GUIDANCE DOCUMENT FOR REEF MANAGEMENT AND RESTORATION TO IMPROVE COASTAL PROTECTION

Recommendations for Global Applications based on lessons learned in Mexico

2018

CALINA ZEPEDA-CENTENO, ISMAEL MARIÑO-TAPIA, ELIZABETH MCLEOD, ROSA RODRÍGUEZ-MARTÍNEZ, LORENZO ÁLVAREZ-FILIP, ANASTAZIA BANASZAK, MIREILLE ESCUDERO-CASTILLO, RODOLFO SILVA-CASARÍN, EDGAR MENDOZA-BALDWIN, MICHAEL BECK, AND ELIZABETH SHAVER.

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Limones Reef, Puerto Morelos Reef National Park / © Lorenzo Álvarez-Filip

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Aerial view from Puerto Morelos, Quintana Roo / © Lorenzo Álvarez-Filip

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CONTENT

MAPS, FIGURES, TABLES (TOC) V
ABBREVIATIONS, ACRONYMS VI
GLOSSARY OF TERMS VII
EXECUTIVE SUMMARY VIII

CHAPTER ONE
INTRODUCTION 1
Coral Reefs: A Natural Defense 2
Reefs Under Threat 4
Reef Restoration as a Risk Reduction Strategy 5

CHAPTER TWO
OCEANOGRAPHIC, ECOLOGICAL AND GEOLOGICAL FACTORS THAT DRIVE THE COASTAL PROTECTION CAPACITY OF REEFS 7
Reef coastal protection linked to wave breaking processes 9
Reef profile shape 9
Reef physiography and configuration 11
Reef coastal protection related to friction and rugosity 12
Reef coastal protection by supporting sand-generating organisms (fish and invertebrates) 14

CHAPTER THREE
FACTORS LINKED TO ANTHROPOGENIC ACTIVITY THAT REDUCE THE COASTAL PROTECTION CAPACITY OF REEFS 15
Effects of climate change (large scale effects) 15
Increasing ocean temperatures and acidification 15
Sea Level Rise 16
Effects of local stressors on reef degradation 16
Threats facing coral reefs and coastal communities in the Yucatan Peninsula: The case of Quintana Roo 17

CHAPTER FOUR
ASSESSING RISKS AND IDENTIFYING RISK REDUCTION SOLUTIONS ON COASTLINES 19
Assessing Coastal Protection Service of Reefs

CHAPTER FIVE
REEF RESTORATION AND OTHER COASTAL EROSION MITIGATION MEASURES 27
How to meet ecological and risk reduction objectives? 27
Ecological Reef Restoration 28
Asexual propagation 28
Sexual Propagation 29
Benefits and Limitations of Asexual and Sexual Propagation Methods 30

CHAPTER FIVE

Physical Reef Restoration and Physical Mimicry (Concrete Artificial Reefs and Breakwaters) 31

Benefits and Limitations of Asexual and Sexual Propagation Methods 31

Physical Mimicry (Concrete Artificial Reefs and Breakwaters) 32

Benefits and Limitations of Physical Reef Restoration and Physical Mimicry Methods 35

Costs associated with reef restoration 36

Ecological Reef Restoration Costs 36

Physical restoration costs 36

CHAPTER SIX

MANAGEMENT MUST HELP SUPPORT COASTAL PROTECTIVE SERVICES 37

Threats to be addressed for restoration success 38

Controlling Pollution 38

Eliminating overfishing/destructive fishing 39

Managing coastal development 40

Managing tourism impacts 40

Adapting to climate change 41

Promoting marine protected areas (MPAs) 41

Management, maintenance and monitoring of a restoration site 43

Management of a restoration site 43

Maintenance of a restoration site 43

Monitoring of a restoration site 44

CHAPTER SEVEN

Project Planning and Key Consideration 46

Project Planning 46

CHAPTER EIGHT

Recommendations 48

References 50

MAPS, FIGURES, TABLES (TOC)

TABLE 1	Threats to Coral reefs	**4**
FIGURE 1	Schematic effects of the bathymetric profile of barrier reefs on wave attenuation at the beach. This does not consider energy loss by friction and turbulence.	**9**
FIGURE 2	Schematic effects of the 2D bathymetry on wave attenuation at the beach. This is a stretch of coast in Quintana Roo, Mexico (from Punta Nizuc to Puerto Morelos). The arrows represent the main direction of wave approach.	**12**
FIGURE 3	Cross-reef bathymetric profile at a Caribbean barrier reef (Puerto Morelos), and associated benthic cover.	**12**
FIGURE 4	**a.** Estimates of roughness (in m) obtained from the filtered small scale bathymetric measurements as 4σ. **b** Bathymetry filtered from wave effects measured with a single beam echo-sounder and differential GPS. **c.** Larger scale bathymetry of the transect presented in b., obtained with supervised classification of satellite data (source: CONABIO).	**22**
FIGURE 5	**a.** Offshore wave climate from 2005 to 2016 for the northern Caribbean (NOAA buoy 42056). Wave rose for wave height. **b.** Wave propagation for the Puerto Morelos region showing in colors wave heights, and bathymetric isobaths of 20 m and 1.5 m marked in solid lines. Reefs are visible offshore.	**23**
FIGURE 6	Volume of sand present on the beach per meter alongshore	**24**
FIGURE 7	Wave energy flux comparison between 8 m depth (dashed lines) and close to shore (solid lines) under different scenarios of reef roughness, mimicking restoration actions. Kw values indicate the roughness increments close to shore.	**25**
TABLE 2	Overview of breakwater concrete armor units (after Muttray and Reedijk 2008).	**32**
FIGURE 8	Reef ball submerged breakwater for shoreline stabilization in Dominican Republic (1.2-1.3 m high, in water depths of 1.6-2.0 m) (Harris 2009).	**33**
FIGURE 9	WADs used in the construction of a submerged breakwater located in the Mexican Caribbean, specifically in Puerto Morelos, outside the protected area (Silva et al. 2016).	**33**
FIGURE 10	Artificial submerged dike composed of prefabricated 2B concrete blocks (Bilyay et al. 2017). Coral reef restoration costs	**34**
TABLE 3	Coral reef restoration costs (Environmental Protection Agency 2012).	**36**

ABBREVIATIONS, ACRONYMS

May or may not be included based on how prevalent they are used in text

ADCP	Acoustic Doppler Current Profiler
BETI	Beach Erosion Tendency Index
CARMABI	Caribbean Research and Management of Biodiversity
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CENAPRED	National Center for Disaster Prevention – Mexico. Centro Nacional de Prevención de Desastres (in Spanish).
DGPS	Differential Global Positioning System
ESE	East South East
GDP	Gross Domestic Product
GPS	Global Positioning System
ICZM	Integrated Coastal Zone Management
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
LIDAR	Laser Imaging Detection and Ranging
LCS	LOW-CRESTED STRUCTURES
MAR	Mesoamerican Reef System
MARPOL	International Convention for the Prevention of Pollution from Ships
MPA	Marine Protected Area
MSL	Mean Sea Level
N	North
NMFS	National Marine Fisheries Service, USA
NOAA	National Oceanic and Atmospheric Administration
NNE	North-northeast
OPRC	London Convention and Protocol and the International Convention on Oil Pollution Preparedness, Response, and Cooperation
PMRNP	Puerto Morelos Reef National Park
REF/DIF	Refraction-diffraction model
RZ	Replenishment Zones
SECORE	SECORE International
SWAN	Simulating Waves Nearshore Model
UNEP	United Nations Environment Programme
UTM	Universal Transverse Mercator Coordinate System
UNAM	Universidad Nacional Autónoma de México
WADs	Wave attenuation devices
WAPO	Wave propagation model
WAVES	Wealth Accounting and the Valuation of Ecosystem Services

GLOSSARY OF TERMS

ASEXUAL PROPAGATION — The process of cutting/pruning/ fragmenting a large coral into smaller pieces called "fragments."

CLONE — Exact genetic copy of parent colony.

COLONY — A coral unit with the typical *Acropora* morphology; with an attachment to the bottom and a complex multi-branch canopy.

FRAGMENT — A section of a coral colony branch used for nursery propagation and outplanting.

GENETIC DIVERSITY — The number of variants ("alleles") of each gene that are present in the population and how these variants are distributed among individuals.

MITIGATION — The reduction or control of the adverse environmental effects of a project, including restitution for any damage to the environment through replacement, restoration, or creation of habitat in one area to compensate for loss in another.

POPULATION ENHANCEMENT — Addition or outplanting of nursery-grown coral fragments and colonies to wild stocks.

PUCK — A cement disk, cone or pyramid used to secure fragments to propagation platforms during the nursery stage or to the reef substrate for outplanting activities.

REHABILITATION — The act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been diminished or lost, or the substitution of alternative qualities or characteristics to those originally present with the provision that they have more social, economic or ecological value than that which existed in the disturbed or degraded state.

RESILIENT CORALS — Coral colonies or populations that withstand disturbance without undergoing significant mortality and/or that recover quickly from a disturbance.

RESTORATION — The act of bringing a degraded ecosystem back to, as closely as possible its original condition.

WAVE PROPAGATION — Any of the ways in which waves travel.

EXECUTIVE SUMMARY

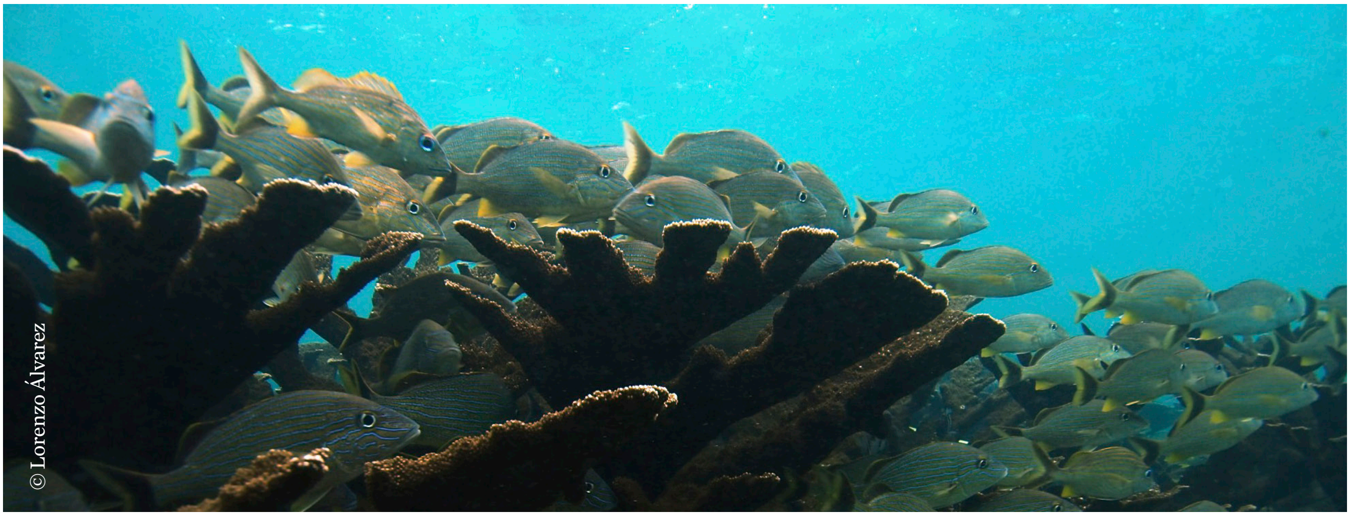
This guidance document aims to provide a review and recommendations on reef management and restoration for risk reduction. It synthesizes evidence of the role coral reefs play in coastal protection and the reduction of risks during disasters. It presents ecological, geological, and oceanographic factors that contribute to the coastal protection capacity of reefs, and the factors that reduce this capacity. It also presents an array of risk reduction solutions to restore reef protection services, and management approaches that can help support its coastal protection values. Finally, it provides a series of recommendations for assessing when, where, and how to apply reef restoration for risk reduction.

This guidance document is not intended to provide detailed practical advice on how to carry out reef restoration, neither to provide detailed techniques and methods.

CHAPTER ONE
INTRODUCTION

The impact of rising sea level, combined with more frequent and severe storms, threaten coastlines and coastal communities worldwide. Extreme storm surges can raise local sea levels several meters through severe wind, waves, and atmospheric pressure conditions (Resio and Westerink 2008). The exposure of people and assets to coastal risks has grown rapidly, and this trend is expected to continue (Wong et al. 2014). The loss of coastal habitats that offer protection from shoreline hazards, land subsidence, and the accelerated pace of coastal development and population growth are increasing the number of people and properties at risk. For example, a recent global analysis projected a population growth in the low-elevation coastal zone from 625 million (year 2000) to 1.4 billion people by 2060 (Neumann et al. 2015). Thus, the lives and wellbeing of over a billion people are at risk (Sheppard et al. 2005).

Flooding and erosion also cause significant economic impacts. For example, in the last 30 years, the amount of the world's gross domestic product (GDP) annually affected by tropical cyclones has increased by more than US$1.5 trillion. Insurers alone have paid out more than US$300 billion for coastal damages from storms in the past 10 years, with payments often going towards rebuilding similar coastal infrastructure that is equally vulnerable to coastal storms and flooding (World Bank 2016). By 2050, flood damage in the world's coastal cities is expected to cost US$1 trillion a year (Hallegatte et al. 2013).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CORAL REEFS: A NATURAL DEFENSE

The economic value of coral reefs globally is an estimated

$9.9 trillion USD

Costanza et al. 2014

Coral reefs cover less than 1% of the Earth's surface, yet they harbor 25% of all marine fish species (Burke et al. 1998). Coral reefs create highly diverse and productive habitats that provide key ecosystem and environmental services, including food, shelter, livelihood, medicine, and cultural values to billions of people globally (Spalding et al. 2001). Reefs are a source of employment and income from tourism and fishing. Over 1 billion people depend on reefs for protein; millions are employed in reef-dependent industries in Asia alone, including tourism and fisheries (Whittingham et al. 2003; Spalding et al. 2017). The economic value of coral reefs globally is an estimated $9.9 trillion USD (Costanza et al. 2014). Of critical importance is the role that reefs play in protecting coasts from tropical storms and hurricanes, and in generating sand for beaches. However, the persistence of these goods and services depends upon the ecological stability of these ecosystems (Alvarez-Filip et al. 2013; Micheli et al. 2014).

A growing body of evidence highlights the role of nature-based solutions for risk reduction (i.e., enhancing communities of coral reefs, salt marshes, and mangroves to reduce flooding and erosion from storms and sea-level rise; Renaud et al. 2013; Ferrario et al. 2014; Spalding et al. 2014a,b). Most of these studies have focused on coastal wetlands that reduce the impacts of flooding and erosion, yet, the role of coral reefs has recently been acknowledged in reducing vulnerability (Ferrario et al. 2014; Beck et al 2018). Vulnerability encompasses sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC 2014). It increases with poverty, scarce resources, and volatile or unstable socio-economic conditions, because these affect the ability of coastal communities to cope with near-term hazards and to adapt to longer-term hazards (Birkmann et al. 2013). The vulnerability of coastal human communities in the Caribbean is likely to increase in response to projected increases in the intensity of Atlantic Ocean hurricanes and sea levels (Hopkinson et al. 2008). Their vulnerability is likely to be compounded by the reduced wave dissipation function of structurally simpler reefs.

Healthy coral reefs reduce vulnerability by a suite of ecosystem services including coastal protection, food security, and income to coastal communities affected during natural disasters and economic hardships. Globally, up to 197 million people live below 10m elevation and within 50km of a reef and may receive risk reduction benefits from reefs (Ferrario et al. 2014). By reducing exposure to strong waves, flooding and erosion, and by providing social, economic, and ecological benefits before, during and after catastrophic events, coral reefs act as a first line of defense for coastal communities. For example, it has been estimated that the countries with the most to gain from reef management in order to reduce sea-level associated risks are Indonesia, Philippines, Malaysia, Mexico, and Cuba, with an annual expected flood savings exceed $400 M for each of these nations (Beck et al 2018).

In the context of disaster risk management, exposure refers to the people, property and resources that may be affected by coastal hazards, including storms, storm surges, floods and sea-level rise. Exposure is measured by calculating the probability of occurrence of coastal hazards (e.g., number and severity of hurricanes) and the people and property that would be affected. Coral reefs reduce exposure to coastal hazards by attenuating the wave energy reaching the shoreline by an average of 97% (Ferrario et al. 2014). Reefs are natural structures that dissipate wave energy at the seaward edge of the reef and through bottom friction and turbulence as waves move across reefs (Gourlay 1994, 1996a, b; Hardy and Young 1996; Wolanski 1994; Sheppard et al. 2005; Gallop et al. 2014). In addition to reducing wave energy, reefs also reduce storm surge and maintain shoreline elevation, naturally protecting coasts from erosion and flooding by supplying and trapping sediment found on adjacent beaches. In many areas, land has been created from sediments derived directly from coral reefs, often shaped into beaches and islands by storms and sometimes enhanced by windblown sediments (Woodroffe 2008). Unlike other coastal habitats, which principally trap sediments, like mangroves, coral reefs generate and replenish sediments (Woodroffe 1992; Milliman 1993).

Coral reefs can provide comparable wave attenuation benefits to artificial defenses, can be cost effective, and can replace or complement engineered solutions to increase the resilience of coastal populations (Simard et al. 2016). Critical to their ability to function as breakwaters is the ability of coral reefs to generate massive amounts of carbonate structure, which allows them to keep pace with sea level. While some scientists predict that reefs can keep up with predicted rates sea-level rise under low emissions scenarios over the next century (van Woesik et al. 2015), others warn that rapid sea-level rise, in combination with reduced net calcification from ocean warming and acidification, may result in reefs drowning (Field et al. 2011; Anthony 2016). If reefs remain healthy, they can provide significant coastal protection benefits, unlike artificial breakwaters that require significant maintenance costs and may increase erosion (Blanchon et al. 2010). However, the combined impacts of climate change (e.g., increasing ocean temperatures, resulting in mass bleaching events, increases in sea level, and more acidic waters; IPCC 2014) and human stressors will reduce the protection that coral reefs provide (Adger et al. 2005; Sheppard et al. 2005).

Coral reefs can provide comparable wave attenuation benefits to artificial defenses, can be cost effective, and **can replace or complement engineered solutions to increase the resilience of coastal populations.**
Simard et al. 2016

REEFS UNDER THREAT

Coral reefs worldwide are threatened with overfishing, pollution, coastal development, habitat degradation and climate change (Burke et al. 2011; Souter and Wilkinson 2008; De'ath et al. 2012; Table 1). The threats of climate change and ocean acidification loom increasingly ominously for the future, but local stressors including an explosion in tourism, overfishing, and the resulting increase in macroalgae have been the major drivers of the catastrophic decline of Caribbean corals up to the present (Jackson et al. 2014). While overfishing receives considerable attention from reef managers, consideration of the problems associated with coastal development and resultant pollution is largely neglected and underfunded (Wear 2016). Despite the collective efforts of many conservation organizations and governments to protect reefs, coral cover continues to decline: 43% to 22% in the Indo-Pacific (from 1980s-2003; Bruno and Selig 2007); 50% to 14.3% in the Caribbean (Jackson et al. 2014; Gardner et al. 2003; Williams et al. 2015); and 28% to 17% in Australia (from 1985–2012; De'ath et al. 2012; AIMS Long Term Monitoring Program).

THREAT TYPE	DEFINITION
Overfishing and destructive fishing	Includes harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons.
Coastal development	Includes coastal engineering, land-filling, runoff from coastal construction, sewage discharge, and impacts from unsustainable tourism.
Watershed-based pollution	Includes erosion and nutrient fertilizer runoff from agriculture delivered by rivers and coastal waters.
Marine-based pollution and damage	Includes solid waste, nutrients, and toxins from oil and gas installations and shipping; and physical damage from anchors and ship groundings.
Thermal stress	Includes warming sea temperatures, which can cause widespread or "mass" coral bleaching and increase coral disease.
Ocean acidification	Increased carbon dioxide concentrations. Acidification can reduce coral growth rates and make them more susceptible to breakage from storm impacts.
Sea level rise	Increase in global mean sea level because of an increase in the volume of water in the world's oceans.

TABLE 1 | Threats to Coral reefs (Burke et al. 2011).

Degraded reefs are less able to provide benefits to adjacent coastal communities. For example, reefs that are degraded or unhealthy may lose their height and complex three-dimensional structure, and have trouble keeping pace with changing environmental conditions. As the water depth over the reef increases, the reef is less effective at reducing wave energy and preventing erosion, and the risk of coastal damage increases. If reef degradation continues, coastal communities will be exposed to increasing wave energy and coastal hazards of inundation and shoreline erosion (Sheppard et al. 2005) and will be less able to reap the benefits that coral reefs provide.

Although dissipation of wave energy by reefs is clearly visible (in waves breaking on reef crests), wave attenuation often goes unnoticed until a reef is degraded to the point that the resulting wave energy increases coastal erosion. In many tropical nations, including Mexico and Indonesia, there are inferred relationships between increases in coastal development, reef degradation and investments in artificial defenses, but only a few direct studies on causality. Further, few scientific publications quantify the impacts of degraded coral reefs on adjacent beaches and coastal infrastructure (Knight et al. 1997; Sheppard et al. 2005; Moran et al. 2007, Ruiz de Alegría et al. 2013, Franklin et al. 2018). The lack of awareness of the protective role of coral reefs, and the difficulties in visualizing reef degradation, pose urgent challenges and may exacerbate both the pace of reef degradation and the increase in coastal risk.

REEF RESTORATION AS A RISK REDUCTION STRATEGY

Despite growing development pressures and climate change projections, there is reason for optimism. The effects of temperature and sea-level rise are species- and site-specific (Anthony et al. 2011; Hughes et al. 2012; Barshis et al. 2013). Many of the direct drivers of reef degradation, such as poor water quality, overfishing and sedimentation, can be mitigated through improved local management efforts (Mumby et al. 2007; Maina et al. 2013). Evidence suggests that reefs are more resilient to large-scale disturbances, such as bleaching and storm damage, when local threats are reduced through effective management (Carilli et al. 2009; Maina et al. 2013). The effective management of coral reefs is essential to maintaining the suite of benefits that they provide. Reducing threats to coral reefs, such as overfishing and poor water quality, and establishing marine reserves, can directly benefit reefs and maintain their shoreline protection services. In areas with degraded reefs, a key component of effective management is reef restoration.

Coral reef restoration is the process of assisting the recovery of a coral reef ecosystem that has been degraded, damaged, or destroyed (Edwards and Gomez 2007). Restoration efforts are designed to assist the natural recovery of reefs. If existing stressors (e.g., pollution) are not addressed, then restoration efforts will not be successful. Therefore, management efforts to control existing stressors are essential prior to initiation of restoration efforts.

Ecological restoration may include both passive and active restoration strategies. Passive restoration involves removing anthropogenic stressors that are impeding natural recovery, such as promoting herbivory and reducing land-based stressors on coral reefs. These actions are often implemented as part of broader **fisheries management, watershed management, or coastal zone management strategies.** Active reef restoration includes direct interventions that speed up recovery. It may include re-attachment of dislodged biota, coral gardening, transplantation of corals and other biota to degraded areas, or substrate stabilization.

Coral restoration objectives differ, depending on management needs. A common objective is to improve a degraded reef's ecosystem structure and function. Others may include restoring biodiversity, species biomass, and productivity. Coral reef restoration may also be implemented to restore key ecosystem services, such as coastal protection, especially if the physical structure of the reef has been damaged.

Restoration for coastal protection, however, is less common than restoration to support other reef benefits, despite evidence supporting its cost effectiveness (Ferrario et al. 2014). Scientists have compared the cost effectiveness of coral reef restoration to the building of traditional breakwaters and so far, demonstrates that the former is significantly cheaper and more cost effective (Ferrario et al. 2014). Reef restoration may provide a more sustainable solution to provide coastal protection, than construction of "grey infrastructure" such as seawalls (CCRIF 2010; Fabian et al. 2013; Ferrario et al. 2014).

Three aspects must be taken into account when considering reef restoration as a risk reduction strategy: a) The time required for restoration, since these ecosystems grow, mature and regenerate depending on various factors, consequently, the ecosystem services they provide are variable and not constant; b) The area of influence is very broad, going beyond the area in which the corals develop, and; c) Because coral reefs are living structures, the associated uncertainties are greater than those associated with conventional structures. However, when coral recovery is feasible, the benefits are greater than with conventional structures, and the economic costs involved are lower.

A management focus on coral reefs for risk reduction will require new collaborations between conservation, coastal engineering, coastal tourism industry, and impacted communities. Conservation organizations are increasingly recognizing the importance of focusing conservation efforts where people live (as opposed to remote and pristine areas) (Kareiva et al. 2012). Effective management and restoration of coral reefs for protective services could meet conservation, resource management and disaster risk reduction objectives simultaneously, while providing additional multiple socio-economic benefits to millions of people along the world's coastlines. Such efforts are more likely to be effective when local communities and social and cultural values are incorporated into management. Finally, incorporating nature-based principles (e.g., the biomorphology and geohydrology of the existing reef, existing and potential natural values) into the design of restoration projects can potentially yield greater benefits (Waterman 2008).

CHAPTER TWO

OCEANOGRAPHIC, ECOLOGICAL AND GEOLOGICAL FACTORS THAT DRIVE THE COASTAL PROTECTION CAPACITY OF REEFS

Oceanographic, ecological and geological factors act synchronously and with intricate interactions that affect the capacity of coral reefs to provide coastal protection. Therefore, it is difficult to make a clear distinction between these. A key feature of the coastal protection benefit of reefs is derived from their ability to attenuate wave energy. This is achieved by considering the oceanographic factors, which provide the most immediate response (O [seconds – months]), the ecological components with longer response times (O [months-years]) and the geological factors which act over hundreds to millions of years.

Reefs protect the coast by reducing wave height (generating wave breaking and increasing friction, which is a function of reef rugosity), and by supporting sand-generating biomass (fish, echinoderms and calcifying macroalgae). The elements that generate wave breaking are primarily linked to the large-scale bathymetric shape of the reef, whereas those related to friction or sand generation are more linked to the reef ecological balance and the species present.

Coral reefs are not isolated ecosystems. There is great interdependence with other ecosystems nearby (e.g. seagrass beds, mangroves). Some of these dependencies are continuous in time and space, while others are linked to extreme events (e.g. hurricanes). Therefore, the importance of corals should not be isolated, since their existence is part of the connectivity with other ecosystems.


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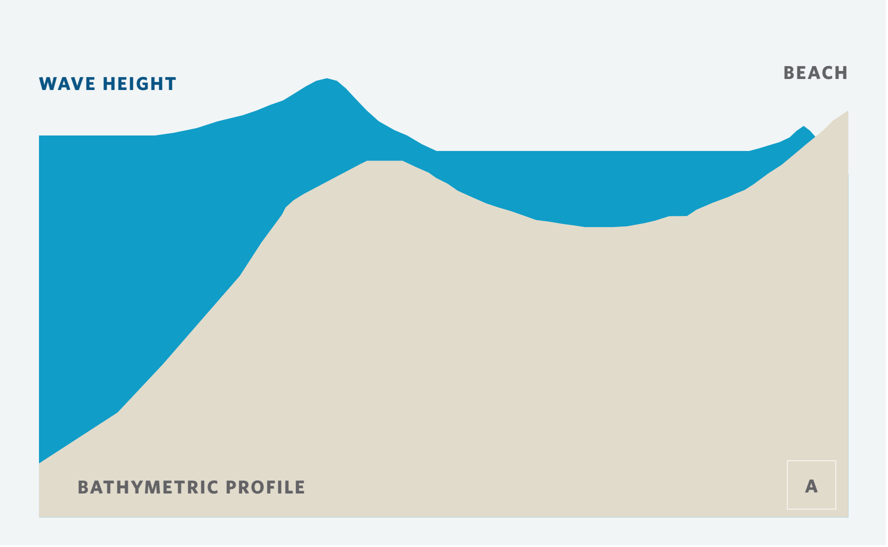
REEF COASTAL PROTECTION LINKED TO WAVE BREAKING PROCESSES

REEF PROFILE SHAPE

While patterns of bathymetry differ depending on reef type (e.g., fringing, barrier, atoll), a typical pattern consists of an abrupt slope, a reef crest (shallowest section of reef), and a reef flat/lagoon of shallow bathymetry close to the coastline. The reef's bathymetric shape alters wave characteristics making them "shoal" (grow in height), and eventually break, dissipating their energy. Shallow reef crests with extended reef flats will achieve the largest reduction in wave energy, which will generate a diminished wave height at the beach (Figure 1a). The deeper (and narrower) the reef crest is, the more energy reaches the beach (Figure 1b and 1c). Moreover, the violent introduction of turbulence produces large amounts of oxygen in the water. This is favorable for many species that depend on a large amount of oxygen and live around coral reefs.

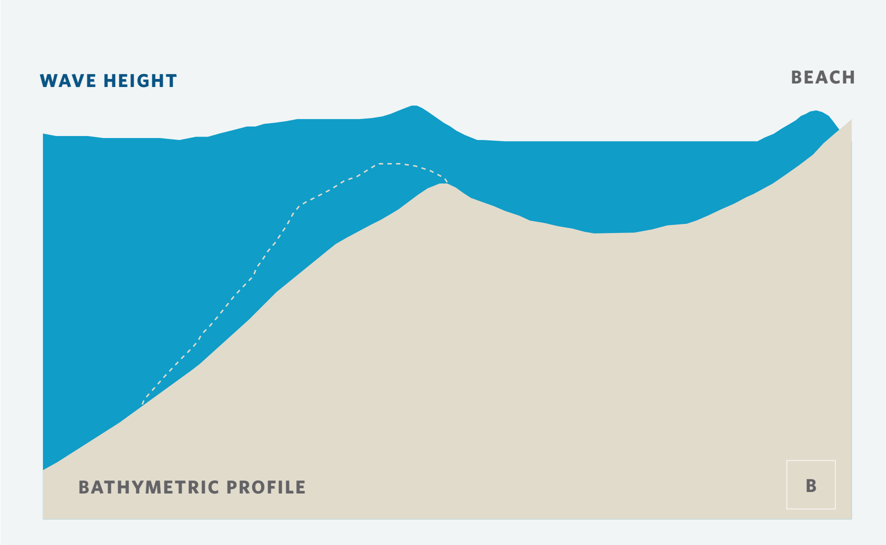
One of the phenomena induced by corals is the breaking of the waves. In addition to inducing energy dissipation through wave breaking, the violent introduction of turbulence produces large amounts of oxygen in the water. This is favourable for many species that depend on a large amount of oxygen can live around coral reefs.

FIGURE 1 Schematic effects of the bathymetric profile of barrier reefs on wave attenuation at the beach. This does not consider energy loss by friction and turbulence.



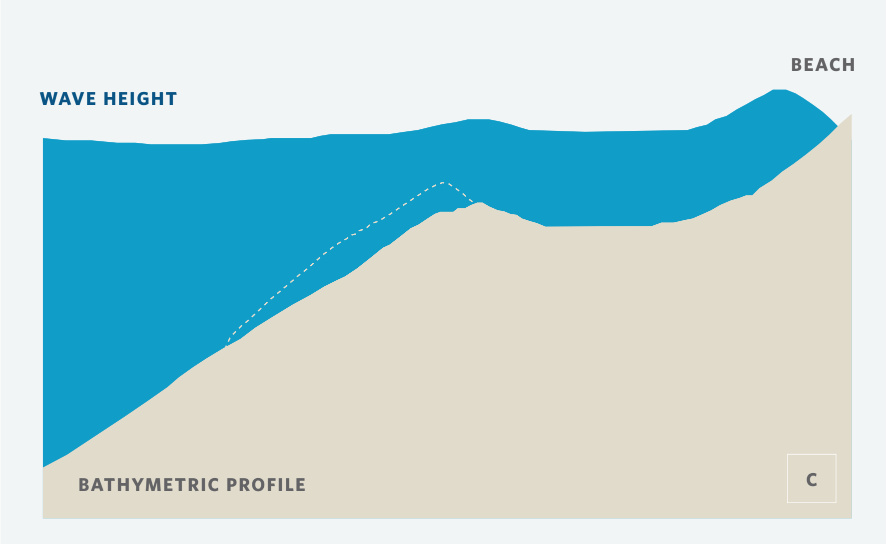
HIGH BEACH PROTECTION

- Reef profile promotes wave shoaling
- Waves dissipate their energy considerably by breaking.
- Wave energy that reaches the beach is considerably reduced.
- Beaches are prone to be stable



MEDIUM BEACH PROTECTION

- A deeper reef crest generates less wave shoaling.
- Dissipation by breaking only by larger waves.
- Wave energy that reaches the beach is increased.
- Beaches are more dynamic but still protected.



SPORADIC BEACH PROTECTION

- Deep reef crest barely affects waves.
- Waves rarely break on reef crest.
- Beaches are more dynamic and prone to erosion, especially during storms.

Short term variability in sea level (induced by tides and storms) is a critical factor that modulates the depth of the reef crest and the breaking process. At low water, the greatest amount of wave energy is dissipated by the reef crest and only short-period waves tend to make it across a reef flat. At higher water levels, longer period waves (for example, swell and infragravity waves) can pass across the reef crest onto the reef flat and back-reef areas Lugo-Fernández et al. 1998; Brander et al. 2004). Changes in oceanic current intensity (Coronado, et al. 2007), atmospheric pressure and water temperature (World Bank, 2016) also result in inter and intra-annual variations in water levels around reefs. During extreme high-water events driven by hurricanes, such as Hurricane Wilma in the Yucatan Peninsula, shallow reef crests continued to dissipate most of the wave energy (Blanchon et al. 2010). In other reef settings, such as the Great Barrier Reef, cyclone-generated 10-meter waves were reduced to 6 meters in the lee of the coral reef matrix with further dissipation because of bottom friction (Young and Hardy 1993).

In the long term, large scale shape of the reef will depend on the processes of reef accretion and erosion and changes in rates of sea level over evolutionary timescales. Vertical reef growth depends upon the balance between carbonate production and erosion (World Bank 2016). Rates of carbonate production for coral reefs have been measured from 910 to 4,500 grams of calcium carbonate per square meter per year (Mallela and Perry 2007). Geological investigations of recent Holocene reefs have shown that reef accretion can be as high as 14 millimeters per year in the Pacific, but more commonly averages 3.5 millimeters per year (Buddemeier and Smith 1988). The rate on the coral species that influence building of the reef framework, and hence their ability to reduce wave energy. Corals that build reefs are called "hard" or "reef-building corals." The rate of coral accretion differs between hard coral species. For example, large branching corals, such as *Acropora palmata*, contribute significantly to calcium carbonate accumulation in Caribbean reefs, whereas small-weedy species, such as Agaricia spp. or Porites astreoides, despite being very abundant, contribute much less to reef accretion. These differences help to understand how species contribute to the building and growth of the reef framework.

Erosion causes a loss of the reef structure and flattening of the reef surface over time. It can be driven by biological (e.g., bioerosion by fishes, echinoderms, and other bioeroding organisms), physical (storms) and chemical processes (Perry et al. 2014). Reef areas that are more susceptible to flattening include poorly managed reefs and those with fewer species of reef-building coral or those near the environmental limits of coral growth. A recent study in the Caribbean found that recent losses of large reef-building acroporid corals has resulted in many shallow reefs (< 5m water depths) accreting at much lower rates of about 0.68 millimeter per year (Perry et al. 2013). Under current rates of erosion, Caribbean reefs are thought to need at least 10% live coral cover to maintain their reef surface (Perry et al. 2013).

Erosion
causes a loss of the reef structure and flattening of the reef surface over time.

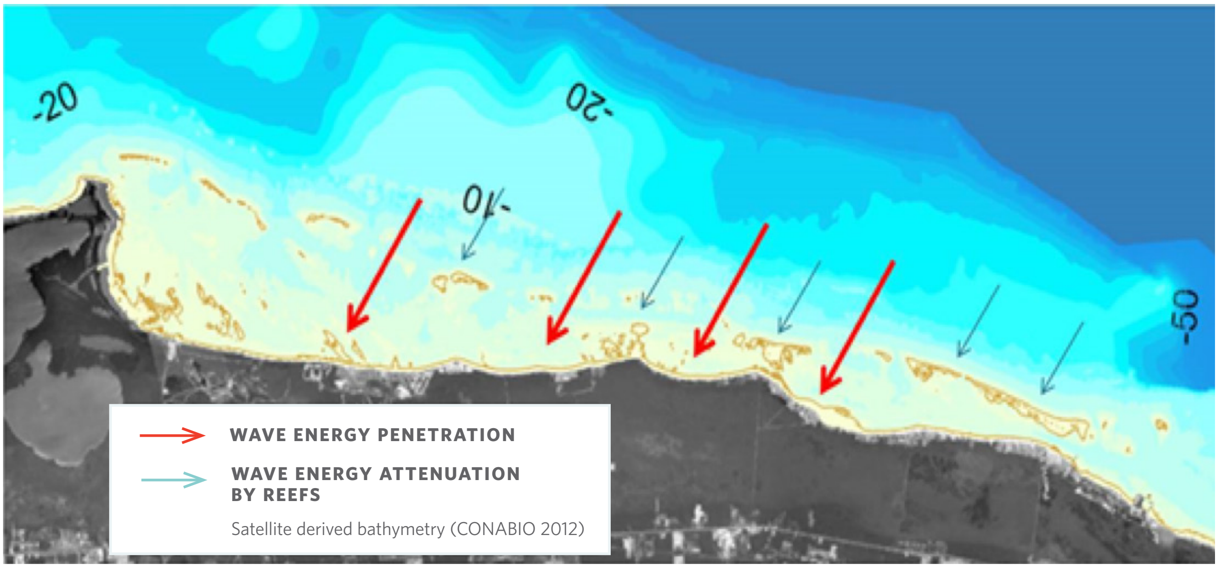
REEF PHYSIOGRAPHY AND CONFIGURATION

The distance between the reef crest and the beach is another important factor that affects a reef's coastal protection capacity. If the distance is too large, there will be enough fetch (i.e., distance over which winds blow and generate waves) for local waves to grow and cause erosion. Similarly, if the reef is too close to shore, there will not be enough space for waves to dissipate, especially under energetic conditions such as those generated by large storms (Roeber and Bricker 2015).

As mentioned before, the height of the reef crest is the most critical variable in coastal defense considerations (Hoeke et al. 2011; Sheremet et al. 2011; Storlazzi et al. 2011); 86% of wave energy is dissipated by the reef crest (Ferrario et al. 2014). Half of the remaining wave energy is dissipated by the reef flat. Thus, the length and width of the reef flat also affect wave attenuation. Wider reef flats dissipate proportionally more wave energy up to a width of about 150 meters, after which wave energy reduction remains fairly constant (Ferrario et al. 2014). The presence of patch reefs and lagoon sediment banks also help to increase wave attenuation.

Finally, the length and number of discontinuities on the reef crests can allow waves to reach the coast with much less attenuation (World Bank 2016), locally increasing erosion. Breaks in the reef crest provide outlets for reef lagoon waters, and a continuous reef crest decreases the wave energy that enters the backreef. In the Caribbean, discontinuous and semi-continuous reef crests were found to reduce significantly less (~27%) wave energy than continuous reef crests (Roberts 1980). An example from the Mexican Caribbean coast (Figure 2), shows reef crests and the discontinuities of the reef barrier. There are tombolo-like features (i.e., protrusions on the mainland formed by diffraction of waves and sand accumulation) at the coast associated with each reef crest, showing evidence of the long-term protection that reefs provide to this site. The stretches of coast where discontinuities in the reef crest exist, are prone to erosion (red arrows) inducing unstable beaches (see Puerto Morelos case study in Chapter 4).

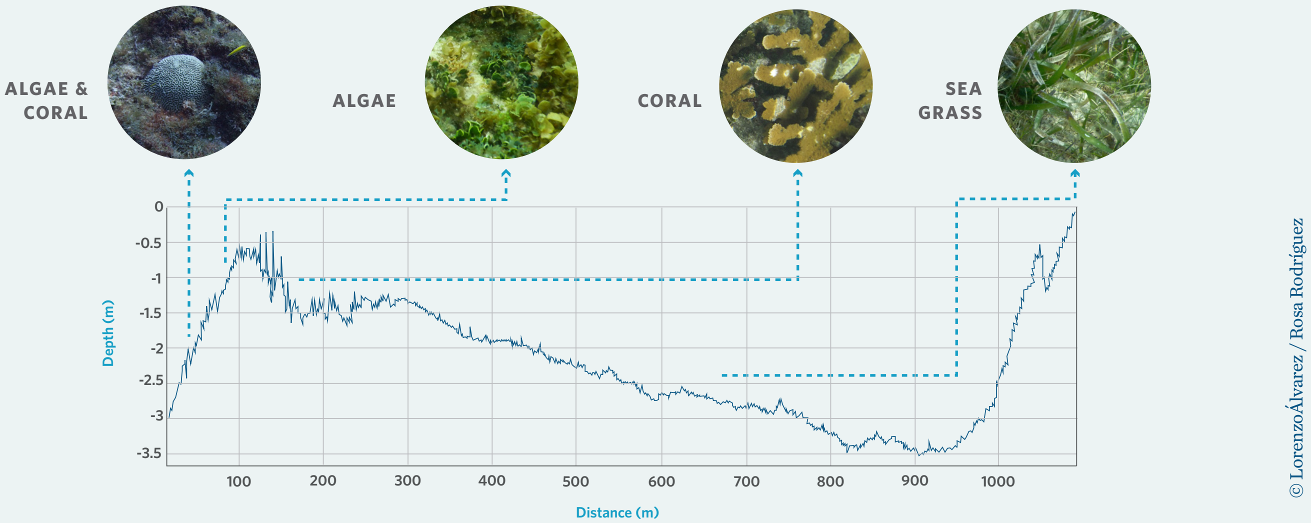
FIGURE 2 | Schematic effects of the 2D bathymetry on wave attenuation at the beach. This is a stretch of coast in Quintana Roo, Mexico (from Punta Nizuc to Puerto Morelos). The arrows represent the main direction of wave approach.



REEF COASTAL PROTECTION RELATED TO FRICTION AND RUGOSITY

One of the main characteristics of coral reef environments is the high complexity of its structure, a product of the fixation of large quantities of calcium carbonate that corals accumulate. This complex three-dimensional framework can generate very high rugosity values which depend on the species that live at a given reef. Figure 3, shows an example of a measured cross-reef bathymetric profile with photographs of the associated benthic composition.

FIGURE 3 | Cross-reef bathymetric profile at a Caribbean barrier reef (Puerto Morelos), and associated benthic cover.



It is evident in Figure 3 that regions where bathymetric features vary the most (between 100 and 200 m) are associated with the largest presence of coral colonies, in this case, *Acropora palmata*. Reef rugosity, or surface roughness, is an important factor that affects wave attenuation. Healthy coral reefs with high rugosity create high rates of frictional wave energy flux dissipation (Young 1989, Lowe et al. 2005, Franklin et al. 2013, Franklin 2015, Rogers et al. 2016). This is because as waves and currents pass over the reef, surface roughness creates small scale turbulence, friction and drag. Simulation models predict that a reduction in reef surface roughness of ~50% could produce a doubling of the wave energy reaching the shores behind those reefs (Sheppard et al. 2005).

The type of substrate affects rugosity. For example, large coral formations (>30 cm) on the reef surface are important for wave attenuation as they create greater friction compared to sand or pavement (World Bank 2016). Drag is greater over a reef flat (up to 10 times greater) than over a sand bed, and both the reef crest and the reef flat are important for reducing wave energy (Lugo-Fernández et al. 1998). The importance of friction for energy dissipation seems to depend on wave conditions. Under small waves (normal conditions), friction accounts for 80% of the energy dissipation, but under large waves (extreme storms), breaking (see previous section) dominates the energy flux dissipation (Lowe et al. 2005). The effect of roughness on wave energy dissipation is a topic of current research which needs further corroboration with in situ measurements (Rogers et al. 2016).

There are several drivers of reef degradation, and nowadays this is a topic of great concern, which has been strongly linked to anthropogenic activity (see Chapter 3). Hurricanes and tropical storms are recognized as natural determinants of both the structure (Geister 1977; Blanchon 1997) and function (Connell 1978; Rogers 1993; Harmelin-Vivien 1994) of reef ecosystems. Several studies have documented the severe immediate consequences of hurricane impacts at single sites in terms of reduced coral cover (Woodley et al. 1981; Harmelin-Vivien and Laboute 1986). Direct physical impacts from storms include erosion and/or removal of the reef framework, dislodgement of massive corals, coral breakage, and coral scarring by debris. Increasing storm impacts are also likely to cause fragile branching species (responsible for most structural complexity on reefs) to decline more rapidly than the proportion of massive corals, resulting in lower structural complexity on impacted reefs (Fabricius 2008). However, hurricanes can also sometimes have minimal or indiscernible impacts (Shinn 1976; Bythell et al. 1993). Variability in effects of hurricanes has been ascribed to natural patchiness in reef structure, the presence of other overriding stresses (Bythell et al. 1993), and/or the scale of observation (Rogers 1992; Bythell et al. 2000).

When storms reduce the structural complexity of reefs, their ability to reduce wave energy and hence, their coastal protection value, decreases. Decreased structural complexity is expected to offer less resistance to water flow, thus affecting other ecosystems (i.e. seagrass and mangroves) and increasing the risks of coastal erosion and flooding of low-lying areas, with associated heightened economic and social costs for coastal communities. Additionally, decreased capacity for wave energy dissipation can also have serious implications for ecosystem functioning since wave-driven flows control circulation in reef lagoons and ultimately the dispersion and transport of sediments, nutrients, pollutants and heat (Franklin et al. 2013). Further, extreme loss of structural complexity could alter the cross reef bathymetric shape, which can affect other coastal ecosystems. For example, researchers suggest that the retreat observed in many Caribbean beaches is linked to coral degradation due to an increase in wave energy reaching the coast (Ruiz de Alegría-Arzaburu et al. 2013). It is important to note that even if reef growth declines and rates of erosion increase, some wave protection services will continue due to the inert limestone matrix underlying living reefs. However, wave protection services will diminish over time, in response to reef health decline.

When storms reduce the structural complexity of reefs, their ability to reduce wave energy and hence, **their coastal protection value, decreases.**

REEF COASTAL PROTECTION BY SUPPORTING SAND-GENERATING ORGANISMS (FISH AND INVERTEBRATES)

Another important asset of living coral in terms of natural coastal protection is the fact that healthy reefs attract several species of fish (parrot, surgeon, etc.) and invertebrates (sea urchins, worms and gastropods) that constantly generate sand by bioeroding coral structure while feeding. This sand nourishes beaches. Of all the species, parrot fish and sea urchins are recognized as the most important. For example, Caribbean beaches (Puerto Morelos, México) experiences changes on the order of 5 m^3 of sand per meter of beach every year (Ruiz de Alegría- Arzaburu, et al. 2013), which means 30,000 m^3yr^{-1} of sand transported over a 6 km extension. In comparison, the contribution of sea urchins to the sand budget might be around 275 m^3/yr, assuming a population density of 1.2 ind/m^2, a production of 0.592 $kgCaCO_3$/ind/yr (Carreiro-Silva and McClanahan, 2001) and a reef area of 1.044x106 m^2. On the other hand, Parrot fish species (*Scaridae* family) are known to be the most important bioeroding organisms on coral reefs. Direct estimates of sand production by parrot fish in the Great Barrier Reef provide values of 1,017.7 $kgCaCO_3$/ind/yr (Bellwood, 1995). Given the overfishing situation of many reef areas, sand deficit from these sources should be large. It would be expected that contribution of bioeroding organisms to the generation of carbonate sand from coral reefs is considerable, and the healthier the reef ecosystem is, the more sand will be added to the sediment budget of reef lagoons through this mechanism. Proper and thorough assessment of this component is needed.

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CHAPTER THREE

FACTORS LINKED TO ANTHROPOGENIC ACTIVITY THAT REDUCE THE COASTAL PROTECTION CAPACITY OF REEFS

In this chapter we will analyze all the factors linked to human activity that contribute to the reduction of the coastal protection service of reefs. This includes two basic scales: a large temporal and spatial scale, linked to the effects of human-induced global warming due to excess greenhouse gas emissions to the atmosphere, and a local scale associated with changes in land use (pollutants) and overfishing.

EFFECTS OF CLIMATE CHANGE (LARGE SCALE EFFECTS)

INCREASING OCEAN TEMPERATURES AND ACIDIFICATION

Coral reefs are among the most rapidly changing and valuable ecosystems in the world (Halpern et al. 2007). It is estimated that nearly 70% of the world's coral reefs are threatened by anthropogenic activities (Wilkinson 2008) and are experiencing unprecedented rates of degradation (Veron 2008). Climate change is regarded as one of the most significant threats facing coral reefs globally (Hoegh-Guldberg 1999; Hughes et al. 2003), driving regional to global-scale episodes of mass coral bleaching. Increases in ocean temperatures are predicted to increase the frequency and severity of coral bleaching events in the coming decades. Corals can tolerate a narrow range of environmental conditions and live near the upper limit of their thermal tolerance. Abnormally high ocean temperatures (e.g., sea temperatures 1–2°C greater than average summer maxima) can cause coral bleaching, and can result in coral mortality, declines in coral cover and shifts in the population of other reef-dwelling organisms. If the thermal stress decreases, corals may recover, but if the stress is sustained, mass mortality can occur. The time between bleaching events at each location has reduced five-fold in the past 3-4 decades, from once every 25-30 years in the early 1980s to an average of just once every six years since 2010 (Hughes et al. 2018). Elevated sea temperatures also lead to increases in coral disease (Harvell et al. 2002). Interestingly, while climate change is a major driver of reef decline globally (Hoegh-Guldberg et al. 2007), a recent analysis did not find a correlation between heating frequency and intensity (DHWs) and change in coral cover in the Caribbean (Jackson et al. 2014). Coral cover at several locations increased or held steady following extreme bleaching events due to high parrotfish abundance and/or low macroalgal cover.

An added effect of increased atmospheric CO_2 and warming, is ocean acidification, which may result in the dissolution and/or reduced deposition of the calcium carbonate skeletons of reef building corals (Kleypas and Yates 2009).

SEA LEVEL RISE

Sea level is rising primarily due to thermal expansion resulting from global warming, which may directly drown some reefs (Veron et al. 2009). Nevertheless, increases in mean sea level are thought to adversely affect coral communities more by their effect on the deterioration of the quality of the environment than by the direct drowning effects. This is because even modest increases in sea level will cause radical changes in coastal erosion-deposition processes, as well as increasing the vulnerability of reefs to the impact of high-intensity storms. One of the consequences would be increased flooding, which is also projected to change the dynamics of coastal processes and negatively affect water quality needed to support healthy reef development (IPCC 2007).

Corals, in most cases, are able to keep pace with sea level increases of up to 12-14 mm/year, as recorded during the last glaciation 14,000 years ago (Blanchon and Shaw 1995). However,under the current ecological conditions, for many reefs across the world, rates of reef growth are slowing due to coral reef degradation, and therefore is likely that many coral reefs will be unable to keep growing fast enough to keep up with rising sea levels, leaving tropical coastlines and low-lying islands exposed to increased erosion and flooding risk (Perry et al 2018). Even under modest climate change prediction scenarios (RCP4.5) only about 3% of Indian Ocean and Caribbean reefs will be able to track local sea-level rise projections without sustained ecological recovery, whilst under continued high emission scenarios (RCP8.5) most reefs will experience water depth increases in excess of half a meter by 2100 (Perry et al 2018).

Changes in atmospheric pressure patterns associated with an increase in temperature, could also result in the modification of wind and wave patterns. The effect this could have on reefs has not been assessed properly.

Research in Quintana Roo has suggested that under future scenarios of sea-level rise, reefs could potentially tolerate an increase of ~ 5 mm/year with minimal adverse effects, although higher increments would produce progressive crest dipping and withdrawal of the coastline due to the increase in wave energy (Blanchon et al. 2010). However, the ability of Caribbean reefs to maintain high accretion rates is currently doubtful, considering the drastic decline (80%) in coral cover due to diseases and coral bleaching (Gardner et al. 2003). If the capacity of the reefs to accrete is reduced by 80% (e.g., to ~3 mm/year), sea level rise scenarios modeled above (Blanchon et al. 2010) will progressively submerge the ridge and lead to an increase in wave height, resulting in beach erosion.

> Exacerbating this erosion, less reef sediment will be available to feed the beach and lagoon system; such sediment input normally contributes up to **~30% by volume of sediment.**

EFFECTS OF LOCAL STRESSORS ON REEF DEGRADATION

In addition to climate impacts, local stressors on reefs (e.g., overfishing, coastal development and pollution) are threatening the ability of reefs to maintain their structure and function. Overfishing can alter the ecological balance of the reef when herbivores are overfished (e.g., from coral to algal dominance). This is because herbivores graze on the algae and help to prevent them from overgrowing corals or occupying space for coral recruitment. Overfished reefs appear to be less resilient to stressors and may be more vulnerable to disease and slower to recover from other human impacts (Burke et al. 2011).

Development in the coastal zone, related to human activities (settlements, tourism infrastructure, etc.), has mayor effects on nearshore ecosystems, either through direct physical damage such as dredging or land filling, or indirectly through increased runoff of sediment, pollution, and sewage. Large quantities of sediments can be washed into coastal waters during land clearing and construction (Burke et al. 2011). Sediment can smother corals, or at the very least, reduce their ability to photosynthesize, thus slowing coral growth. Excessive nutrients from agricultural or unregulated tourism activities can cause eutrophication and stimulate macroalgal growth that can out-compete or overgrow corals. If too extreme, phytoplankton blooms might arise, blocking light from corals, and leading to hypoxia, since the excess microalgae and other organisms consume oxygen in the water, leading to ecosystem collapse. Sewage and solid waste also threaten the health of coral reefs. Recent analyses in the Caribbean shows that phase shifts are more linked to eutrophication than overfishing (Suchley et al 2016, Arias-Gonzalez et al. 2017)

Finally, tourism and recreational impacts to reefs include: breakage of coral colonies and tissue damage from direct contact such as walking, touching, kicking, standing, or gear contact; breakage of coral colonies from boat anchors; changes in marine life behavior from feeding or harassment by humans; invasive species, and trash in the marine environment. Ship groundings also can cause substantial damage to coral reefs.

THREATS FACING CORAL REEFS AND COASTAL COMMUNITIES IN THE YUCATAN PENINSULA: THE CASE OF QUINTANA ROO

The Yucatán Peninsula is located in southeastern Mexico and separates the Caribbean Sea from the Gulf of Mexico, and it is home to more than 1.5 million people living less than a mile from shore. Just offshore is the Mesoamerican Reef (MAR), the largest coral reef in the Atlantic Ocean, and one of the largest barrier reefs in the world. The MAR has been recognized as one of the most biodiverse regions in the wider Caribbean. Its reefs are vital contributors to the local economy of the region, as reef-based tourism is a major source of income. A recent paper showed that reef-related tourism income in Mexico is worth 3,000 million USD per year (Spalding et al. 2017). The MAR also supports commercial and subsistence fishing and provides shoreline protection, reduction of coastal erosion, maintenance of habitats, such as mangroves and seagrass beds, and climate regulation (Moberg and Folke 1999).

Due to its geographic location, the Yucatan Peninsula is highly vulnerable to hurricanes and other climatic events. According to CENAPRED 2015, 96.2% of the country's disaster-related damages were associated with hurricanes (1,079 million UDS). Flooding and erosion have caused significant losses to the national economy. In Quintana Roo alone, hurricanes Emily and Wilma in 2005, caused USD$1,810 million in direct and indirect damages (CENAPRED 2006).

Despite extensive conservation efforts in the region over the last 20 years, substantial changes in the ecological composition of the MAR have occurred. Coral reefs in the Yucatan Peninsula have been damaged by increased coastal development and associated nutrient enrichment, sedimentation, overfishing of herbivore populations (Almada-Villela et al. 2002; Metcalfe et al. 2011; Baker et al. 2013; Jackson et al. 2014) and increases in coral disease and bleaching (Hughes et al. 2003; Eakin et al. 2010).

The lack of adequate sewage treatment is driving increased eutrophication and pollution that adversely affect coral reefs in the region (Chérubin et al. 2008). Such impacts disrupt coral symbioses, lead to coral diseases and mortality, increased macroalgal cover, and change the structure of reef communities (Suchley et al. 2016, Arias-Gonzalez et al. 2017). Additionally, repeated ship groundings and tourism have further degraded the reef system. Five ship groundings were recorded within the Puerto Morelos Reef National Park (PMRNP) in Mexico between 2005 and 2016, which together affected an area of 2,500 m^2 (CONANP, Unpubl. Data). During the same period, an average of 150,000 tourists visited the PMRNP annually (CONANP, Unpubl. Data) and estimates suggest that 21% made contact with the reef, especially with their fins (Reyes-Bonilla et al. 2009).

Other threats include the massive arrival of pelagic Sargassum, which have led to significant increases in nutrient inputs into the reef ecosystem. The monthly influx of nitrogen and phosphorus by drifting Sargassum spp. into the lagoon of Puerto Morelos reef, during the peak month (August 2015) of the massive event of 2014-2015, was estimated at 6150 and 61 kg km^{-1} respectively, resulting in eutrophication (van Tussenbroek et al. 2017). Nitrogen input in one month was three times more than the estimated annual influx of nitrogen from the aquifer to the Mexican Caribbean Sea (Hernández-Terrones et al. 2011). Sea level is projected to rise by another one meter or more by the end of this century (IPCC 2013). Further, invasive lionfish (*Pterois volitans* and *P. miles*) also may adversely affect coral reef communities (e.g., resulting in decreased survival of native reef species due to predation and competition).

IMPACTS ON CARIBBEAN REEFS THAT REDUCE COASTAL PROTECTION SERVICES

The structural complexity of Caribbean reefs has declined substantially over the past forty years, with the loss of ~80% of the most complex reefs (Alvarez-Filip et al. 2009). Widespread loss of fast-growing, reef-building corals has occurred in the broader Caribbean (Jackson et al. 2014). Although coral skeletons can persist after coral mortality, the region-wide loss in Caribbean coral cover has been rapidly followed by the loss of structural complexity (Alvarez-Filip et al. 2011a). This suggests regional-scale degradation and homogenization of reef structure (Alvarez-Filip et al. 2009). Reef flattening in the Caribbean occurred in the early 1980s, followed by a period of stasis between 1985 and 1998 with increasing declines in complexity continuing to the present. Contributing factors to reef flattening include the mass mortality of the grazing urchin *Diadema antillarum* and the 1998 El Nino Southern Oscillation-induced mass bleaching event (Alvarez-Filip et al. 2009). A recent analysis suggests that other primary drivers of reef flattening in the Caribbean are damage from hurricanes, direct physical impacts (e.g., ship groundings, anchor damage), and reef bioerosion (Alvarez-Filip et al. 2011b), despite bleaching and disease being the primary drivers of coral mortality in the region (Aronson and Precht 2006).

The combined effects of decreasing coral cover (specifically, the structurally complex *Acropora* corals) and increases in weedy corals and algae species, have resulted in reduced ecosystem services that are provided by coral reefs in the region, notably, their coastal protection benefits. This has significantly increased the risks posed by flooding and erosion in Quintana Roo. There are however, some encouraging examples, such as the *Acropora*-dominated reefs in the Cordelia Bank (Roatan, Honduras) and Limones (Puerto Morelos, Mexico) (Rodríguez-Martínez et al. 2014, Kramer et al. 2015).

To regain the levels of structural complexity that were prevalent prior to 1980, the recovery of large branching corals (i.e., *Acropora* spp.) and the maintenance of healthy populations of massive robust species (e.g. *Orbicella* spp.) are essential within the region. Not meeting these challenges is likely to result in a continued flattening of reefs throughout the region and seriously compromise biodiversity and environmental services (Alvarez-Filip et al. 2009).

CHAPTER FOUR

ASSESSING RISKS AND IDENTIFYING RISK REDUCTION SOLUTIONS ON COASTLINES

ASSESSING COASTAL PROTECTION SERVICE OF REEFS

Shorelines change in a wide range of temporal and spatial scales from both natural and human-induced factors (Stive et al. 2002). Coastal erosion is a major global problem but becoming more acute as climate change converges with coastal development and natural geomorphic changes (Kron 2013). Coral reefs constitute a first line of defense from erosion through wave attenuation and the production and retention of sand (Elliff and Silva 2017; Ferrario et al., 2014; Pascal et al., 2016). Coral reefs also generate fine coral sand supplying shores with sand generated by physical forces as well as the biota (Bellwood 1995).

However, there is limited information on how coral reefs prevent coastal impacts such as erosion. This section suggests a methodology to assess beach protection services provided by reefs. The focus is on chronic beach erosion, leaving aside aspects of inundation and extreme events which have been included in similar efforts by TNC (Beck et al. 2018 and Reguero et al. 2018). The methodology includes a study case for a beach in the Puerto Morelos Reef National Park (PMRNP), Mexican Caribbean.

THE COMPONENTS OF SUCH RISK ASSESSMENT SHOULD BE:

HIGH RESOLUTION BATHYMETRY

A proper evaluation of the protection services provided by a reef requires an analysis of the amount of wave energy that the reef barrier dissipates. According to Chapter 2, the first step to do so is to know the characteristics of the large scale bathymetric shape. Given the horizontal variability of the reef physiography, the bathymetric data should have the best resolution possible, and encompass the area of influence of reef crests and discontinuities. Preferably in the order of several (~10) km. These bathymetric data will be used to implement numerical models for the evaluation of the wave dissipation by reefs. Several methods could be used to obtain bathymetry. LIDAR is one of the best options to achieve the necessary bathymetric resolution, but it is highly dependent on the financial capacity and the appropriate environmental conditions. If LIDAR is not feasible, good options to obtain appropriate data are: multibeam echo-sounding, supervised classification of satellite images, or single beam echo-sounding. An additional parameter to evaluate with the bathymetric data should be the roughness or rugosity of the reef, which also contributes to wave dissipation (Chapter 2).

BENTHIC COVER

To assess the importance of coral cover (rugosity) in wave dissipation, the first step is to generate maps that define regions where reefs exist and assign friction coefficients from estimations of roughness (rugosity). It is important to include these data in the numerical model of wave dissipation. In order to achieve this, centimeter-scale resolution bathymetry, at least over the reef crest, would be necessary. If the spatial resolution of the bathymetry does not allow the direct estimation of reef roughness, alternative methods should be used, such as the chain method or better alternatives (see study case below). This has to be combined with video-transects of benthic cover in order to assess, at least to a first approximation, the integrity of the reef environment and the frictional characterization of other habitats such as sea grasses and sandbanks. Assessments of reef roughness are necessary to estimate its effect on wave dissipation and when combined with video information works as an indirect indication of reef integrity.

TOPOGRAPHIC MEASUREMENTS

Once bathymetry, reef roughness and benthic cover are obtained, the next step is to obtain topographical data that can give a clear idea of the sand volume available on the beach and the elevations above a given datum (e.g. Mean Sea Level) that the dune or the buildings have. This information is necessary to include in the numerical models and to estimate the erosion tendency of the beach, which will give an indication of the degree of protection that the coral reef provides to a given stretch of coast. It is important to do the topography (beach profiles) with the adequate resolution so that sand volumes are properly evaluated. Usually there is a clear correlation between beach width and sand volume. This relation should be analyzed with the data because if they hold, satellite images could be used to approximate beach volumes for larger areas and different dates, to have an idea of the beach dynamics and history of erosion.

URBANIZATION AND COASTAL DEVELOPMENT

It is important to have the geographic location and type of coastal development that exist along the coast, mainly to link this information with the wave attenuation and the beach sand availability, and to understand if the beach is naturally at risk of erosion, or if erosion has been triggered by a badly planned development that is too close to the sea and therefore endangers long-term beach stability. Developments that are too close to shore reduce the sand availability on the beach and make it vulnerable to erosion.

WAVE CLIMATE AND WAVE PROPAGATION TO SHORE

All the elements that influence wave attenuation (reef profile shape, physiography and horizontal distribution of reef crests and reef roughness) should be included in an analysis of wave propagation, in order to consider all the phenomena responsible for the transformation of waves nearshore (shoaling, refraction, diffraction, reflection and breaking). This is performed using a numerical model that is set up with the bathymetry, reef roughness, the beach profile data and the offshore wave climate of the region. Understanding the causes of erosion is crucial, in order to provide adequate and long-lasting beach protection actions. Historic offshore wave data (several years of information) should be obtained with in situ instrumentation, offshore wave buoys, or large scale numerical models (i.e. WAVEWATCH III) available on the web. It is impractical to run the model for a whole-time series;therefore, statistical analysis should be used to reduce the information to only the representative cases to run the model. Wave propagation can be calculated with several numerical models. These are some of the widely used models to solve the action-balance equation (SWAN, XBEACH), or the mild slope equation (REF/DIF, WAPO).

VOLUMETRIC SEDIMENT TRANSPORT AND EROSION INDEXES

Once all the elements that contribute to the protection services provided by the reef are evaluated, it is necessary to combine the wave dissipation information from the model, with the sediment availability from the beach, to generate an index of beach tendency to erosion. There can be several methodologies to achieve this, but this document suggests the analysis of wave-driven sediment transport volume (from the numerical model) and compare it with the capacity of the existing beach to accommodate the transport (i.e. beach with enough sand volume, despite the development). If the potential transport exceeds the beach reservoir of sand, erosion will occur. This information can show where most of the protection from the reef is located and where it needs to be improved.

HOW TO ASSESS WHETHER REEF RESTORATION IS THE BEST APPROACH FOR COASTAL STABILIZATION?

Once we know where the beach has a strong tendency to erode, we should start thinking on the protection options, including the economic considerations. The numerical model could be used to estimate the efficiency of the coral restoration options by locally increasing the friction coefficients and eventually considering the loss by turbulence. The time required to restore reef protection services shall also be estimated. There will be cases where the restoration of coral colonies will not contribute immediately to prevent erosion at the coast (developments in front of reef openings, or where dune systems are too damaged). In these cases, hybrid solutions (natural restoration and structures) might be needed. The numerical model could be used to evaluate the efficiency of these artificial structures for wave energy attenuation. It would be ideal that these structures could promote coral growth and ecosystem enhancement. Success can vary greatly between sites. Resources, funding, and capacity are often limited, so active ecological restoration, should only be utilized when there is a high chance of success over the long term. To increase the likelihood of success, existing local threats affecting coral reefs in a potential restoration site better be reduced before restoration is implemented.

CASE STUDY

ASSESSMENT OF BEACH PROTECTION SERVICES THAT A REEF PROVIDES IN PUERTO MORELOS, MEXICO.

Location: Puerto Morelos Reef National Park.

Summary: As many other regions of the Caribbean, coral reefs in the Puerto Morelos Reef National Park show notorious effects of phase shifts and degradation. On the other hand, it is a region where the tourist industry has a rampant and under-regulated growth, showing many detrimental effects on the ecosystem such as pollution and beach erosion. This section includes an application of the methodology described earlier to assess the protection role of reefs in the site.

Vulnerability Addressed: Beach erosion.

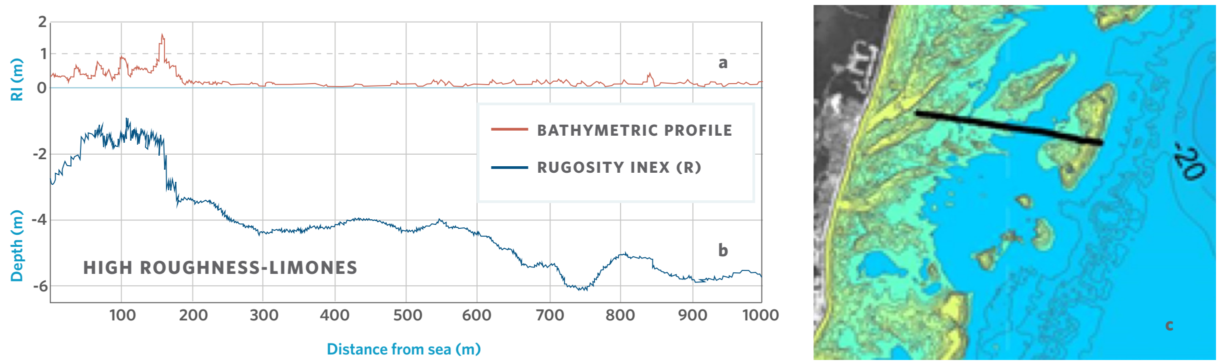
STUDY RESULTS

BATHYMETRY, ROUGHNESS AND TOPOGRAPHY MEASUREMENTS

Large scale bathymetry (30 x 5 km) was obtained at the site using a combination of methodologies including single beam echosounding and World View 2 satellite images (8 multispectral bands, 2 m spatial-resolution) which were analyzed using the standardized physics-based data processing of EOMAP´s Modular Inversion and Processing System (MIP). Figure 4c shows a fraction of this bathymetry in the region of Limones Reef, and the Moon Palace Hotel.

Since satellite data resolution is not enough to estimate reef roughness, complementary information was measured with an echo-sounder/DGPS/video camera system. The data is presented in Figure 4a and b. The system has proven to give resolutions of ~30 cm, which seems good enough to assess reef roughness (Acevedo-Ramirez 2015; Franklin 2015). The site of Figure 4 has been documented as the reef with the highest cover of *Acropora palmata* in the whole Mesoamerican Reef. The estimation of roughness in Figure 4a is based on 4σ, where σ = standard deviation of cm scale bathymetry. This has been used to approximate the Nikuradse roughness (Lowe et al. 2005; Rogers et al. 2016). Maximum values of roughness are on the order of 1.85 m, an indication of the size of the coral colonies.

FIGURE 4 **a.** Estimates of roughness (in m) obtained from the filtered small scale bathymetric measurements as 4σ. **b** Bathymetry filtered from wave effects measured with a single beam echo-sounder and differential GPS. **c.** Larger scale bathymetry of the transect presented in **b.**, obtained with supervised classification of satellite data (source: CONABIO).

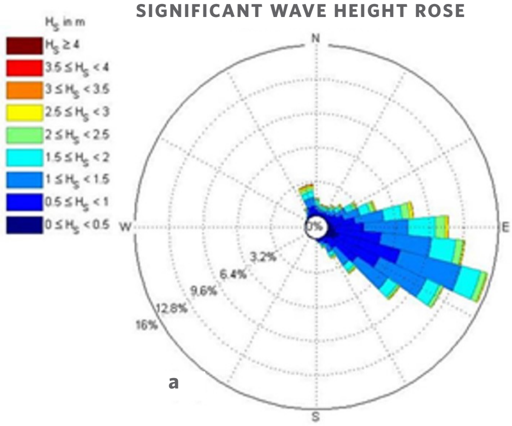


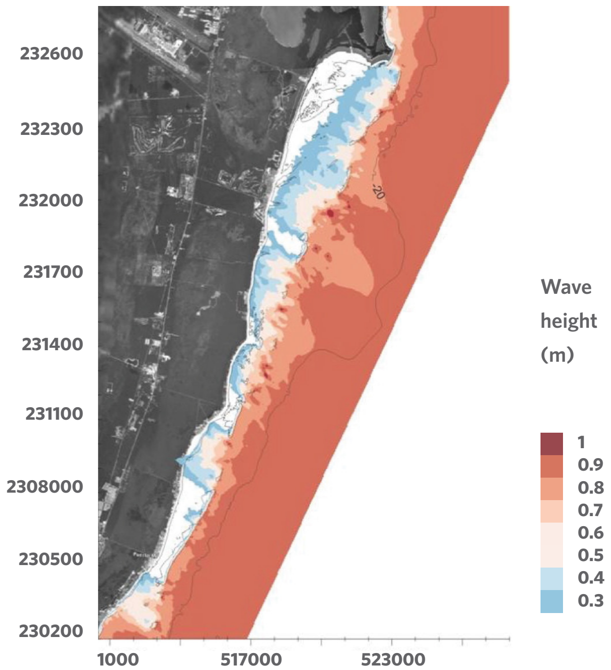
Topographic information of the beach was also obtained with a DGPS system. The land limit of the beach profiles usually is some type of obstacle such as a house, fence or hotel. The alongshore resolution was of ~20 m which gives a very good approximation of sand volumes. Information of the coastal development that exist along the coast (hotels and houses) was obtained using satellite images from Google Earth.

WAVE CLIMATE AND WAVE PROPAGATION TO SHORE.

Offshore wave climate for 11 years (2005 – 2016) was obtained from NOAA buoy 42056, located at 4000 m depth in the Yucatan Basin. Figure 5a presents wave rose of the measured offshore wave conditions affecting the Puerto Morelos region.

FIGURE 5 **a.** Offshore wave climate from 2005 to 2016 for the northern Caribbean (NOAA buoy 42056). Wave rose for wave height. **b.** Wave propagation for the Puerto Morelos region showing in colors wave heights, and bathymetric isobaths of 20 m and 1.5 m marked in solid lines. Reefs are visible offshore.





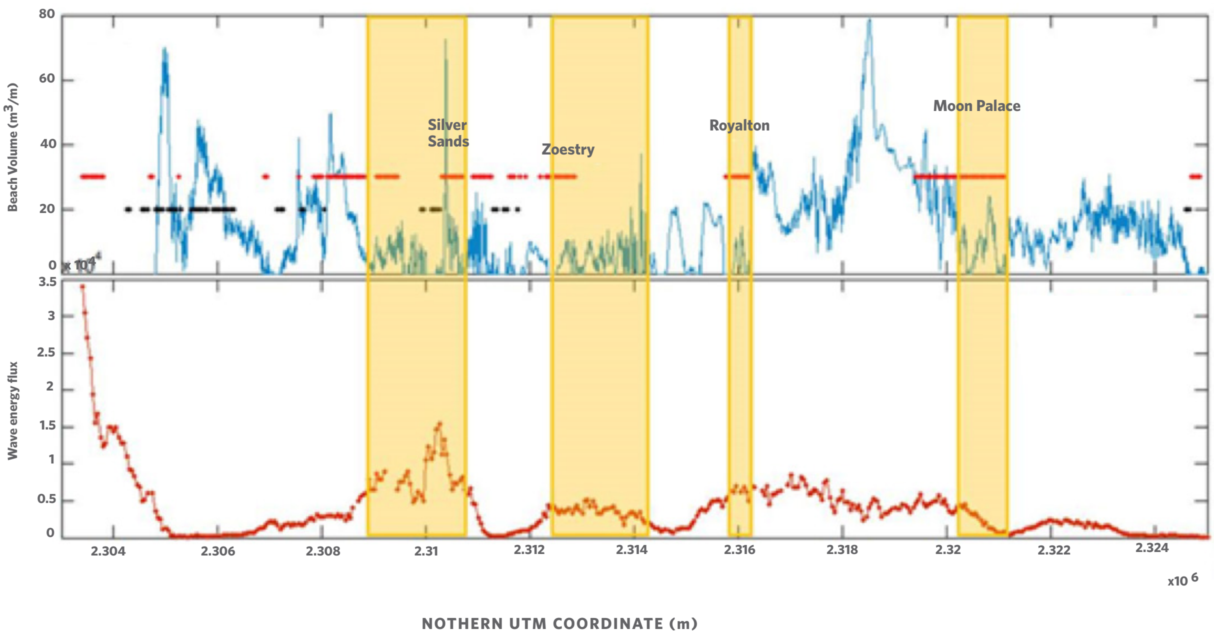
Ruiz de Alegría-Arzaburu et al. (2013) using simultaneous wave measurements from May to September 2007, have shown that the offshore wave climate of the Caribbean (buoy 42056) resembles closely the data measured nearshore (~20 m depth), with the largest differences found in wave direction with larger directional spreading closer to shore. Most incident wave heights (90% of the time) are below 1.5 m, with an associated period of 4 to 6 seconds approaching predominantly from the ESE quadrant, which at the site, is approximately normal to the shore. From May to November tropical storms can occur, which can generate extreme wave conditions. For example, during hurricane Wilma, in October 2005, waves had Hs~15 m at ~20m depth (Silva-Casarín et al. 2009). But during winter there can be strong wave events from the N and NNE (Hs ~ 2-3 m and Tp ~ 6 -8 s). The most common conditions from the measured data were propagated using the SWAN model. Figure 5b shows the wave propagation for SE waves, 1 m height, 6 seconds period. Note the efficiency of the reef in the dissipation of wave energy; the regions presented in white show very attenuated wave heights (< 0.3 m). Wave propagation should be made with the friction factors estimated with the observed values of reef roughness.

BEACH TENDENCY TO EROSION.

The wave height closer to shore (isobath of 1m), once the reefs have attenuated their energy, is extracted from the numerical model and used to calculate the wave energy flux, for the more frequent wave conditions. This energy flux is used as a proxy for the potential sediment transport due to waves. The wave energy flux along the shore is compared (plotted) with the measured sand volume available on the beach, and the presence of human infrastructure (Figure 6). This information is used to identify the stretches of coast where the potential sediment transport can exceed the capacity of the existing beach to accommodate it, and therefore erosion may occur. These areas are represented by the yellow stretches of coast shown in Figure 6.

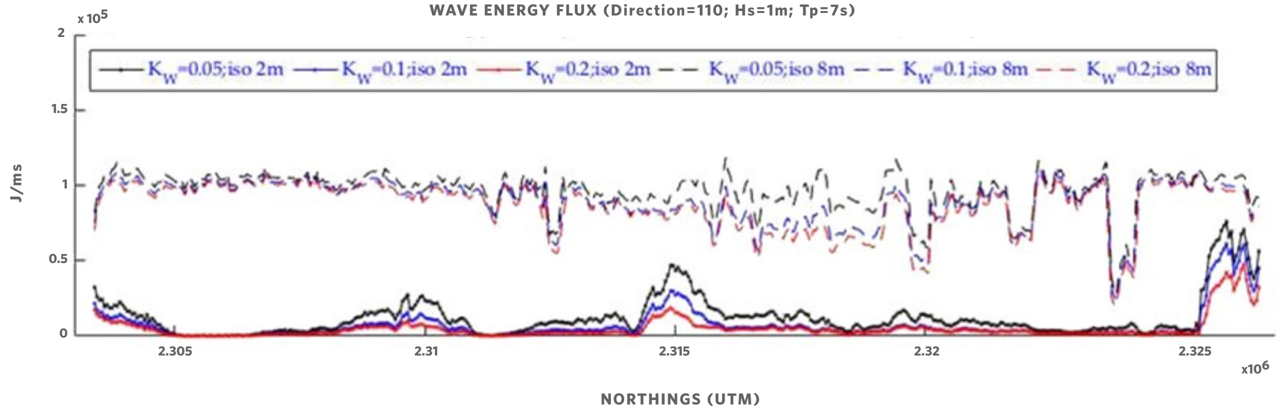
Sand volume was obtained with measurements of beach profiles with a resolution of 20 m and completed with data from satellite images. This can be done since beach width and sand volume have a clear linear relationship for the site. This type of information could help managers to plan the tourist development and avoid constructing in regions where the tendency for erosion is high. Moreover, if the development already exists, this tool could help to plan solutions (e.g. through reef restoration, artificial structures, dune or beach replenishment).

FIGURE 6 Volume of sand present on the beach per meter alongshore **a.**, Wave energy flux that moves sand **b.**. Red markers present large hotel buildings, black markers are smaller hotels and houses. The sections shaded in yellow represent portions of the beach where wave energy flux is high (i.e. large sediment transport) and beach volume is small.



If we artificially increase roughness in the numerical model, we could potentially assess the efficiency of reef restoration activities. Figure 7 shows a preliminary example of the effects that increasing reef roughness (restoration actions) could have on modeled wave energy close to shore. It is evident that by affecting reef roughness, wave energy flux approaching the shore could be diminished.

FIGURE 7 Wave energy flux comparison between 8 m depth (dashed lines) and close to shore (solid lines) under different scenarios of reef roughness, mimicking restoration actions. Kw values indicate the roughness increments close to shore.

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CHAPTER FIVE

REEF RESTORATION AND OTHER COASTAL EROSION MITIGATION MEASURES

This section includes an introduction to natural solutions to restore reef´s protection services, an array of options and other engineered artificial solutions.

HOW TO MEET ECOLOGICAL AND RISK REDUCTION OBJECTIVES?

Coral reef restoration may be implemented to meet a variety of biological and/or socio-economic objectives. Biological objectives may include the promotion of biodiversity, increasing commercially-important reef species, biomass and productivity, supporting recovery of corals or ecosystem processes (e.g., coral recruitment), and repairing damage to the coral reef framework. Socio-economic objectives may include education and public awareness of the importance of reefs and increasing ecosystem services for local communities (e.g., coastal protection).

It is important to know whether restoration is the best strategy to use compared with other management actions (e.g., coastal zone management, MPA implementation/enforcement). To determine whether restoration is a viable approach, it may be helpful to ask the following questions:

1. Did the site support a coral community prior to disturbance?
2. What was the cause of disturbance or coral degradation?
3. Have the causes of degradation stopped or are they now under effective management?
4. Could the site recover naturally from high coral recruitment?
5. Does the substrate require stabilization?

More information on tips for planning a reef restoration project can be found here: http://www.reefresilience.org/restoration/project-planning/deciding-on-restoration/.

Reef Restoration can be implemented through ecological or engineered approaches, or a combination of the two. Historically, restoration efforts focused on designing and building complex engineering projects to quickly rebuild and stabilize the three-dimensional structure of damaged reefs impacted by disturbance (e.g., ship groundings) (Precht 2006). However, large-scale ecological recovery did not often occur (Lirman and Schopmeyer 2016), thus ecological restoration efforts have been increasingly applied to improve the chances of restoration success. Coral reef restoration has evolved dramatically over the last few decades. Ecological reef restoration aims to re-establish the living components and processes of the reef (e.g., increasing the density of reproductive individuals; reinstating key ecological functions such as enhancement of sea urchin and herbivorous fish populations to support algal control where algae inhibit coral recovery).

ECOLOGICAL REEF RESTORATION

The focus of most reef restoration projects to date has been to re-establish coral cover on degraded reefs by transplanting artificially propagated corals (Guest et al. 2014). Less than 20 percent of reef restoration projects are designed with coastal protection benefits in mind (Fabian et al. 2013). Transplants can be produced sexually (collecting and rearing larvae or gametes from reproductively mature colonies) or asexually (culturing fragments from donor colonies). Asexual propagation has been implemented for decades with well- established techniques for many species and locations (Shafir et al. 2006; http://www.reefresilience.org/restoration/population-enhancement/coral-propagation/), whereas sexual propagation is largely at an experimental stage in terms of rearing large quantities of larvae and best practices for transplantation (Guest et al. 2010).

"The focus of most reef restoration projects to date has been to **re-establish coral cover on degraded reefs by transplanting artificially propagated corals."**

Guest et al. 2014

ASEXUAL PROPAGATION

Asexual coral colony propagation methods use fragments of corals from donor colonies or wild populations that are generated by disturbances ('corals of opportunity' and may include fragments broken from storms, anchoring, or vessel grounding). Broken fragments can then be reattached to existing corals or other substrates PH neutral (e.g., PVC, pipes, tiles, and concrete; Chavanich et al. 2014) to support growth and maintenance of coral populations.

Typically, for asexual propagation, a small piece of coral (≤ 5 cm) is collected or clipped from a donor colony and maintained in nurseries and protected from reef stressors (e.g., sedimentation and predators) (NMFS 2016). Practitioners in the Caribbean have found that utilizing larger *Acropora* fragments (>5 cm) promotes higher survivorship and productivity than with smaller fragments (Young et al. 2012), although recent advances in microfragmentation techniques demonstrate the potential for small coral fragments to encrust and fuse over surfaces (Forsman et al. 2015). As the fragments grow, additional fragments may be taken from them and outplanted onto the reef. Recommendations for best practices collecting coral fragments have been developed (NMFS 2016). By maintaining nurseries with broodstock that provide corals for restoration, wild populations are not depleted.

Careful selection of coral species to transplant is one of the most crucial steps in successful restoration. When considering which species to use, it is best to select corals that occur naturally at the restoration site and are relatively common on nearby potential source reefs. Species that are known to have occurred naturally at the rehabilitation site in the recent past may also be considered. Fast-growing branching species may provide a rapid increase in coral cover and topographic complexity, but also may be more susceptible to bleaching, disease and coral predators (Loya et al. 2001).

Coral nurseries can be established to supply corals to support restoration activities. Nurseries may be either ex situ (located on land; may be expensive and require technical expertise to maintain) or in situ (located in the ocean). Guidance for nursery establishment and maintenance can be found in in the Reef Rehabilitation manual: http://www.reefresilience.org/pdf/Reef_Rehabilitation_Manual.pdf; including information on: nursery site selection, how to build the nursery for asexual rearing of corals, and methods for nursery maintenance, http://www.reefresilience.org/restoration/population-enhancement/coral-propagation/

The success of restoration projects using asexual propagation methods varies based on the methods implemented and the local site conditions. Factors that may cause coral mortality following transplantation include storm damage, bleaching events, disease, predation, and poor water quality (Young et al. 2012), thus effectively managing local stressors and monitoring of current and future impacts is essential. High variability in restoration success has been noted in the Caribbean (Young et al. 2012); fragment survival ranged between 43% and 95% during the first year, with some studies documenting an increase in biomass of up to 250% for transplanted *Acropora* (Quinn and Kojis 2006). Other studies showed much lower success rates (>50% fragment mortality in the first year due to fragment dislodgement or storm damage with mortality increasing to 80%–100% after 5 yrs; Bruckner et al. 2009; Garrison and Ward 2012). Factors that increased survival of fragments included fragment stabilization (e.g., using cable ties or epoxy) and transplanting larger fragments (>5 cm), which resulted in higher growth rates and survivorship of outplanted corals (Young et al. 2012). Research suggests that restoration success is increased when more than one propagation method is used to culture coral fragments and multiple attachment methods are implemented based on local environmental conditions (Bowden-Kerby et al. 2005; Quinn et al. 2005; Williams and Miller 2010; Johnson et al. 2011).

SEXUAL PROPAGATION

Restoration using sexually derived coral recruits differs from asexual propagation in two major ways (Jantzen 2016). First, sexual propagation produces corals as a result of fertilization, thus, the developing corals need to be nurtured through their vulnerable early life stages. Second, every coral that is produced is genetically unique. Coral recruits derived from sexual reproduction can be grown in either land-based or ocean-based nurseries and can be outplanted to a restoration area. Recent advances in sexual propagation of corals for reef restoration have been developed to increase coral settlement and transplantation success (Okamoto et al. 2008; Guest et al. 2010; Nakamura et al. 2011).


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In sexual propagation, the gametes (eggs and sperm) are captured in collecting nets during natural mass coral spawning events. Once the gametes are collected, they are fertilized, thus promoting many different combinations of genes to form new genotypes. This practice contributes to maintaining or even enhancing the genetic diversity of natural populations. Settlement of the fertilized coral planulae onto small limestone tiles or fragments is done in a lab or *in situ*, and settled coral spat are then seeded onto the degraded reef site.

Transplants obtained through sexual propagation are also potentially more resilient because many parent donor colonies have survived decades of dramatic environmental changes and major losses in coral cover, with some parent *Acropora* colonies as much as 6,500 years old (Devlin-Durante et al. 2016). Therefore, new genotype combinations from theses donor colonies may be favored, cope better and survive under climate change conditions. In addition, by outplanting early-stage sexual recruits, we ensure that the survivors are adapted to the surrounding local environment.

Historically, sexual coral restoration was considered to be expensive in terms of the time and money required (Jantzen 2016), requiring sophisticated expertise and laboratories to culture corals. Recently several laboratories, most notably the Universidad Nacional Autónoma de México in Puerto Morelos, Mexico and CARMABI in Curacao, in conjunction with SECORE International have implemented pilot studies to reduce costs with shorter nursery periods before seeding coral on the reef (Chamberland et al. 2015), and upscaled coral culturing and outplanting techniques using low technology approaches. Upscaling outplanting is needed to apply restoration on a meaningful scale while reducing the costs, especially relative to the costs of transplanting corals by hand, which is not feasible at the scale needed to address reef decline globally.

With these efforts, the process of collecting large numbers of gametes from genetically diverse colonies (e.g., *Acropora* species, *Orbicella faveolata*, and *Diploria labyrinthiformi*s), assisting in their fertilization, culturing the embryos and larvae under optimal conditions and settling large numbers of larvae onto settlement substrates has become routinely successful. SECORE has developed auto-attaching coral settlement substrates to reduce the costs of seeding by not requiring each transplant to be attached by hand. Low technology and low-cost approaches are being developed in Mexico and Curacao to implement these methods at the scale of hectares with reduced land-based and ocean-based nursery times.

BENEFITS AND LIMITATIONS OF ASEXUAL AND SEXUAL PROPAGATION METHODS

Asexual propagation methods generally can be implemented with little training and are likely to be less expensive and less labor intensive than sexual propagation; sexual propagation can require hatchery facilities and expertise in larval rearing techniques (Epstein et al. 2001; Omori 2011; Guest et al. 2014). Asexual propagation also can be an important community outreach activity because it can be implemented with simple methods and can engage locals and tourists in reef conservation (Jantzen 2016). Fragmentation can create broodstock and supplement sexual propagation when coral colonies are far apart (Jantzen 2016).

Benefits of sexual propagation are that is does not damage the donor coral/ colony because it does not require fragments, unlike asexual propagation. Further, sexual propagation results in much greater genotypic diversity of transplanted corals and potentially providing access to millions of propagules because corals often are highly fecund (Guest et al. 2014). Asexual propagation does not promote genetic diversity because fragments are genetically identical to the donor colony. Another key concern of asexual reproduction restoration strategies is that it is unknown if the transplanted coral fragments have undergone periods of natural selection which weed out the less viable individuals, as sexual recruits would have done, so the long-term viability of transplanted fragments is questionable and may explain the high mortality rates of fragment outplants after 5 years. Notable exceptions include the large-scale restoration efforts implemented on Cousin Island in the Seychelles (Maya et al. 2016) and in Belize (Carne et al. 2016). In addition, there is a fear of "swamping the population" with a small number of genotypes (NMFS 2016).

To address this, researchers suggest that nurseries should aim to culture, collect, and outplant diverse genotypes (e.g., by collecting from as many separated reefs as possible to increase the chance of acquiring unique genotypes to support propagation efforts). Such practices help to ensure that a diverse set of genotypes will be represented in transplantation projects.

Another limitation with sexual and asexual propagation is that transplanted *Acropora* corals can be affected by white-band and white-pox diseases, which are still present in Caribbean reefs, and this cause corals to die rapidly. Future research should focus on finding resistant genotypes and to use these in both sexual and asexual restoration projects and on evaluating the success of transplants.

"Physical reef restoration involves **repairing a damaged reef or creating new structure to enhance the natural reef, adding to the structural integrity of the reef framework."**

PHYSICAL REEF RESTORATION

In addition to enhancing coral populations, restoring the physical structure or substrate of coral reefs may be needed when these have become damaged, degraded, or unsuitable for coral larval settlement. Acute physical impacts to the reef crest result from ship groundings, coral mining, blast fishing and major storm events, causing fractures through the limestone matrix, craters, loss of live coral, coralline algae, and the overall reduction in reef rugosity (World Bank 2016).

Destruction caused by large ship groundings can be explosive, particularly when a large moving mass, like a ship, is forced directly into a carbonate reef framework (Hudson and Diaz 1988). Hurricanes also inflict considerable damage to reefs, but they rarely damage reef framework. In cases where acute impacts have cracked coral boulders, overturned massive corals, dislodged and fragmented coral colonies and other sessile organisms, or deposited foreign objects on the reef, restoration in the short term can greatly assist recovery (World Bank 2016).

Physical reef restoration involves repairing a damaged reef or creating new structure to enhance the natural reef, adding to the structural integrity of the reef framework, typically with some combination of limestone and cement. Most examples of physical restoration of a reef crest come from the United States. One of the largest physical restoration projects took place in the Florida Keys using concrete and limestone to rebuild the shallow reef buttresses following the grounding of a large vessel (Precht et al. 2005).

Under natural circumstances, coral reefs can take decades to grow back or may never naturally recover. An unstable bottom does not provide suitable habitat for settlement and growth of corals and is likely to be a major reason why damaged sites do not recover naturally (Miller et al. 1993). Creating substrate to replicate reef structure can help speed up this recovery process. Structural approaches may be implemented to achieve the following restoration objectives:

- Repairing the reef: Physical restoration may involve applying cement or epoxy to large cracks in the reef framework, or righting and re-attaching stony and/or branching corals, soft corals, sponges and other reef organisms. In some cases, restoration of the physical environment may be required before ecological restoration of the coral and fish communities occur.
- Replacing damaged or lost reef structure: In cases where reef relief and rugosity has been lost by degradation or by direct physical impact (e.g. ship groundings, coral mining, blast fishing and major storm events), dead coral rubble and/ or rock piles can be placed on the seafloor to create substrate for corals to settle and grow and/or to replace the lost three-dimensional structure of the reef. This is only suggested in areas with no remains of live coral cover, but where reef naturally develops (not in seagrass beds, neither sand banks).
- Stabilizing damaged reef structure: Man-made materials (e.g. cement, wire, string, biodegradable nets) can be used to stabilize reef framework and reduce negative effects of unconsolidated rubble on coral settlement and growth.

Combining coral enhancement and nature-based artificial structures into sustainable coastal defense designs can provide multiple benefits over traditional gray designs. Nature-based materials are increasingly used that incorporate natural coral skeletons, rubble, or biologically friendly materials, such as pH-neutral concrete or lightweight concrete with an organic matter matrix to accelerate biological colonization (World Bank 2016).

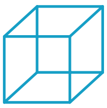
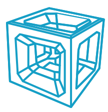
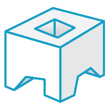
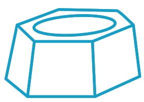
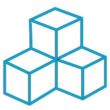
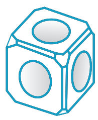
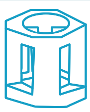
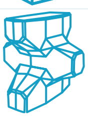
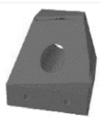
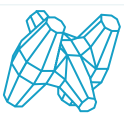
Without active physical restoration interventions, the degraded reef-crest surface deteriorates further from secondary impacts (e.g. displaced coral heads can continue to break apart and move around, causing further damage) or rates of physical erosion to back reef areas may increase from larger waves getting through the reef (World Bank 2016).

PHYSICAL MIMICRY (CONCRETE ARTIFICIAL REEFS AND BREAKWATERS)

Human-made underwater structures (artificial reefs) and, particularly, low-crested structures (LCSs) have become common as innovative means of protecting coastlines around the world. Their design aims to reduce coastal erosion vulnerability with low economic and environmental costs . The main hydrodynamic effects of these structures are to break waves, to dissipate wave energy into their porous media, to partially reflect wave energy or to perform a combination of these processes (Sawaragi, 1995; Hawkins et al., 2010; Burcharth et al., 2015).

According to Sánchez-González et al. 2012, prefabricated concrete structures provide greater structural stability than submerged rocks, but can be more expensive and more aggressive toward the environment (Muttray and Reedijk 2008). Some concrete structures require specific placement, whereas others can be randomly placed, and their stability will vary depending on their typology (i.e., stability governed by a structure's own weight or by friction between different units of concrete). Different types of concrete armor units are used to create WWblocks are massive units that resist reduce wave action well and are structurally stable, based on their heavy weight, but they can be expensive, due to the amount of concrete required and specialized equipment needed to install the large blocks on site (Muttray and Reedijk 2008). Accropode and core-loc interlock well, but require precise placement, specialized equipment and experienced staff to install. Strong storm waves may damage and completely displace core-locs, calling into question their long-term viability (Mesa 2005).

TABLE 2 | Overview of breakwater concrete armor units (after Muttray and Reedijk 2008).

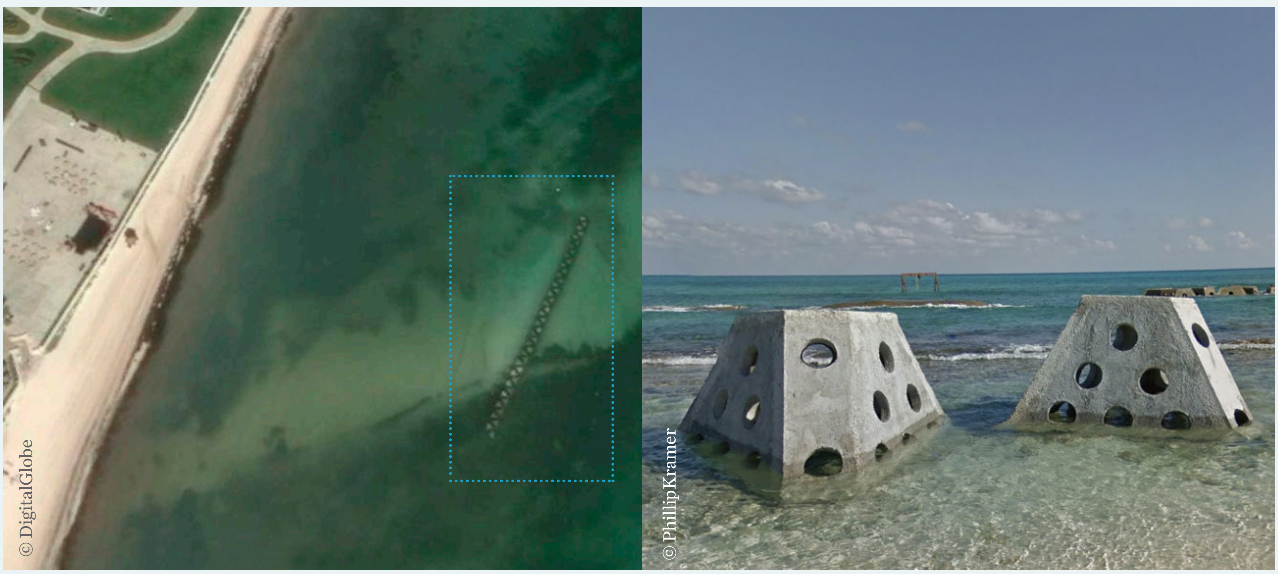
RANDOMLY PLACED ARMOR UNITS (SINGLE OR DOUBLE LAYERS)	UNIFORMLY PLACED ARMOR UNITS (SINGLE LAYER)	
STABILITY FACTOR: OWN WEIGHT	STABILITY FACTOR: FRICTION	
CUBE 	COB 	P.E.P REEF UNIT 
MODIFIED CUBE 	SEABEE 	BEACHSAVER UNIT 
TRIPOD 	SHED 	DOUBLE-T SIL 
ANTIFER 	DIAHITIS 	REEF BALL 
ACCROPODE 	WADS 	2B BLOCK 
CORE-LOC 		3D PRINTED CORAL REPLICA 

An innovative experiment was carried out by Mendoza et al. (2018) to test scale model replicas, to compare their performance as wave energy attenuators. An artificial reef made with 3D printed coral replicas based on the morphology of the coral *Acropora palmata*, was proposed to mimic the dissipation of wave energy and the capacity to be colonized rapidly by other organisms.

Advances in research on prefabricated concrete units in addition to real-life experiences have highlighted the advantages of using concrete blocks with cavities in the construction of submerged breakwaters for coastal protection. Reef balls are one of the most commonly implemented methods for artificial reefs by using concrete with holes and cavities. These are structures composed of semi-circular or semi-spherical prefabricated concrete pieces, which are hollow and contain cavities in their walls. While initially designed for use in artificial reefs, they are increasingly applied for submerged breakwaters. Figure 8 shows the installation of reef balls in the construction of a submerged breakwater in the Dominican Republic in 1998 (Harris 2009).

FIGURE 8 | Reef ball submerged breakwater for shoreline stabilization in Dominican Republic (1.2-1.3 m high, in water depths of 1.6-2.0 m) (Harris 2009).

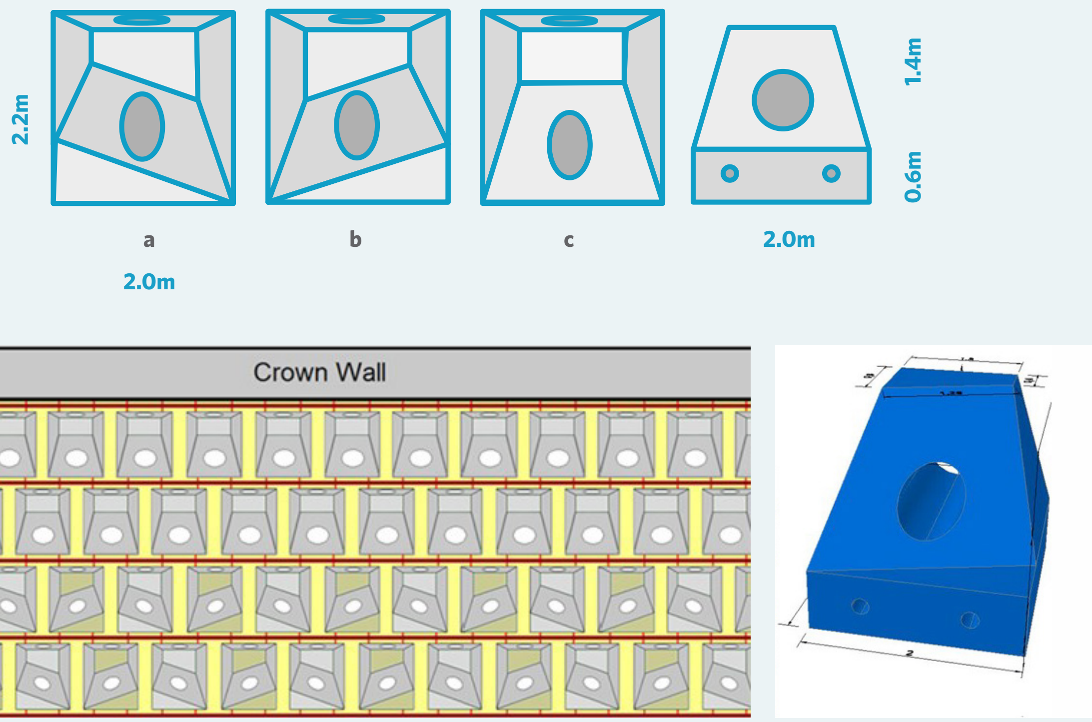
FIGURE 9 | WADs used in the construction of a submerged breakwater located in the Mexican Caribbean, specifically in Puerto Morelos, outside the protected area (Silva et al. 2016).



Wave Attenuation Devices (WADs) are designed in a pyramid shape that can be triangular or parallelepiped (Figure 9). WADs have shown a greater hydraulic efficiency in relation to other types of breakwaters such as geotextile, concrete tubes or traditional jetties. These concrete structures with holes (e.g., WADs, Reef balls) require less concrete to build, and can favor the settlement of marine organisms.

Other prefabricated concrete units are 2B Blocks (A, B, and C in Figure 10), were developed to address limitations in earlier designs (e.g. stability, interlocking, and cost and maintenance of the units) (Bilyay et al. 2017). 2B Blocks are placed in a single layer and come in three different models. Their main advantages are that they can be applied to any slope of desired breakwaters, no special placement method is required, and they successfully reduce wave run-up and wave energy.

FIGURE 10 | Artificial submerged dike composed of prefabricated 2B concrete blocks (Bilyay et al. 2017).



Nature-based materials are increasingly used that incorporate natural coral skeletons, rubble, or biologically friendly materials, such as pH-neutral concrete or lightweight concrete with an organic matter matrix to accelerate biological colonization (World Bank 2016). From an environmental perspective, the main feature that affects the colonization and development of benthonic organisms is topographic complexity Roughness of concrete fabricated structures is one of the main factors that influence the capacity of marine species to establish. The stability of structures is another important parameter that guarantees the assembly and succession of species, whereas the need to frequently maintain structures can cause greater disturbances of the formed epibiotic associations (Hawkins et al., 2010).

Proper placement of engineered structures on the seabed is critical to prevent these to directly influence wave and current patterns that could affect shorelines, and further degrade coastal habitats and displace erosion problems to other sections of coastline.

In addition, artificial reefs (structures) must not be placed in areas with presence of seagrass, coral patches and gorgonians, as they can kill benthic organism's underneath. Similarly, they should be placed with caution not to pose a navigational hazard or be of aesthetic impact (Edwards and Gomez 2007).

When concrete structures are considered a more suitable option, the most efficient and cost-efficient unit should be selected based on site characteristics, the hydraulic and structural stability of the breakwater, the manufacturing method, and the required manipulation, installation, and maintenance of the unit, as well as its longevity. Most concrete structures can last between 20-50 years.

BENEFITS AND LIMITATIONS OF PHYSICAL REEF RESTORATION AND PHYSICAL MIMICRY METHODS

Engineered structures can provide significant coastal protection benefits as they are designed primarily with the objective to meet the demand for people living along the coasts but if they are ecologically enhanced, they can also provide relevant natural benefits. However, when they are planned and designed inadequately, engineered structures can cause environmental damage by removing natural habitat and altering circulation and sediment transport to adjacent habitats (Martin et al. 2005; Chapman and Underwood 2011).

Poorly designed structures can become dislodged during storms, break apart, and cause further damage to the reef and coastal infrastructure (World Bank 2016). It is known, that they can be transported, buried and destroyed by the passage of even distant (> 150 km) hurricanes (Kilfoyle 2017). For this reason, both, physical reef restoration and physical mimicry projects can be riskier than ecological restoration projects.

Besides, two main drawbacks have been identified in the behavior of concrete units that should be considered during the design process: possible displacement of the structure as it settles and scours. Scouring can appear at the foot of a structure on the side exposed to waves, at roundheads or in holes between units (in the case of artificial reefs composed of various segments; Blacka et al., 2013). In addition, the success of projects that implement submerged prefabricated concrete breakwaters has been determined to be dependent on the crest width of the utilized structures, the arrangement of the structures and the design of the foundations (Basco and Pope, 2001).

In the other hand, engineered structures with holes or cavities provide several benefits. They can support the colonization of marine organisms, often are smaller in size which facilitates easier installation, and have relatively high porosity. Some benefits of reef Balls is that are made with special concrete additives and with a pH similar to seawater to ensure compatibility with the marine environment and to support colonization of marine organisms. But reef balls have some limitations. They can be can be expensive, and their longer-term durability and function for coastal defense applications have been questioned (Fabian et al. 2013). Several other alternatives have been presented that can show better performance both; in shore protection and environmental terms.

Engineered structures, in a similar way to ecological restoration, require costly and labor-intensive maintenance actions (Blacka et al. 2013; Bilyay et al. 2017), and in some cases specialized equipment. Therefore, both types of projects require detailed planning (including environmental impact assessments) and must incorporate the expertise of qualified coastal engineers and restoration specialists in their design and installation (World Bank 2016), and the guidance from government agencies related, which can be costly and timely.

However, when ecological restoration is expensive, uncertain, slow or incompatible with the space available or with the demands of coastal communities, a balance between risk, vulnerability and certainty is needed to get the optimal solution for shore protection.

Poorly designed structures can become dislodged during storms, break apart, and cause further damage to the reef and coastal infrastructure.

World Bank 2016

COSTS ASSOCIATED WITH REEF RESTORATION

Costs for reef restoration varies considerably. Community or volunteer-based marine restoration projects usually have lower costs. Also, restoration costs are lower in countries with developing economies (Bayraktarov et al. 2016). Costs also vary between ecological and physical restoration.

ECOLOGICAL REEF RESTORATION COSTS

According to the Environmental Protection Agency (2012), restoration costs must include capital costs (cost for planning, purchasing, land acquisition, construction, and financing), operating costs (cost for maintenance, monitoring, and equipment repair and replacement), and in-kind cost (donations or volunteer labor). Table 3 presents median values of overall restoration cost per unit area and total restoration cost for coral reefs.

TABLE 3 | Coral reef restoration costs (Environmental Protection Agency 2012).

		RESTORATION COST		TOTAL RESTORATION COST		PPP-ADJUSTED RESTORATION COST		PPP-ADJUSTED TOTAL RESTORATION COST	
Ecosystem	Economy	*N*	(2010 USS per ha)	*N*	(2010 USS per ha)	*N*	(2010 IntS per ha)	*N*	(2010 IntS per ha)
Economy	Overall	42	165,697 (5,411,993)	16	162,455 (2,915,087)				
	Developed	18	1,826,651 (12,125,179)	8	282,719 (5,501,636)	19	1,489,964 (11,499,412)	8	207,247 (5,479,769)
	Developing	24	89,269 (377,104)	8	162,455 (328,537)	28	9,216 (60,726)	8	19,510 (48,309)

Notes: *Cost data are represented in 2010 U.S. dollars per ha accounting for inflation [consumer price index (CPI)] and in 2010 Int$ per ha taking into account the gross domestic product as estimated by the purchasing power parity (GDP; PPP). Total restoration cost includes only observations in which both capital and operating cost were reported. Data are represented as overall observations as well as projects in countries with developed and developing economies. The number of observations is indicated by N.*

In the case of the Mexican Caribbean, reef restoration costs range between US$100,000 – US$500,000/ha considering about 10,000 transplants per hectare. This cost does not include medium- to long-term monitoring of the restoration site. Compared to physical restoration, costs are less expensive. But sometimes, ecological restoration can be expensive, mostly when processes need to be accelerated.

PHYSICAL RESTORATION COSTS

Major physical restoration is generally a very expensive engineering exercise (costing on the order of US$100,000-1,000,000's per hectare) that requires expert advice (Johnson et al. 2011). On the other hand, data from ship grounding restoration costs in the Caribbean, which involves physical restoration of the sites, suggest costs of US$2.0 million – 6.5 million per hectare.

CHAPTER SIX

MANAGEMENT MUST HELP SUPPORT COASTAL PROTECTIVE SERVICES

The worldwide decline of coral reefs calls for an urgent reassessment of current management practices. Managing for improved resilience by incorporating the role of human activity in shaping ecosystems, provides a basis for coping with uncertainty, future changes and ecological surprises (Bellwood et al. 2014). Reducing impacts and threats to reefs that protect shorelines before, they become degraded, is a much more cost-effective approach to maintaining their defense services (World Bank 2016).

Reefs face growing threats yet there is an opportunity to guide adaptation and hazard mitigation investments towards reef restoration to strengthen this first line of coastal defense (Simard et al. 2016). The extent that reef health and wave protection services will be lost over time will depend in large part on how well human-caused threats are reduced and managed. Effective management of reefs is currently poor in many areas, although management improvement efforts are underway (Burke et al. 2011).

Coral reef conservation and restoration efforts focused on providing risk reduction and adaptation benefits require conservation efforts to be focused on reefs close to the people who will directly benefit from the implementation of such efforts. Therefore, coupling active restoration with improved reef management strategies will be essential for meaningful long-term restoration success of degraded reefs (Fabian et al. 2013).

THREATS TO BE ADDRESSED FOR RESTORATION SUCCESS

Research highlights the critical need to address existing local stressors before restoration projects are implemented, otherwise restoration efforts may fail (Johnson et al. 2011). Controlling pollution, overfishing and destructive fishing, coastal development, recreational use and tourism impacts, and planning for climate change are all important considerations when designing and implementing restoration projects. Furthermore, because reef deterioration commonly occurs in response to combinations of different stressors acting simultaneously, restoration and conservation actions need to be design in a broad management framework that aim to mitigate the combination of threats acting at local and regional scales. For example, Suchley and Alvarez-Filip 2018 forecasted for the Mexican Caribbean that, despite the increasing coverage of Marine Protected Areas in the region, highly degraded sites with very low coral cover would become increasingly common if land-based threats are not controlled. However, integrated coastal zone management, particularly if combined with a regionwide ban on herbivorous fish extraction, could mitigate the negative impacts of planned developments and improve coral cover at local and regional scales beyond current levels (Suchley and Alvarez-Filip 2018).

CONTROLLING POLLUTION

Poor water quality, due to pollution, is an important driver of coral restoration failure (Young et al. 2012) and coral decline, more broadly. Thus, efforts to improve water quality are vital support for coral restoration efforts. Efforts to control sedimentation and nutrients into coastal waters provide improved conditions for corals to recruit, settle, and grow. Furthermore, research highlights the role of poor water quality in lowering the thermal tolerance of corals (Wooldridge 2009), highlighting the critical need to address poor water quality to support coral reef conservation and restoration efforts.

Deforestation and agricultural practices can result in sediment, nutrient, and pesticide run-off into rivers and eventually coastal waters. Sediments can smother and kill corals. Excessive nutrient levels (e.g., nitrogen and phosphorous in coastal waters) can lead to eutrophication where phytoplankton blooms block light from corals or stimulate algal growth that can out-compete or overgrow corals. This can also lead to hypoxia, where decomposition of algae and other organisms consumes all of the oxygen in the water, leading to "dead zones." Raw sewage and solid waste also threaten the survival of coral reefs. Thus, improving water quality is a critical strategy to support healthy coral reef ecosystems.

To maintain coastal water quality and reduce the nutrients and toxins that reach coral reefs, wastewater (including sewage and industrial effluent) must be treated and controlled. Ideally, sewage should be treated to the tertiary level (that is, a high level of nutrient removal). Tertiary treatment provides a final treatment stage to improve the effluent quality before it is discharged to the receiving environment. However, such treatment is often too costly for many coastal communities without the help of outside donors (Burke et al. 2011). The tourism industry can play an important role in improving wastewater management (e.g., tertiary treatment and use of biodegradable cleaners by the tourism industry to reduce pollution from harmful chemicals that leach into coastal water).

Less expensive interim solutions include managing the flow and release of wastewater. Such management options include directing effluent to settling ponds for natural filtering by vegetation, or routing discharge far offshore, well beyond reefs. Improvement in the collection and treatment of wastewater from coastal settlements benefits both reefs and people through improved water quality and reduced risk of bacterial infections, toxic algal blooms, and fish kills (Burke et al. 2011).

Land-based pollution can be addressed through a variety of land-use policies, plans and management practices. These include improved agricultural methods that can reduce erosion and runoff, increased fertilizer efficiency, preservation of coastal ecosystems (mangroves and seagrasses) that filter and trap sediments and nutrients before reaching reefs, and maintenance of vegetation along rivers to reduce nutrient and sediment run-off into waterways. Agroforestry and reforestation can greatly reduce the release of nutrients and sediments into waterways and improve the reliability of year-round freshwater supplies. Integrated coastal zone management is an important tool to address issues of land-use impacts on coastal ecosystems.

Marine-based pollution can be addressed through developing infrastructure at ports to dispose of ship-generated waste; improving wastewater treatment systems on cruise ships and cargo ships; routing shipping lanes away from reefs; disposing of ballast water offshore to reduce the spread of invasive species in coastal waters; and developing effective oil-spill contingency plans. Removing the massive amounts of pelagic Sargassum spp. washing up on beaches should be prioritized to prevent the adverse effects on nearshore marine communities (i.e. increases in nitrogen and phosphorous, anoxia, and light reduction). Guidelines for appropriate removal and disposal practices are urgently required as inadequate beach clean-up practices cause erosion, as inevitably large amounts of sand are removed together with the algal biomasses (Van Tussenbroek et al. 2017).

Further, adopting and enforcing national legislation in all countries bordering coral reefs to incorporate international agreements on marine pollution would greatly help to reduce marine-based threats to reefs. Besides MARPOL, other International Maritime Organization (IMO) treaties include the London Convention and Protocol and the International Convention on Oil Pollution Preparedness, Response, and Cooperation (OPRC), which address waste disposal and oil spills at sea, respectively (Burke et al. 2011).

"Controlling pollution, overfishing and destructive fishing, coastal development, recreational use and tourism impacts, and planning for climate change are all important considerations when designing and implementing restoration projects. "

ELIMINATING OVERFISHING/DESTRUCTIVE FISHING

Fisheries management can take many forms, including seasonal closures to protect breeding sites; restrictions on where and how many people can fish; and restrictions on the sizes or quantities of fish they can take or on the types of fishing gear they can use. Areas closed to fishing can show rapid recovery, with more and larger fish within their boundaries, associated benefits for corals and other species, and "spillover" of adult fish stocks at the perimeter that can enhance fisheries in adjacent areas. In all cases, size and placement are important for achieving success. Further, enforcement is critical, and local support and community involvement in management are essential for effective management (Burke et al. 2011).

Control of destructive fishing practices is important for protecting the reef framework. Destructive fishing methods include the use of explosives to kill or stun fish (i.e., dynamite fishing), which can reduce corals to rubble, destroying large sections of reef. Cyanide is also used to stun and capture fish and can also damage and kill corals. Some types of fishing gear, including gill nets and beach seines, can also damage reef ecosystems. Therefore, policies and management actions that control destructive fishing practices are needed to prevent the destruction of coral reefs.

Another key management strategy to support healthy coral reefs, is controlling the overexploitation of herbivores. When herbivores are depleted, especially in combination with increasing pollution in coastal water, a phase shift may occur from coral to algal-dominated systems. Healthy herbivore populations not only control macroalgae, but may increase crustose coralline algae, which is an important substrate for coral settlement, can increase coral growth and recruitment, and can decrease coral mortality (Hughes et al. 2007; Burkepile and Hay 2008).

Coral reef managers can regulate the removal of herbivores through MPAs and through fisheries management strategies and legislation. Fisheries management tools that support herbivore protection include: area closures, gear restrictions, herbivore species bans, temporal closures (e.g., following bleaching or storm damage), and active restoration of herbivores.

In addition to controlling overfishing and destructive fishing practices, reef managers may consider prioritizing restoration efforts in areas with high levels of natural herbivory (high grazing intensity sites) to promote the survival and growth of out-planted corals. Future research needs to include the identification of what herbivore community composition provides sufficient herbivory to promote reef recovery (Hunt and Sharp 2014). Such studies should be combined with broader research that assesses key ecological processes (e.g., herbivory levels, recruitment, benthic and fish community composition) and site characteristics (e.g., water quality, sedimentation rates, temperature, etc.) at existing restoration sites to determine key drivers of outplant success (Hunt and Sharp 2014).

MANAGING COASTAL DEVELOPMENT

Managing coastal development is important for maintaining healthy coral reefs, based on the potential impacts of poorly planned development in the coastal zone. Ecological impacts of poorly planned coastal development include: construction of piers, dikes, and channels that can kill corals, removal of the reef structure which can exacerbate erosion, land retreat and sedimentation, impeded hydrodynamic flow, and sewage and industrial discharges. Furthermore, poorly planned development that leads to the destruction of the reef will reduce the socioeconomic benefits reefs provide including coastal protection and potentially tourism revenue.

The impacts of coastal development can be greatly reduced through effective planning and regulations. Integrated coastal zone management (ICZM) is an important strategy to implement environmentally, culturally, and economically sustainable uses of the coastal zone. It is important because it requires collaboration among the many regulatory agencies that oversee coastal development and private sector stakeholders. A number of strategies have been identified to protect coral reefs from unplanned or poorly planned development (The Coral Reef Alliance 2005): assess whether resource management measures exist and could support coastal resource management; engage local stakeholders in policy planning and implementation; collect baseline data on coastal environments, resources, and management efforts; create and enforce a strong legal and institutional framework, including economic incentives to support desired behaviors; develop strong coastal management partnerships at local to national levels, establish MPAs, perform Environmental Impact Assessments (EIAs) for all development projects in the coastal zone; assess and monitor pollutants entering coastal waters and implement pollution control measures (The Coral Reef Alliance 2005).

Specific planning and management approaches that support ICZM include land-use zoning plans and regulations, protection of coastal habitats (such as mangroves), coastal setbacks that restrict development within a fixed distance from shoreline, watershed management, improved collection and treatment of wastewater and solid wastes, and management of tourism within sustainable levels. Such approaches reduce the need for future coastal engineering solutions by allowing for the natural movements of beaches and vegetation over time, thus saving future costs and unintended consequences (Burke et al. 2011).

MANAGING TOURISM IMPACTS

Recreational users and tourism operators have an important role to play in coral reef management. Impacts to coral reefs caused by recreational use and tourism may include anchor damage, coral breakage from snorkelers and divers, trash, changes in animal behavior due to human interactions, and wastewater discharge. Recreational use can be effectively managed through setting limits for sustainable use, managing reef activities and encouraging best practices. Management strategies to support recreational use include: limiting the number of tourists visiting coral reefs based on assessments of carrying capacity; regulation/permitting of marine activities (e.g., setting and enforcing bag and size limits for fishing); enforcement; installation of mooring buoys; and educational campaigns that support environmentally sensitive behavior as well as providing alternative sites for tourism activities such as the Musa underwater museum in Cancún.

Coral restoration projects can provide important opportunities to engage local communities and tourists in reef conservation. Thus, restoration practitioners can explore partnerships with local dive shops and tourism agencies to help raise awareness of threats facing corals, environmentally friendly dive practices, and engagement in activities that support coral reef conservation and restoration

ADAPTING TO CLIMATE CHANGE

Controlling the drivers of climate change, specifically reducing greenhouse gas emissions, is essential to protect coral reefs into the future. While it is beyond the scope of most coral reef managers to address, reef managers can be important voices calling for reduction of atmospheric CO_2 levels to maintain coral reef and the benefits that they provide.

Climate change is likely to increase the disturbance regime for coral reefs, and the fate of coral reef ecosystems will increasingly be determined by their potential for recovery and long-term maintenance of structure, function and goods and services. Therefore, it is critical for managers to prioritize management efforts toward restoring and maintaining coral reef resilience. Specific strategies include: managing local stressors on reefs (e.g., through MPAs, fisheries management, ICZM); ensuring connectivity within and between protected areas to maintain diversity, fish stocks, and ecological resilience; protecting natural refugia (areas where coral reefs are positioned to survive future climate impacts); and implementing adaptive management based on monitoring and evaluation of management practices.

> **“Recreational users and tourism operators”**
>
> have an important role to play in coral reef management.

PROMOTING MARINE PROTECTED AREAS (MPAS)

MPAs are a critical management tool to support reef resilience (Hughes et al. 2003; Bellwood et al. 2004; Mora et al. 2006), as research suggests that reducing local stressors may increase coral resilience to climate change (Carilli et al. 2009). Effectively managed MPAs can protect species, habitats, and the maintenance of ecological processes, structure, and function.

There are a wide variety of MPAs with different levels of protection, management approaches, and levels of allowable exploitation (McClanahan et al. 2006). Management objectives range from cultural subsistence use, strict protection and exclusion of humans to broad-scale multi-use approaches, such as protecting seascapes and traditional use of marine resources with ecotourism (Dudley 2008; Day et al. 2012).

A key component of MPAs are replenishment zones (RZs) or no-take areas. RZs are areas of ocean that are protected from all extractive and destructive activities. They allow marine species, especially those targeted by fisheries, to live longer, grow larger and reproduce more through a spill-over effect of adults, juveniles and larvae to adjacent areas. Implementing a network of RZs will produce larger benefits than establishing multiple RZs independently, and increases the ability of species to move between patches, helping marine resources thrive even when resources outside the network may be depleted or individual RZs have been disturbed (Green et al. 2017). Therefore, well-designed and effectively managed RZ networks can reduce local threats, and contribute to achieving multiple objectives regarding fisheries management, biodiversity conservation and adaptation to changes in climate and ocean chemistry (Green et al. 2014).

MPAs are an important tool to manage human activities and ultimately reduce stressors on the environment. They can play a key role in bringing together local stakeholders to implement the most appropriate management measures to increase or maintain resilience of ecosystems and the sustainable use of ecosystem services (Simard et al. 2016). Furthermore, evidence suggests that some protected reefs can recover more quickly from disturbance (Mumby and Harborne 2010; Steneck et al. 2014; Mellin et al. 2016 but see Selig and Bruno 2010; Graham et al. 2015). To ensure that MPAs deliver their intended benefits, attention is given to support increasing management effectiveness and improving financing to regulate human activities detrimental to reefs and support enforcement (World Bank 2016).

MPAs aim to protect habitats and biota in situ, and thus can serve to protect the structural components of habitats critical for coastal protection purposes. However, they are susceptible to disturbances from local to global scales, such as those associated with climate change (e.g. sea-level rise, increasing sea temperatures, ocean acidification, magnitude and frequency of storms, storm surge, spread of invasive species, and species range shifts). MPAs can also be adversely impacted by poor land use practices (e.g., deforestation causing increasing sediment in coastal water. Therefore, they are most effective when combined with broader management frameworks such as integrated coastal management or marine spatial planning to address threats originating outside of the MPA boundary. In some cases, co-management approaches may more effectively deliver social and ecological benefits of protection to local communities, as management designed to support community goals may achieve greater compliance and conservation success than approaches designed primarily for biodiversity conservation (McClanahan et al. 2006).

Increasingly, resilient networks of MPAs are being implemented to increase conservation benefits across broader areas and to spread the risks of potential loss of biodiversity in any one area. The scaling up from individual MPAs to resilient MPA networks allows for the protection of species and habitats, in addition to the maintenance of ecological processes, structure, and function. The long-term stability of coral reefs requires a holistic and regional approach to control human-related stressors in addition to the improvement and establishment of new MPAs (Mora 2008). Improving the design and management of MPAs and MPA networks for increasing the resilience of coastal communities and maintenance of natural coastal protection services is urgently needed (Brock et al. 2012; Dudley et al. 2010; Toropova et al. 2010).

A key research need is to explore how existing design criteria for MPAs can be expanded to support coral reef restoration projects. Often protection and restoration are not integrated in management programs (e.g., protection from anthropogenic stressors may not be a prerequisite for reef restoration, and restoration may not be considered in MPA management plans; Abelson et al. 2016). When they are integrated, management plans are often developed specifically for a restoration objective (e.g., population enhancement for target species) (NMFS 2016) and do not include broader management objectives (biodiversity, fisheries, or climate adaptation). By developing restoration plans that integrate multiple objectives (e.g., restoration, biodiversity, climate change, and fisheries management), there is a higher likelihood that existing stressors will be controlled, and restoration projects will be more successful.

In summary, restoration activities must be conducted in conjunction with local and regional management strategies that address the impacts of land-based sources of pollution, habitat destruction, and overfishing because reef restoration efforts can prove futile if the initial source of degradation has not been controlled (Jaap 2000; Precht 2006; Young et al. 2012). Existing management strategies (e.g., MPAs) cannot protect corals from thermal stress or storms, thus, researchers have suggested avoiding fragmentation and outplanting activities during warm summer months when water temperatures and bleaching and disease prevalence are higher decreasing fragment survival (Young et al. 2012) or during high or low temperature anomalies (NMFS 2016). But contrastingly, these are the months when the sea is calm, and it is easier to carry out restoration work on the reef crest.

Establishing coral nurseries both in situ and ex situ in a variety of locations reduces the risk of impacts (e.g., from storms, mass bleaching event). Other recommendations include strategically placing nurseries and restoration sites away from land-based sources of pollution, within MPAs, and/or in deeper habitats where temperature impacts may be lessened (Johnson et al. 2011; Schopmeyer et al. 2011).

MANAGEMENT, MAINTENANCE AND MONITORING OF A RESTORATION SITE

MANAGEMENT OF A RESTORATION SITE

The identification of the agents or actions causing reef degradation is the first step in conducting a restoration effort. Many ecosystem restoration projects have failed because they have not accounted for the stressors that influence the system. Coral reefs, especially those near urban settings, are subject to cumulative large-scale stressors from human activities. These stressors influence a reef at different scales and intensities, which can make it difficult to identify the major reef stressors (Precht et al. 2016). To properly identify the major stressors, one must examine the individual reef and its landscape setting at numerous spatial and temporal scales (Precht el al. 2016).

The effective implementation of a management plan can ensure the best possible holistic management of a restored area. It should address threats to the reef and include the following measures:

- Protecting the restored area against physical damage
- Maintaining adequate water quality standards
- Regulate fishing, navigation, snorkeling and scuba diving activities in the area

The management strategy should seek to support (Johnson et al. 2011):

a. Improved understanding of population abundance, trends, and structure through monitoring and experimental research.
b. Development and implementation of strategies for population enhancement through restocking and active management to increase the likelihood of successful reproduction and to increase wild populations.
c. Ecosystem-level actions to improve habitat quality and restore keystone species and functional processes such as herbivory to sustain adult colonies and promote successful natural recruitment.
d. Curbing ocean warming, and acidification impacts to health, reproduction, and growth, and possibly disease threats.
e. Reduction of locally-manageable stress and mortality threats (e.g., predation, anthropogenic physical damage, acute sedimentation, nutrients, contaminants).
f. Determination of coral health risk factors and their inter-relationships and implement mitigation or control strategies to minimize or prevent impacts to coral health.

MAINTENANCE OF A RESTORATION SITE

Properly maintaining a restoration project can ensure its longevity by providing early warning signs of problems and triggering adaptive management responses when necessary.

Basic maintenance should be conducted regularly to ensure coral competitors or predators do not harm corals attached to the reef structure. The frequency of regular checks will be based on the local environmental conditions. If water quality is good and fishing pressure moderate, then little maintenance may be needed to control macroalgae and coral predators. On the other hand, if water quality is poor and fishing pressure high, considerable maintenance may be needed. Indeed, in such circumstances transplantation may be a high-risk venture that is unlikely to be sustainable (Edwards 2010).

Depending on the method of transplantation used and the amount of care taken, some corals may become detached due to physical disturbance (e.g., waves, fish, diver damage). Furthermore, fish appear to be attracted to freshly attached coral transplants with some species feeding directly on the coral polyps and others feeding on invertebrates embedded in the coral skeleton (Edwards 2010).

Maintenance activities for corals attached to structures include (Based on Edwards 2010; Johnson et al. 2011)

- Removal of algae and other fouling organisms (tunicates, sponges, hydroids, etc.) by hand or with small brushes as they can overgrow transplants.
- Removal of invertebrate coral predators (e.g. snails, fireworms) and/or protect transplants from predators with plastic mesh cages or netting for several days after attachment.
- Stabilization of broken or damaged fragments (e.g., using epoxy).
- Isolation, removal, or treatment of diseased corals.
- Reattachment of detached transplants.
- Removal of loose materials, whether in the form of man-made flotsam (e.g. garbage, fishing net) or natural items like loose seaweed fronds that can smother new coral recruits

Basic maintenance should also be conducted regularly in site with physical restoration and / or with physical mimicry, to ensure concrete structures continue to be properly secured as these can break, sink and move during storms, or erode at the base (World Bank 2016).

Because maintenance activities do not require extensive knowledge of coral biology, training volunteers and recreational divers to assist with maintenance provides a valuable resource (Johnson et al. 2011). Maintenance costs will depend largely on how far you need to travel to the floating nursery and boat requirements (Edwards 2010).

MONITORING OF A RESTORATION SITE

Monitoring to support coral restoration typically focuses on the survival and growth of coral transplants. Guidance for reef restoration monitoring has been developed (http://www.reefresilience.org/restoration/population-enhancement/monitoring/).

It is important to note that most reef monitoring plans were developed to monitor ecological conditions and may not focus on monitoring the coastal protection services that reef provide. To monitor reef protectives services, it is necessary to assess the following factors: changes in reef structure, loss of reef rugosity, and the carbonate production and erosion of the reef framework.

It may be necessary to develop a general monitoring plan, that includes monitoring objectives, activities, criteria and an estimation of resources needed. Monitoring activities should also include the effects of restoration actions on beach protection and environmental quality.

Physical oceanographic monitoring should be conducted at grounding sites to help detect episodic events that might facilitate or hinder recovery and restoration efforts.

Physical oceanographic monitoring should be conducted at grounding sites to help detect episodic events that might facilitate or hinder recovery and restoration efforts. The following factors should be evaluated to monitor the protection services provided by a reef restored with artificial structures:

- Wave energy on shor
- Beach or shoreline erosion rates
- Coastal impacts and damages due to storms

ReefBudget is a non-destructive approach to assess reef carbonate budgets. It is census-based and focuses on quantifying the contributions made by different biological carbonate producer/eroder groups to net reef framework carbonate production. Rates are calculated using data on organism cover and abundance, combined with annual extension or production rate measures. Resultant data provide a measure of net rates of biologically driven carbonate production (kg $CaCO_3$ m-^{2} yr-^{1}). These data can be integrated into ecological assessments of reef state, to aid monitoring of changes in rates of biological carbonate production and to provide insights into the key ecological drivers of reef growth or erosion. The ReefBudget protocol and on-line data entry spreadsheets can be found at http://www.exeter.ac.uk/geography/reefbudget (Perry et al. 2012).

Also, establishing a routine method for assessing overall coral condition in the restoration site is important to measure success. The monitoring should include a visual census of survivorship, with notes on condition that can be achieved quickly and with minimal effort. Monitoring should include at least the following factors/ indicators (English et al.1997; Edwards and Gomez 2007; Edwards 2010; Johnson et al. 2011; NMFS 2016):

a. Growth and survival of individual coral transplants through time.
b. How the area of live coral cover (% of restored site area) changes through time (e.g., using line intercept transect or quadrats).
c. Changes in biodiversity at the restoration site.
d. Status (dead, alive, missing, broken) and condition (e.g., amount of live tissue, amount of recent tissue loss, suspected cause of recent tissue loss (disease, predation), presence of bleaching/paling, algal and other overgrowth, breakage.
e. Mortality: number of fragments or colonies with complete tissue loss.
f. Attachment or stabilization of fragments or colonies – e.g., loose or cemented to platform, loose or intact cable ties.
g. Water quality: water quality indicators such as nutrients and light (e.g., using Hobo loggers) which can provide information on conditions in a nursery.
h. Environmental measurements: temperature at the transplant site to establish the annual temperature regime for the site and warning of unusually high temperatures. In a warming event, there may be little you can do except shade transplants (e.g. by floating plastic mesh on the sea surface above them) but at least you will know the cause of coral transplant mortality.
i. Algal growth.

As well as systematic monitoring discussed above, a simple check on the status of the restoration site by a snorkeler or diver every few weeks can be very useful. (Edwards and Gomez 2007). Monitoring of temperature, current speed and direction, and salinity at restoration sites is recommended (Miller et al. 1993). Additionally, monitoring of spawning activity of colonies and genotypes should occur after out-planting (NMFS 2016).

CHAPTER SEVEN

PROJECT PLANNING AND KEY CONSIDERATION

Before embarking on a physical restoration project, significant time should be allocated for strategic planning to help identify the best approaches to achieve your project goals. Restoring coral reefs for their risk reduction and protection services should seek to meet conservation, resource management, and disaster risk reduction objectives simultaneously, and provide multiple socio-economic benefits to coastal communities. Such efforts are more likely to be effective when local communities and social and cultural values are incorporated into management. Involving key stakeholder groups from the beginning is critical for getting community support and managing stakeholder expectations of the project. Below we list key considerations that are specific to restoration projects focused on coastal protection and risk reduction.

PROJECT PLANNING

IS REEF RESTORATION THE RIGHT APPROACH?

The first question to ask when considering coral reef restoration is: what caused the reef to degrade in the first place? Understanding the primary threats and stressors causing reef loss will help determine whether other management strategies should be in place to mitigate or control threats before restoration begins. Purely structural approaches may not need additional management actions but approaches that include live coral colonies should seek to control threats to coral survivorship, settlement, or growth prior to restoration.

ARE YOU REPAIRING OR ADDING REEF STRUCTURE?

Physical reef restoration projects are appropriate when attempting to stabilize and restore lost or degraded reef structure to support critical ecosystem services provided by reef structure like coastal protection. Consider that projects involving hard structures can be riskier than ecological restoration projects.

WHO DO YOU NEED TO WORK WITH?
Structural restoration projects should seek to work closely with the following groups (World Bank 2016):

- Local municipal or governmental agencies to obtain the necessary permits and environmental impact assessments.
- Professionals such as coastal engineers to help in the design and planning process and with constructing artificial structures.
- Local communities to reduce potential impacts to the aesthetics of the area, which may be important for the tourism industry.
- Reef restoration practitioners and reef managers.

DO YOU HAVE SUSTAINABLE FUNDING?
Costs for reef restoration vary considerably and can be lower for ecological coral restoration projects (e.g., asexual propagation) compared with physical restoration projects. When estimating project costs, all expenses of the project should be considered, including: capital costs (planning, purchasing, land acquisition, construction, financing), operating costs (maintenance, monitoring, equipment repair and replacement), and in-kind cost (donations or volunteer labor). It is also important to determine the length of time needed for maintenance and monitoring to ensure that funding sources are sustainable and support long-term monitoring.

KEY CONSIDERATIONS

General factors to consider for different approaches include placement on the reef, design of the structure, and materials used.

PLACEMENT

Practitioners should work with experts to obtain detailed assessments of the existing bathymetry and dynamics of water currents around the coral reef. Natural factors may also dictate where structures are placed, such as the geomorphology of available reef habitat or areas where coral recruitment most likely occurs.

DESIGN

Natural reefs have a variety of formations and morphologies that create small and complex spaces and shapes. These formations increase reef rugosity that reduces wave energy and promotes biological diversity through increased habitat. The design and shape of structures should attempt to mimic natural reef formations. Incorporating nature-based principles (e.g., the biomorphology and geohydrology of the existing reef, existing and potential natural values) into the design of restoration projects can potentially yield greater benefits (Waterman 2008).

MATERIALS

Materials affect a structure's durability, resistance to abrasion and corrosion, cost, availability, transportation, maintenance, aesthetics, and environmental impacts. Rock piles can be placed on the seafloor to create substrate for corals to settle and grow, or to replace three-dimensional reef structure. Nature-based materials using natural coral skeletons or biologically friendly materials like pH-neutral concrete can help to accelerate natural coral settlement (World Bank 2016).

COSTS

Since structural restoration projects can be costly, they can benefit from economic cost analyses that evaluate return on investment. Investments include building structures, putting structures in place, and maintaining structures.

CHAPTER EIGHT

RECOMMENDATIONS

This section includes a series of recommendations based on the prior chapters for assessing where and how to do reef restoration for risk reduction. These recommendations are mainly focused on restoration considerations following storm damage. However, they are also relevant to other catastrophic events such as ship groundings and mass coral bleaching events.

1. Identify the objectives of the proposed restoration project (e.g., restoring ecological functioning, ecosystem conservation, or ecosystem services, such as coastal protection (erosion and/or flood reduction), fisheries, or tourism/recreation (For more information, see http://www.reefresilience.org/restoration/project-planning/project-objectives/).

2. Assess reef losses and impacts from storms and other natural and human-made hazards. Where possible, identify historical and present data on reef condition, height and rugosity. Following ship groundings, providing a rapid and accurate assessment of the damage of the reef is important because they are necessary to access monetary fines from responsible parties and to inform the development of reef restoration plans.

3. For coastal protection (i.e., risk reduction) projects, assess the potential flood or erosion reduction benefits from the restoration project. This assessment will require data on offshore wave climate, bathymetry, topography, rugosity (reef roughness), reef condition, and assets.

4. Assess the degree of protection that the coral reef provides to a given stretch of the beach, e.g., by constructing the Beach Erosion Tendency Index (BETI)

5. Perform an analysis of wave propagation to understand how waves travel and influence coastal erosion and flooding.

6. Assess other factors that contribute to flooding, erosion and declines in reef condition including development along the coast (poor designs may cause erosion) or pollution.

7. Determine which coral reef restoration approaches are most applicable to your determined project objectives (ecological, physical, hybrid) and whether restoration aligns with broader management strategies in the area.

8. Determine whether a given restoration approach is logistically and financially feasible in your location over the long term to ensure project sustainability.

9. Engage key stakeholder groups (local communities, coastal management agencies, tourism agencies, etc.) from the beginning and throughout the entire planning process.

10. For coastal protection, it will be critical to restore height and then rugosity. Where reef height needs to be restored (quickly), it may be necessary to use physical restoration measures. These measures are most often going to be focused on or near the reef crest in the shallow parts of the reef where the most wave-breaking and attenuation occurs.

11. Assess feasibility of directly planting corals onto reef crests or whether a combination of artificial structures and coral transplantation is possible.

12. For artificial structures, work closely with professional partners such as government agencies, coastal engineers, and restoration specialists to ensure good design and construction practices are used and structures do not pose a hazard during strong storm conditions.

13. Where possible, use materials that promote growth and settlement of marine organisms, particularly hard corals and crustose coralline algae and use natural or biologically-friendly materials (e.g., coral skeletons/rubble, terracotta, or pH neutral concrete).

14. Avoid outplanting corals during warm summer months, when bleaching and disease prevalence are higher, during high or low temperature anomalies, or during seasons with high storm or hurricane/cyclone activity.

15. Promote reef management actions to control threats to reefs including those that the impede natural regeneration of corals (e.g., pollution, overfishing, removal of herbivorous fishes, physical damage, coastal development, etc.).

16. In cases of acute physical impacts and damage to the reef, direct restoration can greatly assist recovery. This may involve applying cement or epoxy to large cracks in the reef framework, stabilizing loose debris, or righting and re-attaching corals, sponges and other reef organisms.

17. Define criteria and indicators for measuring restoration success such as percent live coral cover; abundance of coral recruits or juvenile corals; reef height; and wave attenuation (For more information, see http://www.reefresilience.org/restoration/coral-populations/monitoring/reef-sites/).

REFERENCES

- **Abelson A, Nelson PA, Edgar GJ, Shashar N, Reed DC, Belmaker J, Krause G, Beck MW, Brokovich E, France R and Gaines SD. 2016.** Expanding marine protected areas to include degraded coral reefs. Conservation Biology 30(6): 1182-1191.
- **Acevedo-Ramírez C. 2015.** Análisis de la complejidad arrecifal con métodos acústicos y su efecto en la hidrodinámica. MSc Thesis, CINVESTAV-Mérida, México.
- **Adger WN, Hughes TP, Folke C, Carpenter SR and Rockström J. 2005.** Social-ecological resilience to coastal disasters. Science 309(5737):1036-1039.
- **AIMS Long Term Monitoring Program.** http://www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html.
- **Almada-Villela P, Mcfield M, Kramer P, Kramer PR and Arias-Gonzalez E. 2002.** Status of Coral Reefs of Mesoamerica-Mexico, Belize, Guatemala, Honduras, Nicaragua, and El Salvador (chapter 16). In: Wilkinson CR (ed) Status of coral reefs of the world: 2002. GCRMN Report, Australian Institute of Marine Science, Townsville, pp 303-324.
- **Alvarez-Filip L, Carricart-Ganivet JP, Horta-Puga G and Iglesias-Prieto R. 2013.** Shifts in coral-assemblage composition do not ensure persistence of reef functionality. Scientific Reports 3: 3486.
- **Alvarez-Filip L, Côté, IM, Gill JA, Watkinson AR and Dulvy NK. 2011a.** Region-wide temporal and spatial variation in Caribbean reef architecture: is coral cover the whole story? Global Change Biology 17(7): 2470-2477.
- **Alvarez-Filip L, Dulvy NK, Gill JA, Côté IM and Watkinson AR. 2009.** Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proceedings of the Royal Society Biological Sciences 276:3019-25.
- **Alvarez-Filip L, Gill JA and Dulvy NK. 2011**b. Drivers of region-wide declines in architectural complexity on Caribbean reefs. Coral Reefs 30:1051-1060.
- **Anthony KRN, Maynard JA, Diaz-Pulido G, Mumby PJ, Cao L and Hoegh-Guldeberg O. 2011.** Ocean acidification and warming will lower coral reef resilience. Global Change Biology 17(5): 1798-1808.
- **Anthony KRN. 2016.** Coral reefs under climate change and ocean acidification: Challenges and opportunities for management and policy. Annual Review of Environment Resources 41: 59-81.
- **Arias-González JE, Fung T, Seymour RM, Garza-Pérez JR, Acosta-González G, Bozec YM, and Johnson CR. 2017.** A coral-algal phase shift in Mesoamerica not driven by changes in herbivorous fish abundance. PLoS One 12(4): e0174855.
- **Aronson RB and Precht WF. 2006.** Conservation, precaution, and Caribbean reefs. Coral Reefs 25(3):441-450.
- **Baker DM, Rodríguez-Martínez RE and Fogel ML. 2013.** Tourism's nitrogen footprint on a Mesoamerican coral reef. Coral Reefs 32(3): 691-699.
- **Basco D.R., Pope J., 2001.** Shore protection projects. In Coastal Engineering Manual, Chapter 3, Part V Coastal Project Planning and Design. Pages 1-110.
- **Barshis DJ, Ladner JT, Oliver TA, Seneca FO, Traylor-Knowels N and Palumbi SR. 2013.** Genomic basis for coral resilience to climate change. Proceedings of the National Academy of Sciences 110(4): 1387-1392.
- **Bayraktarov E, Saunders M, Abdullah S, Mills M, Beher J, Possingham HP, Mumby PJ, and Lovelock CE. 2016.** The cost and feasibility of marine coastal restoration. Ecological Applications 26(4): 1055-1074.
- **Beck MW, Losada IJ, Menéndez P, Reguero BG, Díaz-Simal P, and Fernández F. 2018).** The global flood protection savings provided by coral reefs. Nature Communications 9: 2186.
- **Bellwood DR, Goatley CHR, Brandl SJ and Bellwood O. 2014.** Fifty million years of herbivory on coral reefs: fossils, fish and functional innovations. Proceedings of the Royal Society of Biological Sciences 281: 20133046.
- **Bellwood DR, Hughes TP, Folke C and Nystrom M. 2004.** Confronting the coral reef crisis. Nature 429: 827-833.
- **Bellwood DR. 1995.** Carbonate transport and within-reef patterns of bioerosion and sediment release by parrotfishes (family Scaridae) on the Great Barrier Reef. Marine Ecology Progress Series 117(1-3):127-136.
- **Bilyay E, Ozbahceci B, Kiziroglu G and Bacanli S. 2017.** A new approach to breakwater design-2B Block. Coastal Engineering Proceedings 1(35):1-6.
- **Birkmann J, Cardona OD, Carreño ML, Barbat AH, Pelling M, Schneiderbauer S, Kienberger A, Keiler M, Alexander D, Zeil P and Welle T. 2013.** Framing vulnerability, risk and societal responses: the MOVE framework. Natural hazards 67(2): 193-211.
- **Blacka MJ, Shand TD, Carley JT and Mariani A. 2013.** A review of artificial reefs for coastal protection in NSW, WRL Technical Report 2012/08, Australia.
- **Blanchon P and Shaw J. 1995.** Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse. Geology 23: 4-8.

- **Blanchon P, Iglesias-Prieto R, Jordán Dahlgren E and Richards S. 2010.** Arrecifes de coral y cambio climático: vulnerabilidad de la zona costera del estado de Quintana Ro.p. 229-248. In A.V. Botello, S. Villanueva-Fragoso, J. Gutierrez, and J.L. Rojas Galaviz (eds.). Vulnerabilidad de las Zonas Costeras Mexicanas Ante el Cambio Climático. SEMARNAT-INE, UNAM-ICMYL, Universidad Autónoma de Campeche. 514.
- **Blanchon P.1997.** Architectural variation in submerged shelf-edge reefs: the hurricane-control hypothesis. Proceedings of the Eighth International Coral Reef Symposium 1: 547-554.
- **Bowden-Kerby A, Quinn N, Stennet M and Mejia A. 2005.** *Acropora cervicornis* restoration to support coral reef conservation in the Caribbean. NOAA Coastal Zone 05, New Orleans, Louisiana. 8 p.
- **Brander RW, Kench PS and Hart D. 2004.** Spatial and temporal variations in wave characteristics across a reef platform, Warraber Island, Torres Strait, Australia. Marine Geology 207(1): 169-184.
- **Brock RJ, Kenchington E and Martínez-Arroyo A. 2012.** Scientific guidelines for designing resilient marine protected area networks in a changing climate. Commission for Environmental Cooperation, Montréal, Canada. 95 p.
- **Bruckner A, Bruckner R and Hill R. 2009.** Improving restoration approaches for *Acropora palmata*: lessons from the Fortuna Reefer grounding in Puerto Rico. Proceedings of the 11th International Coral Reef Symposium 24:1199-1203.
- **Bruno JF and Selig ER. 2007.** Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. PLoS ONE 2(8): e711.
- **Buddemeier RW, Smith SV. 1988.** Coral reef growth in an era of rapidly rising sea level: predictions and suggestions for long-term research. Coral Reefs 7(1): 51-56.
- **Burcharth H.F., Zanuttigh B., Andersen, T.L., Lara J.L., Steendam G.J., Ruol P., Sergent P., Ostrowski R., Silva R., Martinelli L., Nørgaard J.Q.H., Mendoza E., Simmonds D., Ohle N., Kappenberg J., Pan S., Nguyen D.K., Toorman E.A., Prinos P., Hoggart S., Chen Z., Piotrowska D., Pruszak Z., Schönhofer J., Skaja M., Szmytkiewicz P., Szmytkiewicz M., Leont'yev I., Angelelli E., Formentin S.M., Smaoui H., Bi Q., Sothmann J., Schuster D., Li M., Ge J., Lendzion J., Koftis T., Kuznetsov S., Puente A., Echavarri B., Medina R., Díaz-Simal P., Rodriguez I.L., Maza M., and Higuera P., 2015.** Chapter 3 - Innovative Engineering Solutions and Best Practices to Mitigate Coastal Risk, Coastal Risk Management in a Changing Climate, Butterworth-Heinemann.
- **Burke L, Bryant D, McManus J and Spalding M. 1998.** Reefs at risk: a map-based indicator of threats to the world's coral reefs. World Resources Institute. Washington, D.C. 56 p.
- **Burke L, Reytar K, Spalding M and Perry A. 2011.** Reefs at risk revisited. World Resources Institute. Washington, D.C. 115 p
- **Burkepile DE and Hay ME. 2008.** Herbivore species richness and feeding complementarity affect community structure and function on a coral reef. Proceedings of the National Academy of Sciences of the United States of America 105:16201-16206.
- **Bythell JC, Gladfelter EH and Bythell M. 1993.** Chronic and catastrophic natural mortality of three common Caribbean reef corals. Coral Reefs 12:143-152.
- **Bythell JC, Hillis-Starr ZM and Rogers CS. 2000.** Local variability but landscape stability in coral reef communities following repeated hurricane impacts. Marine Ecology Progress Series 204: 93-100.
- **Carilli JE, Norris RD, Black BA, Walsh SM and McField M. 2009.** Local stressors reduce coral resilience to bleaching. Plos one 4(7): e6324.
- **Carne L, Kaufman L and Scavo K. 2016.** Measuring success for Caribbean acroporid restoration: key results from ten years of work in southern Belize. ICRS Proceedings in review.
- **Carreiro-Silva, M and T.R. McClanahan. 2001.** Echinoid Bioerosion and Herbivory on Kenyan Coral Reef: the Role of Protection from Fishing. Journal of Experimental Marine Biology and Ecology. 262: 133-153.
- **CCRIF. 2010.** Enhancing the Climate Risk and Adaptation Fact Base for the Caribbean: Preliminary Results of the Economics of Climate Adaptation Study, Vol. 28 (Caribbean Catastrophic Risk Insurance Facility, 2010).
- **CENAPRED. 2006.** Características e impacto socioeconómico de los principales desastres ocurridos en la República Mexicana en el año 2005. Serie Impacto socioeconómico de los desastres en México: 491. http://www.proteccioncivil.gob.mx/work/models/ProteccionCivil/Resource/375/1/images/no_7.pdf
- **CENAPRED. 2015**. Impacto socioeconómico de los desastres en México durante 2015: Resumen ejecutivo: 17. http://www.cenapred.gob.mx/es/Publicaciones/archivos/340-NO.17-RESUMENEJECUTIVOIMPACTO2015.PDF
- **Chamberland VF, Vermeij MJA, Brittsan M, Carl M, Schick M, Snowden S, Schrier A and Petersen D. 2015.** Restoration of critically endangered elkhorn coral (*Acropora palmata*) populations using larvae reared from wild-caught gametes. Global Ecology Conservation 4: 526-537
- **Chavanich S, Gomez E, Chou L, Goh B, Tan LT, Tun K, Toh TC, Cabaitan P, Guest J, Ng CSL, Omori M, Thongtham N, Chankong A, Viyakarn V and Zhu W. 2014.** Coral Restoration Techniques in the Western Pacific Region. UNESCO-IOC/WESTPAC, Bangkok Office.
- **Chérubin LM, Kuchinke CP and Paris CB. 2008.** Ocean circulation and terrestrial runoff dynamics in the Mesoamerican region from spectral optimization of SeaWiFS data and a high resolution simulation. Coral Reefs 27(3): 503-519.
- Coastal Engineering Proceedings 47:211-235.
- **Connell JH. 1978.** Diversity in tropical rainforests and coral reefs. Science 199:1302-1309.
- **Coronado CJ, Candela R, Iglesias-Prieto J, Sheinbaum M, López**

and Ocampo-Torres FJ. 2007. On the circulation in the Puerto Morelos fringing reef lagoon. Coral Reefs 26,149–163.

- **Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S and Turner RK. 2014.** Changes in the global value of ecosystem services. Global Environmental Change 26: 152-158.
- **Day J, Dudley N, Hockings M, Holmes G, Laffoley D, Stolton S and Wells S. 2012.** Guidelines for applying the IUCN Protected area management categories to marine protected areas. Gland, Switzerland: IUCN.
- **De'ath G, Fabricius KE, Sweatman H and Puotinen M. 2012.** The 27–year decline of coral cover on the Great Barrier Reef and its causes. PNAS 109(44): 17995-17999.
- **Devlin-Durante MK, Miller MW, Caribbean Acropora Research Group (Carne L, Smith TB, Banaszak AT, Greer L, Irwin A, Fogarty ND, Williams DE), Precht WF and Baums IB. 2016.** How old are you? Genet age estimates in a clonal animal. Molecular Ecology 25(22): 5628-5646.
- **Dudley N, Stolton S, Belokurov A, Krueger L, Lopoukhine N, MacKinnon K, Sandwith T and Sekhran N. 2010.** Natural Solutions: Protected Areas Helping People Cope with Climate Change. IUCN WCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland, Washington DC and New York, USA.
- **Dudley N. 2008.** Guidelines for applying protected area management categories. Gland, Switzerland. IUCN: 86 p.
- **Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Álvarez-Filip L, Baca B, Bartels E, Bastidas C, Bouchon C, Brandt M, Bruckner AW, Bunkley-Williams L, Cameron A, Causey BD, Chiappone M, Christensen TRL, Crabbe MJC, Day O, de la Guardia E, Díaz-Pulido G, DiResta D, Gil-Agudelo DL, Gilligam DS, Ginsburg RN, Gore S, Guzmán HM, Hendee JC, Hernández-Delgado EA, Husain E, Jeffrey CFG, Jones RJ, Jordán-Dahlgreen E, Kaufman LS, Kline DI, Kramer PA, Lang JC, Lirman D, Mallela J, Manfrino C, Maréchal JP, Marks K, Mihaly J, Miller WJ, Mueller EM, Mueller EM, Orozco Toro CA, Oxenford HA, Ponce-Taylor D, Quinn N, Ritchie KB, Rodríguez S, Rodríguez Ramirez A, Romano S, Samhouri JF, Sánchez JA, Schmal GP, Shank BV, Skriving WJ, Steiner SCC, Villamizar E, Walsh SM, Walter C, Weil E, Williams EH, Roberson KW and Yusuf Y. 2010.** Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. PLoS ONE 5(11): e13969.
- Ecosystem Services, Elsevier, vol. 21(Part A): 72-80 p.
- **Edwards AJ and Gomez ED. 2007.** Reef Restoration Concepts and Guidelines: making sensible management choices in the face of uncertainty. Coral Reef Targeted Research and Capacity Building for Management Programme. St Lucia, Australia. 38 p.
- **Edwards AJ. 2010.** Reef rehabilitation manual. Coral Reef Targeted Research and Capacity Building for Management Program. St Lucia, Australia. 166 p.
- **Elliff CI and Silva IR. 2017.** Coral reefs as the first line of defense: shoreline protection in face of climate change. Marine Environmental Research 127 (2017): 148-154.
- **English S, Wilkinson C and Baker V (eds).1997.** Survey manual for tropical marine resources. Australian Institute of Marine Science: 390 p.
- **Environmental Protection Agency. 2012.** Evaluating the cost effectiveness of restoration. United States Environmental Protection Agency, Washington, D.C., USA.
- **Epstein N, Bak RPM and Rinkevich B. 2001.** Strategies for gardening denuded coral reef areas: the applicability of using different types of coral material for reef restoration. Restoration Ecology 9(4): 432-442.
- **Fabian R, Beck MW and Potts DC. 2013**. Reef restoration for coastal defense: A review. Internal report for The Nature Conservancy 58 p.
- **Fabricius KI. 2008.** Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. Limnology and Oceanography 53: 690-704.
- **Ferrario F, Beck MW, Storlazzi CD, Micheli F, Shepard CC and Airoldi L. 2014.** The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nature Communications. 1-9.
- **Field M, Ogston AS and Storlazzi CD. 2011.** Rising Sea Level May Cause Decline of Fringing Coral Reefs. Eos 92(33): 273-280.
- **Forsman ZH, Page CA, Toonen RJ and Vaughan D. 2015.** Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover. PeerJ 3: e1313.
- **Franklin GL, Mariño-Tapia I and Torres-Freyermuth A. 2013.** Effects of reef roughness on wave setup and surf zone currents. Journal of Coastal Research Special Issue 65: 2005-2010, ISSN 0749-0208.
- **Franklin GL, Torres-Freyermuth A, Medellin G, Allende-Arandia ME and Appendini CM. 2018.** The role of the reef–dune system in coastal protection in Puerto Morelos (Mexico). Natural Hazards Earth Systems Science 18:1247-1260.
- **Franklin GL. 2015.** Effects of roughness on wave-dominated coral reef environments. PhD Thesis CINVESTAV-Merida, Mexico.
- **Gallop SL, Young IR, Ranasinghe R, Durrant TH and Haigh ID. 2014.** The large-scale influence of the Great Barrier Reef matrix on wave attenuation. Coral Reefs 33(4): 1167-1178.
- **Gardner TA, Côté IM, Gill JA, Grant A and Watkinson AR. 2003.** Long-term region-wide declines in Caribbean corals. Science 301: 958-960.
- **Garrison VH and Ward G. 2012.** Transplantation of storm-generated coral fragments to enhance Caribbean coral reefs: a successful method but not a solution. Revista de Biología Tropical 60: 59-70.
- **Geister J. 1977.** The influence of wave exposure on the ecological zonation of Caribbean reefs. Proceedings of the Third International Coral Reef Symposium 1: 23-39.
- **Gourlay MR. 1994.** Wave transformation on a coral reef. Coastal engineering 23(1-2): 17-42.
- **Gourlay, MR. 1996a.** Wave set-up on coral reefs. 1. Set-up

and wave-generated flow on an idealised two-dimensional horizontal reef. Coastal Engineering 27(3-4): 161-193.

- **Gourlay, MR. 1996b.** Wave set-up on coral reefs. 2. Set-up on reefs with various profiles. Coastal Engineering 28(1-4): 17-55.
- **Graham NAJ, Jennings S, MacNeil MA, Mouillot D and Wilson SK. 2015.** Predicting climate-driven regime shifts versus rebound potential in coral reefs. Nature 518: 94-97.
- **Green AL, Chollett I, Suárez A, Dahlgren C, Cruz S, Zepeda C, Andino J, Robinson J, McField M, Fulton S, Giro A, Reyes H and Bezaury J. 2017.** Biophysical Principles for Designing a Network of Replenishment Zones for the Mesoamerican Reef System. Technical report produced by The Nature Conservancy, Comunidad y Biodiversidad, A.C., Smithsonian Institution, Perry Institute for Marine Science, Centro de Estudios Marinos, Healthy Reefs Initiative and Universidad Autónoma de Baja California Sur: 59 p.
- **Green AL, Fernandes L, Almany G, Abesamis R, McLeod E, Aliño P, White AT, Salm R, Tanzer J and Pressey RL. 2014.** Designing marine reserves for fisheries management, biodiversity conservation and climate change adaptation. Coastal Management 42: 143-159.
- Guest JR, Baria MV, Gomez ED, Heyward AJ and Edwards AJ. 2014. Closing the circle: is it feasible to rehabilitate reefs with sexually propagated corals? Coral Reefs 33(1): 45-55.
- **Guest JR, Baria MV, Gomez ED, Heyward AJ and Edwards AJ. 2014.** Closing the circle: is it feasible to rehabilitate reefs with sexually propagated corals? Coral Reefs 33(1): 45-55.
- **Guest JR, Heyward A, Omori M, Iwao K, Morse ANC and Boch C. 2010.** Rearing coral larvae for reef rehabilitation. In: Edwards A (ed) Reef rehabilitation manual. The Coral Reef Targeted Research & Capacity Building for Management Program, St. Lucia, Australia, ii + p166.
- **Guest JR, Heyward A, Omori M, Iwao K, Morse ANC and Boch C. 2010.** Rearing coral larvae for reef rehabilitation. In: Edwards A (ed) Reef rehabilitation manual. The Coral Reef Targeted Research & Capacity Building for Management Program, St. Lucia, Australia, ii + p166.
- **Hallegatte S, Green C, Nicholls RJ and Corfee-Morlot J. 2013.** Future flood losses in major coastal cities. Nature climate change 3(9):0 802-806.
- **Halpern BS, Selkoe KA, Micheli F and Kappel CV. 2007.** Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conservation Biology 21:1301-1315.
- **Hardy TA and Young IR. 1996.** Field study of wave attenuation on an offshore coral reef. Journal of Geophysical Research 101: 14311-14326.
- **Harmelin-Vivien M and Laboute P. 1986.** Catastrophic impact of hurricanes on atoll outer reef slopes in Tuamotu (French Polynesia). Coral Reefs 5: 55-62.
- **Harmelin-Vivien M. 1994.** The effects of storms and cyclones on coral reefs: a review. Journal of Coastal Research 12: 211-231.
- **Harris LE. 2009.** Artificial reefs for ecosystem restoration and coastal erosion protection with aquaculture and recreational amenities. Reef Journal 1(1): 235-246.
- **Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS and Samuel MD. 2002.** Ecology - Climate warming and disease risks for terrestrial and marine biota. Science 296: 2158-2162.
- **Hawkins SJ, Burcharth HF, Zanuttigh B and Lamberti E. 2010.** Environmental design guidelines for low crested coastal structures. Elsevier. 448 p.
- **Hernández-Terrones L, Rebolledo-Vieyra M, Merino-Ibarra M, Soto M, Le-Cossec A and Monroy-Rios E. 2011.** Groundwater pollution in a karstic region (NE Yucatan): Baseline nutrient content and flux to coastal ecosystems. Water Air Soil Pollution 218: 517-528.
- **Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A and Hatziolos ME. 2007.** Coral Reefs Under Rapid Climate Change and Ocean Acidification. Science 318: 1737.
- **Hoegh-Guldberg O. 1999.** Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research 50: 839-866.
- **Hoeke R, Storlazzi C and Ridd P. 2011.** Hydrodynamics of a bathymetrically complex fringing coral reef embayment: wave climate, in situ observations, and wave prediction. Journal of Geophysical Research 116: C04018.
- **Hopkinson CS, Lugo AE, Alber M, Covich AP and Van Bloem SJ. 2008.** Forecasting effects of sea-level rise and windstorms on coastal and inland ecosystems. Frontiers in Ecology and the Environment 6: 255-263.http://coral.org/wordpress/wp-content/uploads/2014/02/coastaldev.pdf
- **Hudson JH and Diaz R. 1988.** Damage survey and restoration of M/V Wellwood grounding site, Molasses Reef, Key Largo National Marine Sanctuary. Proceedings of the Sixth International Coral Reef Symposium., Australia. Vol 2: 231-236.
- **Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC, Eakin CM, Gilmour JP, Graham NAJ, Harrison H, Hobbs JPA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch M, Pandolfi JM, Pratchett M, Schoepf V, Torda G and Wilson SK. 2018.** Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359(6371): 80-83. ISSN 0036-8075
- **Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldeberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Paumbi SR, Pandolfi JM, Rosen B and Roughgarden J. 2003.** Climate change, human impacts, and the resilience of coral reefs. Science 301: 929-933.

- **Hughes TP, Baird AH, Dinsdale EA, Moltschaniwskyj NA, Pratchett MS, Tanner JE and Willis BL. 2012.** Assembly rules of reef corals are flexible along a steep climatic gradient. Current Biology 22(8), 736-741.
- **Hughes TP, Rodrigues MJ, Bellwood DR, Ceccarelli D, Hoegh-Guldberg O, McCook L, Moltschaniwskyj N, Pratchett MS, Steneck RS and Willis B. 2007.** Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current biology 17: 360-5.
- **Hunt J, Sharp W. 2014.** Developing a Comprehensive Strategy for Coral Restoration for Florida State Wildlife Grant Award T-32-R 1169 Final Report. Tallahassee Florida Fish and Wildlife Conservation Commission. https://www.st.nmfs.noaa.gov/coralrestoration/pdf/Hunt%20and%20Sharp%202014.pdf
- **IPCC. 2007.** See www.ipcc.ch/SPM6avr07.pdf.
- **IPCC. 2013.** Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30.
- **IPCC. 2014.** Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros VR, Field CB, Dokken DJ,Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 688 p.
- **Jaap WC. 2000.** Coral reef restoration. Ecological Engineering 15(3-4): 345-364.
- **Jackson JBC, Donovan MK, Cramer KL and Lam W, (editors). 2014.** Status and Trends of Caribbean Coral Reefs: 1970-2012. Global Coral Reef Monitoring Network, IUCN, org/downloads/caribbean_coral_reefs___status_report_1970_2012. pdf. 2014.
- **Jantzen C. 2016.** Coral reef restoration – limitations, challenges and opportunities. Secore. http://www.secore.org/site/newsroom/article/coral-reef-restoration-limitations-challenges-and-opportunities.149.html
- **Johnson ME, Lustic C, Bartels E, Baums IB, Gilliam DS, Larson L, Lirman D, Miller MW, Nedimyer K and Schopmeyer S. 2011.** Caribbean *Acropora* restoration guide: best practices for propagation and population enhancement. The Nature Conservancy, Arlington, VA. 64 p.
- **Kareiva P, Lalasz R and Marvier M. 2012.** Conservation in the Anthropocene: beyond solitude and fragility. http://thebreakthrough.org/index.php/journal/past-issues/ issue-2/conservation-in-the-anthropocene/
- **Kilfoyle AK. 2017.** Exploring the Potential for Artificial Reefs in Coral Reef Restoration: Responses and Interactions of Associated Biota to Varying Experimental Treatments in the Mexican Caribbean (Doctoral dissertation, Nova Southeastern University).
- **Kleypas JA and Yates KK. 2009.** Coral reefs and ocean acidification. Oceanography 22: 108-117.
- **Knight D, LeDrew E and Holden H. 1997.** Mapping submerged corals in Fiji from remote sensing and in situ measurements: applications for integrated coastal management. Ocean & Coastal Management 34(2): 153161-159170.
- **Koerner RM. 2016.** Geotextiles: from design to applications. Elsevier, The Netherlands. 617 p.
- **Kramer P, Mcfield M, Alvarez-Filip L, Drysdale I, Rueda M, Pott R and Giro A. 2015.** Reporte de la salud ecológica del Arrecife Mesoamericano 2015. Healthy Reefs Initiative: 29 p.
- **Kron W. 2013.** Coasts: the high-risk areas of the world. Natural hazards 66(3): 1363-1382.
- **Lirman D and Schopmeyer S. 2016.** Ecological solutions to reef degradation: optimizing coral reef restoration in the Caribbean and Western Atlantic. PeerJ 4: e2597.
- **Lowe RJ, Falter JL, Bandet MD, Pawlak G, Atkinson MJ, Monismith SG and Koseff JR. 2005.** Spectral wave dissipation over a barrier reef. Journal of Geophysical Research: Oceans 110: C04001.
- **Loya Y, Sakai K, Yamazato K, Nakano Y, Sambali H and van Woesik R. 2001.** Coral bleaching: the winners and the losers. Ecology letters 4(2): 122-131.
- **Lugo-Fernández A, Roberts HH and Suhayda JN. 1998.** Wave transformations across a Caribbean fringing-barrier coral reef. Continental Shelf Research 18(10): 1099-1124.
- **Maina J, De Moel H, Zinke J, Madin J, McClanahan T and Vermaat JE. 2013.** Human deforestation outweighs future climate change impacts of sedimentation on coral reefs. Nature communications 4: 1986.
- **Mallela J and Perry CT. 2007**. Calcium carbonate budgets for two coral reefs affected by different terrestrial runoff regimes, Rio Bueno, Jamaica. Coral reefs 26(1): 129-145.
- **Manu K and Rao S. 2013.** Performance of submerged reef of concrete cubes. International Journal of Chemical, Environmental & Biological Sciences 1(4): 643-636.
- **Maya PHM, Smit KP, Burt AJ and Frias-Torres S. 2016.** Large-scale coral reef restoration could assist natural recovery in Seychelles, Indian Ocean. Nature Conservation 16: 1.
- **McClanahan TR, Marnane MJ, Cinner JE and Kiene WE. 2006.** A comparison of marine protected areas and alternative approaches to coral-reef management. Current Biology. 16(14):1408–1413.
- **Mellin C, MacNeil A, Cheal AJ, Emslie MJ and Julian Caley M. 2016.** Marine protected areas increase resilience among coral reef communities. Ecology letters 19(6): 629-637.
- **Mendoza E, Rios A, Mariño-Tapia I and Silva R. 2018.** Energy

flux damping due to coral reefs using modular organic-shaped 3D printed elements. 36th International Conference on Coastal Engineering Abstracts 1438.

- **Metcalfe CD, Beddows PA, Bouchot GG, Metcalfe TL, Li H and Van Lavieren H. 2011.** Contaminants in the coastal karst aquifer system along the Caribbean coast of the Yucatan Peninsula, Mexico. Environmental pollution 159(4): 991-997.
- **Micheli F, Mumby PJ, Brumbaugh DR, Broad K, Dahlgren CP, Harborne AR, Holmes KE, Kappel CV, Litvin SY and Sanchirico JN. 2014.** High vulnerability of ecosystem function and services to diversity loss in Caribbean coral reefs. Biological Conservation 171:186-194.
- **Miller SL, McFall GB, and Hulbert AW. 1993.** Guidelines and Recommendations for Coral Reef Restoration in the Florida Keys National Marine Sanctuary. National Undersea Research Center, University of North Carolina at Wilmington, Wilmington.
- **Milliman JD. 1993.** Production and accumulation of calcium carbonate in the ocean: budget of a nonsteady state. Global Biogeochemical Cycles 7(4): 927-957.
- **Moberg F and Folke C. 1999.** Ecological goods and services of coral reef ecosystems. Ecological Economics 29: 215-233.
- **Mora C, Andrefouet S, Costello M, Kranenburg S, Rollo A, Veron J, Gaston KJ and Myers RA. 2006.** Coral reefs and the global network of marine protected areas. Science 312: 1750-1751.
- **Mora C. 2008.** A clear human footprint in the coral reefs of the Caribbean. Proceedings of the Royal Society 275: 767-773.
- **Moran DK, Salles P, Sanchez JC and Espinal JC. 2007.** Beach nourishment evolution in the Cancun beach, Quintana Roo, Mexico. Sixth international symposium on coastal engineering and science of coastal sediment process, New Orleans, Louisiana, United States.Am. Soc. Civil Eng. 2279–2291.
- **Mumby PJ, and Harborne AR. 2010.** Marine Reserves Enhance the Recovery of Corals on Caribbean Reefs. PLoS ONE 5(1): e8657.
- **Mumby PJ, Hastings A and Edwards HJ. 2007.** Thresholds and the resilience of Caribbean coral reefs. Nature 450(7166): 98-101.
- **Muttray M and Reedijk J. 2008.** Design of concrete armour layers. Hansa. International Maritime Journal 146(6): 111–118.
- **Nakamura R, Ando W, Yamamoto H, Kitano M, Sato A, Nakamura M, Kayanne H and Omori M. 2011.** Corals mass-cultured from eggs and transplanted as juveniles to their native, remote coral reef. Marine Ecology Progress Series 436:161–168.
- **Neumann B, Vafeidis AT, Zimmermann J and Nicholls RJ. 2015.** Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. PloS one 10(3): e0118571.
- **NMFS. 2016.** Management Plan for Caribbean *Acropora* Population Enhancement. NOAA, National Marine Fisheries Service, Southeast Regional Office, Protected Resources Division.
- Okamoto M, Nojima S, Fujiwara S and Furushima Y. 2008. Development of ceramic settlement devices for coral reef restoration using in situ sexual reproduction of corals. Fisheries Science 74: 1245-1253
- **Omori M. 2011.** Degradation and restoration of coral reefs: experience in Okinawa, Japan. Marine Biology Research 7(1): 3-12.
- **Pascal N, Allenbach M, Brathwaite A, Burke L, Le Port G and Clua E. 2016.** Economic valuation of coral reef ecosystem service of coastal protection: a pragmatic approach.
- **Perry CT, Alvarez-Filip L, Graham NA, Mumby PJ, Wilson SK, Kench PS, Manzello DP, Morgan KM, Slangen AB, Thomson DP, Januchowski-Hartley F. 2018.** Loss of coral reef growth capacity to track future increases in sea-level. Nature 588, 396–400 p.
- **Perry CT, Edinger EN, Kench PS, Murphy GN, Smithers SG, Steneck RS and Mumby PJ. 2012.** Estimating rates of biologically driven coral reef framework production and erosion: A new census-based carbonate budget methodology and applications to the reefs of Bonaire. Coral Reefs 31(3): 853-868.
- **Perry CT, Murphy GN, Kench PS, Edinger EN, Smithers SG, Steneck RS and Mumby P J. 2014.** Changing dynamics of Caribbean reef carbonate budgets: emergence of reef bioeroders as critical controls on present and future reef growth potential. Proceeding of the Royal Society B 281(1796): 2014-2018.
- **Perry CT, Murphy GN, Kench PS, Smitters SG, Edinger EN, Steneck RS and Mumby PJ. 2013.** Caribbean-wide decline in carbonate production threatens coral reef growth. Nature communications 4: 1402.
- **Precht WF, Gintert BE, Robbart ML, Fura R, Van Woesik R. 2016.** Unprecedented disease-related coral mortality in Southeastern Florida. Scientific Reports 6: 31374.
- **Precht WF. 2006.** Coral reef restoration handbook. Boca Raton, Florida: CRC Press Taylor & Francis Group, LLC.
- **Quinn NJ and Kojis BL. 2006.** Evaluating the potential of natural reproduction and artificial techniques to increase *Acropora cervicornis* populations at Discovery Bay, Jamaica. Revista de Biología Tropical 54:105-116.
- **Quinn NJ, Kojis BL and Bowden-Kerby A. 2005.** Assessing the potential for natural recovery and coral restoration techniques for enhancing coral habitat in Jamaica. Oceans 3: 2752–2759.
- **Reeve D, Chadwick A and Fleming C. 2004.** Coastal engineering: processes, theory and design practice. CRC Press. 416 p.
- **Reguero BG, Beck MW, Agostini VN, Kramer P, and Hancock B. 2018.** Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada. Journal of Environment Management 210:146-161.
- **Renaud FG, Sudmeier-Rieux K and Estrella M, eds. 2013.** The role of ecosystems in disaster risk reduction. United Nations University Press. 486 p.
- **Resio DT and Westerink JJ. 2008.** Modelling the physics of storm surges. Physics Today 61: 33-38.

- **Reyes-Bonilla E, Cupul-Magaña AL and Vázquez-Vera WL. 2009.** Estudio para establecer la capacidad de carga turística y límites de cambio aceptable para las actividades recreativas del Parque Nacional Arrecife de Puerto Morelos. Informe Final. Universidad Autónoma de Baja California Sur: 107.
- **Roberts HH. 1980.** Physical processes and sediment flux through reef-lagoon systems. Coastal Engineering n.17: 946-962.
- **Rodríguez-Martínez RE, Banaszak AT, Mcfield MD, Beltran-Torres AU and Alvarez-Filip L. 2014.** Assessment of *Acropora palmata* in the Mesoamerican Reef System. PLoS ONE 9: e96140.
- **Roeber V and Bricker JD. 2015.** Destructive Tsunami-like Wave Generated by Surf Beat over a Coral Reef during Typhoon Haiyan. Nature Communications. Nature Publishing Group: 7854. doi:10.1038/ncomms8854.
- **Rogers CS. 1992.** A matter of scale: damage from Hurricane Hugo (1989) to U.S. Virgin Islands reefs at the colony, community, and whole reef level. Proceedings of the Seventh International Coral Reef Symposium 1:127–133.
- **Rogers CS. 1993.** Hurricanes and coral-reefs: the intermediate disturbance hypothesis revisited. Coral Reefs 12: 127–137.
- **Rogers JS, Monismith SG, Dunbar BD and Koweek R. 2016.** Wave dynamics of a Pacific atoll with high frictional effects. Journal of Geophysical Research – Oceans 121: 350-367.
- **Ruiz de Alegría-Arzaburu A, Mariño-Tapia I, Enríquez C, Silva R and González-Leija M. 2013.** The role of fringing coral reefs on beach morphodynamics. Geomorphology 198: 69-83.
- **Schopmeyer S, Lirman D, Bartels E, Byrne J, Gilliam D, Hunt J, Johnson M, Larson E, Maxwell, K, Nedimyer K and Walter C. 2011.** In-situ coral nurseries serve as vital repository for genetic material: implications for coral reef restoration after an extreme cold-water event in the Florida Reef Tract. Restoration Ecology, 20: 696-703.
- **Selig ER and Bruno JF. 2010.** A global analysis of the effectiveness of marine protected areas in preventing coral loss. PLoS ONE 5: e9278.
- **Shafir S, Van Rijn J and Rinkevich B. 2006.** Steps in the construction of underwater coral nursery, an essential component in reef restoration activities. Marine Biology 149: 679-687
- **Sheppard C, Dixon DJ, Gourlay M, Sheppard A and Payet R. 2005.** Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. Estuarine Coastal and Shelf Science 64: 223-234.
- **Sheremet A, Kaihatu JM, Su SF, Smith ER and Smith JM. 2011.** Modeling of nonlinear wave propagation over fringing reefs. Coastal Engineering 58: 1125-1137.
- **Shinn EA. 1976.** Coral reef recovery in Florida and the Persian Gulf. Environmental Geology 1: 241-254.
- **Silva R, Mendoza E, Mariño-Tapia I, Martínez ML and Escalante E. 2016.** An artificial reef improves coastal protection and provides a base for coral recovery. Journal of Coastal Research 75(sp1): 467-471.
- **Silva-Casarin R, Mendoza-Baldwin E, Escalante-Mancera E, Marino-Tapia I and Ruiz-Renteria F. 2009.** Wind waves induced by hurricane Wilma in Puerto Morelos, Quintana Roo, Mexico. Ingeniería hidráulica en México, 24(2): 93-109.
- **Simard F, Laffoley D and Baxter JM (eds.).** 2016. Marine Protected Areas and Climate Change: Adaptation and Mitigation Synergies, Opportunities and Challenges. Gland, Switzerland: IUCN: 52.
- **Souter DN and Wilkinson CR (eds.). 2008.** Status of Caribbean coral reefs after bleaching and hurricanes in 2005 (vol. 148). Global Coral Reef Monitoring Network.
- **Spalding M, Burke L, Wood SA, Ashpole J, Hutchison J and Ermgassen P. 2017.** Mapping the global value and distribution of coral reef tourism. Marine Policy 82:104-113.
- **Spalding M, Ravilious C and Green EP. 2001.** World Atlas of Coral Reefs. University of California Press, Berkeley 424 p.
- **Spalding MD, McIvor AL, Beck MW, Koch EW, Möller I, Reed DJ, Rubinoff P, Spencer T, Tolhurst TJ, Wamsley TV and Wesenbeeck BK. 2014b.** Coastal ecosystems: a critical element of risk reduction. Conservation Letters 1;7(3): 293-301.
- **Spalding MD, Ruffo S, Lacambra C, Meliane I, Hale LZ, Shepard C and Beck M. 2014a.** The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean & Coastal Management 90: 50e57.
- **Steneck RS, Arnold SN and Mumby PJ. 2014.** Experiment mimics fishing on parrotfish: insights on coral reef recovery and alternative attractors. Marine Ecology Progress Series 506:115-127.
- **Stive MJF, Aarninkhof SGJ, Hamm L, Hanson H, Larson M, Wijnberg KM, Nicholls RJ and Capobianco M. 2002.** Variability of shore and shoreline evolution.
- **Storlazzi C, Elias E, Field M and Presto M. 2011.** Numerical modeling of the impact of sea-level rise on fringing coral reef hydrodynamics and sediment transport. Coral Reefs 30: 83-96.
- **Suchley A, McField MD, and Alvarez-Filip L. 2016.** Rapidly increasing macroalgal cover not related to herbivorous fishes on Mesoamerican reefs. PeerJ 4, e2084.
- **Suchley, A., Alvarez-Filip, L., 2018.** Local human activities limit marine protection efficacy on Caribbean coral reefs. Conservation Letters. e12571.
- **The Coral Reef Alliance. 2005.** Coral reefs and sustainable coastal development.
- **Toropova C, Meliane I, Laffoley D, Matthews E and Spalding M. 2010.** Global Ocean Protection: Present Status and Future Possibilities. IUCN, The Nature Conservancy, UNEP-WCMC, UNEP, UNU-IAS, Agence des aires marines protégées, France, Gland, Switzerland, Arlington, USA, Cambridge, UK, Nairobi, Kenya, Tokyo, Japan, and Brest, France: 96 p.

- **Van Tussenbroek BI, Hernández AHA, Rodríguez-Martínez RE, Espinoza-Avalos J, Canizales-Flores HM, González-Godoy CE, Barba-Santos MG, Vega-Zepeda A and Collado-Vides L. 2017.** Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. Marine Pollution Bulletin 122: 272-281.
- **Van Woesik R, Golbuu Y and Roff G. 2015.** Keep up or drown: adjustment of western Pacific coral reefs to sea-level rise in the 21st century. Royal Society Open Science 2: 150181.
- **Veron JEN, Hoegh-Guldberg O, Lenton TM, Lough JM, Obura DO, Pearce-Kelly P, Sheppard CRC, Spalding M, Stafford-Smith MG and Rogers AD. 2009.** The coral reef crisis: The critical importance of < 350 ppm CO2. Marine Pollution Bulletin 58:1428-1436.
- **Veron JEN. 2008.** Mass extinctions and ocean acidification: biological constraints on geological dilemmas. Coral Reefs 27: 459-472.
- **Waterman RE. 2008.** Integrated coastal policy via building with nature. The Hague: Opmeer Drukkerij. 449 p.
- **Wear SL. 2016.** Missing the boat: Critical threats to coral reefs are neglected at global scale. Marine Policy 74: 153-157.
- **Whittingham E, Campbell J and Townsley P. 2003.** Poverty and Reefs, DFID–IMM–IOC/UNESCO: 260 p.
- **Wilkinson CR. 2008.** Status of Coral Reefs of the World: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia. 296 p.
- **Williams DE and Miller MW. 2010.** Stabilization of fragments to enhance asexual recruitment in *Acropora palmata*, a threatened Caribbean coral. Restoration Ecology 18(S2): 446-451.
- **Williams SM, Chollett I, Roff G, Cortés J, Dryden CS and Mumby PJ. 2015.** Hierarchical spatial patterns in Caribbean reef benthic assemblages. Journal of Biogeography 42(7): 1327-1335.
- **Wolanski E. 1994.** Physical oceanographic processes of the Great Barrier Reef. CRC Press. London, UK
- **Wong PP, Losada IJ, Gattuso JP, Hinkel J, Khattabi A, McInnes KL, Saito Y and Sallenger A. 2014.** Coastal systems and low-lying areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: 361-409.
- **Woodley JD, Chornesky EA, Clifford PA, Jackson JBC, Kaufman LS, Knowlton N, Lang JC, Pearson MP, Porter JW, Rooney MC and Rylaarsdam KW. 1981.** Hurricane Allen's impact on Jamaican coral reefs. Science 214(4522): 749-755.
- **Woodroffe CD. 1992.** Mangrove sediments and geomorphology. Tropical mangrove ecosystems: 7-41.
- **Woodroffe CD. 2008.** Reef-island topography and the vulnerability of atolls to sea level rise. Global and Planetary Change 62(1-2): 77-96.
- **Wooldridge SA. 2009.** Water quality and coral bleaching thresholds: Formalizing the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin 58(5): 745-751.
- **World Bank. 2016.** Managing coasts with natural solutions: Guidelines for measuring and valuing the coastal protection services of mangroves and coral reefs. M. W. Beck and G-M. Lange, editors. Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank, Washington, DC.
- **Young CN, Schopmeyer SA and Lirman D. 2012.** Review of reef restoration and coral propagation using the threatened genus *Acropora* in the Caribbean and Western Atlantic. Bulletin of Marine Science 88(4): 1075-1098.
- **Young IR and Hardy TA. 1993.** Measurement and modelling of tropical cyclone waves in the Great Barrier Reef. Coral Reefs 12(2): 85-95.
- **Young IR. 1989.** Wave transformation over coral reefs. Journal of Geophysical Research 94: 9779-9789.

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