long-term ecological function.

2.2 Hydrological Connectivity

Hydrological connectivity refers to the natural movement of water across the landscape, which is critical in shaping wetland ecosystems such as mangroves. Disruptions to tidal flow and freshwater inflows can impact sediment transport, nutrients availability, and vegetation patterns. Krauss et al. (2009) demonstrated that changes in water levels significantly affect mangrove structure and resilience, especially during storm events. In the context of Little River, assessing hydrological barriers or flow disruptions is crucial for guiding restoration.

2.3. Ecosystem Services

Mangroves offer numerous ecosystem services, including shoreline protection, fish nursery habitats, nutrient cycling, and carbon storage. The Millennium Ecosystem Assessment (2005) and work by Sathirathai (1998) highlight the economic and ecological importance of these services. For example, mangrove in Portland Bight, Jamaica, are estimated to contribute approximately US$45 million in annual ecosystem value (Edwards, 2019). Recognizing and quantifying these services help justify restoration and conservation actions.

2.4. Ecological Resilience

Ecological resilience is the ability of an ecosystem to absorb disturbance and maintain its functions. Holling (1973) introduced this concept to explain how systems can adapt or reorganize in the face of external pressures. In mangrove restoration, resilience can be monitored in time to evaluate whether restored sites can continue to thrive after no human aid, intervention or natural stressors. However, it would require adaptative management to guide best practice and enable mangrove ecosystem to reach its recovery potential.

2.5. Global, Regional, and National Context

Globally, restoration efforts are guided by the UN Decade on Ecosystem Restoration (2021-2030) and principles from the Society for Ecological Restoration (Gann et al., 2019), which outline standards for planning, implementing, and evaluating projects. In the Caribbean, Florida´s success with hydrological reconnection projects, like those in Biscayne Bay, offer useful lessons (Webb, 1999). Locally, Jamaica has implemented mangrove restoration projects through the National Environmental Planning Agency (NEPA) and academic partnerships, such as the UWI-led projects in Palisadoes and Portland Bight areas. Gayle and Bailey (2006) provide insights into the environmental management strategies used along Jamaica´s coast.

In Little River, the observed presence of mangrove seedling suggests potential for natural regeneration, indicating ecological resilience. However, full recovery appears to be constrained by disrupted hydrology caused by infrastructure development, as well as additional stressors such as nutrient imbalances and wastewater inflows. These conditions limit optimal growth and survival of key species like *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*.

3. Justification

The Caribbean lies directly in the path of the Atlantic Hurricane Belt and is at significant risk from storm surges, flooding, and other impacts associated with tropical cyclones and hurricanes, which affect both life and livelihood. Hydrometeorological events in Latin America and the Caribbean have caused considerable economic losses, with a reported USD $31.8 billion which was 54% of the total losses from natural hazards between 1970 and 1999 (Cavallo and Noy, 2009). As the effects of climate change intensify, the vulnerability of coastal communities in the Caribbean to flooding is expected to rise due to factors such as increasing sea levels, higher temperatures, and more frequent and intense hurricanes (Caribbean Development Bank, 2025). This is particularly concerning given the high density of human settlements and infrastructure along the Caribbean coastline (Lincoln, 2017). The potential long-term effects of climate change and environmental degradation emphasize the need for effective mitigation strategies such as mangrove restoration, which can contribute to enhance resilience and coastal protection.

Mangrove restoration has the potential for long-term flood protection benefits, as evidenced by research indicating that the Present Value (PV) of this benefit can reach hundreds of thousands of dollars per hectare (Beck al., 2022). Notably, mangrove restoration is more cost-effective compared to traditional approaches such as mangrove planting. In the Caribbean, median restoration costs for hydrological restoration are stimulated at USD $4,000 per hectare compared to USD $23,000 per hectare for planting seedlings and sampling (UWI, 2019). These values demonstrate that, even in areas with high restoration costs, the return on investment (ROI) remains positive. For example, projects near Port-au-Prince, Haiti, with restoration costs under USD $168,000 per hectare, would still yield a positive economic return (Beck et al, 2022). This makes mangrove restoration a viable and financially sound option, especially in regions like Jamaica where the costs of coastal structures per linear kilometer are significantly higher.

Furthermore, mangrove restoration directly aligns with multiple Sustainable Development Goals (SDGs). Restoration project frequently align with six SDGs, including SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). By explicitly identifying how the outcomes of this study align with the SDGs, this research provides a framework for communicating the broader impacts of mangrove restoration in terms of global sustainability objectives. This alignment enhances the visibility and support for the plan among international stakeholders and funding agencies.

Mangrove loss in Jamaica has been significant, with over 770 hectares lost in the last two decades, primarily due to pressures from tourism, informal housing, waste mismanagement, and nutrient overload (FAO, 2023). The degradation of these ecosystems, compounded by pollution, including plastic, severely limits the recovery capacity of mangroves (Trench, 2021). There is currently no comprehensive ecological baseline for the area, underscoring the need for a holistic restoration plan that combines ecological recovery with community engagement. The 2023 Environmental Impact Assessment (EIA) anticipating this study revealed that 94% of local residents are interested in learning about and participating in a mangrove restoration project or plan, signaling strong community support for restoration efforts (Campbell et al., 2023).

Effective mangrove restoration planning requires project managers to consider ecological, social, economic and political dimensions. This comprehensive approach not only target the urgent issue of ecosystem degradation but also foster sustainable management practices that support local communities. By presenting a framework for community-driven mangrove restoration, this research will serve as a foundation for future interventions and monitoring, ensuring long-term ecological recovery and costal resilience to anthropogenic factors and climate change.

4. Problem Statement

The mangrove ecosystem at Little River, St. James, Jamaica, is under increasing threat due to a combination of human-induced pressures and altered environmental conditions, especially land reclamation over the past two decades (Fig.1).

Figure 1. Comparative images of the Little River community showing land use change between 2001 and 2025. Source: Google Earth Pro v7.3 (2025).

Compounding these issues are hydrological disruptions associated with the construction of the North Coast Highway (Segment 2: Montego Bay to Ocho Rios), particularly the Seacastles to Greenwood section. Although two culverts were installed to maintain connectivity between the wetland and the Caribbean Sea, tidal exchange remains limited due to elevation differences that facilitate one-way freshwater drainage while restricting seawater inflow, with only one culvert exhibiting weak tidal movements and salinity levels measured at 14ppt, below the typical 35ppt of seawater, indicating minimal mixing and limited marine influence (Fig. 2a.) (Campbell et al., 2023)

In addition to hydrological disruption, the ecosystem has experienced significant degradation from various ecological and socio-ecological pressures. Key drivers include unregulated housing encroachment, charcoal burning, and pollution from surrounding communities. These activities have contributed to the loss of mangroves coverage and deteriorating water quality, with nutrient levels (nitrates and phosphates), exceeding national standards (Campbell et al., 2023), likely due to residential structures in close proximity to the ecosystem, suggesting a possible influence of domestic runoff on the wetland (Fig.2b).

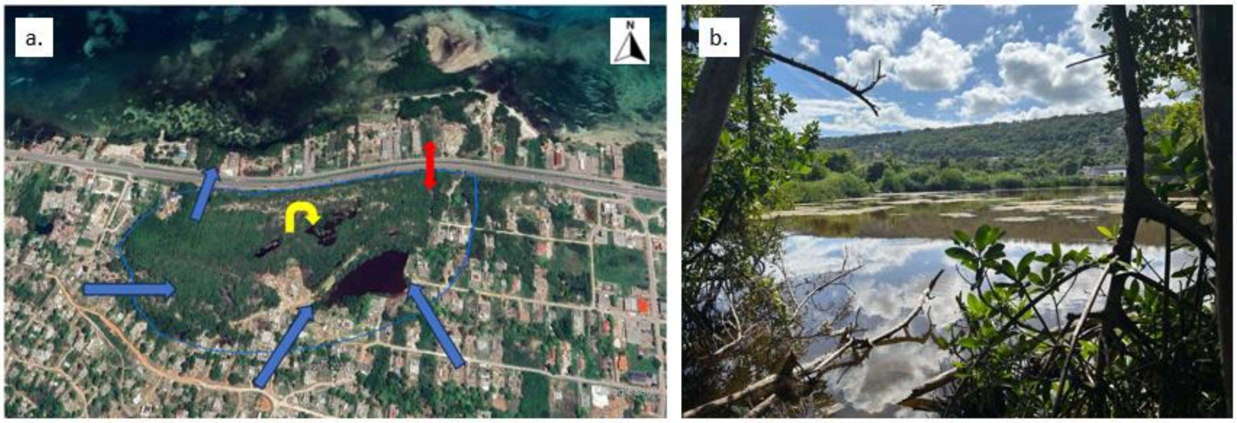

Figure 2. Little River mangrove ecosystem and pond view **a.** where colored arrows indicate freshwater flow (blue) in one direction due to slopes and brackish water flow (red) in two directions, with arrows crossing the North Coast Highway (to the north) marking the location of installed culverts (Campbell et al., 2023). **b**, pond view from within the mangrove, showing nearby residential structures in close proximity to the ecosystem, suggesting a possible influence of domestic runoff on the wetland.

Despite these threats, the local community has limited access to resources or support to address the issue, with no community center for gathering and no formal plans for environmental restoration. Additionally, socio-cultural dynamics, such as informal housing developments and inadequate land survey, further complicate ecosystem recovery. While many community members recognize the importance of mangroves and some have benefited from their protective role (Campbell et al., 2023), there is little structured community engagement or formal restoration activity. Moreover, the community´s economic reliance on unsustainable practices, including charcoal burning and the cutting of wood for informal land development, and pig pens presents major challenges to establishing a viable long-term solution if these activities are not restricted (Fig. 3).

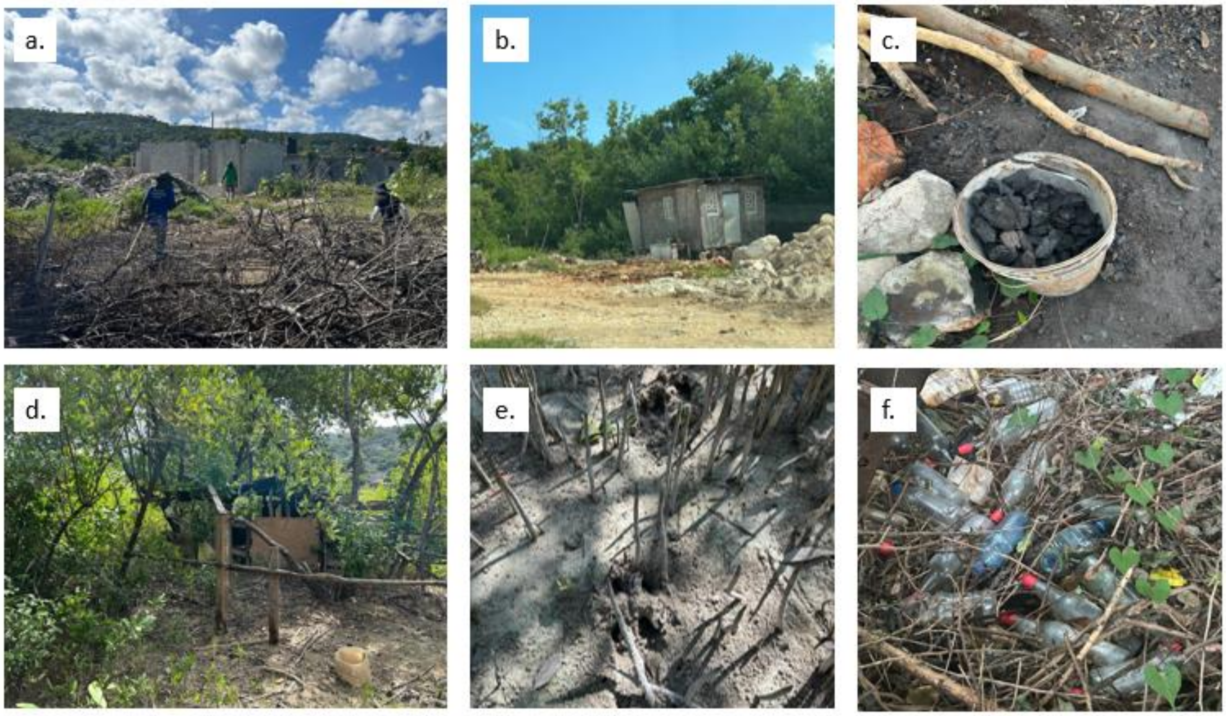

Figure 3. Documented threats to the Little River mangroves: **a.** deforestation, **b.** informal housing development, **c.** charcoal burning, **d.** presence of pig pens, **e.** pig footprints observed within mangrove, **f.** solid waste pollution.

This study will also employ tools such as problem and solution trees, a logic model, and a theory of change to propose sustainable strategies for addressing environmental threats considering for the community´s social-economic needs. However, the success of this restoration effort will depend on active community participation, stakeholder collaboration, and the mobilization of funding.

5. Objectives

5.1. General Objective

To design a restoration plan for the Little River mangrove ecosystem, with focus on guiding early-stage restoration through diagnostic assessment.

5.2. Specific Objectives:

- Evaluate the current hydrological conditions and vegetation status of the Little River mangrove ecosystem to establish an ecological baseline that will guide future restoration actions.
- Evaluate the carbon storage capacity of mangrove soils at control and degraded/restoration sites within the Little River community to assess their role in climate regulation.

6. Methods

6.1 Study Area

The Little River community in St. James is situated just west of the Greenwood Plaza (18°30”33.07 “N, 77°44´42.85 “W) with an average annual temperature of 24°C and precipitation of 134 inches (3,400mm) (Fig. 4). The area is reported to have some number of mangroves present that are currently in need of conservation based on current activities occurring in the area. Clearing the mangroves for construction purposes is a common activity, particularly in the southern section of the mangrove ecosystem near the pond. In addition, some community members live in very close proximity to the mangroves and new establishments are currently underway. This community falls within the boundary of the

North Coast Mangrove Conservation project, spanning from Salt Marsh, Trelawny (main project site) to Little River, St. James.

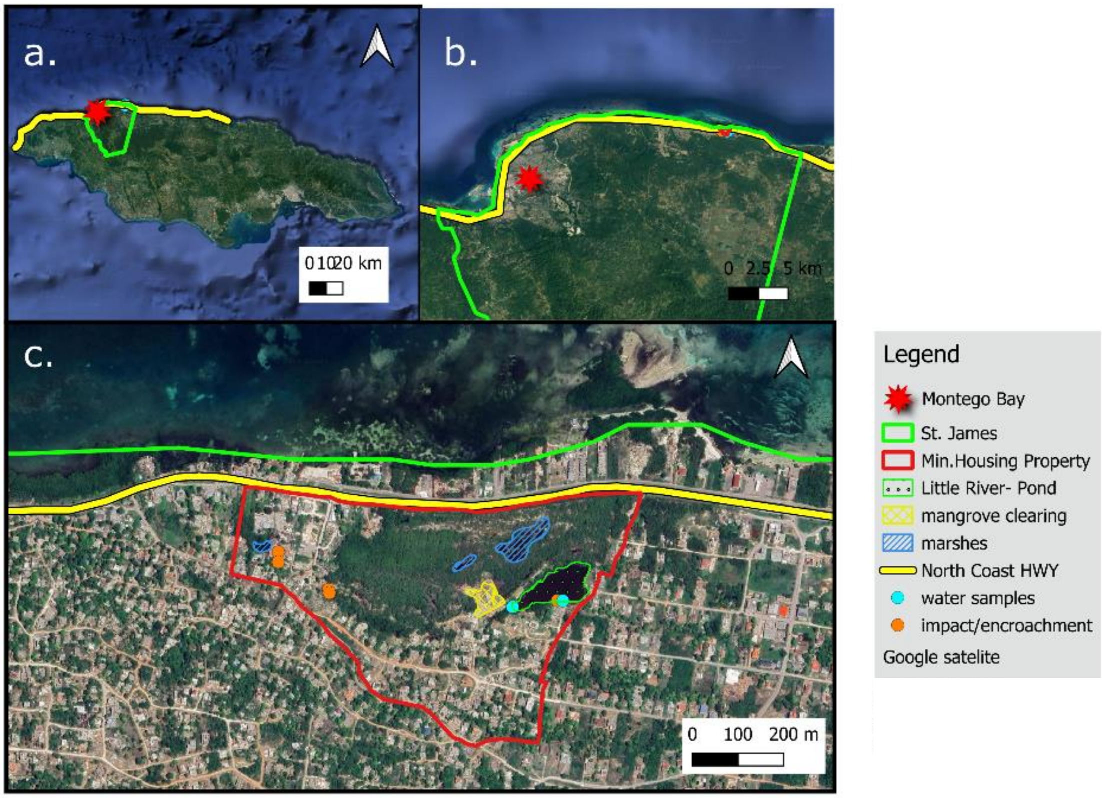

Figure 4. a. Geographic location of the Little River Community: **a.** St. James Parish and the North Coast Highway, **b.** northern coast of St. James Parish, **c.** Little River Community, including the land boundaries of the Ministry of Housing property, waterbodies, and existing threats (such as impacts from encroachment and mangrove clearing, primarily due to informal settlements).

The reference/control site was chosen based on its proximity to the restoration site and its comparable composition, structure, and ecological function, however, has no direct connection to the degraded/restoration site (Fig. 5). Located northwest of the restoration area, the reference site serves as a control for evaluating the effectiveness of restoration efforts. According to system calculations, the degraded/restoration site (Ministry of Housing Land) covers an area of 18.659 hectares. However, due to informal housing, only 12.57 hectares consist of mangrove forest. The control/reference site spans 24.014 hectares, with only 9.55

hectares of mangrove forest. As observed on site, the remaining areas include farms, secondary forest, and a fishing village along the coast.

Both sites have been divided into 10x10m grids for random sampling (Fig. 5). Randomized sampling points were generated using Excel, and GPS coordinates were recorded for each point (See Table. 1.) using QGIS 3.40.0, Google Satellite (2025), with the Coordinate Reference System set to JAD2001/UTM Zone 18N (EPSG:3450).

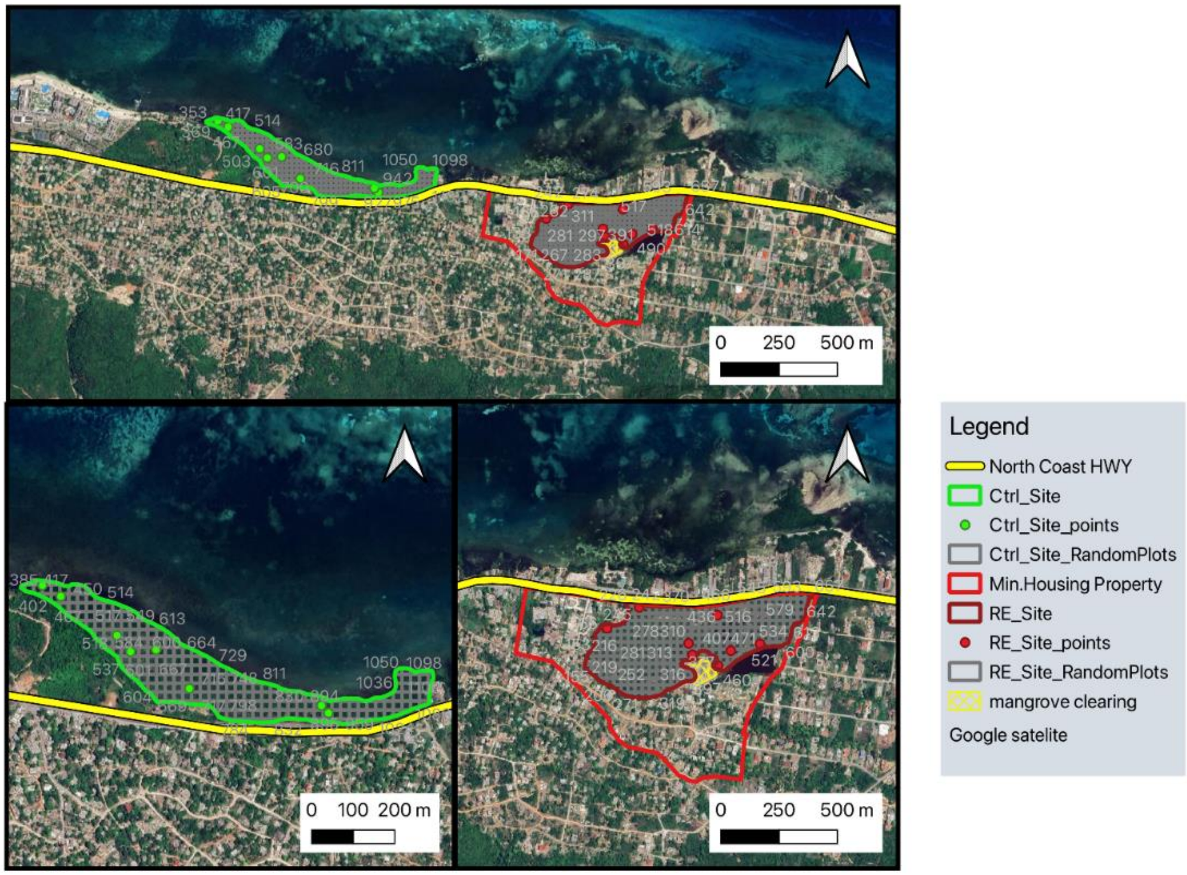

Figure 5. Restoration and reference sites designated for the collection of vegetation data and soil samples to assess carbon stocks in the Little River Community.

Table 1. Geographical locations of sampling plots at mangrove sites at the Little River community.

Site	Random Grids	No. Plot	Longitude	Latitude
C	385	16	18,5147	-77,761568
C	434	15	18,514453	-77.761.147
C	534	14	18,513581	-77,759871
C	568	13	18.513.215	-77.759.556
C	600	12	1.851.326	-77,758978
C	668	11	18,512395	-77.758.214
C	910	10	18,51201	-77,755206
C	927	9	18,511835	-77,755046
RE	198	8	18,510797	-77,748217
RE	259	7	18,51138	-77,747304
RE	436	6	18,511165	-77,74509
RE	376	5	18,510377	-77,745907
RE	393	4	18,510053	-77,745798
RE	443	3	18,509764	-77,745079
RE	473	2	18,510173	-77,744707
RE	536	1	18,510364	-77,743885

C= Control plot; RE= restoration/degraded plot

6.2. Biophysical data collection

During the dry season (January 2025), only water salinity was measured once per plot using a plastic 10ml pipette and a refractometer, but only when water holes were present in plot (Fig. 6 and Fig. 7).

Figure 6. Spatial distribution of plots (blue points and white text) and salinity (yellow text) across the control site of the Little River community. Data are shown as: plot number- salinity (ppt). Source: Google Earth Pro v7.3 (2025).

Figure 7. Spatial distribution of plots (blue points and white text) and salinity (yellow text) across the degraded/restoration site of the Little River community. Data are shown as: plot number- salinity (ppt). Source: Google Earth Pro v7.3 (2025).

6.3. Vegetation data collection

A total of eight randomized plots were established at each site (restoration and control) and all measurements were taken for a single sampling event in the dry season (January 2025). In each plot a minimum of 10 individuals was measured for each species found (red (*Rhizophora mangle*), black (*Avicennia germinans*) and white (*Laguncularia racemosa*). In the case of Buttonwood (*Conocarpus erectus*) "false mangrove" less than 10 individuals were observed, however still recorded. Adult mangrove trees (i.e., trees with height ≥ 1.30m and diameter at breast height (DBH) ≥ 5cm) and seedlings (i.e., individuals with height <1.30m) were measured using separate methods; DBH was recorded for adult trees (to within 0.1cm). For seedlings, number of individuals were determined and densities calculated per square meter within each plot. Densities were calculated similarly for trees.

6.4. Mangrove soil samples collection

Soil samples were taken from three points within each plot using landscape bulb planter (core volume: 452.38cm^3). This tool allowed for the collection of shallow belowground samples, with sampling patterns following the center, north-west (NW), and south-east (SE) borders of each plot. The samples were then combined to form a single statistical representative subsample for each plot. Samples were dried for 24 hours at 60°C in oven, ashed at 450°C in furnace for five hours and weighed on OHAUS Adventurer^{TM} Precision AX4202-E (Maximum Capacity: 420g Readability 0.01, resulting in an instrumental error of ±0.01 g) (Fig 8). Measurements of water salinity and soil organic carbon content were taken for a single sampling event in the dry season (January 2025).

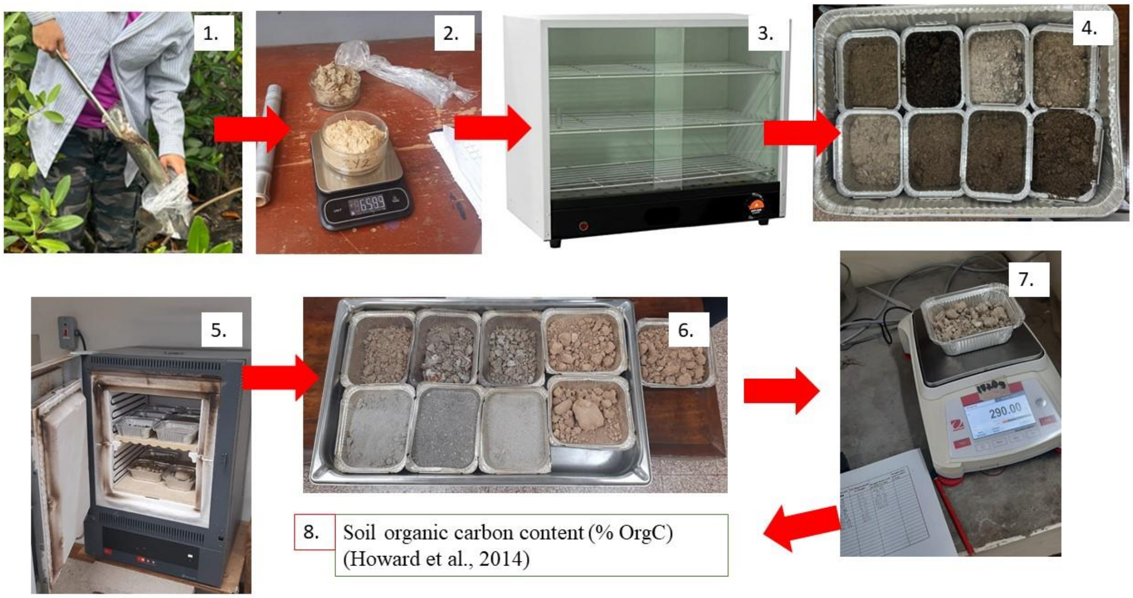

Figure 8. Soil organic carbon content methodology based on Howard et al., 2014 formulas. 1. collection of mangrove soil sample; 2. determine wet weight; 3. dry sample at 60ºC for 24h; 4. determine dry weight; 5. ash samples at 450ºC in muffle furnace for 5h; 6. soil samples removed from furnace; 7. determine ash weight; 8. input data in %C org formula.

6.5. Statistical analysis

For statistical comparison of vegetation factors, the normality distribution was checked using Shapiro Test, and data was transformed if necessary. The homogeneity of variance was also checked using the Bartlett test (n=) on R Studio 3.6.0 (package: writexl). Finally, to compare restoration/degraded (RE) and control (C), variables that followed a normal distribution were tested using the parametric test (T-Student): salinity and mangrove soil carbon samples (LOI (loss on ignition) %OC (percentage of carbon content in soil), CD (carbon density in soil), CDi (carbon density intervals) and OC (carbon content in soil)), while those without normal distribution were tested using non-parametric test (U Mann Whitney): height, DBH and bulk density (BD). Statistical summary was run in on R Studio 3.6.0 then attached to Excel (Microsoft Office LTSC Professional Plus 2021) for reading of tables.

6.6. Use of Strategic Planning Tools

To guide the initial stage of restoration planning for the Little River mangrove ecosystem, a Theory of Change (ToC) and Logic Model were developed following Clark and Anderson (2004). These tools provided a structured framework for outlining the sequence of expected changes, from inputs and activities to short-term outputs and long-term impacts, associated with the proposed restoration interventions. Their application supports clearer interpretations of the 2023 EIA findings helped prioritize interventions, align with the Society for Ecological Restoration´s emphasis on goal-oriented, adaptive, and socially inclusive restoration frameworks (SER,2004), as well as *Standard of Practices for Ecological Restoration* by Nelson et al. (2024) and *International Principles and Standards for the Practice or Ecological Restoration*, Gann et al. (2019).

7.Results

7.1. Biophysical factor: salinity

Salinity levels varied widely across both control and restoration plots, with maximum values ranging from 0 to 41 in the control plots and 0 to 45ppt in the restoration plots. In the control area, plots 11,10,9 and 16 recorded hypersaline conditions (35-41 ppt), while plots 12 and 15 showed no measurable salinity, likely due to reduced tidal flow. Similarly, in the degraded/restoration site, plot 7 reached the highest value (45ppt), whereas plots 4 and 6 recorded zero salinity. This high spatial variability suggests local differences in hydrology or microtopography across sites. However, salinity levels did not differ significantly between control and restoration sites (p-value= 0.8982) (Table 2), indicating that despite localized extremes, the overall salinity regime remains comparable between both site types (Fig.9)

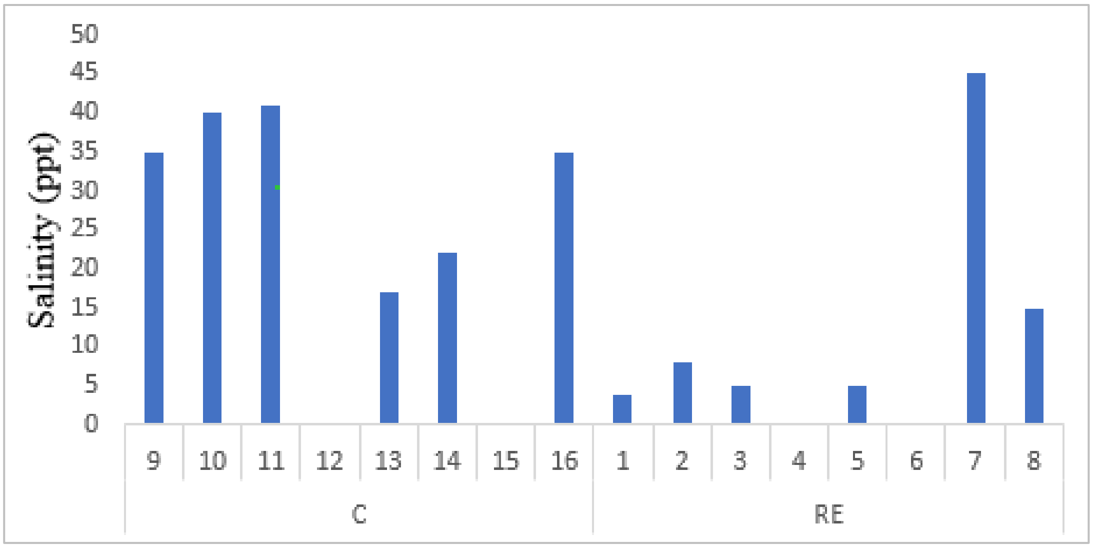

Figure 9. Salinity levels across control (C) and restoration/degraded (RE) areas in the Little River community.

7.2. Mangrove forest vegetation components

To assess the current ecological status of the Little River mangrove ecosystem, data were collected across two sites: a control site (C) representing relatively undisturbed conditions and a degraded/restoration site (RE) identified for future restoration. A total of 237 mangrove individuals were recorded. Of these, 102 individuals were documented in the control site and 135 in the degraded site. The analysis of tree density across both sites revealed that mature mangrove trees were well represented at both the control and degraded/restoration sites. The control site recorded the highest individual tree density, with red mangroves (*Rhizophora mangle*) reaching up to a maximum of 48 mature individuals, while the degraded/restoration site showed a lower maximum density of 20 individuals of red mangroves (*Rhizophora mangle*) (Fig. 10).

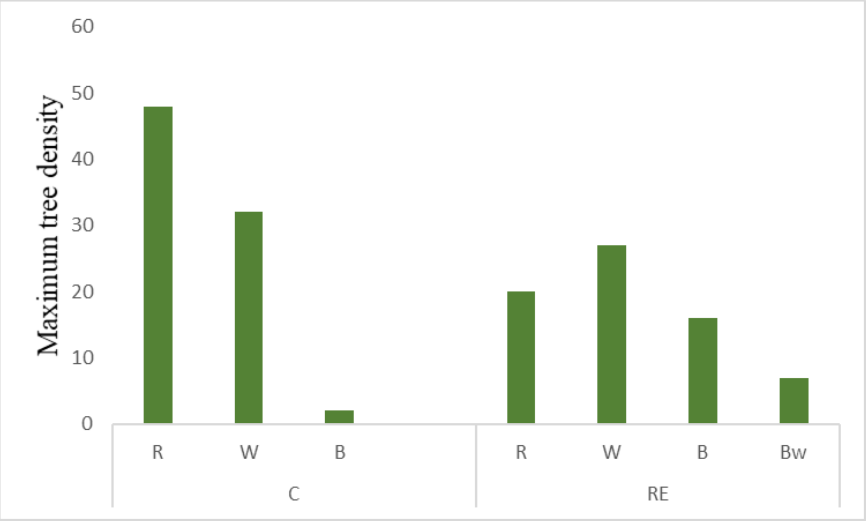

Figure 10. Maximum tree density of mangrove species (Red-R; White-W; Black –B; Buttonwood-Bw) across control (C) and restoration/degraded (RE) sites in the Little River community.

Seedling distribution patterns differed notably between sites. While seedling presence at the control site was relatively limited, with a maximum of 36 individuals observed, the degraded/restoration site exhibited much greater seedling abundance. White mangroves (*Laguncularia racemosa*) and red mangroves reaching maximum counts of 85 and 65 seedlings respectively (Fig. 11).

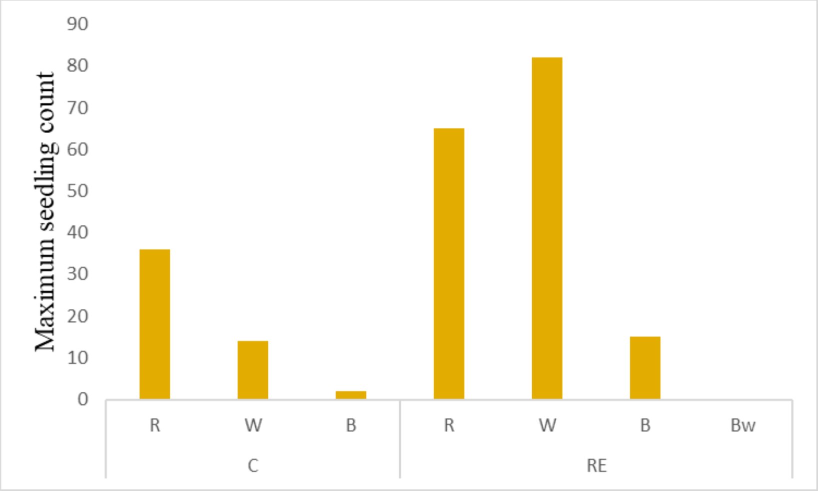

Figure 11. Seedling distribution of mangrove species (Red-R; White-W; Black –B; Buttonwood-Bw) across control (C) and restoration/degraded (RE) sites in the Little River community.

Structural characteristics of mangrove vegetation, including average tree height and diameter at breast height (DBH), demonstrated distinct differences between the control and restoration sites. Tree height differed significantly (p-value=5,62e-11) among sites. Trees in the control site were taller (6.4 m ±3,5) (mean ±SD) than those in the restoration area (4.8 m ± 1.9) (mean ±SD). Red mangroves (*Rhizophora mangle*) exhibited the greatest average height in both locations, measuring 9 m ± 3.5 (mean ±SD) at control site and 5m ± 3.2 (mean ±SD) at the restoration site. Additionally, white mangroves (*Laguncularia racemosa*) also showed taller average individuals in the control site (5.5 m ±3.4) (mean ±SD) compared to the degraded/restoration site (3.9 m ±1.4) (mean ± SD) (Fig. 12). In contrast, the restoration site included shorter average trees and the presence of buttonwood (*Conocarpus erectus*), which increased species richness (Fig.12).

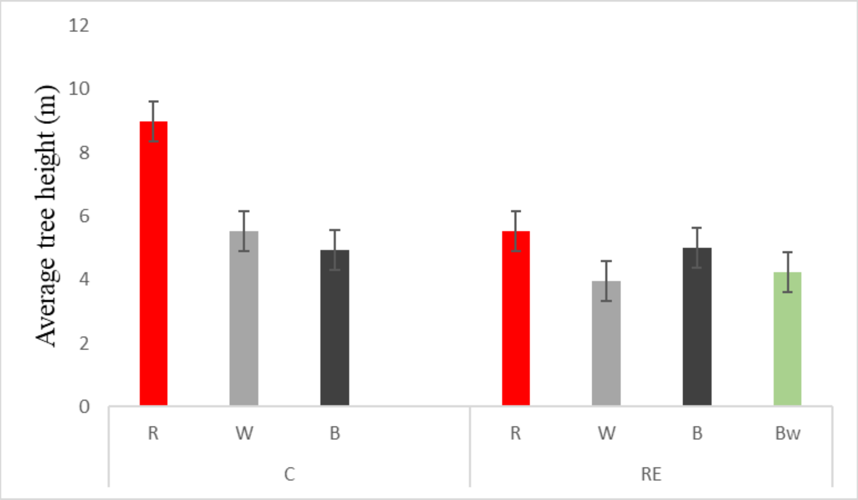

Figure 12. Average height of mangrove species (Red-R; White-W; Black –B; Buttonwood-Bw) in control (C) and degraded/ restoration (RE) plots in the Little River community.

Diameter at breast height (DBH) differed significantly between the control and degraded/restoration sites (p-value < 0.05). The control site had a higher average DBH of 14.4cm ± 13.9 (mean ±SD), whereas trees in the restoration site exhibited thinner trunks, with an average DBH of 10.6 ± 3.2 (mean ±SD) (Fig. 13.)

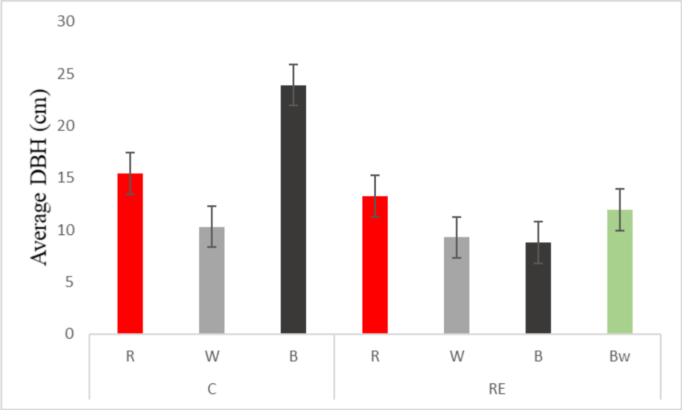

Figure 13. Average diameter at breast height (DBH) of mangrove species (Red-R; White-W; Black –B; Buttonwood-Bw) in control and restoration/degraded site in the Little River community.

Statistical analyses demonstrated significant differences in mangrove vegetation structure between the control and restoration/degraded sites, particularly in tree height and diameter at breast height (DBH), however, no significant differences were found in salinity between sites (Table 2).

7.3. Mangrove soil carbon content

Underground organic carbon content (OC) was assessed to evaluate the carbon storage potential of both the control and restoration/degraded mangrove plots. Average values ranged from 41.26 to 219.57 MgC/ha, with degraded/restoration plots showing slightly higher average storage (124.3 Mg C/ha) compared to control plots (107 Mg C/ha) (Fig. 14). Notable variability was observed among individual plots.

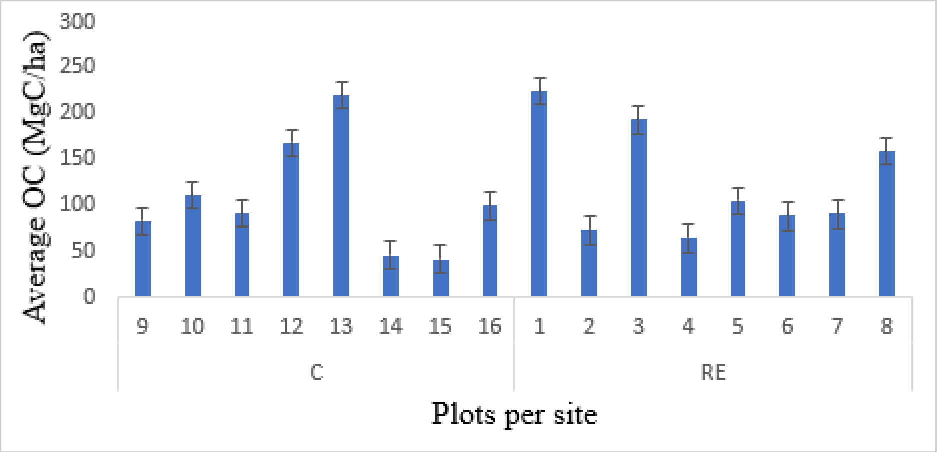

Figure 14. Comparison of organic carbon content (Mg/ha) between degraded/ restoration (RE) and control plots (C).

Soils across both sites exhibited moderate to high organic matter content, with a mean loss-on-ignition (LOI) of 31.9 ± 24.4 (mean ± SD) and an average organic carbon content of 18.5%. Soil carbon density averaged 0.072 g C/cm^2, falling within the moderate range (0.05-0.1g C/cm^2). No significant differences were found between sites for bulk density (BD) (U=247, p=0.82) or carbon density (CD) (t (47) = 0.86, p=0.42). Total soil carbon stocks were estimated at 1,561 Mg C for the degraded/restoration site and 1,026 Mg C for the control site (Table 2).

Table 2. Summary statistics for mangrove parameters at the control and degraded/restoration sites of the Little River community.

Parameters	**Variable**	**Range** (min-max)	**Mean**	**SE**	**p-value**	**stats_test**
Physicochemical factor	salinity	0-45	19,69	1,7	0.8982	T-Student
Vegetation structure	height	1.4- 16	6,435	0,293	5,62E-11	Mann-Whitey U
	DBH	0.5-114	-	-	4,34E-24	
Mangrove soil carbon content	BD (g/cm^2)	0.08-0.84	-	-	0,824	
	LOI (%)	5.59- 93.37	31,9	4,985	2,93E-01	T-Student
	%OC	3.24- 54.15	18,5	2,885	2,93E-01	
	CD (gC/cm^2)	0.01- 0.22	0,072	0,009	4,29E-01	
	CDi (g/m^2)	0.30- 3.57	1,155	0,151	4,29E-01	
	OC (g/m^2)	3062.69- 35767.73	11571	1511,5	4,29E-01	
	OC (MgC/ha)	30.62- 357.67	115,5	15,1	4,29E-01	

8. Discussion

8.1. Vegetation baseline for future restoration guidance

Ecological restoration is inherently a dynamic process, as shifting environmental conditions and external impacts may influence the success of restoration efforts. According to Gann et al. (2019), the concept of *Restoration Continuum* helps determine how far an ecosystem can be brought back from a degraded or destroyed state, either historically or presently by using an ecosystem reference. This framework assesses the extent of conditions to which full ecological restoration would be defined as an ecosystem with the potential recovery to self-sustaining itself requiring no further human intervention to continue its trajectory.

The mangrove system can be considered in rehabilitation phase, reflecting that no formal actions have yet been taken. Degradation has been somewhat limited because water continues to flow through the culvert, but local hydrology disruptions within the mangrove, caused by rubble and informal housing, create conditions for additional human-induced threats such as pollution, charcoal burning, solid waste accumulation, and pig pens. These pressures compromise water quality and vegetation recovery, even though the broader hydrology connection remains functional.

Despite these challenges, the system is not in a critical state. It still maintains important ecological functions such as carbon sequestration and elements of it´s reference structure and biodiversity, and the presence of seedling density further indicates natural vegetation recovery is possible. With targeted efforts to reduce human-driven threats and strengthen vulnerable functions, the ecosystem has a strong potential to be fully restored.

To guide this process, tools such as the Ecological Recovery and Social Benefits Wheel (Gann et al., 2019) offer useful baselines, nonetheless data limitation such as a lack in prior studies and limited sampling may pose a challenge for a comprehensive assessment. This study takes an ecological perspective, focusing on previously undocumented vegetation characteristics and soil carbon data for the area.

The following section outlines key indicators in this study and other restoration projects that can inform best practices, based on goals and outcomes towards ecological restoration planning.

8.1.1. Mangrove tree density and seedlings between sites

In ecosystem restoration, natural regeneration can be a cost-effective strategy when the site still holds recovery potential and environmental conditions such as hydrology, elevation, soil texture, salinity, and nutrient levels are suitable (Kamali and Hashim, 2011). This pathway of secondary succession relies not only on suitable hydrological conditions but also on the presence of nearby parental trees that can provide propagules. Species-specific patterns also play a role, for example, red mangrove (*Rhizophora mangle*) seedling density is strongly influenced by proximity of adult trees explaining 86-94% of variations, whereas black mangrove (*Avicennia germinans*) seedling respond more lo light availability and ammonium levels (NH_4), with long-term success shaped by flood intensity and salinity (McKee, 1995).

The control site exhibited a more established forest structure, characterized by higher densities of mature mangrove forest but limited seedling presence, particularly of red mangrove (*Rhizophora mangle*), which was dominant at this site. This pattern likely reflecting a late successional stage, where dense canopy cover darkens understory and inhibits recruitment within established forest interiors (Sousa et al., 2003), while strong competition for resources in mature stands limit seedling establishment (Peng et al., 2016).

In contrast, the restoration site, while having fewer mature trees showed strong signs of natural regeneration with abundant seedling recruitment, particularly of red and white mangroves (*Rhizophora mangle* and *Laguncularia racemosa*, respectively). The presence of white mangrove (*L. racemosa*) and it´s seedlings in the degraded site may reflect the species´ role as an early successional colonizer (Delgado et al., 2001) capable of establishing in disturbed environments due to species´ physiological plasticity (Pezeshki et al., 1990; Buckmire et al., 2025) and its adaptability to greater light and open soil conditions created by canopy disturbance (Silva and Maia, 2019).

These patterns suggest that, despite the degraded condition, the restoration site holds significant potential for recovery through natural processes. While hydrological rehabilitation remains essential, ongoing small-scale disturbances from land reclamation, though unintended, may also have influenced on regeneration dynamics by creating canopy gaps (Sherman et al., 2000). This also highlights the ecosystem´s resilience and its capacity to adapt to environmental changes by taking advantages of newly sunlit areas.

Other studies support this nature-based approach by emphasizing the need to first address physical and hydrological stressors, for example, López-Portillo et al. (2021) reestablished hydrological conditions of stagnant water by excavating canals that reconnect flow in mangrove areas to lagoon systems or water bodies, this way lowering the concentration of ammonia, sulfur, and salinity in the substrate, which after five years natural seedling colonization and establishment had occurred (López-Portillo et al., 2021). A similar strategy could be applied in the Little River mangrove forest by removing marl-filled soils near roads, reconnecting the areas to surrounding waterbodies, and addressing other stressors, such as reducing nitrogen and phosphate inputs to pond, improving pig pen management, and limiting encroachment to create conditions that support seedling developments into mature mangrove (pers comm. Trench, 2025).

These findings not only support Lewis´s (2005) argument that hydrologically restoration is often more effective than planting, but also illustrate how such interventions can lead to long-term ecosystems recovery when environmental conditions are restored. However, even when those conditions are there, depending on the species, it is possible that vegetation might not establish naturally or when planted because of environmental conditions and seedling adaptability. Therefore, measuring other factors such as water levels for wet and dry periods and lunar tidal cycle could reenforce method for sampling (Van Loon et al., 2016).

8.1.2. Mangrove tree height and diameter at breast height (DBH)

Average tree height and average DBH were greater at the control site, particular for red mangrove (*Rhizophora mangle*) and black mangrove (*Avicennia germinans*), with some individuals reaching nearly 10 m in average height and an 25cm in average DBH respectively, indicating structural maturity under long- standing favorable biophysical conditions. According to Bosire et al. (2008), such parameters are reliable indicators of forest maturity and ecosystem functionality.

In contrast, the restoration site generally had shorter trees, averaging below 6 meters in height and around 5 cm in DBH, reflecting an earlier stage of ecological succession. Despite this, signs of recovery were evident, particularly among red mangroves (*Rhizophora mangle*) and white mangroves (*Laguncularia racemosa*), which showed promising in plots closest to culverts and tidal inlet near the road construction. These species appear to be responding well to local conditions and should be prioritized in restoration planning to support structural development and long-term ecosystem recovery.

These patterns align with Salmo et al. (2013), who found that younger *Rhizophora mucronate* plantations (6-12 months) exhibited the fastest gains in DBH (up to 0.77cm/year) and height (up to 0.35 m/year), with growth rater slowing as trees matured. Similarly, in Matehage Island, Indonesia, *Rhizophora* spp. increased from 7.13cm to 11.69cm in DBH and 4.45m to 7m in height over 22 years (1996-2018) under legal protection of the Bunaken National Park (Djamaluddin et al., 2024), particularly in areas with restored hydrology.

Although the restoration/degraded site at Little River has yet to gain structural maturity when compared to the control site, increases in tree height and DBH, especially when the site improves in hydrological conditions could demonstrate future signs of ecosystem recovery. These parameters remain crucial for assessing the restoration progress and shaping informed decisions, especially since no intervention measures have yet been implemented to address ongoing pressures.

8.2. Mangrove soil carbon storage in control vs. degraded/restoration site

Soil Organic Carbon (SOC) plays a pivotal role in the carbon dynamics of mangrove ecosystems, functioning as a major reservoir for long-term carbon storage and a key indicator of restoration success. In this study, SOC values varied widely across plots in both the restoration and control sites of the Little River mangroves. The spatial heterogeneity within sites was notable, suggesting that differences in vegetation structure, decomposition rates, and possibly age of trees were influencing belowground carbon accumulation.

Plots with the highest SOC (219.57 Mg/ha) were associated with denser vegetation, underscoring the role of plant biomass in promoting carbon input to the soil. This pattern aligns with findings from subtropical and tropical mangrove forest in Taiwan, where high tree density significantly increased carbon accumulation due to elevated productivity and litter input. In those systems, net production rates (including below and above ground biomass) reached up to 27.64 Mg C ha -1 yr-1, surpassing global averages (Li et al., 2018). Although trees species differed, site conditions proved more influential in shaping carbon processes, and observation echoed by our own results, where site-level averages masked substantial plot-level variation.

Interestingly, our below-ground organic carbon storage per site was slightly higher in the restoration/degraded area (124.3 Mg C/ha) than in the control site (107 Mg C/ha), with total below-ground soil carbon stock estimates of 1,561 Mg C and 1,026 Mg C respectively at the Little River community study. While one might expect intact or mature trees to store more carbon, this inversion suggests that restoration areas may have benefited from dense regrowth, organic matter retention, or favorable hydrological conditions that promoted SOC build-up, factors also emphasized in other studies. For example, work across mangrove reserves in southerneastern China found that site characteristics such as geomorphology, vegetation type, and disturbance history drove wide variation in SOC, ranging from as low as 84.8 Mg C/ha in Dongzhaigang to over 400 Mg C/ha in Wenchang (Gao et al., 2019).

Globally, mangrove systems are recognized for their exceptional carbon storage capacity. Mature forest can reach soil organic carbon (SOC) levels exceeding 400 Mg C/ha in below-ground soil (to depth of < 30 cm), over 600 Mg C/ha in the 0-30cm layer when including roots, and more than 800Mg C/ha in above-ground biomass (including live and dead plants), particularly in oceanic or estuarine sites where deep peat layers and low decomposition rates prevail (Donato et al., 2011). Our maximum values (219.57 Mg/ha) were well below these peak global estimates, yet within the mid/to/high range reported in various regional studies, such as Yunxiao and Gaoqiao in China (95.9-260.3 Mg C/ha) and salt ponds mangroves in the U.S. Virgin Islands (~46.3 Mg C/ha) (Krauss et al., 2020). This reinforces the idea that local factors like hydrology, disturbance history, and vegetation regeneration significantly influence SOC dynamics.

Moreover, while some studies have established positive correlations between above- and below-ground carbon, high SOC values in certain restoration plots may reflect intensive root development and organic matter input, rather than just visible aboveground biomass (Meng et al., 2021). This complex interaction between vegetation structure and soil carbon aligns with broader research emphasizing the importance of forest age, species composition, and stand development stage in shaping belowground carbon patterns (Meng et al., 2021).

Overall, the SOC data from the Little River mangroves indicates a moderate to high potential for carbon sequestration, particularly in zones with evident regrowth. The lack of significant variation in bulk density and carbon density between degraded/restored and control plots suggests that there might not be change in soil stability and the buildup of organic matter from leaflitter and its decomposition, despite ongoing differences in vegetation structure, possibly due to historical organic layer accumulation, but also slow decomposition rated in waterlogged and anaerobic soils.

8.3. Incentives and outcomes in ecological restoration efforts

Motivation for engaging in restoration efforts can be both individual and collective, shaped by how people perceive the purpose and goals of restoration. Clewell and Aronson, diagram on a framework developed by Ken Wilber (2001), propose a model for the successful restoration that integrates four key values: personal, ecological, cultural and socio-economic. These are organized into four-quadrant model that captures both individual and collective dimensions, as well as subjective and objectives perspectives. Understanding how these values align with a community´s vision can be explored through participatory surveys, which are essential for shaping relevant and lasting restoration process to support long-term engagement and sustainability (Clewell and Aronson, 2012). In the case of Little River, community motivation appears strong, particularly around ecological values, in which 15 out of 16 respondents in the EIA 2023 expressed an understanding of the importance of the mangrove ecosystem (Campbell et al., 2023). However, to fully grasp the community´s broader values and priorities, further social research would be beneficial.

According to Hallet et al. (2013), in a review of over 200 restoration projects across 54 countries, around 30% incorporated both ecological and social goals, while fewer than a quarter addressed long-term ecosystem sustainability. Most projects focused on restoring ecosystem structure and function, rather than addressing the root causes of degradation or prioritizing ecosystem sustainability. Social goal such as socio-economic benefits, cultural values, education and governance were often included. For Little River, these social aspects are suggested to be implemented, especially towards governance by addressing land tenure and reduce encroachment to further into the mangrove, respecting land boundary. Additionally, the restoration plan outlined below will guide future decision-making, funding applications, and policy support for long-term restoration efforts in this area. It includes indicators of success and monitoring plan, a theory of change, and logic model to help ensure ecological resilience and long-term sustainability.

9. Mangrove Management Plan

This management plan outlines the approach for restoring the Little River mangrove ecosystem with a long-term vision extending to 2050. It integrates ecological restoration efforts with community engagement and institutional governance, aiming to address key environmental challenges in the area. The subsequent sections of this thesis will detail the specific restoration vision, goal, targets, strategies for implementation, indicators, and monitoring methods designed to ensure the successful recovery and sustainability of the mangrove ecosystem.

Between 2025 and 2050, proposed interventions at Little River include installing fencing (1,877.69m^2) and six signage to protect the mangrove boundary, removing 10,013 m^3 of dumped material to restore natural hydrology, establishing a community recreational center and boardwalk for education and eco-tourism; conducting regular water quality monitoring, and removing two pig pens within the conservation area. The estimated cost for these activities ranges from JMD $12,477,500 – JMD $20,142,250, inclusive of a 15% contingency for unforeseen delays or changes in plan.

9.1. Intervention zones

To support conservation efforts in the Little River community, a protective boundary is proposed through the installation of fencing around 1,877.69 m^2 along the outer edge of the remaining 12.57 ha of mangrove forest. Six strategically placed signs will be erected, particularly near residential areas, to discourage unauthorized land encroachment and to limit access to the mangrove ecosystem.

Rubble removal is planned in four key zones: (E1) an area in the northwest where a garage currently exists; (E2) a cleared section of mangrove forest that has been used as a dumping site for future housing construction, though no development has yet occurred; (E3) an informal roadway leading to the North Coast Highway where marl and other fill material from 2008 road construction have been deposited, obstructing natural hydrology flow.

The total estimated volume of material to be excavated is 10,013.911m^3, with off-site disposal recommended (see Fig. 15 and Table 3).

A recreational center is proposed for the southeastern section of the mangrove conservation boundary, designed to facilitate community workshops focused on waste management, educational on ecological importance of mangrove, and training for local residents in ecosystem monitoring. The center will also support birdwatching and kayaking activities, promoting family engagement while offering sustainable livelihood opportunities for the community. Additionally, a of 231.24m^2 boardwalk will be integrated into the site to host school visits and enhance environmental outreach activities.

To assess both ecosystems and community health, water quality will be monitored at five designated points within the mangrove system. This will help identify potential contamination sources, such as sewage or other pollutants. Furthermore, the intervention includes the removal of two existing pig pens located within the newly established conservation area. These activities are included among the planned interventions and cost estimates presented in Table 4.

Figure 15. Intervention zones of the Little River mangrove restoration plan (2025-2050).

Table 3. Excavation estimates for mangrove restoration sites at the Little River community.

Parameter	**E1**	**E2**	**E3**	**E4**	**Unit**
Area	1,626.4	1,752.49	220.99	8,759.35	m^2
Average Depth	0.3	0.4	0.25	0.5	m
Extraction Volume	4,878	700.996	55.24	4,379.67	m^3
Total excavation volume	10,013.911				m^3
Type of material	scrap metal	rubble	rubble	rubble	-

Table 4. Strategies, Interventions, and Budget Estimates for the Little River Community Restoration Plan (2025–2030).

Strategy	Interventions	Intervention Zone / Area	Estimated Budget (JMD)
1. Protect and conserve existing mangrove forest	Install fencing (1,877.69 m^2) along mangrove boundary	Outer boundary of 12.57 ha mangrove forest	JMD $2,480,000 – $3,720,000
	Install six signs to prevent encroachment		
2. Restore natural hydrology and remove physical barriers	Excavate and remove 10,013m^3 of dumped material	E1–E4 (Garage area, Cleared site, Road, Highway dump area)	JMD $9,300,000 – $15,500,000
	Construct recreational center (195.29m^2)		
3. Promote environmental education and community engagement	Build 231.24 m^2 boardwalk for tours and school outreach	Southeastern conservation boundary area	JMD $7,750,000 – $12,400,000
	Install water sampling points (5 locations)		
4. Improve water quality and monitor ecosystem health	Conduct regular water quality testing (monthly first year, then quarterly)	Within mangrove ecosystem	JMD $1,550,000 – $2,480,000 (first 3 years)
5. Eliminate point sources of pollution	Remove two pig pens within conservation area	Within conservation boundary	JMD $620,000 – $930,000
Total budget estimated			**JMD $21,700, – JMD $35,030,000**
Contingency (15%)			**JMD $24,955,000 – JMD $40,284,500**

**Values in Jamaican Dollars (JMD)*

9.2. Scope

This project focuses on the ecological restoration and community integration of the mangrove ecosystem in the Little River community, located in St. James, Jamaica. It aims to address environmental degradation, particularly from informal settlements, unsafe sewage disposal, and unregulated land use, through a community-driven, sustainable restoration plan.

9.3. Vision

To create a clean, vibrant, and thriving coastal environment where residents live in harmony with nature, appreciate the value of mangroves, and actively protect their environment. It envisions a future where community members take pride in a restored ecosystem, practice responsible waste management, engage in sustainable livelihoods, and pass on a culture of environmental stewardship to future generations.

9.4.. Targets

The restoration target is to return the mangrove ecosystem to a condition similar to a healthy reference site, focusing on both biotic (e.g., species richness, seedling density) and abiotic (e.g., hydrological flow, sediment quality) conditions. Social targets include improved community knowledge, reduced encroachment, improved waste management, and increased participation in mangrove protection.

9.5. Goal

By 2050, the Little River mangrove area will be fully restored in ecological, social, economic, and legal dimensions. The local community will sustainably cohabit with the mangrove forest and appreciate its ecosystem value both functionally and aesthetically. This includes adapting sustainable land use and domestic practices that support clean water, waste management, and community-based conservation. Progress will be measured against 2024 baselines with regular monitoring across all dimensions.

9.6. Objectives

- By 2026, complete a hydrological restoration plan and clear at least 75% of identified rubble and blockages affecting tidal flow in the mangrove area.

- By 2027, implement and evaluate a minimum of three community-based training programs on mangrove importance, waste management, and eco-livelihoods, with at least 60% of local households participating.

- By 2028, reduce encroachment incidents by 50% through community education, legal enforcement, and public signage, measured by field inspections and local authority reports

- By 2030, ensure that water quality parameters (nitrate, phosphate, fecal coliform) meet NEPA's marine water standards at all monitoring sites in Little River, maintained through quarterly testing.

- By 2032, establish at least five sustainable income-generating projects (e.g., eco-tourism, mangrove nurseries, craft production) managed by local residents.

- By 2035, secure formal land-use protection or designation for at least 80% of the mangrove area through legal frameworks or policy instruments.

- By 2040, restore and maintain a minimum of 90% mangrove canopy coverage relative to baseline degradation areas, monitored through aerial imagery and field surveys.

- By 2045, ensure that 70% of the community reports positive behavioral change towards mangrove conservation and actively participates in stewardship programs.

9.7. Indicators of Success and Monitoring Plan

This monitoring plan outlines the key indicators, methods, frequency, and responsible parties involved in tracking the ecological, social, economic, and political progress of the Little Rives Mangrove Restoration Plan (Table 5), as well as the estimated monitoring budget for 20 years (2031-2050) for the mangrove conservation area (See Table 6; annexes 1a-1d). It ensures that restoration outcomes are measured consistently and transparency over time. The table serves as reference framework for evaluating the effectiveness of project interventions, guiding adaptive management, informing stakeholders of long-term sustainability. Notably, it highlights the importance of regular water quality testing, community participation, eco-livelihood development, and institutional engagement as core components of the monitoring strategy.

The indicators selected for this monitoring plan align with the SC36 Monitoring and Evaluation Framework, the SC38 Selection of Indicators, and the Standard of Practices for Ecological Restoration by Nelson et al. (2024), ensuring compatibility with global recognized best practices. These indicators of success reflect measurable bio-physical, socio-cultural, economic and governance outcomes that support long-term ecosystem recovery and community resilience.

Table 5. Indicators of success and monitoring plan for Little River mangrove restoration.

Dimension	Indicator	Monitoring Method	Frequency	Responsible Party
Ecological	Water quality (nitrate, phosphate, salinity, turbidity)	Field sampling; lab analysis; reported in annual environmental status reports	Monthly during first year (during wet season), then quarterly	Local monitors, UWI-DBML
	Mangrove seedling density and canopy cover	Fixed transect surveys, drone imagery	Annually	Environmental scientists, forestry partners and local community
	Tidal flow and sedimentation patterns	Flow meters, sediment traps, GIS mapping	Biannually; Maps every 3 years	Hydrologists, GIS specialists

Continuation of table 5. Indicators of success and monitoring plan for Little River mangrove restoration.

Dimension	Indicator	Monitoring Method	Frequency	Responsible Party
Socio-cultural	Participation in community workshops	Attendance logs, pre/post surveys	Per training cycle	NGOs, Community Leaders
	Incidents of illegal dumping and sewage practices	Site inspections, enforcement records	Quarterly	Local authorities, NEPA
	Number of eco-livelihood initiatives	Business registry, community interviews	Every 2 years	NGOs, Community Development Groups
	Effectiveness of public signage	Field inspections, community feedback	Every 2 years	Local NGOs, Municipal Council
Economic	Number of sustainable businesses established	Chamber of commerce and NGO partner records	Annually	Local Business Associations, NGOs
	Income generated from eco-livelihoods	Household surveys, business financial logs	Every 2 years	NGOs, Community Leaders
	Access to restoration funding or grants	Donor agreements, disbursement tracking logs	Annually	Grant Managers, Project Coordinators
	Employment opportunities from restoration initiatives	Employment logs, community job surveys	Every 2 years	Restoration Project Teams, Local Government
Political/Legal	Policy changes and permits granted	Review of NEPA and parish council reports	Annually	NEPA, Parish Council
	Inclusion of mangrove areas in local land-use planning	Review of updated municipal planning documents	Every 3 years	Parish Planners, Land Agencies
	Frequency of enforcement activities	Enforcement logs, stakeholder interviews	Semi-annually	NEPA, Environmental Wardens

Table 6. Total estimated implementation and monitoring budget (2031-2050).

Category	**Month 0**	**Month 3**	**Month 6**	**Year 1**	**Year 5**	**Year 10**	**Year 15**	**Year 20**	**Total Years**
Ecological	$ 600.000,00	$ 250.000,00	$ 300.000,00	$ 400.000,00	$ 500.000,00	$ 600.000,00	$ 500.000,00	$ 700.000,00	**$ 3.850.000,00**
Socio-Cultural	$ 200.000,00	$ 100.000,00	$ 120.000,00	$ 150.000,00	$ 200.000,00	$ 250.000,00	$ 200.000,00	$ 300.000,00	**$ 1.520.000,00**
Economic	$ 200.000,00	$ 100.000,00	$ 120.000,00	$ 200.000,00	$ 250.000,00	$ 300.000,00	$ 250.000,00	$ 350.000,00	**$ 1.770.000,00**
Political/Legal	$ 100.000,00	$ 80.000,00	$ 100.000,00	$ 120.000,00	$ 150.000,00	$ 200.000,00	$ 180.000,00	$ 220.000,00	**$ 1.150.000,00**
Total (No Contingency)	$ 1.100.000,00	$ 530.000,00	$ 640.000,00	$ 870.000,00	$ 1.100.000,00	$ 1.350.000,00	$ 1.130.000,00	$ 1.570.000,00	**$ 8.290.000,00**
Contingency (15%)	$ 1.265.000,00	$ 609.500,00	$ 736.000,00	$ 1.000.500,00	$ 1.265.000,00	$ 1.552.500,00	$ 1.299.500,00	$ 1.805.500,00	**$ 9.533.500,00**

**All values in Jamaican Dollars (JMD)*

9.8. Theory of Change and Logic Model

The restoration of the Little River mangrove ecosystem in St. James, Jamaica, is built on a Theory of change that envisions a resilient, biodiverse mangrove landscape coexisting with a knowledgeable and environmentally responsible community by 2025. This long-term transformation is driven by a chain of cause-and-effect relationships, each step contributing towards the larger goal of ecological, social, economic and political achievements.

The logic model lays out this change process in a structured sequence (Table 7). Activities such as clearing debris and restoring hydrological flow are expected to directly lead to improved tidal exchange and healthier sediments dynamics, which in turn support natural mangrove regeneration. The presence of these long-term ecosystem health, biodiversity recovery, and improved water quality.

Simultaneously, activities like environmental education workshops, public signage, and the development of sustainable livelihood are designed to influence community behaviors and values. These actions are expected to produce immediate outputs such as increased awareness, community participation, and alternative income sources. These outputs justify intermediate outcomes like reduced illegal dumping, greater respect for mangrove buffer zones, and a stronger culture of environmental stewardship.

Each step logically builds on the previous one. For example, as eco-livelihoods gain traction and community members begin to benefit economically from the restored mangrove areas, the incentive to protect and sustain the ecosystem grows. This behavioral change is reinforced by consistent environmental monitoring and visible improvements in mangrove health and water quality. The involvement of institutions like NEPA and municipal authorities in land-use enforcement and policy alignment ensures that gains at the community level are backed by legal and administrative support.

Table 7. Logic Model for Little River Mangrove Restoration outlining a comprehensive strategy addressing the ecological, social, economic, and political factors critical for sustainable mangrove recovery.

No.	Inputs	Activities	Outputs	Intermediate Outcomes	Long-term Outcomes
1	Funding from NGOs (Sandals Foundation), NEPA, MOH	Host community workshops on waste management, sanitation, and mangrove benefits	Training sessions, IEC materials, feedback surveys	Greater awareness of environmental impacts and safe waste practices	Reduction in informal dumping and encroachment
2	Water testing kits, lab access, trained personnel	Monitor water quality (nitrates, phosphates, faecal coliforms) and share results publicly	Water quality reports, community briefings	Early detection of pollution trends, informed local action	Water quality meets NEPA standards consistently
3	Restoration engineers, hydrological maps, excavators, community labour, permits	Reconnect tidal flow by clearing culverts, removing rubble/fill, and regrading mangrove hydrology	Restored hydrology and visible tidal flow; natural regeneration observed	Restoration permits granted; sediment balance and ecosystem function return	Biodiverse, self-sustaining mangrove system resilient to climate impacts
4	Medical team access, health survey tools	Conduct environmental health assessments and link issues to ecosystem degradation	Health impact reports and mitigation recommendations	Residents recognize health risks tied to pollution and drainage	Reduction in disease outbreaks and safer living conditions
5	Community leaders, youth groups, entrepreneurs	Develop alternative livelihoods (eco-tourism, sustainable products); train locals in green jobs	Business pilots (e.g. tours, mangrove nurseries), trained community members	Economic value linked to conservation; income from sustainable activities	Sustainable local economy supports conservation, reduces pressure on mangroves
6	Policy advisors, NEPA officers, planners	Advocate for land-use reform; improve monitoring and enforcement capacity (SDC and TAJ)	Land-use maps; policy briefs; staff trained in EIA/enforcement	Stronger institutional oversight; fewer illegal developments	Institutionalized protection of mangrove ecosystems through legal frameworks

* IEC materials: Information, Education, and Communication materials

*SDC: Social Development Commission

*TAJ: Tax Administration of Jamaica

Ultimately, these linked outcomes, restored ecosystems, engaged communities, sustainable economies, and improved governance, are expected to produce the overarching change: a thriving, well-managed mangrove forest that protects against climate risks, enhances biodiversity, and sustains livelihoods. The cause-and-effect relationship embedded in the logic model demonstrates a clear pathway from targeted activities to long-term benefits, making the desired transformation not only aspirational but realistically achievable through coordinated action and sustained efforts.

These tools were not only instrumental in conceptualizing the planning of objectives and potential outcomes but also interpreting the 2023 EIA and identifying priority areas for intervention (Campbell et al., 2023). This approach aligns with adaptative management principles and improves transparency and stakeholder alignment (Kaplan and Garrett, 2005; Margoluis and Salafsky, 1998). The framework is intended to guide future decision-making, funding applications, and policy support for long-term restoration efforts in this area.

10. Conclusion

Restoring the degraded mangrove forest in the Little River will require prioritizing hydrological rehabilitation. However, a more holistic approach that includes active community involvement could support long-term ecological recovery, not just for enhancing ecosystem function but also for social resilience. As noted in the 2023 EIA, local residents have expressed willingness to participate in restoration efforts, and the proposed plan could serve as a framework for future initiatives.

Significant differences were observed in vegetation variables such as mangrove height and DBH between control and degraded/restoration sites, while biophysical (salinity) did not appear to be a major factor for site comparison indicators, despite the control site´s closer proximity to the coast and its exposure to freshwater input from storm drain and North Coast highway.

Soil carbon content is a key indicator of blue carbon storage and typically varies between degraded areas, sites under restoration, and undisturbed mangrove forest. However, in this study, no significant differences were observed among the sites, likely due to the close spatial range between sites and limited sampling (low sample size per treatment and control).

This study can serve as a foundational project management plan to guide future efforts in the area. Community workshops and stakeholder engagement at every stage will be essential to ensure transparency, local ownership, and alignment with funding goals. Long-term ecological restoration will require dedicated resources for monitoring and evaluation, which should be included in any project´s budget as the plan is implemented by phases.

11. Recommendations

Mangrove species distribution and regeneration are closely tied to environmental conditions, particularly phenology and reproductive maturity, highlighting the importance of continuous vegetation monitoring before and after intervention to track progress and ensure restoration success. Additionally, measuring ecosystem function such as nutrient cycling, carbon sequestration, sediment stabilization, species composition, and structural complexity, as well as the presence and diversity of fauna like birds, crabs, and fish.

For the Little River mangrove ecosystem, hydrological rehabilitation is strongly recommended to improve water flow inside the forest which can enhance seedling dispersal, regulate biochemical cycles, and restore natural tidal exchange. A key first step should involve assessing and potentially removing marl-filled soils that currently reduce soil porosity and inhibit inflow and water retention. Addressing these issues, along with mitigating the identified threats, should align with the Ecological Restoration Plan´s objectives and logic model, helping guide the theory of change towards the community´s vision for the mangrove ecosystem.

Further studies should incorporate advanced methods such as geographical information systems (GIS), drone imagery, and topography surveys. These tools can offer detailed spatial insights, guiding future intervention while minimizing disruption to the landscape. Any physical restoration effort must also be consulted with Ministry of Housing (land owner) and community members, who are direct beneficiaries of the ecosystem.

There is also a need to expand data collection on hydrology and ecological conditions. While this study measured a few variables, besides surface salinity, interstitial water be monitored and other key environmental parameters that influence mangrove establishment and growth be included in future assessments, as well as water quality (nutrient levels, e.g., nitrogen and phosphorus, fecal coliform etc.), water levels, and seasonal variation. For SOC, expanding sampling efforts across both dry and wet seasons would provide a more comprehensive understanding of its dynamics. Additionally, measuring deadwood and above-ground biomass could help determine whether carbon storage is increasing, strengthening the use of carbon indicators in tracking restoration outcomes over time.

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13.Annexes

Annex 1a. Estimated monitoring budget (Ecological indicators)

Time Point	Indicator	Cost (JMD)	Notes
Month 0	Water quality, seedling density, tidal flow	$ 600.000	Equipment, baseline transects, lab fees
Month 3	Water quality, sedimentation	$ 250.000	Lab analysis, flow meter readings
Month 6	All 3 indicators	$ 300.000	Drone imagery, transects, salinity
Year 1	Annual reporting, drone, sediment & canopy analysis	$ 400.000	Includes mapping and stakeholder summary
Year 5	Repeat all ecological assessments	$ 500.000	Mid-term ecological health review
Year 10	Long-term trends & GIS update	$ 600.000	High-resolution ecosystem assessment
Year 15	Vegetation maturity, tidal change review	$ 500.000	GIS maps, flow & salinity check
Year 20	Final ecological report	$ 700.000	Publication-ready synthesis

Annex 1b. Estimated monitoring budget (Socio-cultural Indicators)

Time Point	Indicator	Cost (JMD)	Notes
Month 0	Workshop attendance, signage baseline	$ 200.000	Setup for surveys and signage
Month 3	Illegal dumping, public feedback	$ 100.000	Site inspections
Month 6	Workshop follow-up, signage review	$ 120.000	Training materials, feedback analysis
Year 1	All indicators incl. eco-livelihood check	$ 150.000	Social survey, business registry check
Year 5	Repeat all social indicators	$ 200.000	Includes interviews, feedback assessment
Year 10	Review of signage, illegal dumping, eco-livelihoods	$ 250.000	Mixed methods approach
Year 15	Public feedback, training cycle evaluation	$ 200.000	Participation analysis
Year 20	Final social impact review	$ 300.000	End-line stakeholder interviews

Annex 1c. Estimated monitoring budget (Economic indicators)

Time Point	Indicator	Cost (JMD)	Notes
Month 0	Eco-livelihood baseline, grant & employment tracking setup	$ 200.000	Data system development
Month 3	Short-term business & grant tracking	$ 100.000	Community partner records review
Month 6	Sustainable business growth, employment snapshots	$ 120.000	Field visits
Year 1	Full indicator review, survey updates	$ 200.000	Employment, eco-livelihood, grants
Year 5	Repeat full economic indicator cycle	$ 250.000	Business survey, job logs
Year 10	Trend analysis, grant review, partner meetings	$ 300.000	Community & donor feedback
Year 15	Review of business data and household income	$ 250.000	Cross-check with earlier benchmarks
Year 20	Final economic impact synthesis	$ 350.000	Includes reports and funder communications

Annex 1d. Estimated monitoring budget (Political/Legal indicators)

Time Point	Indicator	Cost (JMD)	Notes
Month 0	Baseline policy and enforcement review	$ 100.000	Collection of existing reports & legal data
Month 3	Enforcement review and stakeholder feedback	$ 80.000	Observation-based
Month 6	Review of permit changes and enforcement trends	$ 100.000	Administrative support
Year 1	Annual permit & policy updates	$ 120.000	NEPA + parish council coordination
Year 5	Legal inclusion check; enforcement trends	$ 150.000	Land-use planning updates
Year 10	Long-term policy effectiveness assessment	$ 200.000	Includes legal workshops
Year 15	Policy continuity and NEPA reporting	$ 180.000	Monitoring of zoning and compliance
Year 20	Final review: enforcement, inclusion, and permit evolution	$ 220.000	Final report and regulatory documentation