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REVIEW ARTICLE

Framework for facilitating mangrove recovery after hurricanes on Caribbean islands

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Mangrove ecosystems in the Caribbean are frequently exposed to hurricanes, leading to structural and regenerative change that elicit calls for recovery action. For those mangroves unaffected by human modifications, recovery can occur naturally. Indeed, observable natural recovery after hurricanes is the genesis of the "disturbance adaptation" classification for mangroves; while structural legacies exist, unaltered stands often regenerate and persist. However, among the >7,000 islands, islets, and cays that make up the Caribbean archipelago, coastal alterations to support development affect mechanisms for regeneration, sediment distribution, tidal water conveyance, and intertidal mangrove transgression, imposing sometimes insurmountable barriers to natural post-hurricane recovery. We use a case study approach to suggest that actions to facilitate recovery of mangroves on Caribbean islands (and similar settings globally) may be more effective when focusing on ameliorating pre-existing anthropogenic stressors. Actions to clean debris, collect mangrove propagules, and plant seedlings are noble endeavors, but can be costly and fall short of achieving recovery goals in isolation without careful consideration of pre-hurricane stress. We update a procedural framework that considers six steps to implementing "Ecological Mangrove Restoration" (EMR), and we apply them specifically to hurricane recovery. If followed, EMR may expedite actions by suggesting immediate damage assessment focused on hydrogeomorphic mangrove type, hydrology, and previous anthropogenic (or natural) influence. Application of EMR may help to improve mangrove recovery success following catastrophic storms, and reduce guesswork, delays, and monetary inefficiencies.

Key words: ecological mangrove restoration, EMR, genetic considerations, hydrogeomorphic type, regeneration, resiliency bottlenecks, tropical cyclones

Implications for Practice

- Mangroves are considered disturbance-adapted communities but anthropogenic influences decrease resilience to hurricanes.
- Recovery actions on Caribbean islands may be more effective through evaluation of specific mangrove species requirements relative to post-storm environmental conditions; planting seedlings may or may not be a beneficial remediation action.
- An approach applied widely to traditional mangrove restoration projects globally, "Ecological Mangrove Restoration," is also applicable in decision support to facilitate mangrove recovery after hurricanes.
- Consideration of potential future unintended vulnerabilities is an important aspect of assisted recovery actions.

Introduction

Mangroves are intertidal ecosystems that colonize and proliferate from approximately mean sea level (MSL) to an upper tidal range. Mangroves have previously been considered one of the world's most threatened ecosystems (Valiela et al. 2001), though rates of deforestation have slowed in the 21st century.

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Since 2000, natural drivers of mangrove loss such as shoreline erosion and extreme weather events have increased in importance, and now account for 38% of overall mangrove cover loss in the 21st century (Goldberg et al. 2020). In the Caribbean, hurricanes are a primary natural cause of disturbance, with many of the Caribbean islands located in the regional belt of major hurricanes (wind speeds >178 km/hour; Andrewin et al. 2015). There, mangroves that develop as disturbance-adapted communities are structured by recent injury and past legacies of cumulative disturbance that can limit long-term ecosystem resilience to other biophysical and human stressors such as sea-level rise, harvesting, or repetitive lightning strikes (Krauss & Osland 2020).

Advances in our knowledge of mangrove resilience thresholds are increasingly incorporated into restoration techniques to improve success (Lewis 2005); many of these protocols do not specifically target natural disturbance but have strong application to facilitating hurricane recovery. System characteristics are also important, as resilience (return to a previous state) versus resistance to damage in the first place are trade-offs dependent on specific stand condition (Patrick et al. 2022); mangroves are often not overly resistant to tropical cyclone injury, but resilience can be high. Although mangroves are categorized as environments that can undergo persistent environmental stress (Lugo et al. 1981), stress is not an optimal state even though the range of mangrove tolerances to salinity, hydroperiod, and nutrient perturbation is broad (Ball 1988; Krauss et al. 2008; Reef et al. 2010).

Noticeable and persistent structural hurricane damage to mangroves often stimulates calls for human-assisted recovery, though the success of management interventions is limited if the various biophysical contributors to recovery are not considered and incorporated into recovery design. In this review, we provide a protocol to assist future mangrove management efforts after hurricane strikes in the Caribbean (but with wider application). Guidance is currently absent or inaccessible to managers undertaking recovery actions. Our protocol (1) provides an overview of different mangrove types commonly found in the Caribbean by which the recovery framework is stratified; (2) presents common pre-hurricane anthropogenic or natural stressors for each mangrove type that needs to be repaired, with examples from the U.S. Virgin Islands, Jamaica, Puerto Rico, and the Bahamas; (3) applies, adapts, and advances an existing mangrove restoration protocol (Lewis 2005) to hurricane recovery; and (4) briefly reviews actionable recovery options (Supplements S1 & S2). We hypothesize that conditions of mangroves as influenced by humans at the time of hurricane impact influence post-storm recovery trajectories, and improvement of these conditions with human-facilitated management actions may be necessary to bolster mangrove forest recovery success and resilience to future storms.

Mangrove Types and Common Pre-Hurricane Vulnerabilities

Mangroves occur in different settings determined by geomorphologic, edaphic, or hydrologic differences that dictate how they establish and grow. Various typologies exist (Lugo & Snedaker 1974; Twilley et al. 1998, 2018; Worthington et al. 2020), and differences in preexisting settings determine mangrove exposure and recovery trajectories associated with hurricane disturbance. For Caribbean islands, at least five types of mangrove forests are relatively common.

Fringe mangroves (Figs. 1A & S1) are located on the edge of open water and are flooded by nearly every tide, including both spring and neap. Sometimes fringe mangrove forests can be large in area but in many instances, fringe mangroves are only two or three trees wide. *Overwash island mangroves* (Figs. 1A & S1), the second type, are continuous on small low-lying islands with similar hydrology to fringe mangroves, but with greater wave exposure (Cahoon & Lynch 1997). When disturbance is limited, sea-level rise can manifest over decades and expose the most seaward trees to their hydroperiod limit (perhaps up to 70% flooded per year), which eventually may preclude the potential for additional in situ regeneration if vertical soil adjustment is not adequate. As trees are killed by hurricanes, the current inundation regime can prevent stand replacement (Smith et al. 1994; Jones et al. 2019).

In contrast, the third type, or b*asin mangroves* (Figs. 1B & S1), is flooded only by high tide events (spring tides), surge, or significant rainfall, and includes a geomorphic depression that allows for continued ponding once tides ebb or rainfall ceases (Lugo & Snedaker 1974). Salinity can increase in the porewater as mangrove canopy transpiration drives porewater salts to concentrate. Small ponds sometimes develop within basins, possibly as legacies of gaps created by hurricanes or lightning. As wind defoliates basin mangrove canopies, those forests stressed by persistent flooding from hurricanes or humans can undergo peat collapse (sensu Chambers et al. 2019). Continued and advanced ponding of basin mangroves may eventually lead to the fourth mangrove type, *salt pond basins* (Figs. 1C & S1). Salt pond basins also form as relicts of bays or convergent reef growth that isolate basins through geomorphic changes (including from storms) or mangrove structural in-growth that close tidal channels (Island Resources Foundation 1977). Many salt pond basins possess no obvious connections to surface water tides except during storm events, and as such fall outside of the classic tidal requirement associated with mangrove development. Salt pond basins can be hypersaline (Jarecki & Walkey 2006) and hypoxic over diel cycles to compound tree stress on their edges (Gedan et al. 2017).

The fifth type is *riverine mangroves* (Figs. 1D & S1), which are influenced by a mix of tidal and river flooding, whereby tides produce more flooding when the river stage is higher, and the river serves as a tidal conveyance to promote surface water flooding and draining (Lugo & Snedaker 1974). Rivers and riverine connections to mangroves are generally highly modified on Caribbean islands. Water diversion or extraction for consumptive use can impede river flows to downstream mangroves, disrupting the distribution of freshwater delivery and salinity regime. Sediment extraction (or settling, e.g. use of gabions) affects in situ surface elevation processes and reduce elevation capital needed for mangroves to respond to sea-level rise (Lovelock et al. 2015).

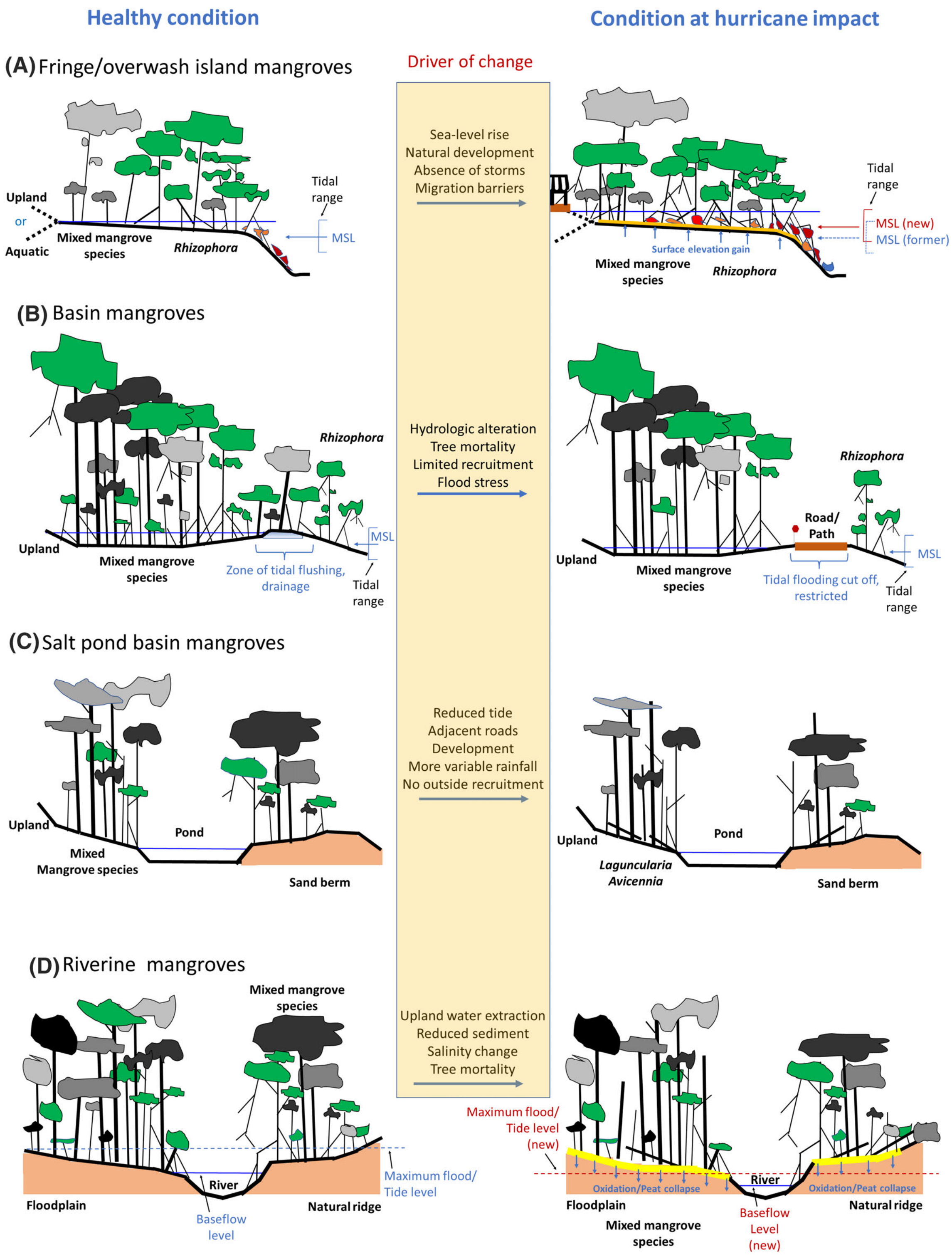

Figure 1. Cross-sectional renderings of mangrove types on Caribbean islands, and their projected initial conditions at some previous point in time versus the state of many of these mangrove types at hurricane impact. "Driver of change" indicates what often causes the mangrove transition between the two states over time by type. Colored polygons in the prop roots of fringe/overwash mangroves represent coral, tunicate, and sponge development common to the Caribbean.

Common hydrological patterns from the different mangrove types are presented in Figure 2. Although hydrographs are not representative of all fringe/overwash island, basin, salt pond basin, and riverine mangroves, any major deviations to these hydrographs should be inspected. Table 1 and Supplement S1 provide experiential examples of the human and natural

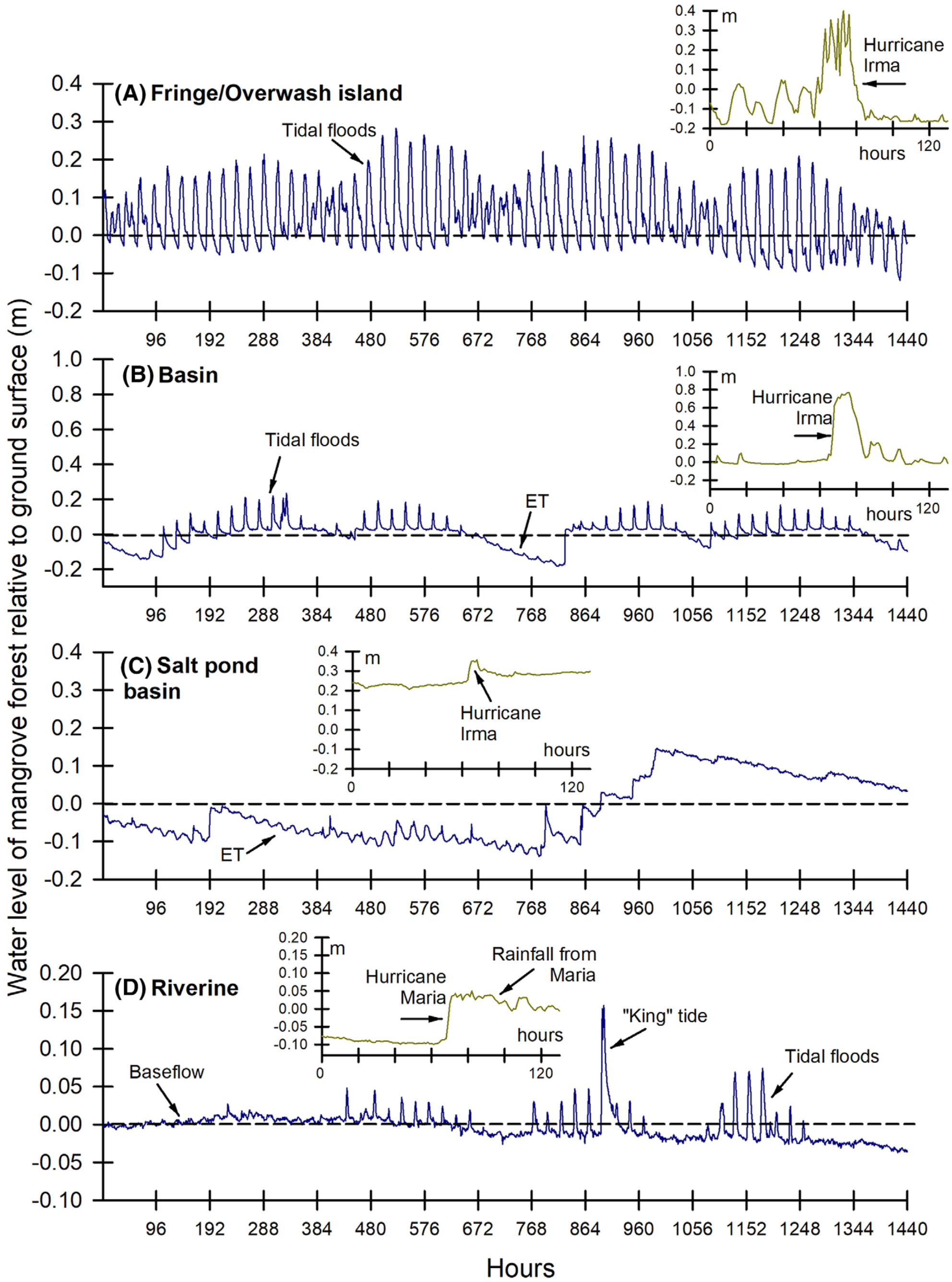

Figure 2. Representative hydrographs from (A) fringe/overwash island mangroves, (B) basin mangroves, (C) salt pond basin mangroves, and (D) riverine mangroves from neotropical locations, including important hurricane storm surge events from either Hurricane Irma or Hurricane Maria, both from 2017. Surge events are not overlapping in time with representative hydrographs. Data for (A), (C), and (D) are from Water Creek (Hurricane Hole, St. John, U.S. Virgin Islands), Mary Creek (St. John, U.S. Virgin Islands), and Salt River (St. Croix, U.S. Virgin Islands), respectively, and are courtesy of U.S. National Park Service, Inventory and Monitoring Program. Data for (B) are from Rookery Bay National Estuarine Research Reserve, Florida. ET, evapotranspiration.

impediments to mangrove recovery (presented conceptually in Fig. 1) from recently damaged Caribbean island mangrove forests on St. John (U.S. Virgin Islands; Fig. S2), St. Croix (U.S. Virgin Islands; Fig. S3), Jamaica, Puerto Rico (Fig. S4), and the Bahamas. There are examples from each of the five mangrove types, most of which have pre-hurricane conditions for which amelioration may enable recovery (Table 1).

Caribbean Mangroves and Recent Hurricanes

The 2017 hurricane season was among the most active for the Caribbean in decades, with 17 tropical storms and 10 hurricanes; at least 1 million ha out of 2.26 million ha of the region's mangroves were affected (Taillie et al. 2020). Maximum sustained wind speeds were often greater than 178 km/hour at landfall (Category 3), a threshold previously noted as causing great

Table 1. Experiential examples of common types of human-caused and natural pre-hurricane factors that influenced mangrove stand recovery after a major hurricane event on specific Caribbean islands.

Type	*Location*	*Concern*	*Human or Natural?*	*Unique hurricane injury*	*Potential ameliorative recovery action*	*Caribbean island relevance*	*Global relevance*	*Source**
Fringe	Mary Creek and Hurricane Hole, St. John, USVI	Sea-level rise, Blocked transgression	Natural, human	Destroyed mangrove-coral associations that require low intertidal and sub-tidal mangrove root structures	Research on how to expedite recovery of mangrove roots into thin bands of low intertidal and sub-tidal environments, and on how to facilitate coral recovery on mangrove roots	Regionally important (e.g. USVI, Belize, Panama)	Unknown	Rogers (2011), Yates et al. (2014), Lord et al. (2020), Rogers (2011)
Fringe/ overwash island	Jamaica	Municipal solid waste	Human	Some soild waste types reduce regeneration, and may cause physical damage to advance regeneration	Removal of plastic bottles, plastic bags, construction wood, and other waste from the intertidal	Regionally important	Pervasive (e.g. Southeast Asia, Brazil, Colombia)	Cordeiro and Costa (2010); Garcés-Ordóñez et al. (2019), Singare (2012), Trench (2021)
Fringe/ overwash island	Grand Bahama and Abaco, Bahamas	Source of propagules	Natural	Lack of propagule sources for expedient natural recovery because of catastrophic wind damage to low-lying, unsheltered islets	Large-scale planting efforts, possibly using the nearest propagule material	Regionally important (e.g., any low-lying island, isolated island, isolated stand within an island)	Relevant (e.g. any nation with low-lying carbonate islands or atolls)	Pathak et al. (2021), Roberts (2022)
Basin	Annaberg, St. John, USVI	Alteration of tidal hydrology	Human	Reduction in natural recruitment; mortality among smaller tree diameter classes with persistent flooding; barriers to ex situ mangrove propagule recruitment	Re-connection of tidal hydrology through strategic breaching or engineering of culverts	Pervasive	Pervasive	Lewis et al. (2016), López-Portillo et al. (2017, 2022), Krauss et al. (2020)
Basin	Malcolm's Bay, Jamaica	Alteration of tidal hydrology	Human	Reduction in natural recruitment; tree mortality (patch) leading to "mangrove heart attack" in wake of hurricane	Re-connection of tidal hydrology through strategic breaching or culverts	Pervasive	Pervasive	Lewis et al. (2016), Trench (2021)
Basin	Secret Spot, Isabela and Punta Tuna, Maunabo, Puerto Rico	Alteration of tidal hydrology, Impoundment by sand deposition	Human, natural	Widespread tree mortality; storm surge and rainfall leading to extended flooding; reduction in natural recruitment	Re-connection of tidal hydrology through strategic breaching or engineering of culverts	Pervasive	Pervasive	Lewis et al. (2016), Branoff et al. (2018)

Table 1. Continued

Type	*Location*	*Concern*	*Human or Natural?*	*Unique hurricane injury*	*Potential ameliorative recovery action*	*Caribbean island relevance*	*Global relevance*	*Source**
Basin	Aguirre Forest, Guyama, Puerto Rico	Alteration of tidal hydrology, development for a sugar mill	Human	Widespread tree mortality; storm surge and rainfall leading to extended flooding; reduction in natural recruitment	Re-connection of tidal hydrology through strategic breaching or engineering of culverts	Pervasive	Pervasive	Lewis et al. (2016)
Salt pond basin	Francis Bay and Lameshur Bay, St. John, USVI	Restricted tide, peat collapse, limited regeneration	Natural	Widespread tree mortality at Francis Pond; Structural damage slowing propagule production	Limited for Francis Pond, but planting larger seedlings may help extend seedlings above flooding; at Lameshur, clearing out semi-blocked tidal channel	Regionally important	Uncommon	Krauss et al. (2020)
Salt pond basin	USVI, British Virgin Islands, Puerto Rico	Hydrologic isolation, Lack of ex situ recruitment, de facto use for stormwater retention	Natural (with isolated human legacies)	Hurricane surge and rainfall leading to salinity pulses and more persistent flooding; Structural damage slowing propagule production; more frequent drought	None specifically, unless previous hurricane caused greater blockage	Pervasive	Uncommon	Jarecki and Walkey (2006), Donnelly (2005), Krauss et al. (2020)
Salt pond basin	Boggy Pond and Old Harbour Bay, Jamaica	Freshwater flows reduced, conversion of basin mangroves to salt pond basin mangroves, de facto use for stormwater retention	Human	Isolation from estuary impeding recovery; greater ponding and irreversible mangrove cover loss	Restoration of freshwater flows; re-connection of salt pond basins to greater tidal hydrologic flows	Regionally important	Uncommon	Trench (2021)
Riverine	Salt River, St. Croix, USVI	Diversion of fresh water, sediment reductions (gabions/dams)	Human	Surface elevation deficit and soil oxidation make trees more vulnerable to wind toppling; Tree mortality and compounded stress before hurricane	Removal of sediment barriers (gabions/dams)	Common for most Caribbean islands with small rivers	Common	Urrego et al. (2014), Lovelock et al. (2015)

Table 1. Continued

Type	Location	Concern	Human or Natural?	Unique hurricane injury	Potential ameliorative recovery action	Caribbean island relevance	Global relevance	Source*
All typologies	Caribbean island wide	Genetic bottlenecks	Human, natural	None specifically documented that would result from limited genetic variability	Development of nursery programs that facilitate genetic diversity among any prescribed post-hurricane planting activity; re-establishing tidal connections in isolated stands to allow propagule exchange	Common for the most isolated of Caribbean islands (or isolated stands within an island)	Unknown	Kennedy et al. (2016), Bologna et al. (2019), Sereneski-Lima et al. (2021)

*Sources represent specific Caribbean accounts and global evidence of relevance for this condition.

injury to the structure of mangroves (Krauss & Osland 2020). However, Normalized Difference Vegetation Index analyses from the 2017 season indicated that even lower windspeeds of 100–150 km/hour yielded substantial damage to the region's mangroves (Taillie et al. 2020). This result stimulated questions about how much the storm damage had been compounded by existing anthropogenic stress across the Caribbean (Walcker et al. 2019). In addition, hurricane damage is cumulative and dependent on recovery from previous hurricanes. Shorter forests created from past hurricane injury sometimes register less relative damage from subsequent storms (Roth 1992; McCoy et al. 1996; Smith et al. 1994; Taillie et al. 2020; Lagomasino et al. 2021). In contrast, longer gaps between hurricanes result in greater relative damage from any one event because forests have gained greater biomass between hurricanes (Kauffman & Cole 2010). When natural recovery from hurricanes is delayed for any reason, intervention may be necessary to facilitate recovery before mangrove soils collapse or shorelines erode.

Restoration and Recovery Goals for Caribbean Island Mangroves

The restoration of structural integrity, functional integrity, and ecosystem resilience to future disturbances are all components of restoration and recovery project success (Harris & Hobbs 2001). For mangroves in the wake of hurricane injury, important damage legacies remain, such that visual structural differences in the recovered system may become the new structural state (Krauss & Osland 2020). Recovery potential is why mangroves are referred to as "disturbance adapted," even as hurricane injury is visible. For example, residual tree stems may be deformed, natural woody debris may cover the forest floor, uneven sedimentation may create microtopography, and regeneration may be patchy for many years after the hurricane. However, given enough time between hurricanes, full forest structural recovery is expected in 20–30 years (Proffitt & Devlin 2005; Osland et al. 2012). In addition, some measure of functional integrity should also be included when assessing recovery success. Have soils developed a pre-impact biogeochemical state of fluctuating oxygen concentration? Has the hydrology of the site been affected through debris jams in tidal creeks or formation of sand berms? Are residual trees producing propagules to facilitate regeneration? Are regeneration barriers lifted such that tides can provide a source of propagules, nutrients, oxygen relief, and in-faunal community integrity? What is the distance from and probability of being colonized by the nearest source of propagules? Sufficient recovery of mangrove structure and function in the wake of hurricane injury contributes to resilience.

Resilience has been defined as "[an ecosystem] returning to the reference state (or dynamic) after a temporary disturbance" (Grimm & Wissel 1997; Patrick et al. 2022). Ameliorating anthropogenic influences that prevent natural recovery of mangroves can help support the success of recovery plans in attaining a mangrove resilient to the next hurricane. Maintaining resilience can also include community engagement and stewardship in the years following a hurricane to prevent future "resiliency bottlenecks," which we define here as *impacts from post-hurricane recovery actions that create future impediments to ecosystem resiliency*. Restoration (and recovery) effort is often associated with repairing damage caused by humans (Jackson et al. 1995) and, therefore, should be cautious not to cause further harm.

A Framework for Mangrove Restoration

Globally, there may be at least 800,000 ha of former mangrove areas that are biophysically suitable for some measure of restoration action (Worthington & Spalding 2018), and countries such as Indonesia are setting ambitious national targets. Success rates for individual restoration projects have generally been considered low. For example, out of 67 mangrove planting efforts in Sri Lanka, more than 50% had complete failure with no surviving saplings, and only 3 sites showed a restoration success rate greater than 50% (Kodikara et al. 2017). Myriad reasons account for restoration failures, but failures are generally driven by unrealistic planting targets (Wodehouse & Rayment 2019) coupled with issues of land tenure in suitable locations (Lovelock & Brown 2019). Issues with land tenure push mangrove afforestation onto uncontested land parcels such as mudflats and seagrass meadows, which are less suitable for mangrove survival and growth, and which results in displacing other important marine ecosystems (Sharma et al. 2017).

A range of mangrove restoration approaches exist, from traditional planting to designed novel systems (Ellison 2000; Ellison et al. 2020; Chen et al. 2022). Increasingly, mangrove restoration has been successful when management actions focus on restoring local hydrodynamic conditions, which facilitates natural mangrove recruitment or ensures that mangroves are planted under the right physical conditions (Lewis et al. 2005). The same management expectations may apply to post-hurricane recovery. For example, if natural hydrodynamic conditions are unaltered by a hurricane and remain adequate, planting can be less successful than simply waiting, such as on Guanaja, Honduras after Hurricane Mitch (Fickert 2020).

Applying an Established Restoration Approach to Hurricane Recovery

Because of the low success rate of mangrove restoration projects, a protocol was developed, and first described in 1997 as "Ecological Mangrove Restoration" (EMR; Lewis & Marshall 1997). The EMR protocol emphasizes the need to consider site level biophysical characteristics (particularly hydrological flows) within the species-specific tolerances of mangroves. The protocol allows for natural regeneration to occur, or for the site to be reengineered if conditions are currently not optimal. EMR has been applied globally, and we re-iterate EMR steps with little modification to guide future mangrove recovery actions after hurricane disturbance on Caribbean islands (Fig. 3). The protocol includes six steps, as follows (Lewis 2009), and is adjusted for the different mangrove types based on their specific hydrological requirements (cf. Fig. 2):

(1) Develop an understanding of specific ecological requirements of the mangrove species present (autecology) to include reproductive strategies, propagule distribution and dispersal barriers, and determine whether seedlings are naturally establishing prior to recovery action, including any advance regeneration present (i.e. seedlings/saplings present before the hurricane). Caribbean islands have eight native mangrove species among five genera (*Rhizophora mangle*, *R. racemosa*, *R. harrisonii*; *Avicennia germinans*, *A. schaueriana*; *Acrostichum aureum*; *Laguncularia racemosa*, and *Pelliciera rhizophorae*), and one common associate (*Conocarpus erectus*).

(2) Identify and understand the hydrological patterns of the site that made the site suitable for the targeted mangrove species originally. Information may be derived through use of water level recorders to evaluate current tidal function and flood elevation of soils relative to MSL.

(3) Evaluate how hydrology differs from what would be optimal to support specific mangrove types. Note changes that may have influenced hydrology prior to hurricane impact, as well as after. Information will vary greatly by the mangrove type and must be evaluated against the type-specific reference hydrology (Fig. 2 may be used as a rough guide).

(4) Select candidate recovery sites for which Steps 1–3 have been applied, and where appropriate funding, land tenure, and community support to ameliorate Step 3 are available (sensu, Community-Based EMR: Brown et al. 2014; Quarto & Thiam 2018). If specific components of Steps 1–3 are not known or other threats become imminent to that location, caution is advised in implementing actions that cost money and time as they may ultimately be unsuccessful.

(5) After proper hydrology is re-established, or if hydrology is already appropriate, use natural recruitment of available seedlings from adjacent mangroves for plant establishment if possible. It is often possible to use natural mangrove recruitment without planting, or in some cases help to facilitate recruitment with nurse species propagation and woody debris retainment.

(6) Finally, plant mangroves using "collect-and-plant" techniques or from nurseries only if Steps 1–5 are not possible without such intervention. Proper rationale for planting may exist when there is a need to establish mangrove sites quickly on organic soils to resist peat collapse (e.g. within a few years of hurricane injury) or if natural hydrologic barriers to dispersal remain, even if barriers relate only to specific target species. Another reason for such plantings, which we add to the EMR hurricane recovery protocol for Caribbean islands, is if the management of mangrove genetic diversity is warranted.

Throughout the implementation of EMR, care must be exercised to avoid resiliency bottlenecks. Resiliency bottlenecks to consider are specific to individual islands (or locations within islands). In some cases, resiliency bottlenecks may be imposed for human protection (e.g. sea walls) or commerce (e.g. airports), and for those, mangroves may suffer impact without much room for intervention.

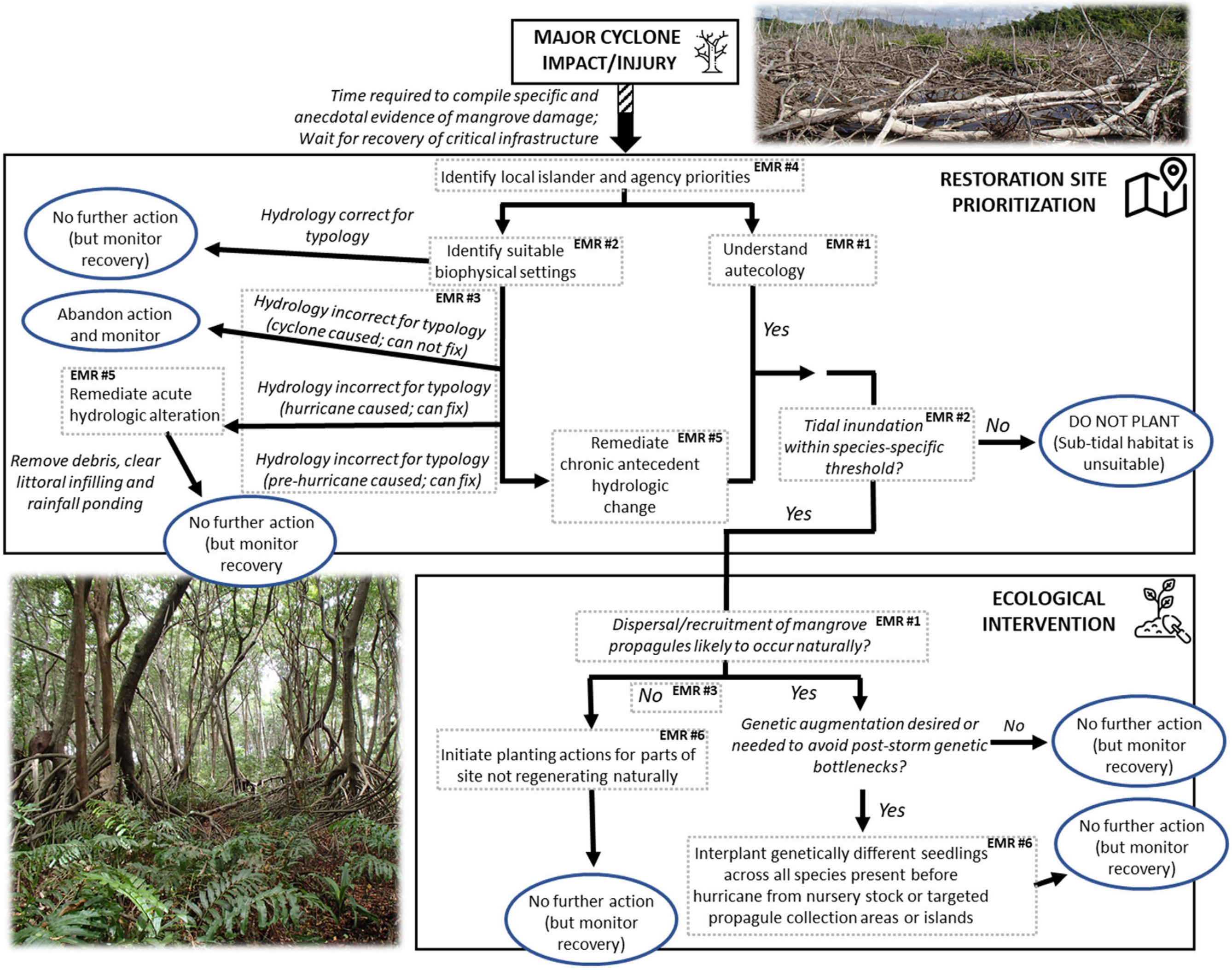

Figure 3. Framework for implementing a recovery plan for Caribbean island mangrove ecosystems that have been affected by a major hurricane. Arrows indicate tenable or untenable recovery pathways. Decisions appear in italics, actions appear as regular text, and end goals are within blue circles. EMR steps are associated with specific decision boxes (dashed grey). Photos of a hurricane damaged mangrove forest on St. John, U.S. Virgin Islands, 3 years after Hurricane Irma (upper right) and a naturally regenerated mangrove forest on San Andres Island, Colombia (lower left) (photo credits, Ken W. Krauss, U.S. Geological Survey).

Establishing Desired Conditions

Caribbean island mangroves are characterized by legacy damage, such that desired conditions might not be the same from site to site depending on previous hurricane damage. For example, different mangrove species might dominate, delayed mortality of the residual forest might continue, woody debris and snags may be abundant, soil elevations might be heterogeneous, or the colonization of plants such as *Acrostichum* ferns (true mangrove) or *Thespesia populnea* trees (non-native, higher elevation mangrove associate) may further limit regeneration of desired mangrove trees on some sites as legacies of past hurricanes.

However, three consistent limitations to establishing desired conditions include: (1) time lapse between hurricane landfall and initiation of recovery actions created by the damage to local infrastructure, depletion of resources, and impact to residents (Fig. S5); (2) time required to develop reasonable site-specific recovery implementation plans, and to navigate contracting and personnel needs; and (3) for situations where recovery action might warrant plantings (EMR Step 6), the lack of propagule and seedling sources to accomplish planting events quickly, balanced by lack of full consideration of EMR Steps 1–5 (Fig. 3).

Considering Past Planting Failures to Establish Realistic Expectations

Although it is generally acknowledged that mangrove restoration failures are common globally, we also have a relatively limited quantitative understanding of post-hurricane planting success on Caribbean islands. Structural recovery of seedlings, saplings, and trees that survived a hurricane can take 6 years or more to re-gain reproductive capabilities (Imbert & Rousteau 2000). During this period, strategic plantings can enhance the speed of ecosystem recovery if implemented early and under appropriate conditions. Among the successful planting efforts in the Caribbean, saplings grew 39 cm in height after 1 year (Ruiz Bruce Taylor et al. 2013) and >2 m in just over 3 years (Proffitt & Devlin 2005). Furthermore, successful mangrove restoration projects are more often communicated while failed projects are more often disregarded. Monitoring the effectiveness of successful projects and learning from past failures are important to improve three aspects of mangrove restoration on Caribbean islands.

First, site monitoring is necessary for managers to transition to adaptive management (Ellison et al. 2020), flagging potential sources of recovery action failure early and allowing for mid-course corrections to improve restoration trajectory. Potential sources of failure may not be associated solely with vegetation. In-fauna, epi-benthic, and macro benthic invertebrates influence functioning of mangroves as forests develop (Bosire et al. 2008), and invertebrate colonization may be considered as linked recovery targets. Second, monitoring allows managers to learn from and share experiences between projects and apply lessons learned. On St. Croix, U.S. Virgin Islands, plantings of 21,000 seedlings (18,000, *R. mangle*; 3,000, *A. germinans*) were made in relatively acceptable hydrologic conditions in 1999 to facilitate quicker recovery after Hurricane Hugo (in 1989) severely damaged the mangrove forest of Sugar Bay (Rothenberger 1999). Survival of seedlings in a pilot project was 31.7% without seedling protection, but as high as 74.3% with seedling protectors (Rothenberger 1999); long-term survival was not reported. However, a previous restoration effort was attempted in 1978, also on St Croix, where 40% of the 86,000 *R. mangle* seedlings survived whereas only 1–2% of the 32,000 *A. germinans* propagules broadcast across 6.15 ha persisted. Compounded mortality from hurricanes (Hurricanes David and Frederic in 1979), which created some wash-out, was partly to blame (Lewis & Haines 1981), but a decision to avoid broadcast sowing of *A. germinans* propagules by the 1999 recovery effort was easily reached.

Third, creative mechanisms to expedite recovery may be necessary. For example, mangrove propagule recruitment and establishment on a Belizean island was facilitated when nurse species (e.g. *Distichlis*, *Sesuvium*) were also present (McKee et al. 2007). Nurse species, which can be more easily established or may be residual after the hurricane, can facilitate early mangrove recovery. Indeed, facilitation on the Belizean sites occurred through propagule trapping, amelioration of soil biogeochemical constraints (especially temperature), and provision of structural support during wind and wave action, all of which facilitated quicker mangrove establishment, persistence, and growth (McKee et al. 2007).

Considering Genetics of Caribbean Island Mangrove Populations

Plant populations on islands are thought to be less genetically diverse than on the mainland because of smaller land areas (Canty et al. 2022). Island plant populations are also assumed to exhibit greater genetic differences from other populations because of the geographic isolation (Frankham et al. 2002; Losos & Ricklefs 2010). Although we lack a comprehensive understanding across the entire archipelago, research into genetic differences among Caribbean island mangrove populations is consistent with these predictions. Compared to continental mangroves, island mangroves possess limited genetic diversity and exhibit pronounced genetic divergence over relatively short geographic distances (Kennedy et al. 2016; Sereneski-Lima et al. 2021), especially in populations from smaller islands (Hodel et al. 2018). For example, there are strong genetic differences between island populations of *R. mangle* (Cerón-Souza et al. 2015; Kennedy et al. 2016; Hodel et al. 2018), *A. germinans* (Cerón-Souza et al. 2015), and *L. racemosa* (Hodel et al. 2018; Sereneski-Lima et al. 2021) and between island and mainland populations.

Recurrent extreme hurricane events within the region have likely played a significant role in shaping the genetic structure of Caribbean island mangroves in addition to reduced population sizes and the greater isolation of insular mangroves. Mass tree mortality can reduce genetic variability, and many isolated stands experience very limited gene flow from outside sources during recovery periods. Pronounced, and potentially prolonged reductions in effective population size can lead to genetic bottlenecks that may drive further losses in genetic diversity (Nei et al. 1975) and may have consequences for the long-term persistence of recovering mangroves (Keller & Waller 2002). *Rhizophora mangle* at Great Lameshur Bay on St. John, U.S. Virgin Islands, exhibited signs of a genetic bottleneck (e.g. higher inbreeding, lower genetic diversity, and greater genetic isolation) compared to other parts of the island decades after Hurricane Hugo severely damaged this stand (Bologna et al. 2019).

If genetic bottlenecks are a natural condition of Caribbean island mangroves severely impacted by hurricanes, how might genetic information inform recovery actions? Replanting from local sources (i.e. the same island or closest neighboring island) could retain the unique genetic attributes of Caribbean mangroves and presumably mimic natural dispersal within these systems. Hurricanes can disperse mangrove propagules over massive distances (>1,000 km), but most post-storm dispersal to an area typically comes from the closest available sources (Kennedy et al. 2020). Further reductions in genetic diversity could limit mangrove resistance to other environmental factors, such as greater flooding with sea-level rise (Guo et al. 2018) or insect outbreaks and disease (e.g. *Cytospora rhizophorae* fungus colonization of *R. mangle* in Puerto Rico; Wier et al. 2000).

Provisioning Nursery Sources of Mangroves

Citizens and group actions often focus on using the mangrove genus, *Rhizophora*, for planting because of their recognizable propagules and ease of collection. However, all native mangrove species on an individual island need to be considered for recovery planning so that the diversity of mangrove species is maintained. Where mangrove injury is high, a natural source of mangrove propagules may not be available for 3–6 years after a hurricane. For example, even 3 years after Hurricane Irma (in 2017), insufficient numbers of propagules were available on St. John, U.S. Virgin Islands to supply expedient recovery action. Poorly informed restoration projects can re-distribute mangroves based on the interest to citizens instead of ecological restoration criteria.

For example, among some plant populations, source population viability may be significantly affected if >20% of seeds produced in one season are removed (Pedrini & Dixon 2020). The following steps can help to ensure the availability of appropriate plant material inclusive of all mangrove species present on a specific island and seed sources after future storms: (1) developing mangrove nursery capabilities, (2) implementing a priori protocols for supplying post-hurricane demand, (3) developing the internal expertise to know under which EMR conditions planting mangroves is appropriate, and (4) implementing a Caribbean-wide protocol for the maintenance of genetic diversity within island-specific out-plantings.

Although there are numerous uncertainties for establishing mangrove nurseries that would service different islands and countries, four important considerations are worth highlighting. First, mangrove plant material will need to be collected and propagated on an annual basis, and therefore, out-planted periodically to Caribbean island mangrove stands (or used experimentally) to ensure that nursery material is always young but of different height classes for specific uses and sites. Periodic out-planting between hurricanes can be used to augment site densities in areas with acceptable hydrology (and location) but with limited natural recruitment, or to contribute to understory advance regeneration knowing that future hurricanes are coming. Having seedling or sapling recruits that ultimately survive hurricane impact is optimal and would provide a resilience benefit to mangroves through expedited recovery.

Second, planting seedlings from one island to another may need to be limited in the interim between storms to some mixing value (e.g. 20% off-island sources versus 80% on-island sources), and this value would optimally be informed by geneticists. Third, is the issue of phytosanitation if mangrove nursery material is transported among Caribbean islands, at least until regulations for inter-island propagule transport are imposed. Finally, multiple nurseries could be established across several islands (or island nations) separated by a reasonable distance. Nursery operations could be replicated on multiple islands to offset catastrophic damage to nursery capabilities on a single island.

Establishing a Database of Neotropical Mangrove Restoration and Recovery Projects

As hurricane recovery actions are undertaken and other types of mangrove restoration or rehabilitation projects are implemented throughout the Caribbean, an interactive and easily accessible database could be developed to inform recovery protocol. If developed, such a database would need to be maintained and updated frequently, and its existence would need wide exposure. This recommendation follows Ellison (2000), who suggested a similar information clearinghouse two decades ago to compile successful and unsuccessful mangrove rehabilitation projects around the world. International groups such as the Global Mangrove Alliance are attempting to address this issue through the creation of a tool to capture information from restoration projects (Gatt et al. 2022), but such international initiatives may struggle to collect data from many local restoration sites across the tropics where projects may not be communicated widely or linked to national or international organizations. Here, we suggest a focal data base of post-hurricane mangrove recovery actions, restoration projects, rehabilitation activities, and creation projects with full disclosure of project successes and failures throughout the Caribbean archipelago; critical details are often omitted from published reports. Many actions implemented in mainland countries of the Caribbean Rim could also provide critical examples for implementation on Caribbean islands; therefore, this database may benefit from inclusion of the broader Caribbean region.

Pertinent information for a database includes the following: location, project planning documents and rationale, specific project goals, engineering designs, project boundaries and elevation data, tidal characteristics from the nearest tide gauge, sources of mangrove plant material and species, implementation designs, lists of issues encountered, summary of hurricane or tropical storm impacts after project establishment, metrics of success, metrics of failure, experimental designs for sampling, raw data (if applicable), key personnel, publications, and a list of other items to be determined. This tool could help to improve upon the framework of post-hurricane mangrove forest recovery over time and include experiential details that may otherwise not be communicated.

Recovery Actions

At least seven recovery actions may be implemented by managers or citizen groups after hurricane injury to Caribbean island mangroves, including (1) cleaning/site preparation, (2) restoration of hydrology to encompass minor site work, (3) restoration of hydrology to encompass major site work, (4) water quality improvement and soil remediation, (5) planting of seedlings, (6) seedling management (Fig. S6), and (7) limited action (avoidance of further harm). Descriptions, implementation details, and guidance for these specific recovery actions from Caribbean islands are provided in Supplement S2.

Social Considerations

Complications in mangrove recovery planning can arise when multiple stakeholder groups (e.g. biologists, recreationists, fishers, engineers, hydrologists, Federal and state agencies, managers of appropriated restoration funds, small businesses, consultants) become involved. Potential challenges include different priorities, disagreements over recovery targets (i.e. desired conditions), unclear roles and responsibilities, and lack of trust (McGowan et al. 2015). Simply declaring that a project will be “collaborative” or “co-produced” is insufficient to avoid these potential pitfalls (Bednarek et al. 2018), but there are methods for building a framework in which differences in stakeholder values and priorities can be incorporated into decision making (Johnson et al. 2015). Guerrero et al. (2017), and, specific to mangroves Rodríguez-Rodríguez et al. (2021), present a formalized approach for working with stakeholders and communities to estimate restoration time frames and clarify expectations. This approach may be used to align the administrative decisions of funding and regulatory agencies with the pace of ecological change and possibly strengthen institutional commitments to post-hurricane ecosystem recovery (Failing et al. 2013; Williams & Brown 2014). Furthermore, contributions from citizen scientists can be a valuable tool. Citizenry engagement provides a means to enable local communities to assist in decisions when the focus is on science, as well as expand spatial scales of potential recovery monitoring over long periods of time (Cousins et al. 2017).

Conclusions

Mangrove recovery action after a hurricane can be more effective by accounting for the physical environment within which Caribbean mangroves are found naturally and ameliorating historical damage to that physical environment. Concepts and tools to incorporate physical attributes into restoration planning do exist for mangroves, and as such, this review builds on the foundation laid by Roy "Robin" Lewis (Lewis & Marshall 1997; Lewis 2005, 2009), who provided a robust scientific framework to incorporate physical and ecological aspects into mangrove restoration action. EMR protocol targeting smaller restoration projects is widely applicable to informing mangrove recovery after hurricanes. Greater awareness of EMR protocols may help to improve the success of mangrove recovery after major hurricane impacts in the Caribbean. These same EMR protocols have wide application globally.

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Supporting Information

The following information may be found in the online version of this article:

Data S1. Experiential examples of impacts and limitations to mangrove recovery after hurricanes on Caribbean islands.

Figure S1. Representative (a) fringe, (b) overwash island, (c) basin, (d) salt pond basin, and (e) riverine mangrove types.

Figure S2. Basal area distribution by diameter size class of six sites representing basin, salt pond basin, and fringe mangroves.

Figure S3. Basal area distribution by diameter size class of two sites representing riverine mangroves.

Figure S4. Aerial imagery of the Aguirre Commonwealth Forest, Puerto Rico, in 1950, 1994, and 2018.

Data S2. Mangrove recovery actions to consider after a hurricane.

Figure S5. (a) Numerous private vessels. (b) *Sargassum* spp.

Figure S6. Non-corrosive, plastic fencing erected around a small mangrove plantation.

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