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Mangrove Ecosystems: A Global Biogeographic Perspective

Structure, Function, and Services

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Foreword

An international symposium on the biology and management of mangrove ecosystems (Walsh et al. 1975) took place at the East-West Center in Honolulu Hawaii between October 8 and 11, 1974. Mangrove experts from all over the world and in different stages of their professional careers were present at this symposium. As I listened to the comprehensive presentation on mangrove biogeography of V.J. Chapman, I had no idea of how important this meeting would turn out to be from the historical perspective of the study of mangrove wetlands. Chapman's presentation was based on his soon-to-be published encyclopedic work on mangrove vegetation (Chapman 1976), which culminated decades of research on mangroves from a natural history perspective. The proceedings of the meeting also included a memorial for William Macnae, the South African zoologist who passed away in 1975 and was known for his comprehensive research in the fauna and flora of the Indo-West Pacific mangrove forests (Macnae 1968). At the time of the Hawaii meeting, Sam Snedaker and I had completed a review that highlighted the application of ecosystem science to mangrove ecology (Lugo and Snedaker 1974). Cintrón et al. (1978) applied this systems perspective to mangrove zonation in arid environments and anticipated the importance of hurricanes to long-term processes in mangrove forests. Later, I tried to capture the ecosystem-level and ecophysiological challenges of mangrove zonation in relation to their successional status (Lugo 1980). Also present in Hawaii was B. J. Thom, who since the 1960s had been interpreting mangrove ecology in relation to geomorphological settings (Thom 1975). His work explicitly related mangrove ecosystem function to regional fluvial and geomorphological processes. The focus on mangrove research after Hawaii was clearly expanding to regional landscapes and long-term processes. The dissertations of W. Odum (1971) and E. Heald (1971) at the University of Miami had the same effect of expanding mangrove research to ecosystems and communities as close or as far as the detritus from mangroves could be traced.

Today, almost 50 years after the Hawaii meeting, mangrove research activity, the technology available for conducting mangrove research and social interest in mangrove environments has exploded. Ernesto Medina, Cathleen McGinley, and I recently reviewed some of the ecosystem-level and ecophysiological advances in mangrove research as well as some of the policy measures that best apply to mangrove ecosystems under Anthropocene conditions (Lugo et al. 2014, see also reviews in Lugo 2002 and Lugo and Medina 2014). Mangroves were in the past a scientific curiosity for their capacity to grow in seawater, but today, they are at the center of the global conservation discussion. This global attention is not due to any discovery unknown in the 1970s, or to any new functional characteristics of mangroves. What has changed is public perception of mangroves coupled to the advent of the Anthropocene, which places mangrove forests at the interface between built infrastructure, raising sea levels, and human needs.

Mangrove ecosystem research has evolved significantly since the Hawaii meeting, and there is so much new information available, hence the need for a new synthesis of the many studies that are dispersed in the scientific literature. Recent books about this ecosystem focus on its global area and distribution (Spalding et al. 2010), energetics (Alongi 2009), silviculture (FAO 1994, Saenger 2002), and the ecology of regional mangroves (Yañez-Arancibia and A. L. Lara-Domínguez 1999, Clough 1982). A comprehensive global synthesis is lacking, one that places mangroves in the context of the Anthropocene that new research tools allow us to assess. Such a synthesis would represent another step in the progression of mangrove research from natural history, to ecosystem level, to a landscape context, to ecophysiological detail, and now the global and biogeochemical levels. The publication of this book might represent that historic moment when mangrove research takes a turn toward greater insight and comprehension by exploring new scales of complexity (both biotic and abiotic). Only time will tell. The title *Mangrove Ecosystems: A Global Biogeographic Perspective* certainly fits the bill; it cranks up the global focus.

After the Introduction, Chap. 2 by N.C. Duke is titled *Revisiting Mangrove Floristics and Biogeography*. This chapter is one of those works that instantly become a classic of the mangrove literature due to their in-depth, rich, and authoritative content. The chapter is organized around ten generalized factors that mostly influence the biogeography of mangroves. Each mangrove taxon gets individual attention, and its evolutionary history is displayed, as are maps of the distribution of all the mangrove tree species in the world. In Chap. 3, *Biodiversity of Mangroves*, by Lee et al., we learn that the total species richness supported by mangrove ecosystems is two orders of magnitude greater than the number of mangrove tree species. In Chap. 2, it was reported that in the mangrove hotspot of the Indo-West Pacific, 54 mangrove tree species correspond to 500 coral and 5000 fish species. I was amused by the statement in Chap. 3 that research in mangroves is hindered by a large number of dangerous or disturbing wildlife that can bite and kill; they were referring to biting insects, crocodiles, tigers, and so on, which can make mangrove research an action adventure when combined with tidal bores, muddy terrain, and dense prop roots! But of greater concern to scientists is that the majority of entries in the group-by-group biodiversity tables in this book chapter are "ND," or no data.

Chapter 4, *Spatial Ecology of Mangrove Forests: A Remote Sensing Perspective*, by Lucas et al. reviews examples of remote sensing applications to mangrove forests worldwide. Authors advocate for the development of mangrove-dedicated remote sensing approaches and present superb images of mangrove landscapes.

Chapter 5, *Productivity and Carbon Dynamics in Mangroves*, by Twilley et al. is a comprehensive global review of carbon fluxes and storages in mangrove environments. The review is authoritative and summarizes a large data set. I was surprised to find that other book chapters make independent estimates of carbon fluxes rather than using those in Chap. 5. Chapter 6, *Biogeochemical Cycles: Global Approaches and Perspectives*, by Kristensen et al. focuses mostly on Australia and North America, where these kinds of data are collected. It also provides a superb level of detail on the sediments, a mangrove compartment that is usually treated as a black box in most mangrove studies. My favorite image of this review is the three-dimensional view of mangroves, which includes the atmosphere, lithosphere, and biosphere. I expect that this approach to mangroves will be instrumental to the future understanding of these ecosystems. Such an approach will require attention to ecosystem interfaces, especially with sediments, an interface between the hydrosphere and lithosphere. Interface work will in turn require studies at smaller molecular and microbial scales. These smaller scales are as challenging as the global scale and together form the basis of future mangrove research and understanding.

Chapter 7, *Climate Change*, by Jennerjahn et al. includes all expected anthropogenic effects on mangrove environments, but excludes the formation of novel mangrove forests as a result of global dispersal of mangrove species. The authors expect a reduction of mangrove services as a result of climate change and identify gaps in ecophysiological understanding relative to conditions in the Anthropocene. Chapter 8, *Mangroves and People: Local Ecosystem Services in a Changing Climate*, by Huxham et al. explains how mangrove carbon stored in the wood of an untouched forest is a desirable future for the global community, while for the local communities, the desirable future is burning that wood to satisfy their energy and cooking needs. This is the old dilemma between preservation and human needs, one that was debated when the conservation focus was on moist and dry forests and their use for fuelwood by needy people. This chapter is important for mangrove conservation because it underscores the usually neglected social-ecological issues, and it is also independent of other book chapters in relation to anthropogenic effects and future scenarios of climate change.

The social-ecological focus of Chap. 9 is stronger than in Chap. 8. In Chap. 9, *Anthropogenic Drivers of Mangrove Loss: Geographic Patterns and Implications for Livelihoods*, Chowdhury et al. use regional case studies to illustrate mangrove-dependent subsistence and poverty traps and relate conservation problems to large-scale use of mangroves by such industries as the global shrimp trade. Chapters. 8, 9, and 11, when dealing with problems of mangrove uses, do not address management solutions that have been documented for mangroves as possible mitigation avenues (below). It appears that the gap between academic study and active management remains open in mangroves.

In Chap. 10, *Mangrove Forest Restoration and Rehabilitation*, López-Portillo et al. review the experience in 90 sites around the world where mangrove restorations were attempted. My colleague Jack Ewel once said that restoration is the ultimate test for ecological understanding, and judging by the lack of success with mangrove restorations, our understanding of mangrove ecology must be limited.

Alternatively, restoration projects might be ignoring what we know about mangroves, which is why a significant portion of Chap. 10 addresses critical ecological theory and operational processes required for assuring successful mangrove restoration projects. To the recommendations in this chapter, I would add the need to eliminate normative thinking and terminology from this literature (i.e., “damage,” “impact,” “deteriorated,” “better,” “improved,” “integrity,” “alien,” “exotic,” etc.), which introduces bias to the evaluation of ecological conditions and ignores directional change and adaptability to prevailing environmental conditions.

Chapter 11, *Mangrove Macroecology*, by Rivera-Monroy et al. promotes macroecology as the approach to use to answer large-scale questions in the future. Ideally, macroecology will encompass all aspects of traditional ecological research: ecology, biogeography, paleontology, landscape ecology, and macroevolution. The fact that only two studies on macroecology of mangroves are available suggests that the future is wide open for this approach. Further research will determine the desirability and effectiveness of this approach.

This book was written at a time when the effects and consequences of the Anthropocene on mangrove ecosystems remain uncertain. The authors of this book are generally pessimistic about the future of mangrove forests, probably because they mostly focus on the areas where mangroves are in retreat. The knowledge that mangrove forests are expanding their territory (mentioned briefly in the book) does not alleviate the pessimism; it increases as authors also worry about the losing ecosystems, i.e., salt marshes or some other coastal community. The book focus is academic (except for Chap. 10) and the integration of the science recorded here with the management of mangrove stands, which has been partially captured by the FAO (1994) and Saenger (2002), is still open for synthesis.

A mangrove paradox is the apparent simplicity of the mangrove forest implicit in the single tree species monoculture zones nicely arrayed over the landscape, when in fact mangrove forests are very complex systems when viewed in three dimensions and temporal succession along endless gradients operating from the microscale of redox potentials in sediments to global latitudinal scales delimited by frequency of frost and strength of wave action on the appropriate substrates. As this book demonstrates, there are still many hurdles and unanswered questions before we can comfortably say that we understand mangrove ecosystems, and the leap into the global aspects of mangrove functioning further stretches the limits of our imagination. This book, however, points the way, much like how the Hawaii meeting led us into ecosystem level research. One of the lessons from the Hawaii meeting is that once the scientific engine is pointed and cranked, there is no turning back, nor limits to the insights to be gained.

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Contents

Chapter 10
Mangrove Forest Restoration and Rehabilitation

Jorge López-Portillo, Roy R. Lewis III, Peter Saenger, André Rovai, Nico Koedam, Farid Dahdouh-Guebas, Claudia Agraz-Hernández, and Victor H. Rivera-Monroy

10.1 Introduction

The historical loss of mangrove wetland distribution is on a worldwide scale approximately 35–50% of the current area with a variable loss rate of 1–3% per year (i.e., ~150,000 ha/y) (Valiela et al. 2001; Wilkie and Fortuna 2003; Giri et al. 2011). The most recent global coverage estimate for 2014 is 163,925 km^2 down from 173,067 km^2 in 2000, providing an annual loss during that period of 0.4% (Hamilton and Casey 2016). The ongoing wetland loss has triggered an increasing interest in implementing a better management of existing healthy mangrove areas (Ong and Gong 2013). Such management includes the return of key ecological functions in

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coastal areas where wetland mortality is widespread and where these valuable ecosystems and their goods and services are beginning to show deterioration because of increasing human activities (Field 1999a, b; Ellison 2000; Lewis et al. 2005, 2009).

Ecosystem restoration is defined as the return from a deteriorated condition to a state similar to a preserved reference site that represents the structural and functional variability within habitats before a devastating natural or human-induced disturbance (Kaly and Jones 1998). For mangrove wetlands, Lewis (1990) defined restoration as "return from a disturbed or totally altered condition by some action of man" underscoring the more active alternative, as opposed to passive restoration through natural secondary succession; the speed of which depends on the ecosystem resilience capacity, past land-use history, and health of the surrounding landscape matrix (Holl and Aide 2011). In contrast, rehabilitation is not defined as a return to previously existing conditions, a view characterized as "the myth of carbon copy" (Hilderbrand et al. 2005), but to a defined "better" or improved state (Lewis 1990). It has been proposed that rehabilitation is aligned with restoration as both management strategies generally take a culturally acceptable original (preanthropogenic era, sensu Crutzen and Stoermer 2000) or historic ecosystem/landscape as a reference for planned initiatives to halt degradation and initiate more sustainable ecosystem trajectories (Aronson et al. 2007). Indeed, there is a recent consensus based on the historical usage of the terms "restoration" and "rehabilitation" in mangrove wetland management programs, where "the use of the term 'rehabilitation' would reduce confusion as it encompasses the widest range of remedial actions for mangrove degradation" (Dale et al. 2014). However, it is also acknowledged that the term "restoration" has a strong ascendancy in the published literature and therefore we maintain this term in our discussion of the state of mangrove restoration/rehabilitation (R/R) approaches (Primavera et al. 2012; Lewis and Brown 2014).

Similarly to the usage and definitions of "restoration" and "rehabilitation", there is also some confusion regarding the meaning of other related terms such as "forestation", "reafforestation", "replanting", and "plantation". For example, the initial planting of mangrove propagules or seedlings is often called "replanting" where it implies that a first planting may have failed and a second one is taking place. Although this might be a minor detail in describing the type of action and timing to initiate a restoration program, such critical steps must be clearly documented when assessing the success or failure of either a mangrove initial planting effort or repeated plantings in a location or set of locations. Thus, clarity on the type of action can help identify problems with site selection that could, as a consequence,

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potentially increase the costs of restoration programs. Well-defined actions become critical indicators of the applicability of any method of restoration, particularly when planting has been proposed as an alternative after natural seedling recruitment during secondary succession is insufficient to promote mangrove regeneration (Lewis et al. 2005, 2009; Lewis and Brown 2014). Therefore, we encourage the provision of detailed descriptions and implementation of management strategies to be as specific as possible within the context of the definition of both restoration and rehabilitation, especially the description of the actions selected to remedy or improve a specific environmental condition (e.g., geomorphic setting, such as deltaic vs. karstic) in a mangrove wetland.

In this chapter, we explore the main motivations to implement mangrove restoration projects and evaluate R/R projects across latitudinal gradients in the AEP (West Africa and America; Fig. 10.1a–c) and the Indo-West Pacific (IWP: East Africa, Asia, and Australasia; Figs. 10.1d and 10.2a, b) regions. We also identify research gaps and delineate a strategy to improve the implementation of R/R projects using lessons learned in different environmental and social contexts through case studies. Our synthesis contributes to recent analyses aimed at developing best practices when implementing urgently needed science-based mangrove restoration projects.

10.2 Original Motivations and Plans for Implementation

Mangrove resource management should rely on R/R approaches to enhance the full potential of sites, either with complete or cryptic impairment (sensu Dahdouh-Guebas et al. 2005a, 2005b), for the conservation and community-based participation in projects. One of the main attributes of these projects is relying on the knowledge of key ecosystem properties and on documented successes or failures from other R/R endeavors (Primavera and Esteban 2008; Zaldívar-Jiménez et al. 2010). Following on the wealth of data and information, several institutions have developed technical reports with guidelines for restoration programs in mangrove wetlands, which have improved the communication of technical details to evaluate, at least in the short term, project success and/or failures (e.g., Pulver 1976; Field 1995; Saenger 2002; Agraz Hernández et al. 2007; Primavera et al. 2012, 2014; Lewis and Brown 2014).

As a result of the increasing recognition of valuable direct (e.g., wood, carbon, shoreline protection) and indirect (e.g., fisheries maintenance, water quality, carbon storage/sequestration) ecosystem services provided by mangroves (see Chaps. 5, 8, and 9), we identified several R/R projects throughout tropical and subtropical regions. A web search using the ISI Web of Knowledge platform for publications from 1995 through 2015 with the keywords “mangrove”, “restoration”, “rehabilitation”, “reforestation”, “forestation”, and “recovery” in the title produced 136 references with 2273 citations. From this search, supplemented with results from the Google search engine, we selected references that included specific project location data. This combined publication search produced 65 references that provided infor-

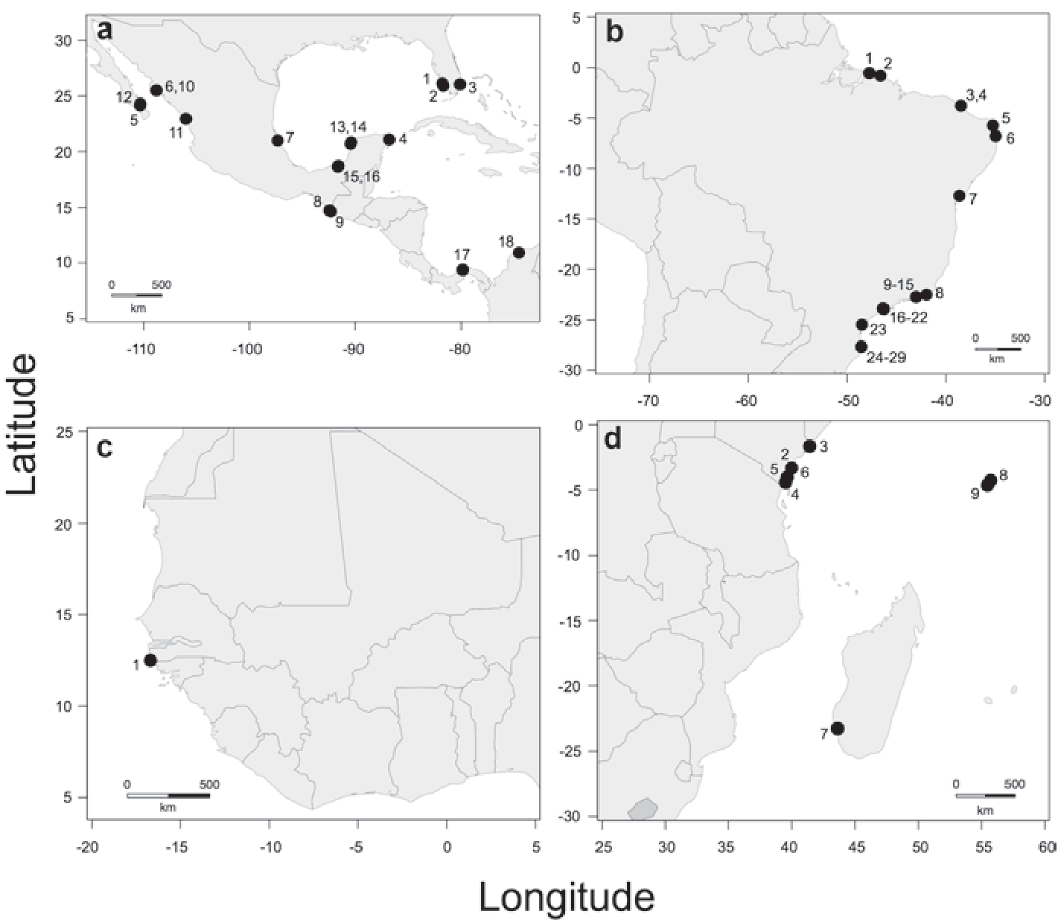

Fig. 10.1 Mangrove R/R projects implemented in the AEP Region (**a–c**) and the Africa sector of the IWP (**d**). Numbers indicating location in each panel are included Tables 10.2 and 10.3. See text for explanation on site identification and selection

mation for our analysis (Table 10.1) and included 90 sites around the world where R/R actions have been implemented (Figs. 10.1 and 10.2). We included each site in a Google Earth KMZ file (available upon request). Given the volume of information in the "gray" literature and other publications not included in the search engines, we acknowledge that this search might not be exhaustive and encourage readers to consult published reports in other coastal regions around the world.

10.2.1 Sources of Mangrove Wetland Damage

The source of damage to mangrove wetlands might be of natural origin (e.g., siltation, erosion, the direct and indirect effect of tropical storms or tsunamis) or induced by anthropogenic activities (e.g., pollution, land use policies, overharvesting, aquaculture, or altered hydrology and hydroperiod; see also Chap. 9). Thus, to

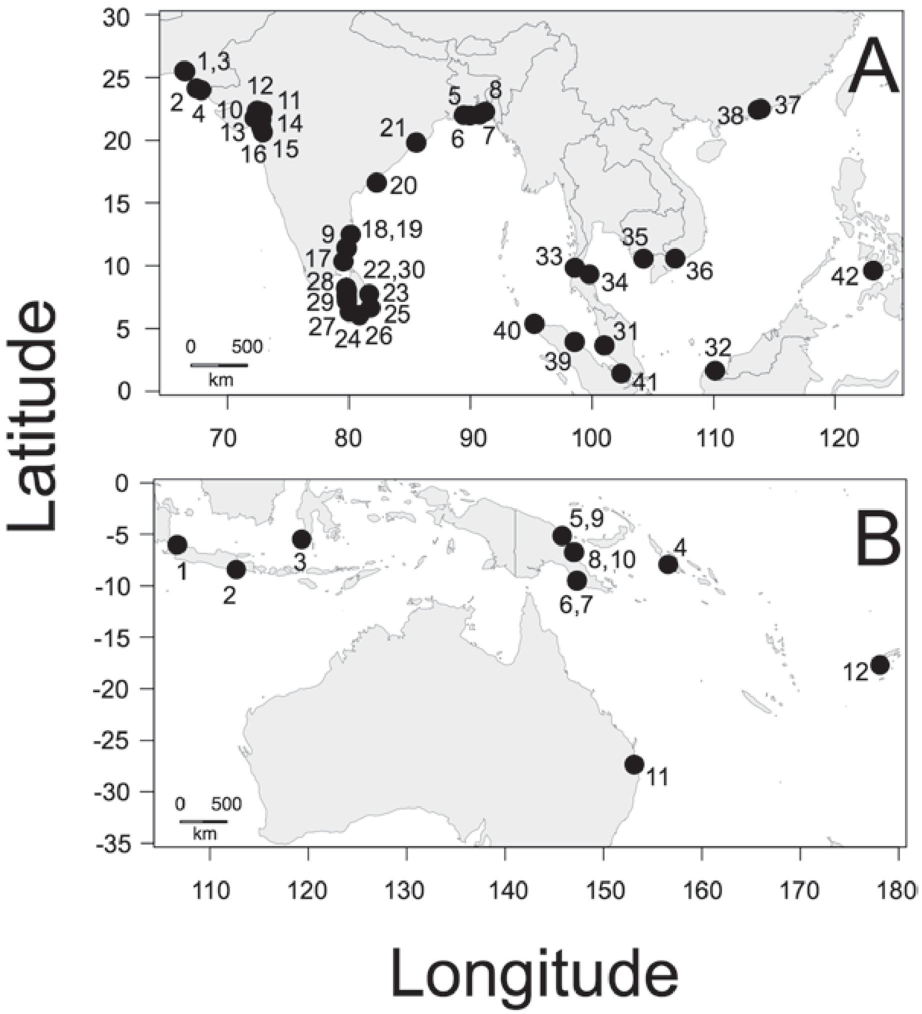

Fig. 10.2 Mangrove R/R projects implemented in the Asia and Australasia sectors of the IWP (**a**, **b**). Numbers indicating location in each panel are listed Tables 10.2 and 10.3 for further information about the sites. See text for explanation on site identification and selection

be effective and efficient, each mangrove wetland project requires a specific R/R approach (i.e., restoration, rehabilitation, or afforestation). There are many causes for mangrove impairment, and because they are frequently mixed and complex, we only assess them according to their frequency in 14 general categories (Table 10.1; percentage [%] of site reports): exposed shores [25%]; impaired hydrological regime [19%]; deforestation [19%]; siltation [11%]; shrimp or fish aquaculture [11%]; conversion to other soil uses, such as palm oil [8%]; blocking of inlets after strong storms such a cyclones/typhoons/hurricanes and tsunamis [7%]; exposure to dredge spoils [5%]; mosquito-preventing dikes [2%]; pollution [2%]; water logging [1%]; soil collapse [1%]; drought [1%]). The quantitative evaluation of the impact by each cause in impairing mangrove wetlands and associated variability in structural and functional properties requires further work at a global scale.

Table 10.1 Mangrove restoration or rehabilitation projects and associated ameloration procedure across Biogeographic regions

Biogeographic region	Project site/country	Cause of impairment	Amelioration procedure	References
Atlantic-East-Pacific (AEP)	Windstar, Florida, USA	Dredge spoil blocked normal tidal flushing	Hydrologic restoration by restoring elevation, Forestation	Stephen (1984), McKee and Faulkner (2000), Proffitt and Devlin (2005)
	West Lake, Florida, USA	Filled wetlands	Excavation of historical fill in mangroves, hydrologic restoration, no planting of mangroves	Lewis (2005), Lewis and Gilmore (2007)
	Florida East Coast, USA	Diked wetlands for mosquito control	Dredged deposits removed, diked mosquito control impoundments breached, very little forestation, natural recovery predominantly	Lewis et al. (1985), Brockmeyer et al. (1997), Rey et al. (2012)
	Rookery Bay, Florida, USA	Incomplete tidal flushing, elevated salinity, waterlogging	Restoring original elevation, excavation of water outlets; Forestation	McKee and Faulkner (2000)
	Bahía de Navachiste, Sinaloa, Mexico	Accumulation of dredging spoils	Channel digging on dredge material terraces and afforestation of nursery plants	Benítez-Pardo et al. (2015)
	Laguna Balandra, Baja California, Mexico	Deforestation	Forestation, natural regeneration	Vovides et al. (2011)
	Laguna de Enfermería, Baja California, Mexico	Block of feeder channel by road	Hydrologic restoration, natural regeneration	Vovides et al. (2011)
	El Mogote, Baja California, Mexico	Hurricane-caused blocking of outlet with a sand dune	Hydrologic restoration	Bashan et al. (2013)
	Huizache-Caimanero, Sinaloa, Mexico	Accumulation of dredging spoils	Forestation with nursery plants	Benítez Pardo et al. (2015)
	Laguna Nichupté, Quintana Roo, Mexico	Hurricane damage, probably including blocking water outlets	Afforestation, Hydrologic restoration	Adame et al. (2014)
	Tampamachoco, Veracruz, Mexico	Water flow obstruction by power line embankments	Hydrologic restoration	López-Portillo et al. (2014)

	Yucatán Peninsula, Mexico	Water flow obstruction by closure of inlets after a strong hurricane	Hydraulic restoration and planting from nursery	Zaldívar-Jiménez et al. (2010)
	Celestún, Yucatán, Mexico	Water flow obstruction by closure of inlets and road construction	Hydraulic restoration and planting from nursery	Miyagi (2013)
	Términos Lagoon, Campeche, Mexico	Water flow obstruction by closure of inlets after a strong hurricane	Hydraulic restoration and planting from nursery	Agraz Hernández et al. (2010)
	Jaina, Petenes BR, Campeche, Mexico.	Water flow obstruction by closure of inlets and road construction	Hydraulic restoration and planting with propagules	Agraz Hernández et al. (2015)
	Isla Arena, Campeche, Mexico	Water flow obstruction by closure of inlets after a strong hurricane	Hydraulic restoration and planting from nursery	Tsuruda (2013)
	Laguna de Cabildo, Chiapas, Mexico	Channel excavation and obstruction of water by bunds	Direct seeding of propagules and nursery plants	Reyes and Tovilla (2002)
	Laguna de Pozuelos, Chiapas, Mexico	Channel excavation and obstruction of water by bunds	Direct seeding of *R. mangle* propagules and nursery plants	Reyes and Tovilla (2002)
	Barra del Río Cahoacán, Mexico	Siltation from upland erosion	Direct sowing of collected propagules and nursery plants	Tovilla et al. (2004)
	Punta Galeta, Panama	Deforestation (?), invasion by *Saccharum spontaneous*	Forestation	Outterson (2014)
	Ciénaga Grande de Santa Marta, Colombia	Interruption of major water flows by road construction	Hydraulic restoration, forestation	Rivera-Monroy et al. (2006), Twilley et al. (1998), Ortiz-Ruiz (2004)
	Parque Nacional Corales del Rosario, Colombia	Unspecified	Seeding and forestation with *R. mangle*	Bohórquez-Rueda and Prada-Triana (1988)-, for other experiments,in Colombia see Álvarez León (2003)
	Two sites, Puerto Rico	Hurricane effects	Natural regeneration by recolonization of *L. racemosa*	Wadsworth (1959)

(continued)

Table 10.1 (Continued)

Biogeographic region	Project site/country	Cause of impairment	Amelioration procedure	References
	Martin Peña Channel, San Juan, Puerto Rico	Urban detritus and siltation, deforestation	Urban renewal, removal of debris, no planting, just natural recolonization	Cintrón-Molero (1992)
	Ajuruteua Peninsula, Bragança, Brazil	Disturbance of hydrological regime by road construction	Natural regeneration by recolonization of *A. germinans*	Vogt et al. (2014)
	Río Jaguaribe, Rio Grande do Norte, Brazil	Deforestation	Seeding and forestation with *R. mangle*	Ferreira et al. (2015)
	Río las Ostras, Río de Janeiro, Brazil	Deforestation	Forestation and natural regeneration	Bernini et al. (2014)
	Baixada Santista, Estuário de Santos, Río Cubatão, Brazil	Deforestation, pollution, dredging	Planting seeds and propagules	Menezes et al. (2005)
Indo-West-Pacific (IWP)	Shenzhen Bay, China	Urban encroachment and pollution, increase in siltation rates	Restoration plan including integration of rustic shrimp ponds (*gei wei*) and mangrove species communities	Ren et al. (2011)
	Qi'ao Reserve, China	Deforestation	Seeding	Chen et al. (2013)
	Barisal, Chitta Gong, Patuakhali, Noakhali, Bangladesh	Newly accreting mudflats	Afforestation	Saenger and Siddiqi (1993)
	Pichavaram, Tamil Nadu, India	Extensive deforestation, soil collapse	Hydraulic rehabilitation by excavating main and secondary channels, forestation	Selvam et al. (2003)
	Nellore, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation with upland dune plants and some mangroves but no distinction is made between the two at all 18 sites	Mukherjee et al. (2015) (Eighteen [18] sites are reported many apparently without mangrove restoration activities)

	Prakasam, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Guntur, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Krishna, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	West Godavari, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	East Godavari, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Visakhapatnam, Andhra Pradesh, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Pulicat Lake, Andhra Pradesh/Tamil Nadu, India		Planting from nursery	Trump and Gattenlöhner (2015)
	Kannur, Kerala, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Kasargod, Kerala, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Thiruvallur, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Kanchipuram, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Nagapattinam, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Thiruvarur, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Thanjavur, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Pudukottai, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)

(continued)

Table 10.1 (Continued)

Biogeographic region	Project site/country	Cause of impairment	Amelioration procedure	References
	Ramanathapuram, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Tutic, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Tirunelveli/Kanyakumari, Tamil Nadu, India	Exposed shores after tsunami or cyclones	Forestation	Mukherjee et al. (2015)
	Trapaing Sangke, Cambodia		Planting from nursery	Trump and Gattenlöhner (2015)
	Kien Giang, Cambodia	Exposure to wave action and erosion	Construction of *Melaleuca* fence and mangrove planting	Cuong et al. (2015)
	Andaman Coast, Thailand		Hydraulic restoration and planting from nursery	Trump and Gattenlöhner, (2015)
	Klong Gnao, Thailand	Wood harvesting, tin mining, aquaculture	Planting of propagules and plants	Macintosh et al. (2002)
	Philippines	Fish/shrimp culture ponds	Multispecies planting	Primavera and Esteban (2008), Primavera et al. (2011, 2012, 2014), Salmo III et al. (2013), Samson and Rollon (2008), Stevenson et al. (1999), Walters (1997)
	Thong Nian, Thailand	Shrimp culture ponds	breaching of banks to rehabilitate water flow, planting of propagules and plants	Matsui et al. (2010)
	Bolgoda Lake, Sri Lanka		Planting from nursery	Trump and Gattenlöhner (2015)
	Madampe Lake, Sri Lanka		Planting from nursery	Trump and Gattenlöhner (2015)
	Pambala-Chilaw lagoon, Sri Lanka	Shrimp aquaculture pond	Remote sensing update, forestation	Dahdouh-Guebas et al. (2002)

	North Sumatra, Aceh Besar, Lhok Nga, Indonesia	Deforestation and erosion due to tsunami	Planting?	Alexandris et al. (2013)
	Banda Aceh, North Sumatra, Indonesia	Deforestation and erosion due to tsunami	Planting?	Alexandris et al. (2013)
	Tanakeke Island, Sulawesi, Indonesia	Shrimp aquaculture pond	Hydrologic restoration of an abandoned shrimp aquaculture pond area followed by limited planting	Brown and Massa (2013)
	Jaring Halus, NE Langkat Wildlife Sanctuary, North Sumatera Province, Sumatra	Shrimp aquaculture pond	Hydrologic restoration in 10 ha of an abandoned shrimp aquaculture pond area followed by limited planting	Brown and Massa (2013)
	Tiwoho Village, North Sulawesi	Shrimp aquaculture pond	Hydrologic restoration in 25 ha of an abandoned shrimp aquaculture pond area followed by limited planting	Brown and Massa (2013)
	Sungai Haji Dorani, Malaysia	Exposed shoreline	Breakwater construction to induce natural establishment of *A. marina*	Tamin et al. (2001), Stanley and Lewis (2009)
	Sungai Haji Dorani, Malaysia	Exposed shoreline	Break water, transplant, natural regeneration	Kamali and Hashim (2011), Stanley and Lewis (2009)
	Sabah, northern Borneo, Malaysia	Areas encroached by oil palms (7 sites) or shrimp ponds (2 sites); five sites are deforested	Forestation in 14 project sites located in five mangrove forest reserves. Additional hydrologic restoration in areas encroached by oil palms (7 sites) or shrimp ponds (2 sites)	Tangah et al. (2015)
	Cabrousse, Senegal	Deforestation, blockage of water flows, droughts	Seeding (propagule planting)	Alexandris et al. (2013)
	Kiunga Marine National Reserve, Kenya	Deforestation, silting	Natural regeneration	Kairo et al. (2001)
	Mida Creek, Kenya	Deforestation, silting	Natural regeneration	Kairo (Kairo et al. 2001)

(continued)

Table 10.1 (Continued)

Biogeographic region	Project site/country	Cause of impairment	Amelioration procedure	References
	Tudor Creek, Kenya	Deforestation, silting	Natural regeneration	Bosire et al. (2014)
	Gazi Bay and Mwache Creek, Kenya	Deforestation, silting	Natural regeneration	Bosire et al. (2003, 2014)
	Gazi, Kenya	Deforestation, silting	Forestation	Kairo et al. (2001)
	Mamelo Honko, Madagascar	Deforestation	Seeding (Propagule planting)	Alexandris et al. (2013)
	Ranongga, Salomon Islands, Melanesia	Deforestation	Replanting to replace vegetation lost after an earthquake	Alexandris et al. (2013)
	Brisbane International Airport, Australia	Filling of main creek and excavation of other channels	Hydrologic restoration by channel digging and forestation	Saenger (1996)

10.2.2 Amelioration Procedures

Forestation practices (Table 10.1) using individual plants from nurseries was the main amelioration procedure ($n = 67$) followed by hydrologic rehabilitation ($n = 29$), although both actions were frequently combined ($n = 22$). Direct seeding or mature propagule planting (mainly the genus *Rhizophora*) was also a frequent action ($n = 11$). Natural regeneration was implemented in 10 sites including cases where it was coupled with transplants ($n = 1$) and forestation ($n = 2$) techniques. We assume that there was afforestation in the 17 sites (covering 43,760 ha) exposed to wave energy and described as "bio-shield" plantations in the states of Kerala, Andhra Pradesh, and Tamil Nadu in peninsular India (Mukherjee et al. 2015).

10.2.3 Spatial Scales of the Amelioration Procedures

The mangrove sites undergoing restoration or just afforestation encompassed a range of area extensions from few square meters to several thousand hectares. The most extensive afforestation sites are located in the Sundarbans, in Bangladesh and India (120,000 ha afforested by 1993, Saenger and Siddiqi 1993), United States (12,605 ha restored, Rey et al. 2012; 500 ha restored, Lewis 2005, Lewis and Gilmore 2007), and other coastal regions in Asia (e.g., Pichavaram Province: >300 ha of restored mangroves, Selvam et al. 2003) and Indonesia at Tanakeke Island (400 ha), where hydrologic restoration was also part of the R/R strategy (Brown and Massa 2013; Brown et al. 2014).

The large mangrove extension in the Sundarbans delta region is characterized by both large spatial scale impacts and management strategies, including erosion, aggradation (i.e., natural sediment accumulation), deforestation, and mangrove rehabilitation programs (Giri et al. 2007). For example, 7300 ha of mangrove wetland were lost to erosion from 1977 to 2000, whereas net aggradation was variable with gains ranging from 2900 ha (1970s) to only 590 ha (2000). Recent estimates show a total loss of 26,200 ha and total gain of 24,000 ha from 1989 through 2014 (Ghosh et al. 2015). Due to the significant new land gains as a result of high sediment deposition, natural mangrove establishment in the newly formed land was combined with active and intense community-based seeding and planting of seedlings to compensate for eroded mangroves (Saenger and Siddiqi 1993; Giri et al. 2007). In contrast to the net gain in mangrove area in this region, a large effort with propagule planting (79 million distributed throughout 7920 ha) in Cabrousse, Senegal, West Africa in 2008, showed no evidence of increase in mangrove coverage as evaluated by changes at the landscape level using remote sensing images obtained up to 2010 (Alexandris et al. 2013).

10.2.4 Mangroves and Aquaculture

Over the last three decades of human impact on mangrove wetlands, shrimp aquaculture and their associated culture ponds have probably been responsible for the greatest losses of mangrove wetland area (see Chap. 9). This activity has been actively encouraged by governments in developing countries (e.g., Brazil, Ecuador, Thailand, Indonesia, and Vietnam) interested in the high earning potential of shrimp as an export product, but also often driven by political patronage (Tobey et al. 1998; Foell et al. 1999; Dahdouh-Guebas et al. 2006; Oliveira-Filho et al. 2016, Table 10.2). A comprehensive work on the total area of mangrove loss to commercial aquaculture indicates that in the eight countries that host about 45% of total world mangrove cover, about 52% of their historic mangrove coverage is lost, including 28% to commercial aquaculture (Hamilton 2013; Hamilton and Casey 2016). Given the proliferation of shrimp farms around the world, many R/R projects have been undertaken in countries where shrimp farms were abandoned due to major disease outbreaks that decimated the industry (e.g., viral diseases) (Stevenson et al. 1999; Matsui et al. 2010; Primavera et al. 2011, 2014; Brown et al. 2014). In fact, some studies have used hydrological models to determine which dikes or artificial barriers should be removed to restore the original hydrology and induce natural mangrove reestablishment and growth (Di Nitto et al. 2013). In other locations, particularly in developed countries (e.g., the USA or Australia), R/R projects were initially used as ecological offsets related to land use and mitigation policies (Teas 1977; Snedaker and Biber 1996; Latif 1996). As an example of this strategy, Brockmeyer et al. (1997) and Rey et al. (2012) reported an accumulated 12,000 ha of successful restoration programs mainly due to reconnection and controlled flooding along the east coast of Florida.

A number of R/R projects have been undertaken to address the problem of extensive abandonment of shrimp ponds due to economic failure in several countries (e.g., Primavera and Esteban 2008; Brown et al. 2014), and as a result, there is growing number of peer-reviewed studies that provides useful insights into designing R/R projects with specific management objectives and goals based on the initial nature of the damage (e.g., Latif 1996; Saenger 1996; Das et al. 1997; Walters 1997;

Table 10.2 Aquaculture pond areas constructed in mangroves in major shrimp producing developing countries (From Tobey et al. 1998)

Country	Pond area (ha)	Number of farms
Indonesia	350,000	60,000
India	200,000	10,000
Vietnam	200,000	2000
Bangladesh	140,000	13,000
Ecuador	130,000	1200
China	127,000	6000
Thailand	70,000	16,000
Philippines	60,000	1000
Mexico	14,000	240
Honduras	12,000	55

Table 10.3 Geographic information of sites where rehabiliation of restoration projects discussed in the text. Figure 10.1 shows the location

Biogeographic region	Country/continent	Site name	Site ID[a]	Latitude	Longitude
Atlantic-East-Pacific (AEP)	Brazil	Pará	A1	−0.551398	−47.735251
		Ajuruteua	A2	−0.8056154	−46.625772
		Sapiranga, Fortaleza	A3	−3.774106	−38.448555
		Sapiranga, Fortaleza	A4	−3.774106	−38.448555
		Jaguaribe	A5	−5.753603	−35.218739
		Barra de Mamanguape, Paraíba	A6	−6.780058	−34.936283
		Baía de Todos os Santos, Bahia	A7	−12.717753	−38.612231
		Estuário do Rio das Ostras	A8	−22.506952	−41.94283
		Angra dos Reis, Rio de Janeiro	A9	−22.733875	−43.018167
		Lagoa Rodrigo de Freitas, Rio de Janeiro	A10	−22.733875	−43.018167
		Ilha do Fundão, Rio de Janeiro	A11	−22.733875	−43.018167
		Ilha do Fundão, Rio de Janeiro	A12	−22.733875	−43.018167
		Ilha do Fundão, Rio de Janeiro	A13	−22.733875	−43.018167
		Ilha do Fundão, Rio de Janeiro	A14	−22.733875	−43.018167
		Ilha do Fundão, Rio de Janeiro	A15	−22.733875	−43.018167
		Baixada Santista, São Paulo	A16	−23.880911	−46.364192
		Baixada Santista, São Paulo	A17	−23.880911	−46.364192
		Baixada Santista, São Paulo	A18	−23.880911	−46.364192
		Baixada Santista, São Paulo	A19	−23.880911	−46.364192
		Baixada Santista, São Paulo	A20	−23.880911	−46.364192
		Baixada Santista, São Paulo	A21	−23.880911	−46.364192
		Baixada Santista, Estuário de Santos	A22	−23.91419	−46.265168
		Baía de Paranaguá, Paraná	A23	−25.463458	−48.475563
		Costeira do Pirajubaé, Florianópolis	A24	−27.652969	−48.539156
		Biguaçu, Santa Catarina	A25	−27.652969	−48.539156

(continued)

Table 10.3 (continued)

Biogeographic region	Country/continent	Site name	Site ID[a]	Latitude	Longitude
		Saco Grande, Florianópolis	A26	−27.652969	−48.539156
		Ratones, Florianópolis	A27	−27.652969	−48.539156
		Itacorubi, Florianópolis	A28	−27.652969	−48.539156
		Saco da Fazenda, Itajaí	A29	−27.652969	−48.539156
	USA	Windstar	B1	26.1196972	−81.782469
		Rookery Bay	B2	25.9102556	−81.703361
		West Lake	B3	26.0384972	−80.119464
	Mexico	Laguna Nichupté	B4	21.099975	−86.793617
		Balandra	B5	24.3234868	−110.32286
		Laguna Enfermería	B6	24.2498611	−110.31276
		Tampamachoco	B7	21.0123861	−97.339694
		Laguna de Cabildo	B8	14.742925	−92.433219
		Laguna de Pozuelos	B9	14.6458278	−92.339764
		Navachiste	B10	25.4980185	−108.79743
		Huizache - Caimanero	B11	22.9458639	−106.00631
		El Mogote	B12	24.1636833	−110.3348
		Celestún	B13	20.8580167	−90.390083
		Isla Arena	B14	20.7124584	−90.44895
		Isla Aguada, Campeche	B15	18.6660821	−91.665588
		Isla Aguada	B16	18.7132933	−91.609765
	Panama	Punta Galeta	B17	9.40270219	−79.862062
	Venezuela	Ciénaga Grande de Santa Marta	B18	10.9371278	−74.541131
	Africa	Cabrousse, Senegal	C1	12.4926172	−16.685131

Indo-West-Pacific (IWP)	Africa	Mida Creek, Watamu, Kenya	D2	−3.3333415	40.0000004
		Kiunga Marine National Reserve, Kenya	D3	−1.668958	41.4066794
		Gazi, Kenya	D4	−4.4273752	39.51063
		Tudor Creek, Kenya	D5	−4.0479108	39.6535163
		Mwache Creek, Mombasa, Kenya	D6	−4.0502697	39.633712
		Mamelo Honko, Madagascar	D7	−23.262529	43.6242508
	Seychelles	Curieuse Island	D8	−4.2791955	55.7277429
		Roche Caiman Sanctuary	D9	−4.6396463	55.4689262
	Pakistan	Sonmiani, Balochistan	E1	25.4890771	66.5182225
		Sha Bandar	E2	23.9882232	67.84664
		Miani Hor	E3	25.5282117	66.4561847
		Keti Bandar	E4	24.1301277	67.4445187
	Bangladesh	Sundarban	E5	22.0026661	89.4464738
		Barguna Sadar	E6	21.9660641	89.9607137
		Char Fasson	E7	22.0397962	90.7422427
		Hatiya	E8	22.2806648	91.1926791
	India	Pichavaram	E9	11.4208443	79.796165
		Ahmedabad	E10	22.3748974	72.4439145
		Bhavnagar	E11	21.7631481	72.2441373
		Anand	E12	22.2613255	72.8892584
		Bharuch	E13	21.6475722	72.8008261
		Surat	E14	21.0542686	72.7628816
		Valsad	E15	20.6380196	72.9119655
		Navsari	E16	20.9294833	72.79864
		Muthupet	E17	10.3408316	79.5378549
		Chidabaram	E18	11.390341	79.8137706
		Krishna	E19	12.4698823	80.1501882

(continued)

Table 10.3 (continued)

Biogeographic region	Country/continent	Site name	Site ID[a]	Latitude	Longitude
		Godavari	E20	16.6170396	82.2825575
		Chilika	E21	19.8101156	85.5365084
	Sri Lanka	Pambala-Chilaw	E22	7.50002222	79.8167167
		Batticaloa	E23	7.73376131	81.6668314
		Kumana National Park	E24	6.64617297	81.7750119
		Rekawa	E25	6.05588762	80.852921
		Madu Ganga	E26	6.31203664	80.0667239
		Negombo	E27	7.19265861	79.8300512
		Arachchikattuwa	E28	7.66656578	79.8014598
		Puttalam	E29	8.00588689	79.832815
		Kalpitiya	E30	8.21745625	79.7638786
	Malaysia	Sungai Haji Dorani	E31	3.65576667	101.009853
	Thailand	Matang	E32	1.66743216	110.121648
		Klong Ngao	E33	9.83335833	98.5833611
		Thong Nian	E34	9.30786852	99.7815087
	Vietnam	Kien Giang	E35	10.5688691	104.230806
		Xuan Thuy National Park	E36	10.576852	106.846581
	China	Shenzhen Bay	E37	22.5045	113.898844
		Reserva Qiao	E38	22.4219186	113.622618
	Indonesia	Jaring Halus, NE Langkat Wildlife Sanctuary	E39	3.94296529	98.5650101
		Bengkalis Island, Riau Province	E40	1.4476312	102.392214
		North Sumatra, Aceh Besar, Lhok Nga	E41	5.36595278	95.2519
	Philipines	Filipinas	E42	9.60581111	123.128139
	Indonesia	Tanjung Pasir	F1	−6.0227622	106.667057
		Segara Anakan	F2	−8.4417594	112.669275
		Tanakeke Island, South Sulawesi Province	F3	−5.4936601	119.307603

	Papua New Guinea	Ranongga	F4	−7.9369326	156.541642
		Madang	F5	−5.2000636	145.784309
		Motupore	F6	−9.5244443	147.285483
		Bottless Bay	F7	−9.4998877	147.283054
		Labu	F8	−6.7546354	146.953832
		Riwo	F9	−5.1321679	145.78296
		Wangang	F10	−6.7334149	147.016566
	Australia	Brisbane airport	F11	−27.353787	153.107414
	Fiji	Fiji	F12	−17.713372	178.065031

[a]As depicted in Fig. 10.1

McKee and Faulkner 2000; Macintosh et al. 2002; Lewis et al. 2005; Darkwa and Smardon 2010; Matsui et al. 2010; Lewis and Brown 2014). Indeed, specific outcomes of mangrove R/R implemented on abandoned shrimp farm locations have been critically reviewed with major emphasis on case studies in the Philippines (Primavera and Esteban 2008) and Costa Rica (Stevenson et al. 1999) and have provided essential and useful practical guidelines (e.g., Brown and Lewis 2006; Lewis and Brown 2014).

10.2.5 Monitoring of R/R Projects

Most R/R projects consist of planting propagules, wildings, or saplings reared in nurseries close to or away from the target site. Few of these projects have detailed monitoring plans, and in most instances, there is no documentation of either positive/negative outcomes or recommendations for modifications of the original planting design (Lewis et al. 2005; Kodikara et al. 2017). An exception is the Ciénaga Grande de Santa Marta (CGSM), Colombia monitoring project (1995–2001), which was carried out after the construction of box culverts to reestablish hydraulic flow in a mangrove area representing the largest restoration project in Latin America (~350 km^2, including freshwater and mangrove wetlands and natural water bodies). The hydrological rehabilitation of the area consisted of dredging and reopening previous tributaries to conduct freshwater from the Magdalena River to the eastern region of the CGSM system, where mangrove mortality was extensive due to hypersalinity (>80 ppt) (Botero and Salzwedel 1999). There was a significant reduction in soil and water column salinity (<30 ppt) in all sampling stations following the hydraulic reconnection, which resulted in a major increase in mangrove forest regeneration promoting a net gain of 99 km^2 from 1995 to 1999 (Rivera-Monroy et al. 2006). Unfortunately, the lack of economic investment in the maintenance of the diversion structures from 2001 to the present has reverted the system to pre-project ecological conditions causing an increase in soil salinity, which has negatively affected the already restored vegetation (Elster 2000; Rivera-Monroy et al. 2006; Rivera-Monroy et al. 2011; Vilardy et al. 2011; Roderstein et al. 2014). In addition, areas where *Avicennia germinans* propagules established and developed into saplings were heavily impacted by the butterfly *Junonia evarete*, further increasing plant mortality rates; yet, some survived and increased plant density in areas with previously extensive mangrove mortality (Elster 2000). Overall, herbivory has not been explicitly addressed as a negative factor in mangrove R/R, but it is probably significant based on reports from other mangrove wetlands (Nagelkerken et al. 2008; Fernandes et al. 2009). Although there are fewer mangrove species in the AEP region (West Africa and Americas; see Chap. 2), such R/R failures still provide essential knowledge on biological, ecological, and hydrological variables that should be considered during forestation or afforestation projects, including the direct impact of trampling, barnacle colonization, and flotsam (Kodikara et al. 2017).

10.3 Geographical Distribution of R/R Projects in Mangrove Habitats

Assessing the geographical distribution of R/R projects (Figs. 10.1 and 10.2) contributes to our understanding of the causes triggering mangrove wetland conversion and its relative impact and how current R/R practices are related to economic or social failure. Indeed, there are some geographical differences (and similarities) concerning the causes of mangrove degradation. In the United States, most of the damage in mangroves and other wetlands was caused by dikes and draglines (which include ditching, dredging, filling, and impounding for land development) to control mosquito and biting midge populations in South East and West Florida and the Florida Keys (Fig. 10.1a). These hydrological modifications at the landscape level had negative consequences by reducing wetland productivity and fisheries abundance (McKee and Faulkner 2000; Rey et al. 2012). In mid-latitudes across the AEP region (Fig. 10.1 a–c), mangrove degradation is generally caused by the construction of highways and embankments that interrupt water (fresh and marine) flow; the opening of artificial inlets, dredging of navigation channels, and deposition of this dredged materials over or nearby mangrove forests; conversion to shrimp farms and the pumping of estuarine/coastal water during operations of shrimp aquaculture (Teas 1977; Twilley et al. 1998; Chargoy Reyes and Tovilla Hernández 2002; Menezes et al. 2005; Primavera 2006; Rivera-Monroy et al. 2006; Pagliosa et al. 2012; Hamilton 2013; Miyagi 2013; Benítez-Pardo et al. 2015; Ferreira et al. 2015).

In West Africa (Fig. 10.1c), the causes of mangrove degradation are related to expansion of agriculture and aquaculture, construction of embankments and access roads, unsustainable wood extraction for fuel wood and charcoal, and fishing and hunting, among other causes (Corcoran et al. 2007). Although mangrove extension and causes of mangrove mortality in these coastal regions are yet to be documented, extensive R/R efforts are implemented at different stages in several sites where most of the same causes of degradation are similar to those observed at the global scale (see Chaps. 8 and 9; Table 10.1; Figs. 10.1 and 10.2). For example, in the IWP region (East Africa, Asia, and Australasia), planting efforts in Gazi Bay, Kenya, were implemented in response to a lack of natural regeneration after the synergetic impact of clear-cut felling of trees about 40 years ago and heavy silting due to major upland deforestation in the middle and upper river basins. This synergy of human impacts along river watersheds from upstream to coastal regions seems to be common for other mangrove forests throughout East Africa (Kairo et al. 2001, Bosire et al. 2003; Dahdouh-Guebas et al. 2004; Fig. 10.1d). Considering mangrove reforestation as an R/R approach, the Payment for Ecosystem Services and REDD+ in Gazi Bay through the Mikoko Pamoja project is a prime example of how important the recognition of mangrove ecosystem services is and how essential it is to clearly identify the social need and economic value of mangrove wetlands (http://www.planvivo.org/project-network/mikoko-pamoja-kenya/; Jerath et al. 2016; see Chaps. 8 and 9).

Human impacts on mangrove-dominated ecosystems in India also include clear cutting and deforestation, fresh water diversions and intensive shrimp farming (Table 10.2, Fig. 10.2a; see also Chap. 9). Mangrove forests in the Pichavaram and Muthupet regions of India have been historically affected by major clear-cut logging (Selvam et al. 2003). In contrast, the impacts of land use changes in the Sundarbans National Park, one of the largest mangrove protected areas in the world (10,000 km^2), seem to be relatively minor; yet, turnover rates "due to erosion, aggradation, reforestation, and deforestation" are apparently significantly greater than the net change estimated using remote sensing techniques (Giri et al. 2007). The estimated actual mangrove wetland area in the vast Sundarbans ecosystem in the year 2000 was 5816 km^2 (Giri et al. 2007). This value includes an area of 1200 km^2 that have been afforested from 1973 to 1990 within the park limits, primarily on new accreting mud deposits as a protection against tropical cyclones (Saenger and Siddiqi 1993). Recent estimates report 1852 km^2 of mangrove cover in 2014 in the Indian Sundarbans (Ghosh et al. 2015); adding this area to the area determined for the Bangladesh Sundarbans (3745 km^2), a total of 5327 km^2 is obtained, which is slightly lower than it has been previously reported (i.e., 5816 km^2 for a deficit of 489 km^2; see Giri et al. 2007). Similar patterns in extensive mangrove loss are also observed in the Seychelles, Sri Lanka, Pakistan, Bangladesh, Myanmar, Thailand, Cambodia, Vietnam, Sumatra, and Java (Macintosh et al. 2012; Alexandris et al. 2013).

Specifically, for the Indian Ocean area, the devastating tsunami of 2004 has been an incentive for mangrove restoration programs through international and national funding initiatives. Unfortunately, most of the funding opportunities do not translate into science-based plans and are often ill prepared and unsuccessful (Jayatissa et al. 2016). A colloquium held in the coastal town of Mamallapuram, India, listed 52 sites where restoration efforts have been implemented, especially in the wake of the tsunami (Macintosh et al. 2012). Similarly, guidelines have been prepared for R/R projects after the tsunami damage to mangroves and coastal forests in Southeast Asia (Chan and Ong 2008; Chan and Baba 2009), or following oil pollution reclamation and camel grazing in the Middle East (Protection of the Environment of the Red Sea and the Gulf of Aden; Saenger and Khalil 2011).

10.3.1 Current Motivations for the R/R projects

Among the main motives identified for the implementation of R/R projects include ecological problems caused by the operation or abandonment of shrimp ponds, altered hydroperiod and tidal circulation patterns, water pollution, loss of habitat (particularly for fisheries of local and regional social and economic value), and significant decrease of soil pH (acid sulfate). In the latter case, some mangrove soils contain pyrite (potential acid-sulfate soils), which remain immobile while waterlogged (see Chap. 6). However, when these soils are used to build pond walls, where they partially dry out, sulfuric acid is produced, which lowers pond water pH values and releases Al^{3+} (Saenger 2002; see Chap. 6). As a consequence, shrimp farms often do not function well in the long term, and shrimp/prawn production dramatically declines leading to bankruptcy of aquaculture farms. In the aftermath of such local/regional socioeconomic failure, soil quality problems are left behind. Pond water acidity and toxic concentration of Al^{3+} must be dealt with before effective restoration or rehabilitation can be implemented, increasing overall R/R project costs. More recently, the motives for the implementation of R/R projects have expanded to include shoreline protection, channel stabilization, fisheries and wildlife enhancement, biodiversity conservation, legislative compliance, or socioeconomic improvement of local communities (Stubbs and Saenger 2002; Mukherjee et al. 2015).

10.3.2 Effective R/R Projects Goal Setting

Based on the experiences described above, it is essential that R/R project objectives are clearly defined and prioritized as a first step. A coastal afforestation project in Bangladesh, for example, had several objectives that included the production of commercial timber, acceleration of the accretion rate to form new land areas, and protection of nearshore agricultural and residential land from storm damage (Saenger 2011). These objectives were gradually achieved, but in some cases, there were conflicts in achieving success for each specific objective. For instance, in planting sites where very high sedimentation rates occurred, trees were buried and timber production was negligible. Thus, when assessing the significance of high sedimentation rates at specific sites in such cases, consideration must be given for both well-prepared and managed production of timber and coastal protection as those objectives were of highest priority, giving way to best practices for mangrove restoration and management.

Other examples in the complex implementation of R/R projects include sites in the states of Tamil Nadu and Andhra Pradesh, India (Selvam et al. 2005) and in Celestún, Campeche, Mexico (Miyagi 2013). In some locations in India, soil collapse was a consequence of extensive forest clear felling (wood revenue) of vast mangrove wetland extensions from 1935 to 1975 (Selvam et al. 2003; for other location, see Cahoon et al. 2003). As a result of direct cutting, trough-shaped areas resulted from soil exposure after tree felling causing water stagnation and high soil salt concentration. The proposed solution was to excavate artificial channels (1 m deep, 1.5 m wide at the base and 3 m wide at the soil surface) and connect them to natural adjacent channels (Fig. 10.3). Feeder channels (0.75 m deep, 0.6 wide at the base, and 1.5 m wide at the soil surface) were also excavated throughout the die-back mangrove area, following a “fish bone” spatial pattern (Fig. 10.3). The excavated sediments were deposited next to the channels, increasing soil relative elevation. This strategy was designed to reestablish water exchange between the mangrove die-back areas and the natural channels with the goal of increasing the survival rate of planted and naturally established seedlings, The technique (i.e.,

Fig. 10.3 Hydrological restoration implemented in mangrove wetlands in Pichavaram, Tamil Nadu, India, showing original main and feeder channels excavated circa 1996. (**a**): March 3, 2003; (**b**): January 29, 2016 (Source: Google Earth Pro; image area: 55.5 ha; eye altitude 881 m; Latitude: 11°25′59.86″ N, longitude: 79°47′28.89″ E at the center of the images

feeder channels) was first tested around 1996 in a pilot study involving 10 ha of dead mangrove wetland and resulted in the recovery of an extensive mangrove forest area (Fig. 10.3). After it was demonstrated to be successful, it was used in other areas covering at least 1200 ha impacted mangrove sites in the states of Tamil Nadu and Andhra Pradesh, India (Selvam et al. 2005). One of the main attributes of the R/R project described above (Fig. 10.3) involved an initial diagnostic and a pilot study to test the proposed solution. The implementation of this approach involved the acquisition of permits before and after project implementation, as well as securing funding from government agencies. Additional critical steps included (1) plan-

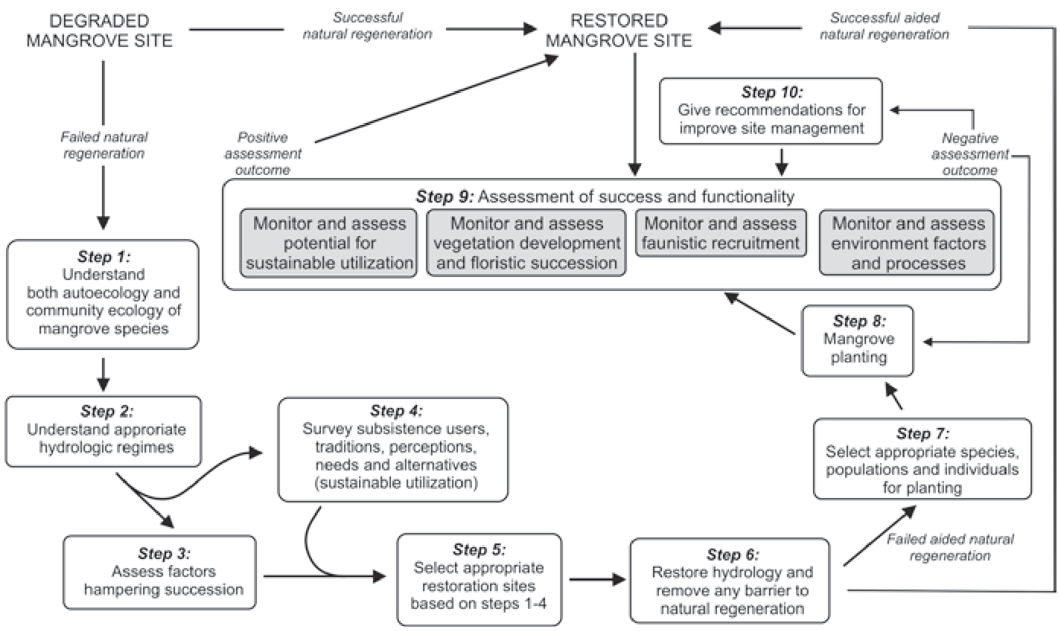

Fig. 10.4 Decision tree showing recommended steps and tasks to restore a mangrove wetland based on original site conditions (From Bosire et al. 2008)

ning to excavate during the period of lowest water level, (2) organizing and working closely in a community-based restoration effort, (3) maintaining nurseries to raise seedlings of several mangrove species for planting in the modified areas, (4) channel maintenance (mainly silt dredging) when required, and (5) monitoring the success or failure of restored areas by means of GIS and ground truthing (Selvam et al. 2003). A similar success history following essentially the same steps was implemented in Celestún, Campeche, and Mexico (Miyagi 2013).

Prioritized objectives underpin the development and implementation of R/R projects as they force the operational identification of the processes that must be included to provide a clear framework that warrant project success. Among other alternatives to ensure a logical selection of steps and clear objectives, we propose the implementation of the Ecological Mangrove Rehabilitation (EMR) protocol as outlined in Lewis and Brown (2014) that includes monitoring and reporting tasks (Fig. 10.4). For example, if the objective is to restore harvestable fish and shellfish habitat, the life history of the target species should be fully understood while monitoring species-specific requirements to document an actual increase in species population density in the restored area (Lewis et al. 1985; Brockmeyer et al. 1997; Lewis and Gilmore 2007). A unique design criterion, such as the restoration of the historical hydrological patterns (e.g., water flow, net volume), and attributes (e.g., cross section area, length) of tidal creeks may also be essential to provide accessibility for migration and reproduction cycles for those targeted species.

An interdisciplinary framework has also been proposed to evaluate coastal “bioshield” plantations (some with mangroves) and involves the consideration of several preplantation, plantation, and postplantation procedures (Mukherjee et al. 2015). In this scheme, one of the major drivers defining the objectives and requirements to ensure success, but usually neglected, is land tenure rights. This consideration is especially critical in plantations established on land under the jurisdiction of the Revenue Department or similar country/regional governance bodies or long-term land grants where projects could become high economic risks if changes in policy occur after project implementation (Primavera 2000; Primavera and Esteban 2008; Mukherjee et al. 2015). In fact, land use change, either in private and public lands, is perhaps the major threat to the implementation of R/R projects given the uncertainty in the change of regional and national policies and economic interests associated to urban and industrial development, particularly in developing countries (see Chap. 9).

10.3.3 Critical Questions: What Were the Ecological Services Sought? What Were the Societal Priorities?

Mangroves have well-defined economic and social values referred to as "instrumental values", "free services", "ecological functions", or "ecological services" (see Chaps. 8 and 9). These values include the provision of habitat and biodiversity conservation, food and wood production, shoreline protection, chemical buffering, water quality maintenance, provision of recreational, aesthetic and education opportunities, and reservoirs of genetic materials. Indeed, coastal protection and socio-economic factors are the main drivers of coastal bio-shield projects in India (Mukherjee et al. 2015). Therefore, in each R/R project it must be decided which of these ecological functions, goods, and services is (are) the most appropriate to be sustainable, including the need to make decisions that are congruent with the priorities of both national governments and local communities.

10.3.4 Implementation Plans

In earlier steps in the implementation of R/R projects, a questionnaire survey is a useful tool for the evaluation of site conditions to compare potential sites. This tool is also necessary in the development of a detailed implementation plan based on the natural conditions of each site (Saenger et al. 1996). Furthermore, this assessment should include a synoptic account of the biotic and abiotic site conditions and, critically important, practical considerations as access, travel time, and land-use status. Since the early 1980s, it has been advocated that the planting of mangroves specifically should occur for the environmental services these wetlands can provide (i.e., Lewis 1982). One of the requirements to implement such an approach is to avoid, as much as possible, the monoculture of mangroves that frequently characterizes restoration projects devoted to timber production. Despite this limitation, few restoration programs have achieved a degree of ecological functioning similar to natural mangrove systems (Latif 1996; McKee and Faulkner 2000; Lewis and Gilmore

2007; Bosire et al. 2008). Based on these experiences, the following conditions should be met to increase the success of a specific mangrove R/R project: (1) it should be viewed by the local people as an economic opportunity and/or offer other tangible benefits; (2) it is compatible with local patterns of resource use and land tenure; (3) local knowledge and skills relevant to restoration are successfully embedded into the project; (4) local groups and organizations are effectively mobilized to support and implement restoration activities; and (5) relevant policies and political factors are supportive of restoration efforts at the local, regional, and national levels (Walters 1997).

10.4 Major Limitations in the Implementation of R/R: Funding Availability and Current Ecological Theory

Funding availability for the implementation of R/R project is generally based on the realization by different countries that a high proportion of mangrove wetlands have been damaged by a complex interaction of human impacts including aquaculture, agriculture, livestock, urban/rural/industrial and touristic development, and misguided practices concerning the construction of roads, extensive dredging and the opening of sand bar inlets along vulnerable coasts. Some of these activities have caused irreversible damage, requiring the implementation of mangrove R/R projects, which may be funded by government agencies/departments and/or Nongovernment Organizations. However, financial support for most of these coastal management projects is limited due, in most instances, to the high cost for implementation. Even when economic resources are available, they are often not appropriately allocated and spent (Kodikara et al. in press). Therefore, current ecological theory and the experience gained through frequent failures, and less frequent successes, must be incorporated in current and future R/R projects to help define the short- and long-term goals and strategies to promote cost-effective small and large-scale mangrove R/R projects (Lewis et al. 2005; Primavera and Esteban 2008; Saenger 2011; Twilley et al. 1998; Twilley and Rivera-Monroy 2005).

10.4.1 Selection of Easily Manageable Species

Among the taxonomic selection of individual for R/R projects, the genus *Rhizophora* has been the preferred taxon used in planting-oriented restoration projects (Ellison 2000). The species within this genus have a worldwide distribution (Tomlinson 1986; Giri et al. 2011; see Chap. 2). Two of the major reasons this genus is used in planting programs are its large hypocotyl nutrient storage that increases survival rates at early developmental stages, even for long-term wood production in natural environments, and its handling versatility (Shamsudin et al. 2008; Goessens et al. 2014).

10.4.2 Planting Seedlings or Saplings from Local or Distal Genetic Sources

Although much is yet to be understood about the effects of planting *Rhizophora* propagules or saplings in a site that is far away from the germplasm source, even when planting the same species, current studies show that genetic diversity decreases toward higher latitudes and under isolation conditions (Sandoval-Castro et al. 2014; De Ryck et al. 2016; Ngeve et al. 2016). This decrease is due to the genetic attenuation (e.g., loss of unique alleles) and an increase in selfing. These findings suggest that genetic recovery of large impacted wetlands areas in tropical latitudes may require more than 30 years (Arnaud-Haond et al. 2009). Similarly, the effect of habitat fragmentation might not influence the genetic makeup of adult populations, although it can occur in cases of higher inbreeding in smaller populations (Hermansen et al. 2015). Perhaps a rule of thumb would be to use, if available, genetic resources from the nearest possible populations, such as transplanting wildings from nearest mangrove wetlands under good or optimal environmental conditions (Ellison and Fiu 2010).

10.4.3 Have Native Species Been Always Used in Restoration Programs?

R/R projects using exotic species in species-rich biogeographic regions have been recently reported in the scientific literature. For instance, the mangrove species *Sonneratia apetala* (originally from India, Sri Lanka, and the Bengal coastal region) has been used in the restoration of physically altered environments lacking natural propagule sources in China (Ren et al. 2008). Over the first decade, the growth performance of the mangrove species *S. apetala* was higher than those of the native species, *Rhizophora stylosa* and *Kandelia candel* (now *K. obovata*); and in some cases, *S. apetala* facilitated the recolonization of native mangrove species (Ren et al. 2008; Peng et al. 2012). However, due to the ecological risk of invasion at broader spatial scales, recent assessments are now recommending that restoration efforts should include competitive control mechanisms and removal of alien plant species once the populations of native species are established (Chen et al. 2013; Ren et al. 2009, 2014). Moreover, the use of exotic species in restoration programs started relatively recently (two decades ago) and was restricted to site-specific experiments. Unfortunately, the lack of adequate monitoring of multilevel performance measures makes it extremely difficult to infer whether these actions will sustain themselves without further human intervention and at higher ecological and economic cost.

The few experiments designed to assess the effects of exotic species on ecosystem functionality include evaluations of macrobenthic faunal communities (Tang et al. 2012; Leung and Tam 2013). These studies revealed that although the exotic mangrove species *S. apetala* seems to be innocuous to the macrobenthic fauna, its presence and dispersion could have negative impacts on other functional groups. For instance, afforestation of mudflats with alien species reduces the feeding ground for water birds (Leung and Tam 2013). Due to the lack of data and information together with an insufficient monitoring timeframe, including the lack of proper spatial and temporal replication, management plans aiming to regulate the use of exotic species and prevent adverse impacts to the estuarine ecosystem are yet to be implemented. Thus, a consensus regarding the use of exotic mangrove species as a good restoration practice remains to be evaluated.

10.5 Implementing R/R Projects in the Context of Climate Change: Carbon Markets and Greenhouse Emissions

R/R projects could be considered a long-term strategy to mitigate carbon emissions given the current estimates of potential carbon storage ("blue carbon") in mangrove wetlands (Donato et al. 2011; Caldeira 2012; Siikamäki et al. 2012). The assessment of carbon stocks in the wide range of mangrove ecotypes (sensu Lugo and Snedaker 1974) throughout tropical and subtropical latitudes confirm that mangrove forests are among the ecosystems with the highest C storage capacity per unit area (e.g., Mcleod et al. 2011; Donato et al. 2011; Alongi 2014; Lovelock et al. 2014; Adame et al. 2015; see Chap. 5). This storage capacity is due to slow decomposition and rapid organic matter accumulation through time in flooded soils. For example, soil carbon sequestration rates in mangroves growing in arid tropical coastal regions (Pacific coast of Mexico) range from 0.1 and 6.9 Mg C ha^{-1} $yr.^{-1}$ in the last 100 years (Ezcurra et al. 2016). However, actual emission rates of previously stored blue carbon into the atmosphere in deforested mangrove areas have not been directly and comprehensively assessed. For example, Kauffman et al. (2015) indirectly estimated a loss of 1464 Mg CO_2 equivalents per ha for the top 1 m soil depth when mangrove forests were converted to pastures in Tabasco, Mexico, representing seven and three times greater emissions than those reported for a tropical dry forest and a tropical forest in the Amazons, respectively. In that study, the carbon stock was lower in older (30-year) than younger (7-year) pasturelands previously occupied by mangroves, suggesting continuous loss to the atmosphere through time (Kauffman et al. 2015), especially when flooded soils are drained and exposed to fast aerobic decomposition (Couwenberg et al. 2010).

It is assumed that some of the carbon emitted could be sequestered again from the atmosphere after these impacted sites are restored; this response has been observed in mangrove forests where superficial soil horizons were similar to preserved forests after 35 years of mangrove tree planting or natural regeneration (Lunstrum and Chen 2014; Nam et al. 2016). Although more information is needed to evaluate the potential sequestration and storage in restored mangrove wetlands, studies suggest that R/R projects could be an efficient strategy to capture carbon from the atmosphere at a relatively low cost (Siikamäki et al. 2013;

Thomas 2014) considering the potentially high estimated economic values of carbon sequestration as an ecosystem service (e.g., Estrada et al. 2015; Jerath et al. 2016). However, adequate species selection and suitable (e.g., middle to upper intertidal) environments must be selected for successful mangrove restoration in contrast to the selection of unsuitable (e.g., lower intertidal) environments, as it has been the case in some coastal regions (Lewis et al. 2005; Primavera and Esteban 2008). Additionally, the economic and social dimension of carbon sequestration valuation and carbon market development require not only community-based mangrove management schemes to achieve restoration goals, but also that local governments are directly aligned to international economic incentives related to carbon markets in the context of climate change (Beymer-Farris and Bassett 2012; Jerath et al. 2016).

10.6 Global, Regional, and Local Perspectives in Mangrove R/R Programs: Beyond Planting Trees

10.6.1 Factors Controlling Long-Term Sustainability of Restored Mangroves

Mangrove R/R strategies have historically been scrutinized to identify both information gaps and operational pitfalls. Despite the broad geographic range of implemented mangrove restoration projects, an analysis of project outcomes from the 1800s until 1999 (Ellison 2000) indicated that the methods used are mainly based on planting of single mangrove species and that the primary focus remained on a silviculture-oriented approach (e.g., fuelwood, charcoal, Lewis 1982). Recently, a number of assessments of R/R practices and methods indicate a limited advance in improving R/R strategies and confirm that planting, rather than eliminating the stressors and assisting natural regeneration, remains the main strategy used worldwide (Bosire et al. 2008; Dale et al. 2014).

Effective mangrove restoration can only be achieved by eliminating environmental stressors, a strategy proposed more than 30 years ago (e.g., Cintrón and Schaeffer-Novelli 1983; Cintrón-Molero 1992). A stressor is any factor or situation that diverts potential energy flows that could be used for the system's own maintenance, stability, and resilience (Odum 1967; Lugo and Snedaker 1974; Twilley and Rivera-Monroy 2005). The ecosystem response to a stressor depends on its effect/impact on the system (e.g., physiological mechanisms, structure, and composition) that influence the recovery rates depending on the type, persistence, and synergy among natural and human-induced stressors (Lugo 1978; Lugo et al. 1981). If we consider that environmental stressors can impair the system's recovery capacity, it is important to prioritize ecological-based restoration strategies over single species planting (Lewis 2000).

Mangroves, as is the case for other wetlands, are flow-through ecosystems. Thus, an understanding of their ecology and hydrology is a critical step in designing successful mangrove restoration plans (Lewis et al. 2005). There are successful wetland restoration projects based on hydrologic restoration (Turner and Lewis 1997; Selvam et al. 2003; Miyagi 2013). In mangrove forests, the hydroperiod (flooding frequency, duration, and depth) regulates biogeochemical processes such as gas exchange (O_2 and CO_2) between plants and the environment, metabolic turnover rates, and the accumulation of sulfide in soil (Twilley and Rivera-Monroy 2005; Lugo and Medina 2014; see Chaps. 5 and 6). Mangrove forests are very sensitive to edaphic modifications, mainly due to shifts in substrate elevation relative to water level; and their ability to return to a more complex level of organization is strongly affected by the intensity and frequency of the stressor (Cintrón and Schaeffer-Novelli 1983). In fact, regrading sites to previous relative elevation is recommended for restoration projects and ignoring this step has led to numerous failures (Lewis et al. 2005 and references therein).

On a mangrove forest scale, the environmental gradient created by the microtopography sets ecological patterns relevant to restoration strategies such as species distribution in response to hydroperiod (Lugo and Snedaker 1974; Twilley et al. 1998; Twilley and Rivera-Monroy 2005; Flores Verdugo et al. 2007; Flores-de-Santiago 2017; see Chaps. 6 and 9), as well as to other regulators (salinity, sulfide, pH, redox potential) and resources (nutrients, light, space) (Twilley and Rivera-Monroy 2005). Moving up one level to the landscape scale, mangrove stands are nested within environmental settings (e.g., deltas, coastal lagoons, oceanic islands) and are necessarily subjected to environmental variability as a result of major changes in hydrology or sediment input and deposition rates (Twilley et al. 1998; Schaeffer-Novelli et al. 2005). Therefore, restoration strategies should not be limited to the local site, but also consider the interconnectedness with regional and global process (Twilley et al. 1998; Twilley and Rivera-Monroy 2005). This is particularly important when considering recurrent large-scale climate phenomena (e.g., El Niño Southern Oscillation) and changes triggered by events that can affect site-level management strategies as shown in large mangrove restoration projects in the Americas (Blanco et al. 2006; Rivera-Monroy et al. 2006; Rivera-Monroy et al. 2011). These hierarchical levels should be considered in mangrove R/R projects to capture the combined effects of geophysical, geomorphic, and ecological processes that control the mosaic and development of mangrove wetlands (Twilley et al. 1998).

In the context of adaptive management of natural resources, there is no "one-size-fits-all solution". Thus, the studies discussed here underscore the constraints and opportunities for successful mangrove restoration. A large body of evidence shows that neglecting ecological baselines is the main factor hindering effective restoration initiatives worldwide, and when appropriate hydrological conditions are restored, mangroves can fully develop and function as natural stands with no further human intervention required (Twilley et al. 1998; Ellison 2000; Lewis et al. 2005; Rivera-Monroy et al. 2006; Lewis and Gilmore 2007; Bosire et al. 2008; Rovai et al. 2012; Rovai et al. 2013; Dale et al. 2014).

10.6.2 Monitoring the Functionality of Restored Mangroves

A number of variables have been proposed to assess mangrove restoration outcomes (Twilley and Rivera-Monroy 2005; Bosire et al. 2008; Dale et al. 2014). Issues related to monitoring of restoration projects are coupled to the economic priorities, timeframe, and diversity of methods. In addition to the lack of standardized methods to monitor mangrove restoration outcomes, assessments often limit their analyses to one specific indicator species or group. This approach does not provide an overview of the functionality, which should reflect the system's capacity to maintain an effective energy flow as well as structural and functional properties considering the multiple pathways and mechanisms by which ecological services are delivered (see Chaps. 8 and 9). Again, because environmental stressors can affect the target ecosystem at different levels of organization, it is important to define and consider multiple functional indicators as performance measures in mangrove restoration strategies (Twilley and Rivera-Monroy 2005).

Most projects are short in duration (<3 years) and do not devote funding for adequate maintenance and monitoring periods (Rivera-Monroy et al. 2006; Lewis et al. 2005; Roderstein et al. 2014). Periods ranging from 2 to 16 years (Bosire et al. 2008 and references therein) and 10 to 50 years (Crewz and Lewis 1991; Lugo 1992; Shafer and Roberts 2008; Luo et al. 2010; Rovai et al. 2012, 2013) may be required to fully ascertain mangrove restoration success based on faunal diversity and vegetation structural (e.g., basal area, species diversity) as well as functional (e.g., net primary productivity, carbon storage, resilience) properties. Based on these studies, we recommend that the monitoring and maintenance of R/R projects cover at least 5 years after project implementation. For example, one functional ecosystem property might be an assessment of the abundance and diversity of fish populations to ensure that both keystone and of economic important species to return to reference condition within 5 years (Lewis and Gilmore 2007). However, depending on the intensity of the damage, ecosystem functionality in wetlands can take over a century to be restored. Moreno-Mateos et al. (2012) found that only 7 out of the 124 references used in their analysis corresponded to mangrove ecosystems with restoration ages ranging from 22 months to 14 years. Appropriate spatial and temporal replication incorporating key and multilevel functional indicators is needed to draw conclusions at a range of population, community, or ecosystem dynamics.

The key set of functional indicators used as performance measures to evaluate the success of a mangrove R/R projects should include physiological and structural attributes as response variables to gradients of environmental factors. These include resources (light and nutrients), regulators (salinity, pH, soil sulfide, redox potential), and hydroperiod (water depth, frequency and duration of flooding; Twilley and Rivera-Monroy 2005; Rivera-Monroy et al. 2011) that account for the main stressors to mangrove development and long-term sustainability. The performance measures should provide information about the restoration trajectory of the ecosystem at specific sites, thus describing the degree and timing of changes anticipated in both structural and functional characteristics and enabling adaptive management actions. The integration of multilevel performance measures, including abiotic and biotic compartments, allows for the identification of cause and effect relationships, documenting the effectiveness of restoration strategies and testing assumptions concerning the stressors that are associated with the system's degradation (Twilley and Rivera-Monroy 2005).

The difficulty and utility of monitoring performance measures in R/R mangrove projects can be illustrated by some examples. The trajectories of vegetation and soil properties of a mangrove rehabilitation project by reconnecting water bodies in the Ciénaga Grande de Santa Marta lagoon complex (Colombia), one of the largest restoration efforts ever implemented (mangrove area: 99 km^2) in the AEP region, indicated a reversal of the initial success (Rivera-Monroy et al. 2006). After a successful response to the large spatial scale hydrological modifications by widespread natural regeneration in 1996 and 1999, the mangrove forest in the region began to show potentially irreversible deterioration due to a lack of a long-term economic strategy that included maintenance of the originally dredged channel to maintain freshwater exchange between the mangrove die-back areas and the natural creeks and estuary (Roderstein et al. 2014). Similarly, extensive canal digging toward river and tidal water sources was carried out in the Pichavaram mangrove area in South India (Selvam et al. 2003) that resulted in the recovery of an extensive area (~300 ha), visible form space (Fig. 10.3) and originally lost due to clear-cutting and soil subsidence. In contrast to the case in Colombia, canal maintenance to avoid siltation is currently performed in this location with the participation of local communities and adequate technical and economic support. Another successful hydrological rehabilitation implemented at both Términos Lagoon and Jaina Island in Campeche, Mexico, has promoted a maintenance-free mangrove restoration areas, enhancing further recovery of vegetation cover and ecosystem services at low investment cost (Agraz-Hernández and Arriaga 2010; Agraz-Hernández et al. 2015).

Another R/R project in the AEP region (Brazil) coupled structural and physiological properties of mangrove vegetation with edaphic conditions to assess the success of different mangrove restoration projects (Rovai et al. 2012, 2013). Those studies demonstrated that although restoration sites did not differ from reference stands in terms of forest structural characteristics, there was impaired photosynthetic performance due to stress caused by soil elevation changes and heavy metal inputs, thus making it difficult to infer possible restoration trajectories. This study shows the advantage of using hierarchical performance measures in restoration strategies, since ecological responses at lower levels of organization may anticipate threats to the system's structure, and reveal critical trends in ecosystem development (Twilley et al. 1998). For example, nitrogen fixation, a functional ecosystem service, has been used successfully as an indicator of success in reforested and naturally regenerated mangroves in Mexico (Vovides et al. 2011)

The mangrove fauna plays indeed a significant role in the functioning of mangrove ecosystems and can thus be a useful indicator of integrity of managed mangroves (Lewis 1982; Lewis and Gilmore 2007; Bosire et al. 2008; Cannicci et al. 2008; Ellison 2008; see Chaps. 3 and 6). The assessment of trends in recolonization of epibiotic, macrobenthic, and sediment-infauna communities and the distribution patterns of benthic macrofauna, fish, and shrimp in R/R stands across the world show significant and short-term response (Bosire et al. 2008). Although selected biota groups seem to be more responsive to mangrove restoration, there are still only few studies on the spatial and temporal changes in biodiversity in restored mangroves (see Chap. 3); the scant information on age range, species composition, and hydroperiod in restored sites make generalizations highly uncertain.

We underscore the premise that there is no "*one-size-fits-all*" solution in restoration ecology. Mangrove restoration monitoring programs should include as many indicators as the budget and timeframe allow and may be amended as required by the specific goals of the initial restoration plan (i.e., adaptive management). An empirical framework that models mangrove restoration trajectories by integrating indicators that reflect ecological processes at different time and spatial scales is strongly recommended (Twilley and Rivera-Monroy 2005). This framework should highlight the opportunities and constraints of monitoring programs and operationally define the basic performance measures that should assist in the advancement of mangrove restoration in all biogeographic regions.

10.7 Future Directions: Lessons Learned and Research Agenda

To advance mangrove R/R efforts worldwide, data sharing and exchange of experiences should be promoted and orchestrated at a comparative level in different geomorphological settings and latitudes within and across the IWP and AEP regions. Below we discuss four proposed R/R protocols that could be considered as a general research agenda to be implemented given the inclusion of critical ecological processes and operational tasks to improve the success of mangrove R/R projects. A critical step is to develop a decision tree that could serve as a guide to optimize the use of available funding in the development, implementation, and monitoring of R/R projects (Fig. 10.4). Future protocols should list clear objectives, goals and deadlines, a robust research agenda that include specific questions (and hypotheses) based on sound ecological theory, and reliable monitoring practices that maximize the usefulness of current and past R/R project experiences (Ellison 2000; Bosire et al. 2008). We propose that these initial steps could be based on the current available protocols for mangrove R/R projects that could be further developed under the specific conditions at each individual location.

The first, and most commonly used protocol, emphasizes that if natural recolonization after site selection or improvement (secondary succession) does not occur or is too slow (Field 1996b; Primavera et al. 2012) a mangrove nursery should be set up as sites for possible planting or out-planting (sensu Primavera et al. 2012) are identified primarily based on the current lack of mangrove cover or on evidence of their historical cover loss. A very large part of this protocol is devoted to successful nursery practices including seed or seedling collection and planting, and the use of some natural seedlings transplants (i.e., wildlings) from healthy forests (Field 1996a, b; Primavera et al. 2012). However, this approach does not emphasize steps to clearly identify the drivers causing mangrove mortality in the first place or factors hindering the lack of natural mangrove regeneration and growth in the proposed planting site. Indeed, Samson and Rollon (2008) documented the failure of a similar mangrove restoration protocol implemented over 40,000 ha during a 20-year period in the Philippines.

The second protocol, called Ecological Mangrove Rehabilitation (or Restoration) (EMR, Lewis and Marshall 1998; Stevenson et al. 1999), was initially described as a five-step process (Brown and Lewis 2006), and later expanded to six steps (Lewis 2009, which have been implemented at a number of sites around the world (Lewis and Brown 2014). For example, Rey et al. (2012) described the success of this "hydrologic restoration" approach (Lewis et al. 1985; Brockmeyer et al. 1997; Turner and Lewis 1997) when implemented in 12,605 ha out of the original 16,185 ha mangrove area that was diked and filled in the East Coast of Florida, USA. The localities were hydrologically reconnected, breached, or restored for the rehabilitation of formerly diked mosquito control impoundments. Nursery establishment and planting of mangroves is only used under this protocol if natural propagule recruitment does not occur after site preparation and monitoring (i.e., "propagule limitation"; Lewis et al. 2005). Thus, planting of mangroves is not precluded under EMR, but is based upon a documented lack of natural establishment of propagules (i.e., secondary succession).

The six steps of EMR (sensu Lewis and Brown 2014) are as follows.

1. Understand the autecology (individual species ecology) of the mangrove species at the site, the patterns of reproduction, propagule distribution, and successful seedling establishment.
2. Understand the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species.
3. Assess the modifications of the previous mangrove environment that currently prevent natural secondary succession.
4. Select appropriate mangrove restoration sites through application of Steps 1–3. These steps increase the likelihood of success in restoring a sustainable mangrove forest ecosystem, and are cost-effective given the available funds and manpower to implement projects, including adequate monitoring to assess quantitative goals established prior to restoration. This step includes resolving land ownership/use issues necessary for ensuring long-term access to and conservation of the site.
5. Design the restoration program at appropriate sites selected in Step 4 to initially restore the appropriate hydrology and utilize natural mangrove propagule recruitment for plant establishment.
6. Only utilize actual planting of propagules, collected seedlings, or cultivated seedlings after determining through steps 1–5 that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization,

or rate of growth of saplings established as quantitative goals for the restoration project.

In a third protocol proposed for mangrove restoration, Bosire et al. (2008) present a ten-step flow diagram that expands even further on the six steps from EMR and that can be used as a decision tree for restoration programs (Fig. 10.4). These steps integrate the essential procedure of consulting with the local communities (Step 4) and post-plantation phases, similar to those discussed by Mukherjee et al. (2015). The step 9 in this approach underscores the need to monitor ecological succession in all main biological groups as well as resource use by local people, which is a much-desired step toward functional integrity when the goods and services mangrove forest provide directly benefit local communities (see Chap. 8).

The fourth protocol explicitly adds economic and social issues and emphasizes the use of local ecological knowledge to substitute for baseline information gaps (e.g., detailed reference site topography and hydrology) (Biswas et al. 2009). This approach is akin to "community based rehabilitation" (Primavera et al. 2012) or "community based ecological mangrove rehabilitation" (CBMER) (Brown and Lewis 2006; Lewis and Brown 2014) and was tested in four R/R projects (Biswas et al. 2009) with "minimum" success for two projects and "uncertain" success for the other two. A major problem when relying on community support to implement R/R project is that funding for the participation of volunteer planting and monitoring is limited, thus "[…] it is not uncommon that the whole effort collapses as soon as the external support is withdrawn" (Biswas et al. 2009; p. 379). This limitation does not invalidate the general approach, but introduces a potential problem by not emphasizing enough ecological engineering considerations such as the assessment of hydrology and topography as important initial step in data gathering efforts before project implementation. An integrated approach similar to that of CBEMR have been implemented in Indonesia relying on community-based data gathering on hydrology and topography, underlining adequate funding and training as key to the overall success of that rehabilitation project (Brown et al. 2014).

Finally, it is paramount to include in any monitoring and reporting program both spatial and temporal replication (Underwood 1997), including reference sites within the restoration site or nearby (see Rovai et al. 2012, 2013 for a detailed spatial and built-in time sampling strategy). In addition, the program should consider establishment of long-term research plots and multiple sequential research programs when and where possible. The results, whether successful or not, should be published, as it is the only sound alternative to learn from past experiences, and further advance mangrove restoration ecological science based on the actual successes and failures of the four protocols previously described. We urge the continental level implementation of these guidelines to advance international initiatives aimed to protect and conserve one of the most productive and threaten coastal ecosystems in the world.

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